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Water and Wastewater Technologies in Ancient Civilizations: Prolegomena

The rapid technological progress in the twentieth century created a delusion of almightiness and a disdain for the past. Past technologies and management practices were regarded to be far behind the modern ones. In water resources science, technology and management, the twentieth century signified major advances. At the same time, it gathered a great deal of unresolved problems, related to the adequacy of water supply and irrigation water and the protection from floods and droughts. In some areas, owing to the explosive population growth, such problems were intensified in an unprecedented degree. Moreover, new problems have arisen such as the contamination of surface and ground water. Naturally, intensification of unresolved problems led societies to revisit the past and to investigate well-tried and successful past solutions. To their surprise, those who attempted this retrospect, based on archaeological and historical evidence, were impressed by two things: the similarity of problems with modern ones and the advanced level of solutions, technological and management.

Thus, it is now well documented that most of the technological solutions related to water are not achievements of present day engineers but date back to two to four thousand years ago. These achievements include massive hydraulic constructions (dams, polders and levees), and urban systems for water conveyance (aqueducts) and removal (sewer and drainage systems). These hydraulic works reflect also advanced scientific knowledge, which for instance allowed the construction of tunnels from two openings (geometry, geodesy) and the transportation of water both by open channels and closed conduits under pressure (hydraulics). Related to this is the departing from the mythological and hyperphysical views of the world and the development of scientific theories and ideas, for instance for the hydrological cycle; this occurred for first time in history in ancient Greece by Ionian philosophers. Certainly, technological developments were driven by the necessities to make efficient use of natural resources, to make civilizations more resistant to destructive natural elements, and to improve the standards of life, both at the private and public level. With respect to the latter, certain civilizations developed an advanced, comfortable and hygienic lifestyle, as manifested from public and private bathrooms and flushing toilets, that can only be compared to the modern one, re-established in Europe and North America a century and a half ago. Technological developments were combined to advanced management practices that included water legislation and institutions both for the operation and maintenance of existing systems as well as for the construction of new works.

Apparent characteristics of technologies and management practices in many ancient civilizations are the durability and sustainability. For instance, there exist several ancient hydraulic works that have been operated for millennia, or are still in operation up to now. Also, there have been integrated management practices, combining both large scale and small scale constructions and measures that have allowed cities to sustain for millennia. The notion of long-term durability is missed in present day engineering designs and constructions, whereas the notion of sustainability was re-considered only in the last couple of decades, yet its meaning being unclear and further explored to date.

With the increasing worldwide awareness of the importance of water resources management in the ancient civilizations, the responsibility for organizing a Specialist Group on Water and Wastewater in Ancient Civilizations was undertaken by the International Water

Association (IWA) Head Quarters a few years ago. The provisional objectives of the Group are:

(a) To study water and wastewater technologies from ancient civilizations with a potential to be adapted and utilized for countries under stress;
(b) To reveal the cultural heritage in several regions of the world to make visible ancient technologies which have contributed to the development of the water sciences; and
(c) To identify research needs for the future improvement and water and wastewater practices, which in a long term may contribute, to the development of integrated methodologies.

In parallel, three years ago, the 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Civilizations, was announced. The Symposium was organized by IWA, in collaboration with the National Agricultural Research Foundation, the Hellenic Municipalities Association, the Prefecture of Iraklio, the Hellenic Union of Municipal Enterprises for Water Supply and Sewerage, and other national and international agencies, in Iraklio, Greece, from 28 to 31 October 2006. The aims of the Symposium are:

(a) To reveal the cultural heritage in several regions of the world and to make visible the archaeological remnants of technologies which have contributed to the development of the existing technologies in water and wastewater management.
(b) To describe and evaluate the old technologies, which on a long term may contribute to water and wastewater management systems and to the development of integrated methodologies.
(c) To develop small systems based on old technologies using new equipment, which may be of great significance for water, wastewater and environmental management in the future, particularly in developing countries.

The main themes of the Symposium are:

(a) Methods and techniques of water management
(b) Farmers and citizens: the socio-economic role of water
(c) Water use
(d) Wastewater and stormwater technologies
(e) Historical development of water technologies
(g) Ideology and the Power of Image: water as symbol

The Symposium aimed to bring together a wide body of knowledge from the newly emerged and expanding field of water and wastewater management technologies in ancient civilizations. Over 100 papers were submitted, out of which 93 (84 full and 9 short papers) were selected and are included in this volume. The papers have a wide geographical coverage: Asia (Japan, China, India, Sri Lanka, Iran, and Near East), America, Africa and Mediterranean, with the prominence of the Ancient Greek and Roman worlds. The time frame of the themes presented in the papers extends from prehistorical to medieval and contemporary times; a few papers examine modern themes trying to trace old influences. Some papers have more philosophical and scientific, rather than technological, content, examining the birth and historical evolution of water sciences.

We are impressed by the information gathered and processed by all authors of the papers. Some of the papers are of very of high quality – but not all of them. Despite the efforts of reviewers and the members of the Organizing and the Programme Committees, it was very difficult to bring all papers into a high level, particularly in terms of language. We hope that the readers of this volume will tolerate an occasionally lower level of processing and presentation of the information given. We did the same deliberately, for two main reasons. First, we found it very useful to collect as many information bits as possible with the widest coverage. With think that in this initial, exploration phase of research, this is more important than the language and the quality of presentation. Second, we are aware that most of the contributions do not originate from formal and funded research projects. Many authors were motivated by personal interest or even by hobby and made their contributions in parallel to their many duties and under the stress of their heavy workload.

We would like to thank all authors and the Organizing and the Programme Committees for their devoted contributions. Special thanks are due to Dr. Iosif E. Kapellakis for his excellent editorial assistance. Also, we are grateful to the AKTOR S.A. for its financial support.

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Introductory Themes

Selected Topics of Water Technology in Ancient Greece

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Abstract: Hydraulic Technology in Ancient Greece is briefly described. Selected examples are presented from three periods of the Greek History. From the Mycenaean period, large scale flood-control projects are described, including the drainage of Copaïs lake. Subsequently, water supply facilities of greek cities are presented, starting with subterranean source-houses and going up to the Hellenistic period sophisticated aqueducts, including the most daresome inverted siphon of Pergamos. Finally, the consecutive steps of mechanization of water lifting devices in Greece are presented.

Keywords Ancient Greek Technology; land-reclamation; pumps;water supply.

Introduction

Impressed by the genius of the greek hydraulic works…

H. Fahfbusch (von Zabern, 1991: 162)

As opposed to Mesopotamian and Egyptian civilizations, which flourished in abundance of cultivable lands and wealthy rivers, the regions occupied by the Greek tribes, since the 2nd millennium B.C., were mountainous, with few (semiarid and occasionally flooded) cultivable lands. Consequently, in the respective Cultures, one should expect differences reflecting somehow these different natural environments. In the specific subject of this Congress, we may reasonably expect that the Greeks had given the emphasis to land reclamation, mechanisation of water-lifting devices, and sophisticated water-supply of Cities. These are the topics I wish to elaborate upon in this lecture. I purposely left out the theme of urban drainage and wastewaters for one additional reason: it was successfully covered by Angelakis *et al.* (2005).

Flood Control and Land-Reclamation Works

Mycenaean period

The advanced hydraulic technology developed by the Mycenaeans since the middle of the 2nd millennium B.C., is very impressive by its rationality, the large scale of its applications, as well as by its efficiency. Based on the examples of such flood-control works executed in Pheneos, Tiryns, Thisbē and Kopais (Knauss, 2003) one may describe their basic characteristics as follows.

First solution. The waters of the flooding torrent are contained in an artificial lake produced by means of an earth dam, covered by a protective layer of masonry. During summertime, these waters are used for irrigation through a system of small channels; this was the case e.g.

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of the arcadian Orchomenos (Pausanias 8.23.2), as well as lateron of Mantineia (Thukydidēs, 5.65). The pertinent dams (containing a clay core) had a height of 3 m and they were some hundred or occasionally some thousand m long.

Second solution. When such an artificial lake was not sufficient (or perhaps was not feasible at all), another solution was followed. First, the torrent is deviated outside the cultivated lands by means of an appropriate large channel. Secondly, this channel is extended towards the perimeter of the valley, close to the surrounding hills, so that the outflow of water be facilitated through existing cesspits in the karstic limestones of these hills. The internal high fill shaping this channel (to the side of the valley) has a width of 20 to 30 m and is covered by an appropriate masonry, protecting the fill against erosion. In this category of solutions belong the marvelous works of the second drainage system of Kopais, during the 14th and the 13th century B.C.

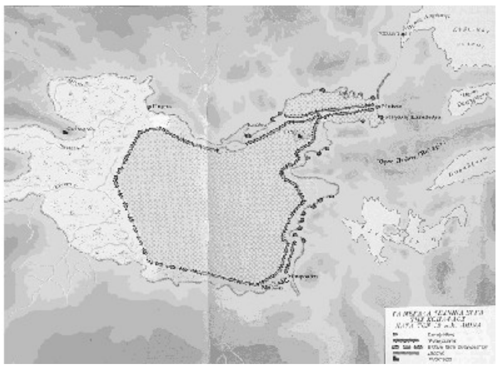


Figure 1 The giant project of land reclamation of the Kopais lake (14th century B.C.) (Iakovidis, 1970).

This giant technical achievement merits a more detailed description:

(a) By means of a 1 km long dam, north to (Boeotian) Orchomenos, the waters of Melas river are collected in an artificial lake (12 km²).

(b) 2 km northeast of Orchomenos, the waters of the Boeotian Kēphissos are deviated by means of an impressive channel, 25 km long, which conveys these waters along the north bank of the valley – in direct contact with the karstic limestone of the mountain, up to the east end of the valley. This channel has a width of 40 m and a depth of 2.5 m; it was navigable and served efficiently the transportations between the capital city of Orchomenos and the very fertile agricultural areas of Glas (Iakovidis, 1970).

(c) Geomorphology of the northeast end of the valley of Kopaïs allows for an area of 20 km² to be drained by means of 3 km long dam and a 5 km long ditch, heading north and meeting the large channel. In the middle of this reclaimed land is located the hill "Glas", headquarters of the management of this local rich agricultural enterprise.

(d) Subsequently, our large channel ends up in a large water-containment area characterised by a local system of cesspits.

(e) Yet, it seems that occasionally these cesspits were not sufficient to drain these waters to the sea. Thus, a tunnel was driven (of a cross section roughly equal to 1.45 m x 1.75 m and a 10% longitudinal slope), conveying these waters to the bay of Larymna in the gulf of Euboea. However, it should be noted that this tunnel has not been completely investigated up to now. Incidentally, Kakavoyannis (2000: 121) has maintained that the people of Temmikes, specialists miners form Lavrion having immigrated (*ca.* 1600 B.C.) to Boeotia, were employed by the Mycenaeans to maintain cesspits or to drive land-reclamation galleries.

Figure 2 The remnants of the lateral hill, shaping one side of the channel collecting river waters.

Figure 3 Masonry cover of the fill.

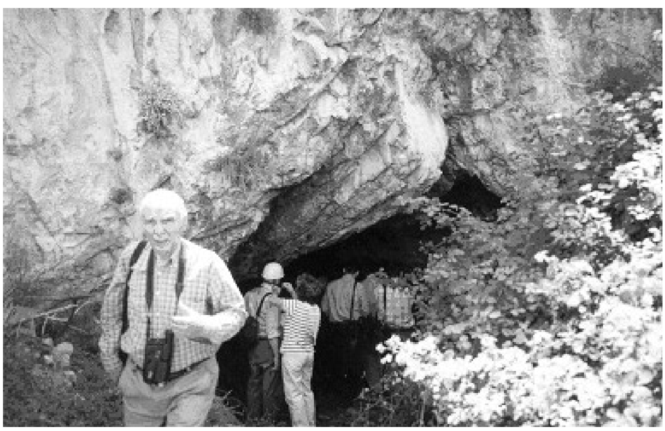


Figure 4 The largest cesspit receiving flood waters.

(f) Thus, assisted by several other peripheral fills, the reclaimed cultivated land is considerably increased. Its central area (140 km²) is rather dry during summertime, serving only as grazing ground. This giant-scale land-reclamation system explains the wealth of the "twelve cities of Kopaïs" mentioned by Homer, and it is another proof of the fundamental technophilia of the Achaeans. In the same context, it is worth noting another category of flood-control mycenaean works to protect the ground of Olympia, where the hippic Games used to take place. That piece of land was eroded both by the river Alpheios and its tributary Kladeos, near the area of their intersection. The works consisted of two major components: (a) a 500 m long regulatory wall along the east river-bank of Kladeos; the wall containing a core (made of clay and small stones) and masonry covered sides (made of 0.70 m large stones), had a cross-section of 3 x 3 m² and (b) A large fill along the north river-bank of Alpheios (see also Pausanias, *Ηλιακά*, 20/15). The area included in the corner of these two protective works, was subsequently infilled, and is still kept intact up to our days.

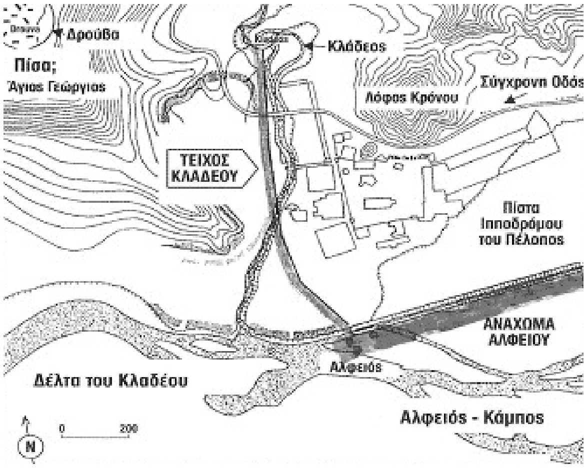


Figure 5 Flood protection in Olympia (Mycenean times) (Knauss, 2006).

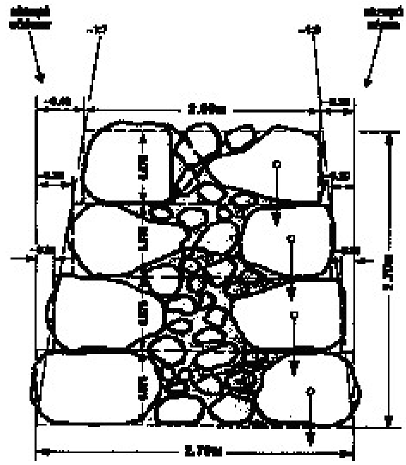


Figure 6 Cross-section of the wall deviating the Kladeos torrent (Knauss, 2003).

Classical and Hellenistic period

I will deal only with a better documented BOT project of the greek antiquity, i.e. the drainage of the lake Ptekhae, belonging to the city of Eretria, in the peninsula of Euboea, during the 4^{th} century B.C. The advantages of such a scheme are well known in our days: The Owner does not pay anything in cash. The Contractor is self-financing the execution of the works; he also offers his know-how to construct a technically perfect facility, and to operate it for an agreed period of time. All revenues are received by the Contractor to cover his initial capital and his profit. Subsequently, the facility is transferred to the Owner, in fully operational condition.

The first full contract of such a "capitalistic" construction - scheme in history, seems to be the text written on the stele EM11553, Museum of Inscriptions, Athens, Greece.

(a) Where, when and who

- (i) The name of the lake ("Ptekhae") is not used in Eretria region today. Thus, the precise location of the land reclamation is not known. However, the two candidate locations are at about 6 to 8 km distance, east/south-east of the historic town of Eretria. Both are valleys at 100 m a.s.l., covered by clay formations with underlying inclined alternated layers of marbles and schists. The second candidate location coincides with the actual marshy area of Dystos, periodically flood, even in our days (another argument in favour of Dystos is its large dimensions: The conditions of the Ptekhae - contract insinuate a remarkably large and fertile area, matching the large costs and long schedules provided in the contract).
- (ii) The Contractor of this remarkable public work is Hairephanēs (probably originated from Megara, a city famous for its great Engineers). But he is not acting alone in the present case: The financial and technical importance of this facility necessitated a larger joint-venture. Thus, Hairephanēs acts as a representative of several partners (line 31 of the contract) or collaborators (line 39); this is another remarkable innovation in civil engineering businesses in ancient Greece. On the other hand, the other Covenanter is the city-state of Eretria (as a matter of fact, a larger area

including around 50 villages).

Figure 7 Geological map of the area of the city of Eretreia, Euboia, Greece.

(iii) The contract was initially dated around the year 500B.C. (when the Athenians liberated Eretria from the regime of tyranny) ; however, actual views refer the event to the middle of the 4th century B.C., just after a similar intervention in the lake of Kopaïs (Strabo, IX, 2,18).

(b)The general conditions (Tassios, 1997)

The contract contains rather detailed financial, taxation and legal provisions, as follows:

(i) All expenses are paid by the contractor (lines 2, 20).

(ii) Time schedule: 4 years (lines 6-9), extended in case of war (lines 13-15).

(iii) Exemption of taxes is granded regarding imported materials (lines 3, 4).

(iv) Expropriations were allowed, but as distantly as possible from cultivated fields.

(v) Hairephanēs and his staff were granted immunity from the local law.

(vi) Remuneration in kind was provided; the contractor was granted the exclusive right to cultivate and retain the products of the reclaimed land for 10 years; an extension period was also provided in the event of war (line 17). Nevertheless, a lamp sum of 30 talents was agreed to be paid to the city.

(vii) In case of death of Hairephanēs, his collaborators and heirs were obligated to continue the works (line 28).

(viii) The contractor was obliged to appoint six Eretria-citizens as guarantors; their names appear at the addendum of the contract (line 40), containing the final enactment voted by the eretrian Parliament and the Assembly.

(ix) In compensation, extreme sanctions were voted by the Eretrians to be applied against anyone attempting to cancel the execution of the contract (line 30).

(x) Moreover, the contract was "signed" by as many as 230 citizens of Eretria; all of them (their names appear on the back side of the stele) had taken oath to respect the agreement.

(c) The technical provisions

Unfortunately, half of the contract is lost. However, an overview of the several clauses of the preserved text allow for the following technical description of the works (Karapa, 2002):

(i) Drainage ditches and irrigation channels (ποταμοί) were described (line 22).

(ii) Underground drains (φρεατίαι) were also mentioned (line 18).

(iii) All drains were leading to a central drainage tunnel (υπόνομος), (lines 18, 23, 25, 27).

(iv) For irrigation purposes, a reservoir (δεξαμενή) was provided – not larger than four hundred m (lines 22 to 27).

(v) Appropriate sluices (δρύφακτοι) were provided (line 24) for the water distribution, to and from the reservoir.

(vi) The maintenance (επισκευή) of all parts of the facility was clearly imposed (line 23) to the contractor, for 10 years.

(vii) Environmental provision: Trenches and channels should be located outside cultivated lands (lines 20, 21).

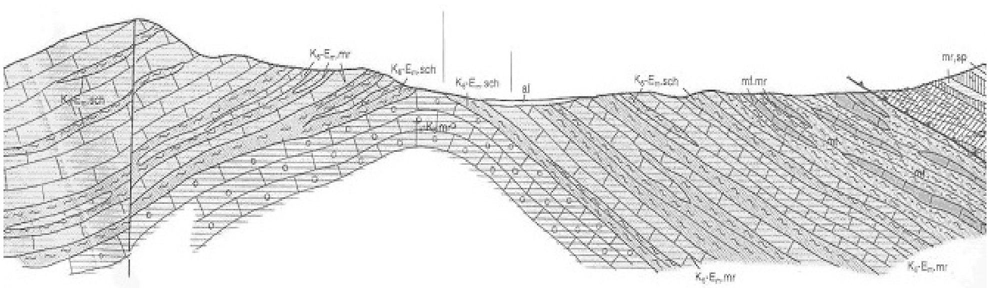


Figure 8 Geological section through the lake of Dystos

(d) Discussion

(i) For the most probable location of Ptekhae (the actual marsh of Dystos), there would be a technical possibility to effectuate a drainage to the sea, following the actual torrent "Megalo Rema" ; however, this would necessitate deep ditches, 5 km long through hard and extremely variable rock formations. Along half of this length, surface marble and cipolin formations encountered would possibly contain large carsts, able to receive large water discharges. In any event, these technical uncertainties should have rather discouraged Hairephanēs to undertake the enormous economic risk of such a huge contract, especially since he was also obliged to pay a lampsum, independently of the results. That is why another hypothesis may be formulated: It cannot be excluded that our Engineer had a better knowledge of the location and the importance of local cesspools, which periodically allowed for a quasi-spontaneous drainage: Cleaning the accumulated clay layers around those areas, and enlarging and protecting the mouths of these cesspools, might had assured permanent draining conditions. This working hypothesis is supported by the example of Kratēs (a famous Engineer of Alexander the Great) who had undertaken a similar job at the Kopaïs lake, only some years ago (Strabo, op.cit.). The geological cross-section through the Dystos area shows steep marble formations, frequently with schist intercalations. These data combined with the high degree of tectonic ruptures of the region, are indeed favorable for such a hypothesis. Unfortunately, there are no further historic data on the outcome of this project.

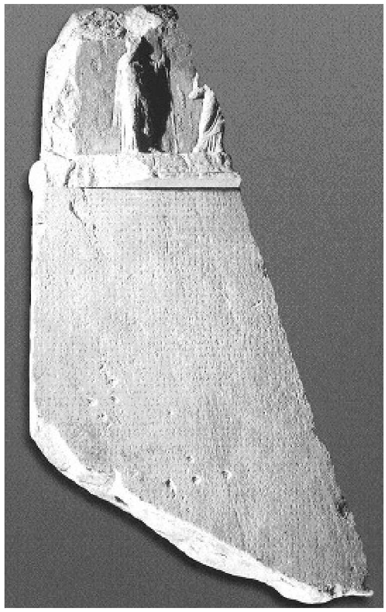
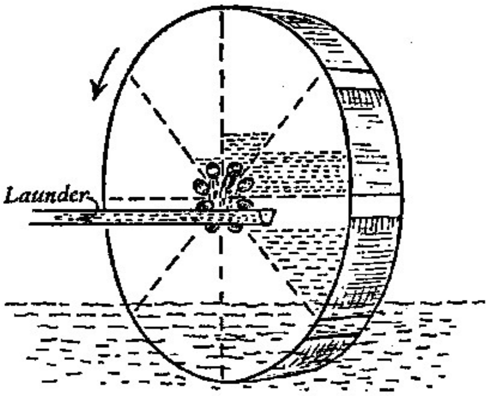


Figure 9 The stele where part of the BOT contract is engraved (Athens Museum of Inscriptions).

(ii) b) Nevertheless, the technical and juristic information contained in the "Ptekhae" stēlē, confirm the admiration for "this first truly entrepreneurial business culture [..], an economic system distantly related to the Anglo-American consumer and shareholder capitalism of our day" (Zenakis *et al.*, 2003).

Water-lifting Devices

Water-lifting installations were devised since the very early times in Mesopotamia. The technology of lifting water, however, did not become mechanised until the Hellenistic period (Humphrey *et al.*, 1998). In what follows, a brief reminder is presented of these mechanised lifting-water devices of the Greeks, who had the chance to live or just to study in Alexandria of those times (3rd century B.C. to 2nd century A.D.). To this end, "the best single surviving description of the water-lifting devices developed in the Hellenistic period at the Museum of Alexandria is Vitruvius" (Humphrey *et al.*, 1998: 310). Afterall, this first Roman technical writer (middle of 1st century B.C.) is generous in making more than one hundred references to greek sources and he is constantly using greek technical terms. In our specific content, the word «αντλία» (pump) for all water lifting devices was already used by Lucretius (one generation older than Vitruvius) (Oleson, 1984: 62).
The "tympanon" (drum) (Vitruvius, 10.4.1-2). A timber-made box-like wheel (turned by means of labourers treading within a parallel wheel) is separated in eight cyclic sectors (partitions), in which water is taken-up, and subsequently discharged through lateral holes located around the axle of the wheel. Drawing height equal to the radius of the wheel (~ 2.50 m) (Landels, 1981).



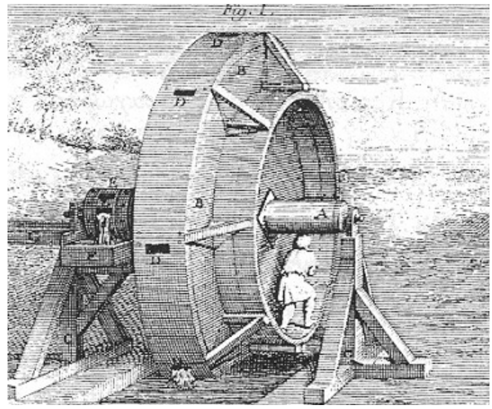
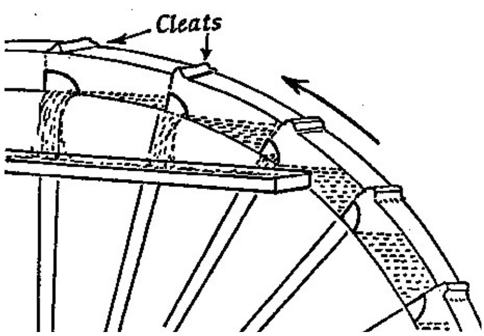


Figure 10 The Tympanon (Landels, 1981).

Figure 11 Treading of Tympanon.

Wheel with "Compartmented Iron" (Vitruvius, 10.4.3). A tympanon-like wheel is constructed, with however the following modifications: (a) It is more densely spoked and (b) along with circumference, a second circle of planks is fixed. Together with the other planks, this new series of planks creates several rectangular compartments which carry-up water to the top of the wheel. In this case, the drawing height may be higher than in the case of tympanon, since the radius may be larger.

The "Manganon" or wheel-driven Backet-Chain (Vitruvius, 10.4.4). In this version, the tread-wheel is kept much higher than the water-level, but a double iron chain is wound around the axle of the wheel coming down to plunge into water (This is the πολυκαδία" of Hero of Alexandria): Bronze buckets are connected along the chain (their capacity being equal to 3.3 L each) and carry water to the top; as they are borne over the axle of the wheel, they turn over and pour water into a channel or a reservoir.



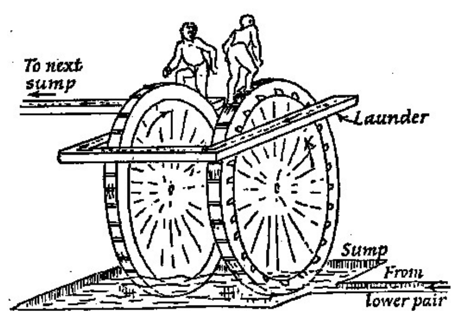


Figure 12 Water compartments of a water wheel (Landels, 1981).

Figure 13 Wheels with compartments rim; representation based on archaeological finds in Spain (Landels, 1981).

Water powered wheel with bucket-chain (Philo of Byzantium, Pneumatics, 65). Now, take a Manganon, bring the large wheel back down to the water of a river – not to collect water this time, but to be driven by running waters. Subsequently, wind around it the chain with its buckets, and do the same around another rotating disc, up to the level of the discharge: The buckets will bring water up – this time being driven by water-power, not by labourers' treading.

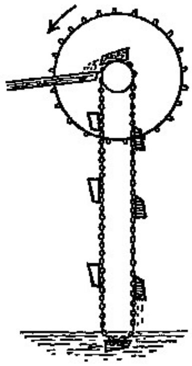


Figure 14 The wheel-driven bucket-chain (Landels, 1981).

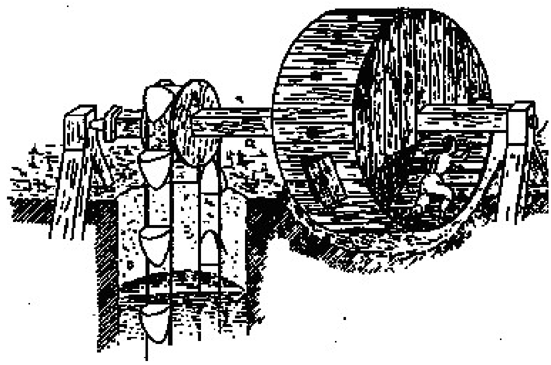


Figure 15 The wheel-driven bucket-chain, following the tradition of Philo (Oleson, 1984).

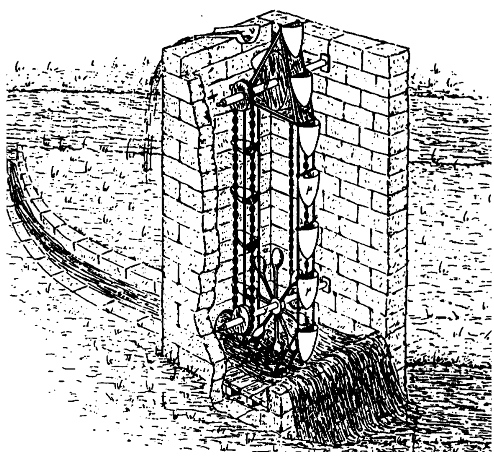


Figure 16 Philo's paddle wheel driven bucket-chain.

The Arcimēdēs water-screw (Vitruvius, 10.6.1-4). Take a cylindrical free-trunc (its length being 16 times its diameter). The circumference of either end is divided up into eight parts, precisely corresponding to each end. On the lateral surface of the trunc, engrave spirals under an angle of 45º and with a pitch equal to the eighth of the circumference. Along these spirals, affix a thin timber strip. The whole is finally put in an external wooden cylindrical box. Set now the lower end of this contrivance into the water level, at an angle 3 to 4 vertical to horizontal. Rotating the trunc, puts water in a motion along the spirals up to the upper end of the machine, where it flows out. It seems that for at least two millennia, this device was used in Mediterranean Countries for several purposes, the most "industrial" ones being the drainage of mines: "Sometines, (in Spain) the miners encounter subterranean rivers […]. They draw the gushing waters by means of the Egyptian screws invented by Archimēdēs[1], (Diodoros of Sicily, History, E', 37.3). Mechanisation, that is, offered the possibility for considerably broader productive applications of Hellenistic engineering inventions.

[1] It is interesting to note here the admiration of Diodoros both for the machine and for its inventor:
«Διά τῆς τυχούσης εργασίας, ἄπλατον ὕδωρ ἀναρριπτεῖται παραδόξως»
«θαυμάσαι δ' ἄν τις εἰκότως τοῦ τεχνίτου τήν ἐπίνοιαν»…

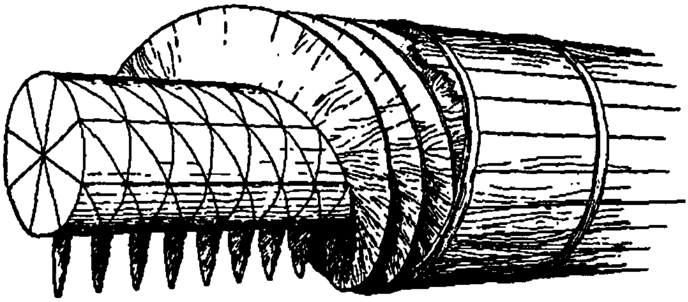


Figure 17 Tracing of spirals and affixed elicoidal strips in an Archimedes screw pump.

The Ctesibian force-pump (Philo of Byzantium, Pneumatics, app.1, chap. 2) (Hero of Alexandria, Pneumatics, 1.28). And this brings us to the culmination of the greek Technology of the 3rd century B.C., "the most complex highly mechanised device which sits in the water it is intended to lift, and pushes it up a discharge tube, by the movement of pistons working in a pair of cylinders", (Humphrey *et al.*, 1998: 318). We are not going here to further describe this pump since it is precisely the pump used up to our days and it is well known. Instead, I wish to conclude with some comments regarding the sufficiency of technical and scientific knowledge of that period, for such a complex device to be conceived and manufactured. In fact,

(a) Theoretical geometry was extremely advanced; very precise drawings were feasible.
(b) The theory about compressibility and elasticity of fluids was known (Straton of Lampsakos, 3rd century B.C., as well as Archimēdēs himself).
(c) Metallurgy of bronze was very well known, at least one thousand years ago; casting of complicated bronze items was easy, and beating was used for further hardening.
(d) Lathe was used to smooth the interior of the cylinders in order to achieve airtight motion of the piston. Philo (book IV of Pneumatika, 77.7) clearly describes these techniques:

> «καί τοῦ ἐντός μέρους μή διηθῆναι ῥεῦμα δι' αὐτοῦ τήν πᾶσαν λαβὸν βίαν».

That is why we should not wonder today that such technical achievements were feasible. Philo himself made the same suggestion to his readers, 2,300 years ago:

> «Μὴ θαυμάσῃς δέ μηδέ διαπορήσεις εἰ δυνατὸν οὕτως χειρουργηθῆναι»!

("You should not wonder at or doubt that such craftsmanship is possible", op. cit.).

Water Supply

> «…εἰ γε ὀνομάσαι τις πόλιν καὶ τούτους οἷς γε οὐκ […], οὐχ ὕδωρ κατερχόμενον ἐς κρήνην»!
>
> Παυσανίας, Φωκικά, 4-1

There was no greek city without an elaborated water supply system; that is why Pausanias does not condescent to call "city" the destituted old glorious town of Panopeus: its inhabitants had no water-supply system anymore! Out of the vast data on the water supply facilities of greek cities through the centuries, I will select only few examples in order to describe the typical components of such a facility, i.e. water-collectors, header tanks, galleries and terminal reservoirs and krēnae (fountains). In doing so, I intend to examine a prehistoric, a couple of archaic/ classical, and an hellenistic case.

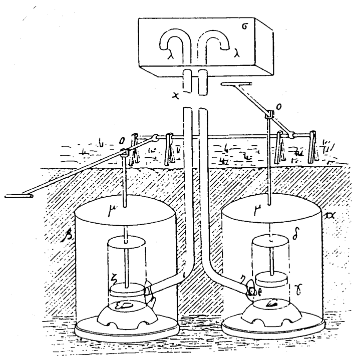


Figure 18 Philo's force pump (Oleson, 1984).

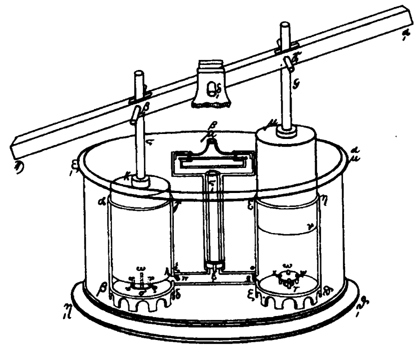


Figure 19 Force pump with swivelling nozzle (Humphrey *et al.*, 1998).

Mycenaean cities. I will briefly describe first the underground well-houses, following the views of Knauss (2006), and I will restrict this presentation only to those structures which are more characteristic to the building techniques of the Mycenaeans, i.e. the v a u l t i n g of access tunnels and spring chambers. The main features of these structures are the following:

(a) A series of retaining walls (approx. 3 m high) are securing (i) the stability of the sloped hillsides and (ii) a better infiltration of surface - waters.

(b) A small entrance is built on the ground, leading to the spring chamber via an inclined tunnel, stabilized by means of a corbelled strong-vault. Slope of the tunnel: 1 to 2 (up to 4), width: 0.8 to 1.4 m.

(c) An underground well-house (or spring chamber) stabilized by a bidimensional or three-dimensional stone-vault. Total depth of the installation: 5 to 15 m.

In this category of water facilities belong the finds of Tiryns and Ithaka (in the area of the so called "Homer School"). To another category of underground water-supply facilities belong the highly sophisticated mycenaean structures at the Acropolis of Mycenae and the Acropolis of Athens: The access-tunnels are hug in the rock of the hill, and lead down to a depth up to 25 m. In Mycenae, the lowest flight of the tunnel is plastered with a waterproof lime mortar, still in place.

Athens: The Peisistration Aqueduct. The subterranean aqueducts of Peisistratos are a typical example of water-supply facilities in greek cities during the archaic and classical period. In fact, many other Greek cities had such underground water-supply networks: Sycacuse: its catacombs were previous main aqueducts, (Crouch, 2004), Acragas: 15 km of water-collecting galleries of a cross-section 1 x 2 m², were running under the city itself. Finally, the emblematic case of Samos and its Eupalinian tunnel is very well known and it will not be further described here.

The Peisistratian aqueduct. The descendants of Peisistratos, as genuine tyrants ("bread, shows and water") are to offer the Athenian people a truly gigantic technical work (*ca.* 510 B.C.). The aqueduct comes out of the city to seek the waters of the river Ilissos, either on the surface with the speculated Nine-tap Fountain (perhaps somewhere around the intersection of Kallirhoi and Anapafseos streets, or, more likely, to the north-eastern sources of Ilissos). In some respects, (e.g., Camp, 1977), the Peisistratian aqueduct was collecting water from the springs situated at the north-eastern foot of the mount Hymettus (approx. 130 a.s.l.), Goudi, (somewhere around Ag. Lavras street, at the level of Agios Thomas), next to the bed of Ilissos and its many tributaries there. Its distance from the Acropolis is 3.5 km. According to others, (e.g., Kastenbein, 1994), the Peisistratian aqueduct was going much more uphill, following the bed of Ilissos high up to Cholargos: somewhere between the monastery of Saint John the Theologian, further up to Anastaseos street towards Hymettus (245 m a.s.l.), and up to 1 km or so to the south-east of Papaflessa square (Ano Cholargos).

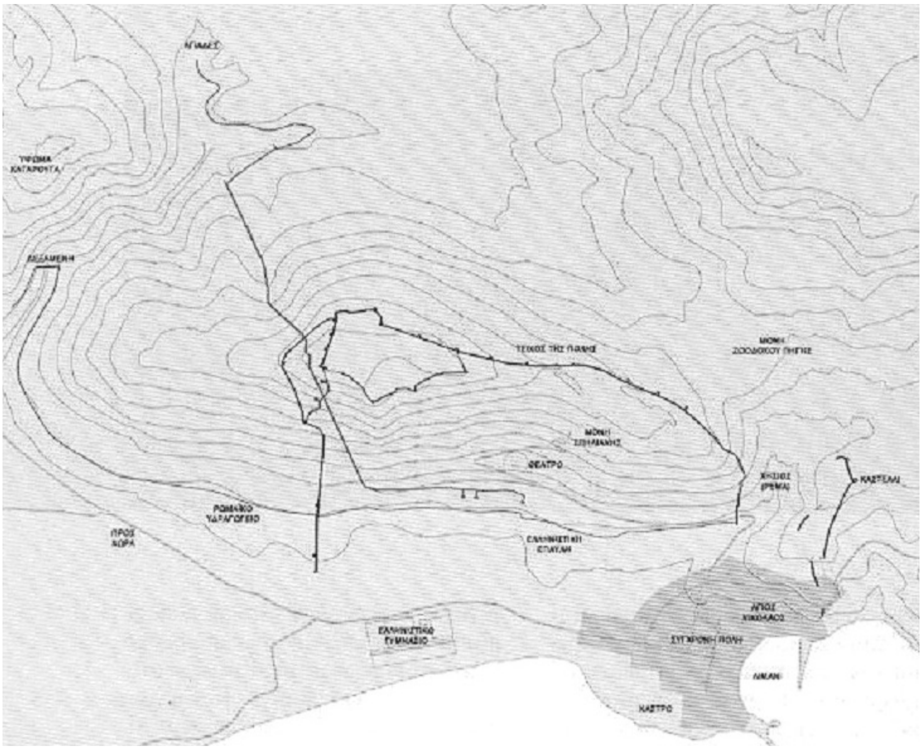


Figure 20 Layout of the eupalian aqueduct in Samos (*ca*. 550 B.C.).

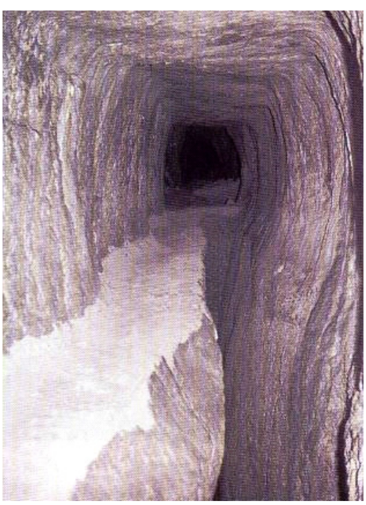


Figure 21 Typical cross-section of the Eupalinos tunnel.

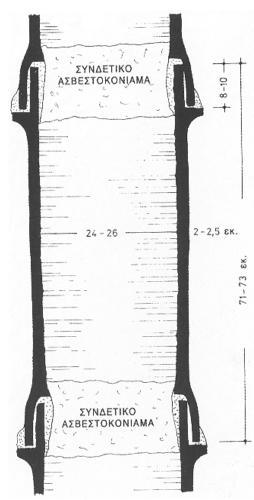


Figure 22 The ceramic pipes of the eupalinian aqueduct.

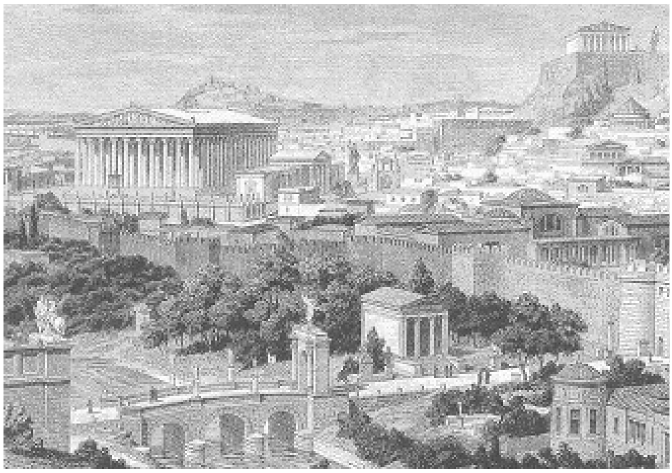


Figure 23 Ancient Athens.

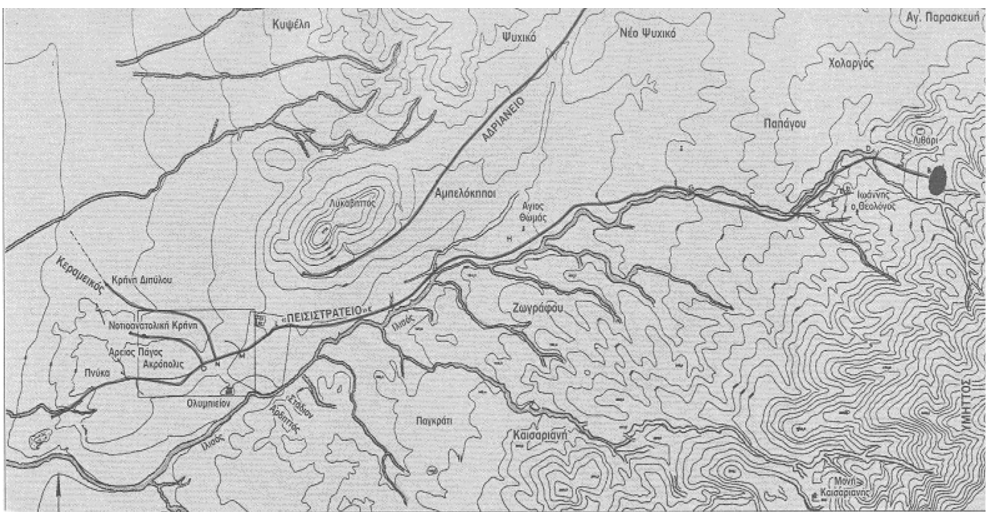


Figure 24 Layout of the Peisistratos and Hadrian aqueducts in Athens.

Its distance from the Acropolis is about 7.5 km. It is indeed a huge technological achievement, definitely more important than the Attic Metro of our days. This aqueduct is situated for the most part in a tunnel, up to 14 m deep. Parts of the tunnel have been located in too many places (with lower or higher degrees of certainty as to whether they belong to this very aqueduct), with a typical cross-section of up to one and a half m height. Pipes of terracotta with internal diameter of approximately 20 cm are placed inside the cross-section of the tunnel, with sleeves of extraordinary conception, openings for cleaning, orientation engravings and other technical elements (and with the name of the manufacturer, of course!).

The gradient of the aqueduct is extremely favourable (over 2%). In the area of the present Hilton hotel alone, the gradient falls to approximately 0.5%. But perhaps even this was enough – such was the gradient at the tunnel of Eupalinos in Samos, constructed at the same age and for the same purpose (water supply of the city of Samos). Likewise, such is the minimum gradient that Vitruvius would suggest 500 years later.

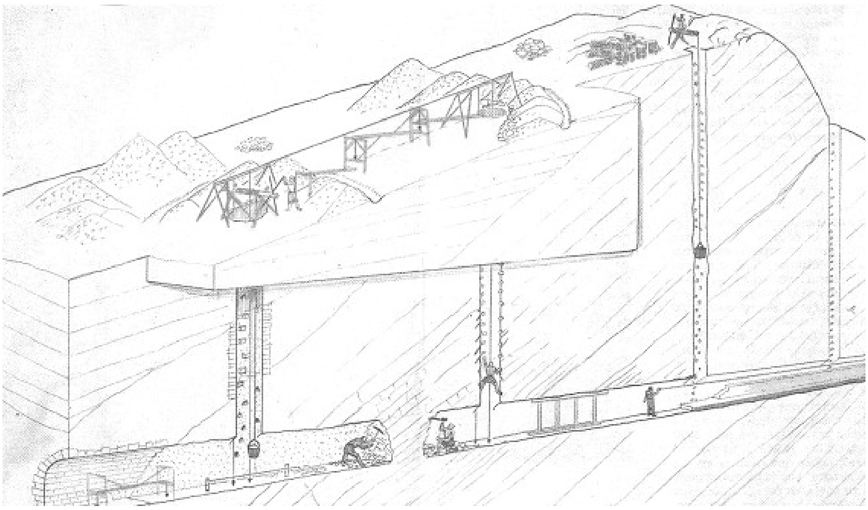


Figure 25 Technical details of the tunnels of Peisistratos aqueduct.

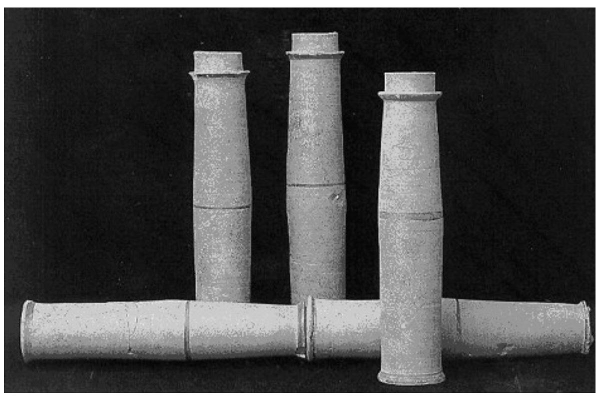


Figure 26 Ceramic pipes from the Peisistratos aqueduct. A high Quality Assurance scheme was followed.

However, the masterpiece of this aqueduct was the internal distribution network. Past the National Garden (depth of tunnel 14 m), the pipe heads for the Russian church (depth 5 m) and it starts branching at the corner of Kydathinaeon and Chrysostomou street (almost at the surface) to the south and north of the Acropolis. Along these branches, the number of the reservoirs, the public fountains, the sanctuaries etc., surprise us with their richness and closeness, up to the other side of the ancient Agora, the posterior Fountain of Dipylos in Keramikos. The network will be maintained, implemented and enriched systematically during the democracy of the Classical period, especially with the foundation of new fountains, impressive public constructions that is, for the water supply of the citizens. The fountain had already been such a widespread social/cultural establishment that within a period of a century alone (560-460 B.C.) we find a hundred and fifty fountain depictions in Attic vessels.

Moreover, it has been said that this artistic obsession involved perhaps a sort of propaganda of the Athenians to the entire known world where the Attic vessels were exported ("behold what kind of a city we are"). The care extended to the handling of the waste-water through a completed sewer network, elaborately constructed. Such was the social importance of these works, that even Periklēs himself offered to contribute of his own expense for the foundation of a new fountain in Keramikos!

Fountains and reservoirs. But let us hear more about fountains and reservoirs from Tanoulas (1992): "The fountains or the springs that are known and are water-bearing to this day, are the following: the Mycenean fountain at the north of Ariforio, the Klepsydra spring, the fountain at the west of the Asclepieion and the Asclepieion spring in Athens. The richest natural spring of all, the ones surrounding the basis of the rock of the Acropolis, is Klepsydra at the basis of the north-western corner of the rock. The Klepsydra spring itself was late to be discovered, but its water was indirectly used early on. Thus, in the Neolithic period shafts were dug to the north of it, while in the 13th century B.C. the mouth of the spring was found and its water began to be systematically drawn.

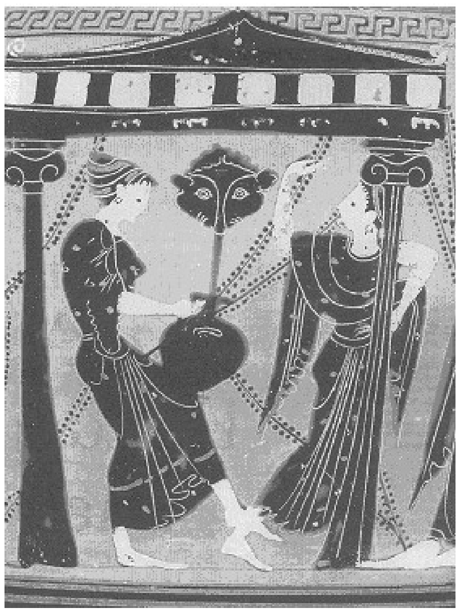


Figure 27 Representation of an ancient fountain on ceramic pottery.

The spring was preserved in this natural state up to the 5th century B.C., and the access to the old Embedo (that is now renamed to Klepsydra) was facilitated with the construction of a parapet on ground level, from which a few steps were leading to a lower ground. From there, one could draw the water that was collected in a rectangular reservoir, from the walls of which, (from the exits of the natural cavities of the rock), the water was gushing. The water technology used for the exploitation of the water of the fountain that gushes up to these days at the basis of the rock of the Acropolis, at the north-eastern corner of Asclepius' sanctuary, was also rudimentary. The hewing of the natural cavity of the rock in order to take the regular form of a geometrical vaulted room is interesting, mostly from the aspect of the art of hewing.

The word "fountain" has come, synecdochically, to mean every kind of construction from which one can obtain water, regardless of whether this water comes from a local spring (or well) or it comes from one or more distant springs through a system of water pipes (and regardless of whether the water is collected in basins from where it is drawn or is flowing from taps). Fountains of this kind were playing an important role in Athens' daily life and they were very often depicted on vessels, mostly on urns in which the water was transported and kept. These depictions are of a great decorative and genre-painting value, and they also provide many clues regarding the architectural formation of the fountains.

Important relics of a large reservoir constructed in the first years of the democracy, before the destruction of the Acropolis by the Persians, that is between 510 and 480 B.C., are preserved at the Acropolis. It so happens that it is the only early Athenian reservoir that we know so well, but it is also unique regarding the size and the quality of the hydraulic technology applied to it. This remarkable technological work is part of a grandiose building program aiming at the monumental construction of the access and the entrance in the Acropolis. The reservoir was constructed in order to collect the water that was streaming on the surface of the Acropolis' rock – a surface that was extending to the south-east of the reservoir, that is in the area among the Propylaea, the Parthenon and the Erechtheum.

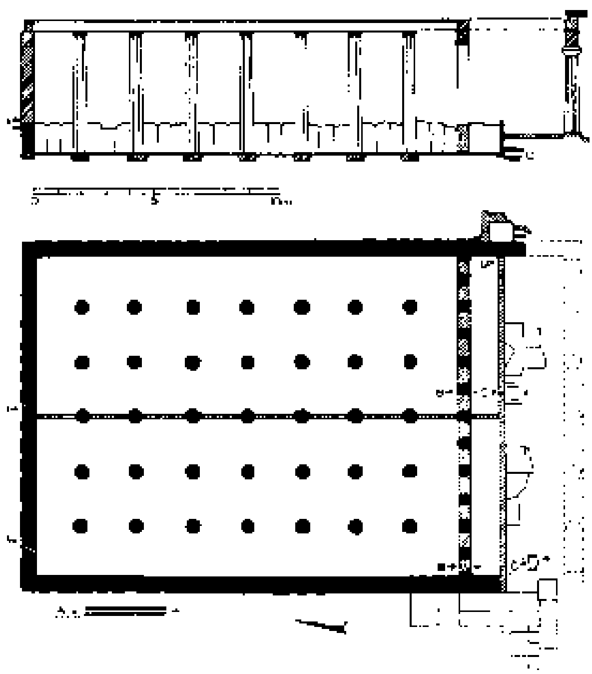


Figure 28 The Theagenes krene, Megara (5^{th} century B.C.) (von Zabern, 1991: 113).

Most of the water impurities settled down on the northern and deeper part of the vestibule, while the upper water layers remained relatively still and clear. Between the two chambers of the reservoir there was a wall lower than the external walls. At some point, the water in the vestibule reached the height of the top of that wall and began to overflow to the west chamber, which was the main chamber of the water collection.

The Premnesiclean reservoir was probably destroyed by the Persians in 480 B.C. Thus, the water on the surface of the rock, which the pipe was still collecting, had to be conveyed outside of the northern wall of the Acropolis. This diversion took place between 437 and 432 B.C. by Mnesicles, architect of the Propylaea, in order to protect his building from the water that was flowing into the western end of the Acropolis. A new branch of the pipe, heading to the north-west and going further up to the north with a sewer built of limestone, was hewed on the rock, conveying the rainwater outside of the northern wall of the Acropolis up to this day".

Hard times. However, the water works of Athens are deteriorating during the 4th century B.C. First of all, at the Agora area, the number of the 32 wells of the 5th century in use (average depth 12 m), is now limited to only 16 (with a depth of 15 m). Of course the Persian tornado and the degradation due to Peloponnesian war had already taken place – so, once more, the history of wells reflects the history of the city. However, it appears that a few years after 350 B.C., severe lowering of the underground horizon of Athens took place because of an extended draught (with corresponding "malnourishment") all over Greece.

In the face of this situation, it appears that the Athenians are taking several measures: The third category of measures that the Athenians took in order to cope with the extended draught of that period, regarded the right management of the water resources: The first component of this effort was the extended maintenance (cleaning, repairs) of the network of reservoirs and fountains. The second component was the intensification of the role of the functionary called "caretaker of the fountains" – or the general manager of maintenance and function of the water works of the city, as he would be called today. He was (according to Aristotle, Athen. Politeia, 43.1) one of the few city officials who was not appointed by lot, but was elected by vote – such was the importance of this functionary's honesty and know-how. (Themistoclēs himself had served in this post once.) Now, in 333 B.C., the Athenians honor with a golden wreath the efficient caretaker of the fountains Pytheas (from Alopekē), because he repaired and cleaned several fountains and pipelines in Attica. Such was the new hierarchy of the city's needs. But it will be only after five centuries that Athens will be given a second aqueduct – the Hadrianian one.

Megara: The typical water-reservoir of Theagenēs.

«Ἔστι δε ἐν τῇ πόλει κρὴνη ἣν σφὶσιν ᾠκοδόμησε
Θεαγένης τυραννήσας […], μεγέθους ἕνεκα καὶ κόσμου καὶ
ἐς τό πλῆθος τῶν κιόνων θὲας ἀξὶαν» Παυσανίας, 1, 40-1

Megara was a glorious (and unlucky) Doric city in the middle of two rival cities, Korinth and Athens, and native land of the larger number of good Engineers of the greek Antiquity. The aqueduct of Megara (*ca.* 500 B.C.) is not yet completely uncovered, but its terminal water-tank and krēnē is preserved up to a height of some meters. The protective roof was supported by five rows of seven octagonal columns, mostly preserved in situ.

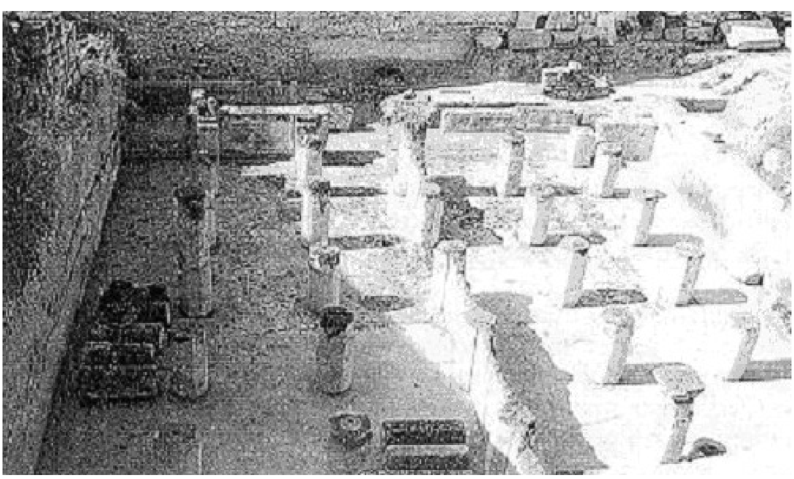


Figure 29 The Theagenes krene (von Zabern, 1991: 139).

In-plan (dimensions 14 x 19 m²), the reservoir was divided into two basins of 164 m³ capacity each. On the wall between the collecting and the drawing basin, there is a hole: a flow-regulating bronze-mechanism is provided. The surrounding walls of the reservoir (up to a height of 1.4 m) are plastered with a pozzolanic mortar, 12 mm thick. The entire floor is covered by a 50 mm pozzolanic plaster, and on top of that it was covered by a thin black layer of asphalt, mixed with animal fats, in order to avoid the grow of calcite layers (Hellner, 2005). In general terms, this Megarian facility arrangements will be followed in several other cases, such as the krēnē of Glaukē and Peirene in Corinth, or the famous Enneacrounos in Athens.

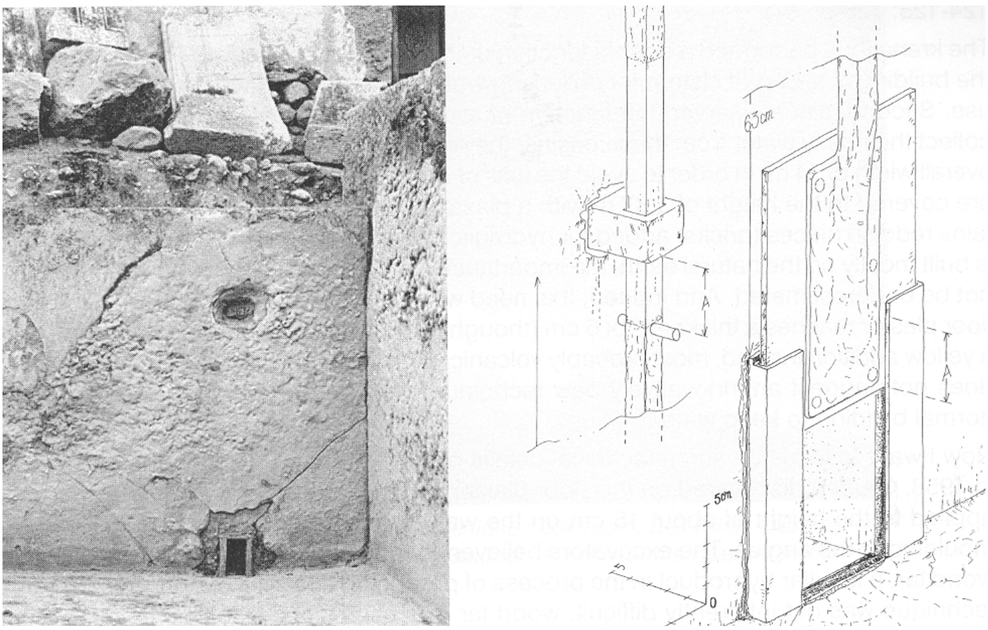


Figure 30 The regulating mechanism (Hellner, 2005).

Pergamos: The masterpiece of water supply of hellenistic cities.

"It is with the Hellenistic age that the great breakthrough comes [in Hydraulics]" A. Trevor Hodge, 1992

Following the views of A. Trevor Hodge, the Hellenistic breakthrough is due to (a) the political and economic developments due to the successors of Alexander the Great, and (b) the progress in Hellenistic science which gave to the hydraulic Engineer a whole new dimension of technical expertise (p. 31, 32). During this period, aqueducts outside the city were much longer (40 km stretches were now feasible). The main characteristics of the greek engineering, however, was still observed: Valleys were crossed by means of subterranean conduits–not bridges[2]. Thus, inevitably "inverted siphons" under pressure were to be built! And this was precisely the new greek invention, and it will be rapidly spread to numerous

[2] Why not, one may ask. Not because the greeks ignored the true vault; this was well known and used in subterranean structures: hidden architectural elements like tombs, sewage covers, or inside city-walls, since the 5th century B.C. (Orlandos, 1959-1960: 353). Thus, only aesthetic preferences and perhaps defensive traditions imposed to Greeks the subterranean solutions of aqueducts, instead of bridges.

greek cities in Asia Minor; both before and after the arrival of Romans[3]. To my opinion, the precise dating is of no technical significance: A technology initiated today, will obviously persist under the new rulers of tomorrow. Thus, the most prevailing technical conditions in all these cities, with only one exception, imposed siphons under rather small pressures ranging from only 15 m (Antioch on the Meander) up to 75 m (Tralleis). The solution adopted in all these cases was «stone-pipe[4]»: These were square blocks (~ 0.9 x 0.9 m) accommodating a hole of a diameter roughly equal to d=0.25 m, thus leaving a peripheral stone-ring of t=1/2 (0,90-0,25) = 0.3 m of thickness. Its allowable internal pressure "p" may be roughly estimated as follows:

Acting tensile stress $\max \sigma_t = \dfrac{1+(r_i/r_a)^2}{1-(r_i/r_a)^2} \cdot p$ < ft: γm

Tensile resistance f_t

Safety factor γ_m

Where:

r_i = 0.13m, internal radius

r_a = 0.43m, external radius

f_t ~ 0.45 N/mm² for a rather soft limestone

$\gamma_m \sim 2$

Thus, it occurs p ≈ 1 N/mm², corresponding to a water column of 100 m.

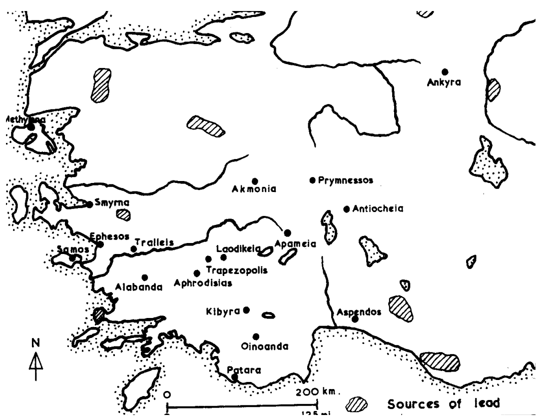


Figure 31 Distribution of stone-pipeline blocks in Greek cities during Hellenistic Age or after the arrival of Romans (Trevor Hodge, 1992: 41).

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3 The dispute about precise dating of most of these siphons (Hellenistic or Roman) still continues today. Initially, the German scholars (G. Weber) were in favour of the Hellenistic origin of most of them. The Patara case is characteristic: Nowadays, J. T. Coulton prefers the Roman date, based on a Vespasian inscription on a venter, whereas H. Fahlbusch explains that this inscription refers to a complete renovation of the aqueduct (In: Trevor Hodge, 1992: 396). Trevor Hodge, however, includes in his chapter "The predecessors of Romans", the siphons of Ephesos, Methymna, Magnesia, Philadelphia, both Antiochias, Blaundros, Patara, Smyrna, Prymnessos, Tralleis, Trapezopolis, Apameia, Akmonia and Laodikeia.

4 Happily enough, all technical evidence of this solution survived almost intact: "The stone pipes of many Hellenistic siphons, more durable and less liable to looting, have often survived", (Trevor Hodge, 1992: p. 37). It has to be noted however, that for further lower pressures, terracotta pipes might have been used, embedded in masonry (e.g. the case of Caesarea) or even hollow tree-trunks (lateron in European roman areas).

Figure 32 Stone-pipes form in the siphon of the city of Patara (von Zabern, 1991: 157).

It seems therefore that these stone-pipes could easily resist the relatively low hydraulic pressures envisaged in the a.m. cases of siphons. It remains however to understand how the tightness was secured through the joints between consecutive blocks, located approx. every one meter: Several answers may be given to this:

(a) In most cases, these stone-interfaces were well worked out and matched; besides, the ends of the holes were all reamed.

(b) A longitudinal compression stress equal to p/2, acting along the pipe, offers a kind of prestressing contributing to the tightness of the joints.

(c) Calcite deposits may further diminish water permeability of these joints.

(d) If however leakages through the joints appear, water losses are expected to be reasonably low.

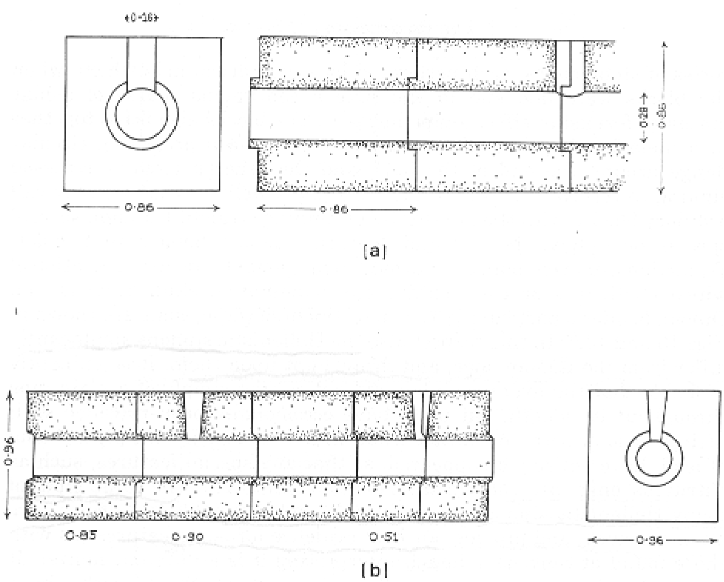

Figure 33 Stone pipeline blocks from Aspendos and Laodikeia. A “vent” (?) is also shown on both of them (Trevor Hodge, 1992: 38).

Let us now describe with more details the most emblematic case of Hellenistic siphons[5], that of the city of Pergamos- the capital city of the Attalides kings 282-133 B.C. (and intellectual cradle of the physician Galen and the writer Pausanias). Four of its aqueducts are Hellenistic. Aqueduct No2 (from actual Madradag up to the Acropolis), was built by Eumenēs II (197-159 B.C.): It has a length of 42 km, with a triple terracotta pipeline (of a diameter of approx. 0.18 m and wall thickness of 3.5 cm), and it contains a last stretch of 3.2 km of siphon, under a maximum water pressure of 200 m. Everything here is gigantic indeed – a culmination of the glorious Alexandrian School of thought. Obviously, for such pressures, stone-pipeline is inadequate; lead-pipes[6] were used instead. Their resistance is confirmed by a simple calculation:

Pressure p = 200 t/m² = 2 N/mm²

Diameter d ≈ 180 mm

Thickness t ≈ 35 mm

Tensile resistance of low quality lead f_t = 11 N/mm² (Hütte Manual)

Acting tensile stress $\sigma_t = \left(\frac{1}{2}dp\right) : t = \frac{1}{2} \cdot 180 \cdot 2 : 35 = 5{,}2 N/mm^2$

Available safety factor $\gamma_{\mathrm{m}} = f_t : \sigma_t = 11 : 5{,}2 \cong 2$ (adequate)

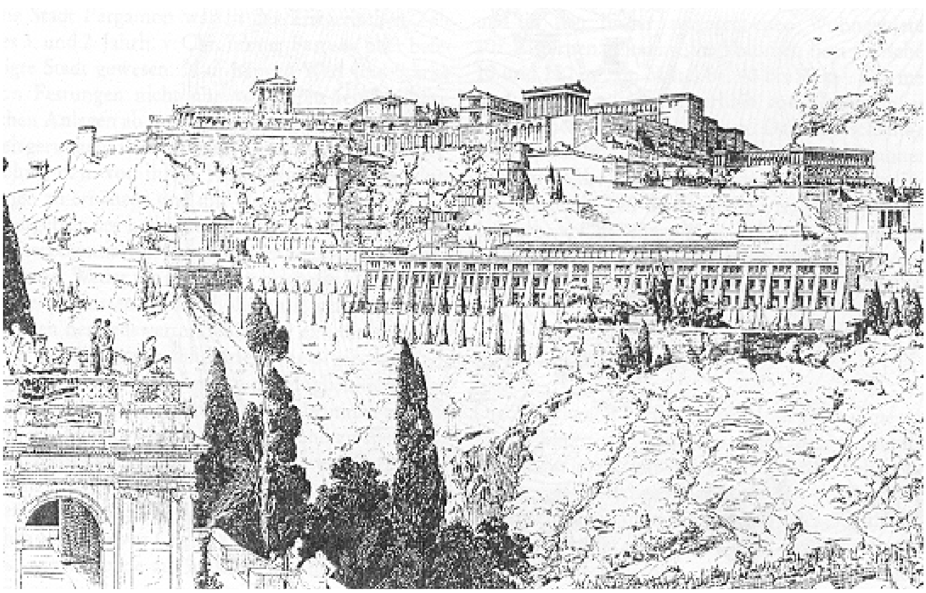

Figure 34 An artist view of Pergamos (von Zabern, 1991: 15).

The tightness of the joints (every 1.2 m) was secured by means of a swelling mortar of sand, silt and clay, interposed underneath the external lead-collars. The pipeline was supported every 1.2 m on vertically standing perforated volcanic stone-plates 0.3 x 0.15 x 1.20 m.

[5] "…that stands apart from all others, Greek and Roman alike, by reason of its gigantic size" (A. Trevor Hodge, p. 42).

[6] No sign of lead-pipes has survived, of course. Soil samples, however, close to the pipeline proved to have 50-time higher lead-content than samples outside the tracing…

Figure 35 Tripartite terracotta aqueduct f the Eumenian aqueduct of Pergamos (von Zabern, 1991: 25).

We will omit here the discussion on the issues of air venters and the inertial thrust of the siphon. But we should conclude with the statement of Prof. G. Garbrecht of the Tech. University of Braunschweig (Germany) maintaining that “the pressure pipeline of Pergamos will be rightly considered among the magnificent achievements of the ancient Hydraulic Technology” (von Zabern, 1991: 26). The same scholar has calculated that this specific aqueduct was discharging on average 2,700 m³/d.

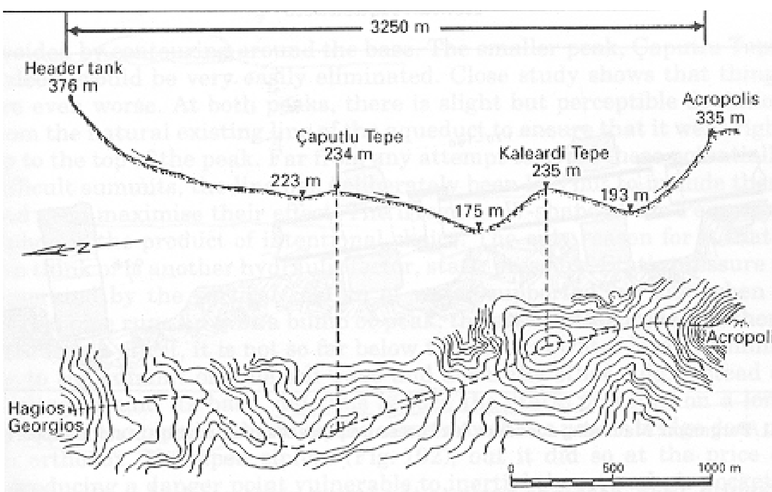

Figure 36 Pergamos: Longitudinal section of the final part of the aqueduct No 2 (from Madradag), under hydraulic pressure up to 200 m of water column (Trevor Hodge, 1992: 43).

Last but not least, it is worth to note here the hybrid solution given to a greek siphon of the archaic period, found in the Ionian city of Ephesos (near the Artemision temple): Lead-pipes, connected with strong stone-collars[7] are described by A. Bammer in “Das Heiligtum

[7] Assuming the following data $d_l = 180mm, t = 35mm, d_s = 800mm, f_{st} \approx 0{,}25N/mm^2$ and $\gamma_m = 2$, one may estimate an allowable internal pressure equal to $p \cong 2 \cdot \frac{f_{st}}{\gamma_m} \cdot \frac{t}{d} = 2 \cdot \frac{0{,}25}{2} \cdot \frac{35}{180} = 0{,}25N/mm^2$

der Artemis von Ephesos", 1985[8]. This archeological find shows how misleading some stereotypes may be, like the affirmation "lead-pipes were used only by Romans".

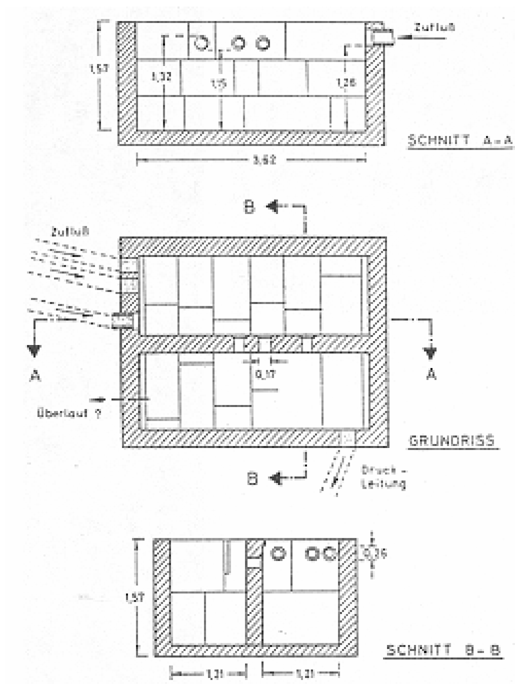

Figure 37 The header tank of the siphon, located on Agios Georgios summit (von Zabern, 1991: 26).

Figure 38 The lead pipes were resting on perforated stone-supports and on underlying stone slabs (von Zabern, 1991: 29).

Or p ~ 25m water column.
[8] Reference in P. von Zabern, p. 180

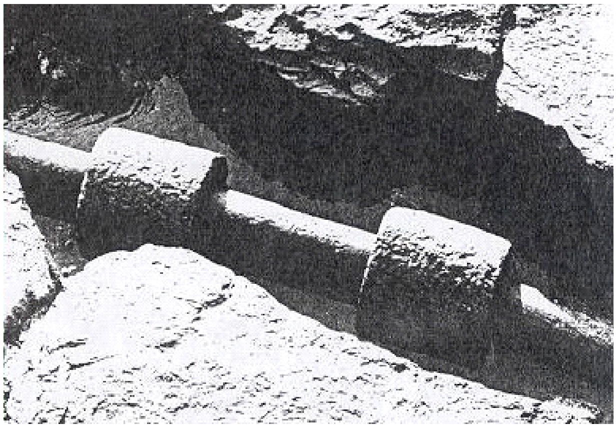

Figure 39 The archaic hybrid solution of lead pipes and stone collars in the Artemision of Ephesos (von Zabern, 1991: 180).

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A Brief History of Ancient Water Distribution

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Abstract: In early civilizations water for urban supply came from rivers, underground sources, and rainfall collection depending upon the civilization. There were not any large-scale lifting techniques such as the shaduf so that water was either carried from the source or by canals or by aqueducts from a higher altitude. Throughout the history of urban centers, a sufficient water supply has been the backbone of each city. This discussion is a brief history of ancient water distribution techniques for urban areas from the earliest civilizations through the Roman times.

Keywords Ancient civilizations; aqueducts; cisterns; urban water distribution.

The Beginning

Humans have spent most of their history as hunting and food gathering beings. Only in the last 9,000 to 10,000 years have we discovered how to raise crops and tame animals. Such revolution probably first took place in the hills to the north of present day Iraq and Syria. From there the agricultural revolution spread to the Nile and Indus Valleys. During this time agricultural revolution, permanent villages took the place of a wandering existence. About 6,000 to 7,000 years ago, farming villages of the Near East and Middle East became cities. The first successful efforts to control the flow of water were made in Mesopotamia and Egypt. Remains of these prehistoric irrigation canals still exist. About 5,000 years ago the science of astronomy began and observations of other natural phenomena were leading to knowledge about water resulting in advances for control and use. In the 3rd millennium B.C. time period the Indus civilization had bathrooms in houses and sewers in streets. The Mesopotamians were not far behind (Adams, 1981). In the 2nd millennium B.C. the Minoan civilization on Crete had running water and flushing latrines (Evans, 1994). The Minoan and Mycenaean settlements used cisterns a 1,000 years before the classical and Hellenistic-Greek cities. Cisterns were used to supply (store runoff from roof tops) water for the households through the dry summers of the Mediterranean.

The Minoans

Knossos, approximately 5 km from Herakleion, the modern capital of Crete, was one of the most ancient and most unique cities of the Aegean and of Europe. Knossos was first inhabited shortly after 6,000 B.C. and within three thousand years it had became the largest Neolithic (Neolithic age, *ca.* 5,700-28 B.C.) settlement in the Aegean. During the Bronze Age (*ca*. 2,800-1,100 B.C.) the Minoan civilization developed and reached its culmination as the first Greek cultural miracle of the Aegean world. During the neopalatial period, *ca*.

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1,700-1,400 B.C., Knossos was at the height of its splendor. The city extended an area of 75,000 to 125,000m² and had an estimated population in the order of tens of thousands of inhabitants. The water supply system at Knossos was most interesting. An aqueduct supplied water through tubular conduits from the Kounavoi and Archanes regions and branched out in to the city and the palace. A pressure conduit within the palace for water distribution is shown in Figure 1. Unfortunately, around 1,450 B.C. the Mycenean palace was destroyed by an earthquake and fire, as were all the palatial cities of Crete.

Figure 1 Water distribution pipe in Knossos.

The Greeks

From the viewpoint of water supply in ancient Greece there are two periods before the Hellenistic period, the archaic period and the classical period, during which time nothing was built in comparison with the grandiose of the Roman aqueducts. In the archaic and classical Greece cities typically had a spring at the center from which it grew, without any aqueducts, at least in comparison to what the Romans built. The aqueducts built during the archaic and classical periods were similar. Terracotta pipelines probably were the usual method of conveying water during the classical Greece period. These terracotta pipes (20 to 25 cm in diameter) fit into each other (Fig. 2). Cities were served by fountains in a central location receiving water either from a local source or a by conduit made of terracota pipes. Pipes were laid along in the bottom of trenches or tunnels, allowing for both protection and access. Two or more pipes in parallel were used depending upon the flow to be conveyed.

Figure 2 Terracota pipes at the Ephesus, Turkey.

During the Hellenistic period the political and economic situation changed leading to much more architectural development and urban beautification, of which aqueducts played a major role. The progress in science during the Hellenistic period provided a new technical expertise. Hellenistic aqueducts usually used pipes, as compared to the Roman masonry conduit. The Hellenistic people did not have the Roman's engineering skill especially in the use of the arch and the building of aqueduct bridges. Greek and Hellenistic aqueducts generally followed the contours, without using any major engineering structures. The one exception was the use of the siphon, which is the method used by the Hellenistics to convey water across valleys. Locations of siphons included Ephesus, Methumna, Laodicea, Pergamon, and many others, and because of difficulties in dating, these may be early Roman or Hellenistic. These siphons obviously provided models for the later Roman work. Hellenistic pipelines were built of stone or terracotta, whereas the Romans used lead pipes.

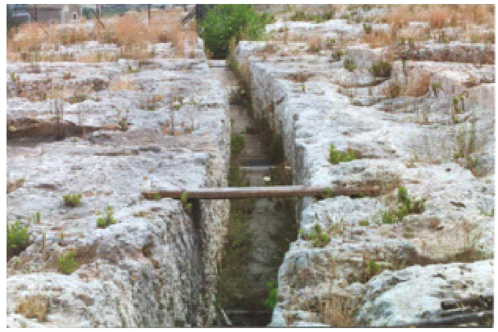
The Acropolis at Athens, Greece has been the focus of settlement starting with the earliest times. Not only the defensive capabilities, but its water supply made it the logical location for groups who dominated the region. Located on a rock outcropping, the naturally occurring water and the ability to save the rain and spring water resulted in a number of diverse water sources including cisterns, wells, and springs. The karst areas of the Italian peninsula and Sicily interested the Greek colonists during the archaic period. An excellent example of this was the founding of Syracuse (on Sicily) as a colony of Corinth in 734 B.C. Among the many things that transferred from the Corinth culture, such as language, religion, government, and farming was the water management. As Crouch (1993) points out, the transfer of knowledge about managing water was facilitated by the similarity of geology and climate between the two sites. From the 8^{th} to 1^{st} century B.C. the knowledge of locating and collecting water was coupled with the increasing knowledge of transporting both fresh and used water.

The water elements of Syracuse during the Greek times were later expanded during the Roman times. The geology of site, with the earlier and later limestone layers above clay created an abundance of water. The Arethusa spring, located at the edge of the sea, was the first settlement on Ortygia (Crouch, 1993). The water supply came from many surface and subsurface openings in the limestone, particularly where the limestone lies above impermeable strata such as marl. The series of grottoes above the Greek theater (Fig. 3) was probably a major factor in the development of Syracuse, because the early Greeks found water flowing here. After time, possibly a couple centuries, water found a new path further downhill and increase demand (because of increased population), new supplies to this location were developed, using the same outlets. These were the Galermi aqueduct and the Ninfeo aqueduct.

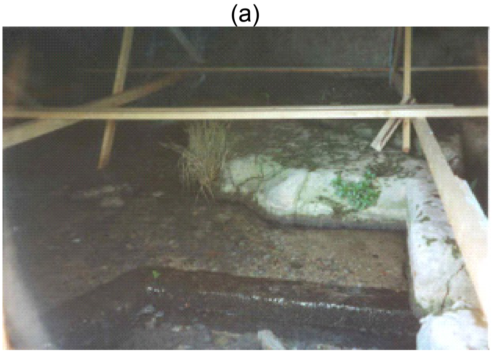
The Roman Water Supply System

The Romans built what can be called mega water supply systems including many magnificent structures. Water flowed by gravity through enclosed conduits (*specus* or *rivus*), which typically were underground, from the source to a terminus or distribution tank (*castellum*). Above ground aqueducts were built on a raised embankment (*substructio*) or on an arcade or bridge. Settling tanks (*piscinae*) were located along the aqueducts to remove sediments and foreign matter. Secondary lines (*vamus*) were built at some locations along the aqueduct to supply additional water. Also subsidiary or branch lines (*ramus*) were used. At distribution points water was delivered through pipes (*fistulae*) made of tile or lead. These pipes were connected to the *castellum* by a fitting or nozzle (*calix*). These pipes were placed below ground level along major streets.

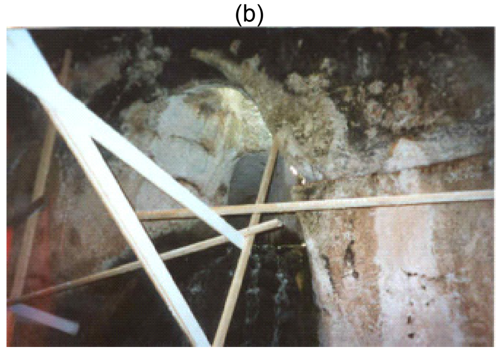
(a)



(b)



(c)



(d)

Figure 3 Water system at Syracuse: (a) Greek theater in Syracuse along grotto formation in background from where water flowed; (b) View of aqueduct above grottoes; and (c) and (d) Outlets of Galermi and Ninfeo aqueducts inside grotto formation, respectively.

To properly discuss Roman water supply we must be aware of the treatises of Vitruvius (De Architecta) (Morgan 1914) and Sextus Julius Frontinus (De acqueaductu urbis Romae) (translation 1973). The following quote from Vitruvius's treatise describes how the aqueduct castellum worked (as presented in Evans, 1994). "When it (the water) has reached the city, build a reservoir with a distribution tank in three compartments connected with reservoir to receive the water, and let the reservoir have three pipes, one for each of the connecting tanks, so that when the water runs over from the tanks at the ends, it may run into the one between them." The three water systems very briefly described are: the water system of aqueducts and dams to Merida, Spain, the system of aqueducts with various structures to Lyon, France (ancient Lugdunum); the system of aqueducts to Rome, and the aqueduct of Nimes (ancient Nemausus).

In 25 B.C. Emerita Augusta (Merida, Spain) became a colony and a century later the Romans had built a water supply system including three aqueducts, two of which were supplied by dams (the Cornalvo dam and the Proserpina dam shown in Figures 4b and d). The three aqueducts were the Cornalvo aqueduct (enters on the east side of Merida), the Proserpina aqueduct (enters on the northeast side of town), and the Las Thomas aqueduct (from springs on the north and northeast side of Merida). The Cornalvo aqueduct was built first and was about 17 km long. Cornalvo dam is an earthen dam approximately 194 m long, 20 m high, and has an 8 m dam crest width. A few remains of the Cornalvo aqueduct are visible near the present day bull ring (Fig. 4c).

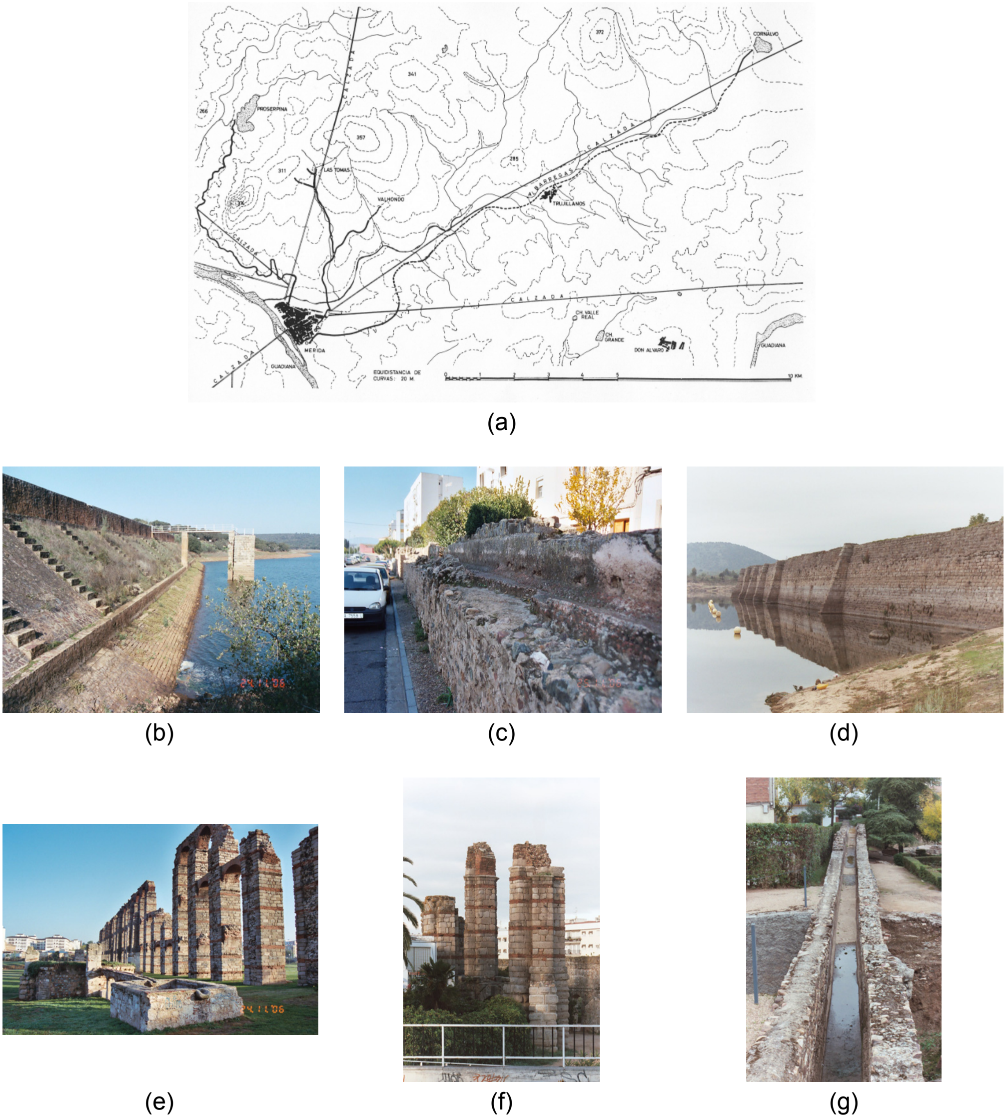


Figure 4 Water system at Merida: (a) Map showing the three Roman aqueducts in Merida, Spain; (b) Cornalvo Dam near Merida; (c) Cornalvo Aqueduct supplies water from Cornalvo Dam to Merida. Only a few remnants of this aqueduct are still visible; (d) Proserpina Dam near Merida; (e) Los Milagro aqueduct bridge across the Rio Albarregas in Merida; (f) Las Thomas aqueduct bridge across the Rio Albarrega and located near the hippodrome. Only the three pillars remain of this aqueduct bridge; and (g) Las Thomas aqueduct in Merida near the Roman theatre and amphitheatre. Shown on the right side of the aqueduct is a lion head of stone which was used as a gutter spout. There are also remains of a castellum nearby.

The Las Thomas aqueduct included an aqueduct bridge 1,600 m long (across the Rio Albarregas), of which only three pillars (16 m high) remain (Fig. 4f). Materials from this aqueduct bridge were used by the Arabs in the 16th century to construct the San Lazaro aqueduct bridge. The Proserpina dam is an earthen dam, 427 m long, 12m high, is located north of Merida and supplied water to the 10-km long Los Milagros aqueduct. This aqueduct entered the town on the north side with an aqueduct bridge over the Rio Albarregas, also referred to as the Los Milagros (the miracles) by the Spanish, with a maximum height of 30 m.

Four aqueducts were used to supply water to the ancient city of Lugdunum (Lyon, France). There were the Mont d'Or, the Yzeron, the Brevenne and the Gier. The aqueduct of the River Gier (Fig. 5) was the longest and the highest of the four aqueducts. Approximately half of the aqueduct was subterranean with at least nine tunnels, four siphons, and over 80 manholes. The aqueduct system in Rome evolved over a 500-year time period, with the first aqueduct the Aqua Appia being constructed around 313 B.C. (Fig. 6). This system with eleven aqueducts that eventually supplied water to Rome from mostly springs, and two were supplied from the Anio River and one from Lake Alsietinus. All the major eastern aqueducts entered Rome at the Porta Maggiore.

Figure 5 Aqueduct of the River Gier near Chaponost, France.

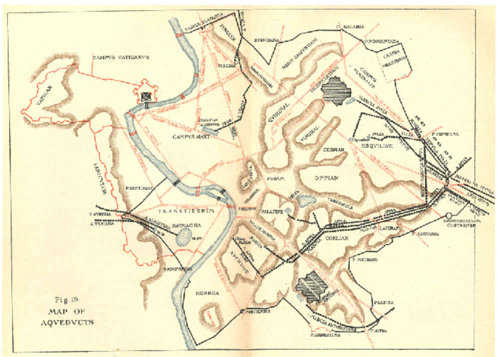
The aqueduct of Nemausus (built around 20 B.C.) conveyed water approximately 50 km from Uzes to the *castellum divisorium* in Nimes (Fig. 7). From an engineering point of view this was a remarkable construction project in that the elevation difference over the length of the aqueduct was only 17 m, making the slope only 0.085 cm/m. The Pont du Gard (Fig. 7a) is one of the most spectacular aqueduct bridges ever built and is the most photographed in the world.

Roman Urban Water Distribution Systems

A diagram of a simple Roman urban distribution system (as based on the Pompeii system) is shown in Figure 8. The main aqueduct ends at the main castellum, or castellum divisorium. The castellum divisorium is a junction where the main aqueduct ends and the urban distribution system begins. A lead pipe or smaller aqueduct was then used to transport the water from the main castellum to a secondary castellum or water tower when the secondary castellum was raised to the top of a brick pier. From the water tower (secondary *castellum*) lead pipes were used to branch the supply to individual customers, public fountains for the domestic supply.

The Greco-Roman city of Pompeii is located on the Bay of Naples, south-southeast of Mt. Vesuvius in Italy. Pompeii is one of the most significant proofs of the magnificence of Roman civilization that was originally founded by Greek colonists probably around the 9th to 8th century B.C. The city was influenced by others including the Etruscans for almost 50 years (until 474 B.C.), after which, it came back under Greek rule. During the 5th century it became part of the Samnite area of expansion, during which time it saw tremendous growth. Pompeii became under the influence of Rome after three long and bitter wars around 290

B.C. In 80 B.C. it became a Roman colony with the name of Colonia Cornelia Veneria Pompeii. Pompeii had a flourishing economy and widespread affluence after it became a colony that experienced a devastating earthquake in about 62 A.D. a few years later on August 24, 79 A.D. Mt Vesuvius erupted and destroyed the city.



(a)

(b)

(c)

(d)

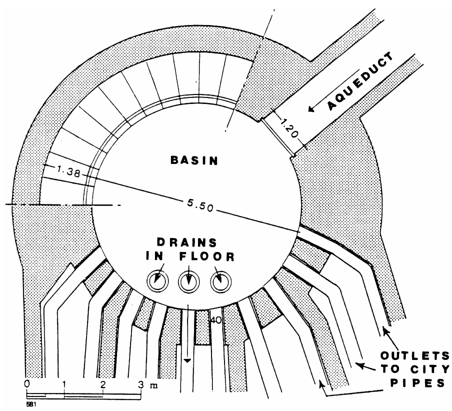
Figure 6 Aqueducts of Rome: (a) Map showing major aqueducts of Rome; (b) View of Porta Maggiore (double-arched gate) on the Aurelian Wall where all the eastern aqueducts entered Rome; (c) Aqueducts Claudia (top) and the Anio Novus (bottom) above the Porta Maggiore; and (d) Three aqueducts Julia (top), Tepula (center), and Marcia (lower).

Sources of water for Pompeii included wells, cisterns and other reservoirs, and a long-distance water supply line (Crouch, 1993, p.178). According to Richardson (1988, p.51) there were no springs within the city of Pompeii. The water table was tapped within Pompeii using wells as deep as 38 m below the surface (Maiuri, 1931, p.546-557). A long distance aqueduct from the hills to the east and northeast also supplied the city. This aqueduct received water from springs at Serino, near Avellino, and then was routed via Sarno around the north side of Mt. Vesuvius to serve Naples and two large cisterns of Cento Camerelle (Baiae) and the Piscina Mirabilis (Misenum). From Sarno a branch aqueduct was routed to

Pompeii terminating at the *castellum* at Porta Vesuvii (Hodge, 1992). The water distribution system elements of Pompeii (*ca.*79 A.D.) is illustrated in Figure 8.

(a)

(b)



(c)

Figure 7 Water system of Nemausus: (a) Pont du Gard aqueduct bridge; (b) Castellum divisorium in Nimes, France; and (c) Plan view of the Nimes castellum divisorium showing the 10 outlets and the 3 drains in the floor of the 1.5-m diameter basin (Adam, 1984; Hodge, 1992).

Two approaches to laying out the network of pipes were used: (a) using a main pipe from the secondary *castellum* with smaller branch pipes attached to serve individual customers, and (b) not using main pipes bust using individual pipes laid from the secondary *castellum* to the individual customer, which was the normal Roman practice (Hodge, 1992, p. 320). Pompeii's water distribution system consisted of pipes along the main streets connecting the main *castellum* at Porta Vesuvii to the various water towers (secondary *castella*), from which smaller pipes were placed under the sidewalks and streets and served the various customers. Not all customers had individual lines from a secondary *castellum* but instead received their supply from taps into the system at their locations.

A public fountain at the base of a secondary *castella* in Pompeii is illustrated in Figure 8c. Also two public water fountains placed back to back along a street with water supplied from a secondary *castella* at another location are shown in Figure 8d. As shown in Figure 8f, the public water fountains were placed somewhat evenly around Pompeii, with the radius of each circle in the map being 50 m. The fountains had an overflow weir so that the water would flow into the streets and then into the drainage system. Terracotta pipes were not used in the water distribution system in Pompeii (Jansen, 2001). The lead pipes (see Fig. 8e) in Pompeii are of the same construction and appearance as found in other Roman cities. The water taps found in Pompeii were also similar to those found in other Roman cities. Only a small number of houses had a water pipe that supplied a private bath or basins in the kitchen in the toilet of in the garden. Overflows were drained into cisterns for rainwater.

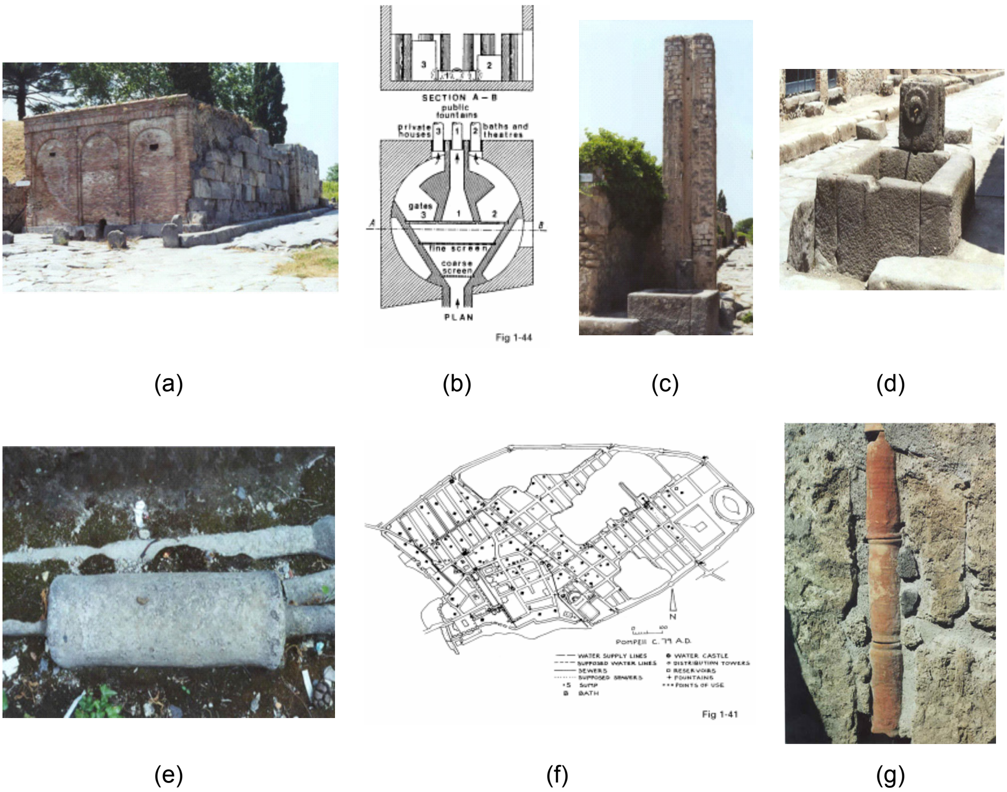


Figure 8 Water system at Pompeii: (a) Castellum divisorium in Pompeii at Porta Vesuvii housed in the large brick building; (b) Distribution arrangements inside building (Kretzschmer, 1966; Hodge, 1992); (c) Brick tower on which secondary castella (lead storage tank) were mounted; (d) Public fountain in Pompeii; (e) Lead pipe with enlarged section of junction box in Pompeii; (f) Location of public water fountain in Pompeii (Crouch, 1993); and (g) Terracota pipe used for drain pipe for rainwater from roofs.

Roman Urban Water Distribution Systems

A diagram of a simple Roman urban distribution system (as based on the Pompeii system) is shown in Figure 8. The main aqueduct ends at the main *castellum*, or *castellum divisorium*. The *castellum divisorium* is a junction where the main aqueduct ends and the urban distribution system begins. A lead pipe or smaller aqueduct was then used to transport the water from the main *castellum* to a secondary *castellum* or water tower when the secondary *castellum* was raised to the top of a brick pier. From the water tower (secondary *castellum*) lead pipes were used to branch the supply to individual customers, public fountains for the domestic supply.

The households and public buildings both had very interesting systems to collect and store rainwater. Buildings with peaked roofs had gutters along the eaves to collect the rainwater and downspouts to carry the water to the cisterns located under the building. Downspouts as shown in Figure 8g were made of terracotta pipes and were often set inside the wall.

After the Romans

The fall of the Roman Empire extended over a 1000 year transition period called the Dark Ages. During this period, the concepts of science related to water resources probably retrogressed. After the fall of the Roman Empire, water sanitation and public health declined in Europe. Historical accounts tell of incredibly unsanitary conditions - polluted water, human and animal wastes in the streets, and water thrown out of windows onto people in the streets. Various epidemics ravaged Europe. During the same period, Islamic cultures, on the periphery of Europe, ad religiously mandated high levels of personal hygiene, along with highly developed water supplies and adequate sanitation systems.

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From Mythology to Water Science

Historical Development of Soil-Water Physics and Solute Transport in Porous Media

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Abstract: The science of soil-water physics and contaminant transport in porous media began a little more than a century ago. The first equation to quantify the flow of water is attributed to Darcy. The next major development for unsaturated media was made by Buckingham in 1907. Buckingham quantified the energy state of soil water based on the thermodynamic potential energy. Buckingham then introduced the concept of unsaturated hydraulic conductivity, a function of water content. The water flux as the product of the unsaturated hydraulic conductivity and the total potential gradient has become the accepted Buckingham-Darcy law. Two decades later, Richards applied the continuity equation to Buckingham's equation and obtained a general partial differential equation describing water flow in unsaturated soils. For combined water and solute transport, it had been recognized since the latter half of the 19th century that salts and water do not move uniformly. It wasn't until the middle of the 20th century that scientists began to understand the complex processes of diffusion, dispersion, and convection and to develop mathematical formulations for solute transport. Knowledge on water flow and solute transport processes has expanded greatly since the early part of the 20th century to the present.

Keywords Darcy's equation; miscible displacement; Richard's equation; soil-water potential concept.

Introduction

The science underpinning the study of soil-water physics and solute transport is only slightly more than a century in development. Little literature exists on the scientific development of soil-water physics prior to the latter part of the 20th century. Fortunately, Philip (1974) published a paper that evaluated progress during the prior 50 years, and Gardner (1977; 1986) expanded on the history. In 2001, Raats discussed developments in soil-water physics since the 1960s. For this paper, I will depend heavily upon the excellent analysis in the papers by Philip (1974), Gardner (1977; 1986), and Raats (2001).

Humans have tilled the soil, irrigated it, and drained it for agricultural purposes for at least 6,000 years. Some of the agricultural practices related to water, nutrients, and compaction were based more on "common sense" than any known physical principles. The recognition that the soil contains ducts or pores that are important for water movement to plants occurred about 2,000 years ago (Philip, 1974). The vital role of pores and pore geometry was further recognized by Evelyn (1676), but little physics was involved. Further developments in the science of soil had to await the development of the physical sciences. The natural sciences, including physics, began in the latter part of the 17th century. Publications by Davy (1813) and Schubler (1830) on agricultural chemistry contained a significant amount of physics.

Little physics-related soil research occurred, however, until the latter part of the 19th century. In Europe, E. Wollny edited a German journal on agricultural physics over the period 1878-98. In the USA, Hilgard, King, and Whitney pioneered physical studies on semi-arid region soils. The state of soil physics at the end of the 19th century was summarized in a textbook by Warrington (1900). Meanwhile, the physics of soil water was scarcely being considered by the beginning of the 20th century. However, the foundations for what would later be considered to be soil-water physics were firmly being established in pure physics and mathematics.

Foundations in Classical Physics

Isaac Newton (1642-1727) in the late 17th century developed the ideas of gravitational force and concepts of pressure, work, and energy so fundamental in understanding soil-water physics. In one of his writings, Newton mentions the puzzling phenomena of capillary forces lifting a wetting fluid in a tube. Leonardo de Vinci, however, is considered to be the discoverer of capillary phenomena. The concept of surface tension is attributed to a Hungarian mathematician, Johann Andreas von Segner. A decisive step in the understanding of capillarity occurred in 1805 in an essay by Thomas Young in using the concept of surface tension to explain various experimental observations (Pomeau and Villermaux, 2006). A little later, the French mathematician, Pierre Simon Laplace (1749-1827), made a fundamental contribution to understanding capillarity by reasoning that the pressure difference across a liquid-vapor interface is related to the interface curvature (Pomeau and Villermaux, 2006). From these developments and those of others to follow, arose the “capillary rise equation” so important to soil-water physics.

Developments related to the flow of fluids, electricity, and heat need to be mentioned inasmuch as they later form the basis for the equations of water flow in porous media. Jean Leonard Marie Poiseuille (1799-1869) was a French physiologist and medical doctor (Kirkham, 2005). Due to an interest in flow of blood in arteries, he discovered the law on velocity of flow of a liquid through a capillary tube. This equation later became known as the Hagen-Poiseuille Law due to experimental testing by Gotthilf Heinrich Ludwig Hagen (1797-1874). Jean Baptiste Joseph Fourier (1768-1830), a French mathematician, conducted important mathematical work on the theory of heat during the period 1804-1807. Although this work was very controversial at the time (O’Connor and Robertson, 1997), the concept of flow of heat in response to a gradient in temperature was a fundamental advancement. Further developments in the flow of electricity by Georg Ohm (1789-1854) and for the diffusion of gases and solutes by Adolf Eugen Fick (1829-1901) resulted in equations similar to the Fourier equation (Kirkham, 2005) and Darcy’s equation to be discussed later. Short bibliographies of Poiseuille, Fick, Ohm, Laplace, Newton, and others are contained in the book by Kirkham (2005).

Soil-Water Potential

European scientists tried to characterize the water regime of soils starting in the early 19th century. The term “water capacity”, an estimate of the amount of water retained in the soil after a rain, was investigated by Schubler (1830), Mayer (1874), and Heinrich (1886). It is generally accepted that Lyman James Briggs (1874-1963), a physicist with the newly formed Division of Soils of the U.S. Department of Agriculture, was the first to clearly classify soil water into categories based on how strongly the water was held by the soil. He published a bulletin (Briggs, 1897) where the water in soil was considered to be of three types:

gravitation water, capillary water, and hygroscopic water (Phillip, 1974). Similar classifications were being proposed in the Russian and German literature (Mitscherlich, 1905; Lebedev, 1919) as discussed by Kutilek and Novak (1997). Although these classifications of soil water were useful means to think about soil water, the categories were arbitrary and artificial and could not be easily quantified.

The next important step in understanding how water is held by soil was made by Edgar Buckingham (1867-1940). Buckingham joined the Bureau of Soils of USDA in 1902. Buckingham brought a revolutionary concept to the study of soil water. He had taught physics for 10 years at Harvard, Bryn Mawr, and the University of Wisconsin and had written a book (Buckingham, 1900) on thermodynamics (Philip, 1974). Philip (1974) states the contribution clearly: "Buckingham's grasp of thermodynamics enabled him to appreciate that, regardless of any qualitative schema of discrete classes of soil water, a continuity of energy states was involved and the whole moisture range was amenable to a unified treatment." He defined the total potential of soil water which consisted of the gravitational potential and what he called the "capillary potential", now generally called the matric potential. Buckingham carried out the first measurements of matric potential and presented data on the dependence of the matric potential on soil-water content (Buckingham, 1907). Two other excellent publications on Buckingham's contributions to soil-water physics are Nimmo and Landa (2005) and Narasimhan (2005).

An important advance in practically measuring the matric potential with an instrument, to be later known as a tensiometer, was made Livingston (1908) and later by Gardner *et al.* (1922), Israelson (1926), and Richards (1942). It is likely that the Russian, Kornev (1924), was not acquainted with the publications of Buckingham and others when he used a term equivalent to suction for the negative pressure of soil water, constructed a "capillarimeter" identical to the tensiometer, and proposed a curve which is today known as a soil-water characteristic curve (Kutilek and Novak, 1997). Haines (1927; 1930) is credited with first recognizing the phenomena of hysteresis.

Soil-Water Movement

To begin a discussion of soil-water movement, one usually starts with the contributions of Henry Philibert Gaspard Darcy (1803-1858), a civil engineer in Dijon France. He was best known for his work on pipe flow. His fundamental contribution to the physics of water movement actually occurred near the end of his life with the publication of a book (Darcy, 1856). The porous medium used was saturated sand, and the experiments were conducted by two engineers, Ritter and Baumgarten using wastewater from a hospital in Dijon (Swartzendruber, 2005). In simplest terms, Darcy's equation stated that the water flux in 1-D flow is directly proportional to the hydraulic gradient and a proportionality constant called the hydraulic conductivity, a composite property of the flowing liquid and the porous medium. Probably independently, von Weitschkowsky (1884) in Germany found empirically the relation now known as Darcy's law (Kutilek and Novak, 1997). It is not clear how quickly Darcy's equation began to be used by practitioners of wastewater treatment, but it appears that several decades passed before it was used for theory development in flow through saturated soils related to drainage of agricultural land. The study of water table heights in drained land using Darcy's Law was pursued by Jules Dupuit, Philipp Forchheimer, and J. Boussinesq resulting in the Colding equation in 1872 and then the equations developed by Childs in the UK, Houghoudt in the Netherlands, and Kirkham in the USA (Youngs, 2005). Details on the origin of these equations related to soil drainage are given by van der Ploeg *et al.* (1997; 1999) and Raats and van der Ploeg (2005).

The foundation for the theory of flow of water in unsaturated porous material was laid by Buckingham (1907). He recognized that water flow in unsaturated soil would be highly dependent upon water content. Buckingham apparently used analogies to Ohm's law, Fourier's law, and Hagen-Pouiseuille flow through a tube for unsaturated flow, but did not mention Darcy's law either because he did not know about it (Sposito, 1986) or he did not recognize that his capillary potential was equivalent to a hydraulic head in saturated water flow (Nimmo and Landa, 2005). In either case, he introduced the concept of "conductivity", dependent upon water content, that today we would call the unsaturated hydraulic conductivity (Philip, 1974). This equation, similar to Darcy's law, is sometimes referred to as the Buckingham-Darcy equation or simply the Buckingham law (Narasimhan, 2005). Buckingham also went on to define the moisture diffusivity which is the product of the unsaturated hydraulic conductivity and the slope of the soil-water characteristic curve. Buckingham did not pursue unsaturated water flow further, because he left the Bureau of Soils to take a position with the National Bureau of Standards and spent the rest of his career working on pure physics problems.

It took nearly 2 decades before the full implications and importance of Buckingham's contributions were recognized. Lorenzo Adolph Richards (1904-1993) applied the continuity equation to Buckingham's extension of Darcy's law and obtained a general partial differential equation (Richards, 1931) describing water flow in unsaturated, non-swelling soils with the matric potential as the single dependent variable (Philip, 1974). More than 15 years passed before the Richard's equation was constructively built upon. Childs and George (1948) recognized the diffusion form of the steady 1-D flow equation and presented data for diffusivity as a function of water content for a sand. Klute (1952) rewrote the Richard's equation for 3-D unsaturated flow in the diffusion form with the volumetric water content as the dependent variable rather than the matric potential (Richards, 1931). Since Richard's equation and Klute's rewrite are highly non linear, the stage was now set for the next phase of the development of soil-water physics, that is the mathematical solutions to water flow problems.

Some advances in understanding soil-water movement were occurring simultaneously in central and eastern Europe during the early to mid 20th century. For example, Zunker (1930) tried to link soil-water physics to the basic equations of hydraulics, apparently formulated the capillary conductivity based on capillary phenomena, and derived an equation for vertical infiltration which was eventually shown to be identical with that of Green and Ampt (1911) (Kutilek and Novak, 1997). The well known empirical equation of infiltration by Kostiakov (1932) appeared. Although some theory development occurred in central and eastern Europe during the early 20th century, there seemed to be little or no awareness of the developments by Buckingham, Richards, and others and little further development of initial theoretical advances. According to Kutilek and Novak (1997), part of the reason for lack of advances was the emphasis on empiricism.

Mathematical Solutions to Water Flow Equations

For saturated porous media, many mathematical solutions were derived for 1-D, 2-D, and radial flow of water to wells, auger holes, agricultural drainage ditches, and tile drains. The practical impetus was to determine the drain spacing in order to effectively drain waterlogged land. These solutions to Darcy's equation and the 2-D form (Laplace's equation) for various types of boundary conditions and usually for steady state flow were started by the development of the Colding equation in 1872. In 1937, Symen Barend Hooghoudt (1901-1953) developed a theory for flow to ditches and drains in shallow, homogeneous soils. He then extended the solutions for cases of heterogeneous soils, and in 1940 removed the restriction of the impermeable base being close to the drain or the bottom of the ditch (Raats and van der Ploeg, 2005). Hooghoudt and his colleagues were responsible for the design of much of the drainage systems of the Netherlands and the export of their ideas to other parts of the world. Don Kirkham (1908-1998) must have picked up on the publications of Hooghoudt and others in early experiments at Utah State University on land drainage pertaining to land overlying an artesian aquifer under pressure. After World War II, he took a position at Iowa State College where he began in earnest the development of numerous mathematical solutions to drainage problems. Many seepage problems are not of simple shape, so Kirkham developed a new mathematical method called the modified Gram-Schmidt method to address this problem. Kirkham's many students carried on his tradition of applying mathematics and physics to solve a variety of water flow problems. For additional information on Kirkham's contribution to the theory of saturated water flow, see the paper by Nielsen and van der Ploeg (2005).

For unsaturated porous media, the quantitative physical theory of water movement has depended heavily on the availability of solutions of the nonlinear Fokker-Planck equation and on the nonlinear diffusion equation. Klute (1952) took the lead by developing a solution to the 1-D form of the diffusion equation for horizontal absorption of water. Philip (1954; 1957) extended the approach of Klute to moisture transfer in the vapour and adsorbed phases with the same mathematical formulation. The contributions of John Philip (1927-1999) to the theoretical development of soil-water physics, infiltration, and evaporation are nicely documented in Smiles (2001; 2005). Parlange also contributed greatly to theory development (Parlange, 1980). The solutions to the flow equation are highly dependent upon the form of the relationships between the water content, the matric potential (head), and the unsaturated hydraulic conductivity. Two groups of parametric expressions describing hydraulic properties of porous media can be defined (Raats, 2001): (a) a group of equations that can be solved analytically, usually by linearization of Richard's equation using some kind of transformation; and (b) a group of equations that are more amenable to numerical solutions. Since Richards' seminal paper in 1931, the number of experimental and theoretical studies on unsaturated water flow has increased many fold. For details on the many types of solutions of the non linear Richard's equation, please see the reviews by Philip (1988) and Raats (2001).

The analysis for unsaturated porous media was also extended to nonisothermal systems by Philip and de Vries (1957). Other researchers including the Miller brothers, Childs, Poulovassilis, Philip, Mualem, and Topp began to develop models and mathematical formulations for hysteresis. By 1975, finite difference solutions of water flow problems were being developed. Since then, faster computers and efficient finite element (Simunek *et al.*, 1996) and control volume (Heinen and de Willigen, 1998) methods made it possible to solve ever more complicated flow problems (Raats, 2001).

Complex Water Flow Processes

Some of the complex processes related to water flow processes such as multiphase flow of water, air, and non-aqueous phase liquids; simultaneous heat and water flow; and flow in shrinking/swelling porous materials have been investigated during the latter half of the 20th century up to the present. Experimental observations and extensions of theory to take into account the effects of soil air on water movement were made by Youngs, Peck, Philip, Morel-Seytoux, Hill, Parlange, and Raats (Philip, 1974). Experimental observations and theory development for the transport of non-aqueous phase liquids in moist porous media has grown rapidly since the 1980s particularly in the engineering and hydrology literature.

In the 1950s and 1960s, two rival theories were formulated for the simultaneous movement of water and heat (Raats, 2001). Philip and de Vries (1957) developed a mechanistic approach, and Taylor and Cary (1964), Lykov and Mikhailov (1965), and Groenevelt and Bolt (1969) developed theory based on irreversible thermodynamics. These two theories were reconciled by Raats (1975). Further developments have been made by Nassar and Horton (1992) and Nassar *et al.* (1992). Movement of water in soils subject to swelling and shrinking adds another complicating dimension to soil-water physics. Extension of the Richards equation to non rigid soils was made by Peter Raats using the continuum theory of mixtures and by Philip and Smiles using a limited, 1-D approach (Raats 2001).

Coupling Solute Transport and Water Flow

The flow of water through porous media is considered as bulk movement which can be described by the Darcy-Buchingham and Richards equations. This description becomes inadequate in defining the movement of transient dissolved solutes and pollutants and their chemical processes (Nielsen and Biggar, 1961). Lawes *et al.* (1881) observed that water and solutes do not travel uniformly within field soils (Kutilek and Nielsen, 1994). Means and Holmes (1901) recognized the complexity of diffusion and convection processes in transporting solutes after rain and irrigation events. Charles Sumner Slichter (1864-1946), a professor of mathematics at the University of Wisconsin, may have been the first to attribute dispersion or spreading of a solute to a distribution of flow velocities within the soil pores (Slichter, 1905). Kitagawa (1934) also demonstrated that lateral dispersion of a salt occurred during water flow through sand resulting in something like a normal distribution. It seems that the next experimental and theoretical developments associated with solute transport occurred in the middle of the 20th century by engineers and petroleum geologists (Danckwerts, 1953; Scheidegger, 1954; Rifai *et al.*, 1956; de Josselin de Jong, 1958; Handy, 1959). Paul Day (1956), a professor of soil physics at UC Berkeley, using exchange resins showed that hydrodynamic dispersion can occur in ion-exchange processes and compared his results with a statistical model of Scheidegger (1954) whose solution was similar to a solution of the diffusion equation (Day, 1956). Nielsen and Biggar (1961) were likely the first to conduct solute transport (miscible displacement) experiments using soil. Nielsen and Biggar (1962) went on to show that the earlier models based on statistical distributions and/or diffusion-type equations were inadequate to describe solute transport and spreading because not all mechanisms were considered. They used the analogy of solute moving through a single capillary tube (Bosworth, 1948; Taylor, 1953) and then a differential equation where solute transport occurs due to molecular diffusion and mass flow of the water of the type used by Lapidus and Amundson (1952). This equation is now the well known "convective dispersion equation" used in most quantitative descriptions of solute transport. As with water flow, the number of experimental and theoretical studies of miscible displacement in porous media has grown enormously since the mid 20th century to include adsorption/desorption processes, irreversible sinks and sources, and miscible displacement of gases (Rolston *et al.*, 1969). Numerous analytical solutions of the convective dispersion equation have been derived for a variety of boundary and initial conditions as well as chemical sorption and degradation processes.

Flow of water and transport of solutes in structured soils has received a lot of attention in the latter part of the 20th century (Raats, 2001). Informative reviews of flow in structured soils are given by van Genuchten et al. (1990), Mermut and Norton (1992), and Selim and

Ma (1998). Most of the models for flow in structured soils are based on distinguishing a mobile and a stagnant water phase and the exchange between the phases (Raats, 2001). The problems related to water resources, wastewater management, and environmental quality are becoming increasingly complex. Thus, these complex problems require innovative solutions developed by interdisciplinary teams, the major challenge and opportunity for the 21st century.

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The Hydrologic Cycle: A Historical Flow of Ideas that still Floods Classrooms

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Abstract: Historical papers relating to water often focus on a physical structure or archaeological artefact that is being investigated in order to achieve insight into the life, times or understanding of a historical culture or people. In this sense, the current paper is a bit of an anomaly in that the "artefact" that motivates this historical review of the hydrological cycle was observed first in the classroom. More specifically, the senior author has taught hydrology for many years and continually witnessed the difficulty that students often have in achieving a broad understanding and a high degree of mastery of hydrological processes. A number of reasons could be proposed for these observed pedagogical difficulties, but what is of interest to this paper is that the student's difficulties are reminiscent of the historical ones of deducing the hydrological cycle in the first place. Thus, a radical hypothesis is tentatively advanced: concepts that were tortuous or taxing to deduce historically often, for quite similar reasons, are challenging to teach, and vice versa. While a comprehensive psychological exploration of this observation is beyond the scope of this article, a few broader additional connections and observations are briefly explored.

Keywords History; hydrologic cycle; hydrologic processes; knowledge structures; learning strategies.

Introduction

There is an inevitable historical component to learning, as new understanding does not occur in a vacuum, but is invariably laid on a foundation of previously existing ideas, words and concepts. Thus, understanding tends to be built up in our minds a little like a sequence of archaeological layers, each one being laid on the dust of the previous, and each supporting subsequent layers. There is, of course, an undeniable complexity to both the learning process and the archaeological one, and older layers are often reworked and incorporated into the present in ways that defy simple linear explorations. In this same way, it is recognized that the current paper, limited by the confines of time and page constraints, will impose a pattern that is far broad, too simple, and too linear, to fully account for the true complexity of what is being described.

Yet, having taught a wide variety of courses to many students over for many years, the senior author has observed that an understanding that was difficult to establish historically will turn out to be difficult to teach; moreover, given no other data, subjects that are difficult to teach, when investigated, often tend to have been difficult and tortuous historically. As a preliminary example, the mathematical concepts of limits and convergence are difficult to teach and learn for the majority of engineering students, and these same concepts caused many ancients to flounder in obscure conundrums, such as Zeno's paradoxes or others.

Perhaps there is no great surprise in this observation. Our brains and minds were no doubt wired or attuned over countless years of natural selection to attend to certain consequences and relations, and to relegate others to subordinate positions. And in this sense our basic intuitive understanding of cause and effect has not perhaps changed nearly as much in the last 10,000 years as we would sometimes like to believe. Certainly, teachers in some of the newer areas of physics, like quantum mechanics or wave-particle duality, sometimes despair that our common sense thinking has almost no rapport with such worlds so far removed our day-to-day experience.

The Hydrologic Cycle

Let's start with the present and quickly review what accepted knowledge about the hydrologic cycle is, and then step back to see what attributes make this concept difficult for students to learn, or past investigators to discover. At the global scale, the hydrological cycle is the set of processes that continually move water over and through the surface of the earth and both into and through the atmosphere. Traditional explanations consider the evaporation of water from the land and oceans, the circulation of the atmosphere, the condensation of vapour into liquid, the formation of rainfall, the complex partition of water between surface and subsurface flow, the role of depression and detention storage, and the minor complications of things like interception and stem flow. There is a lot going on here, as these processes touch not only on water and classical dynamics, but also thermodynamics, meteorology, chemistry, geology, oceanography, cosmology and many other sciences.

Let's pause a moment longer to consider just one component, the apparently simple idea of "evaporation" from the oceans, and the traditional "start" of the hydrologic cycle. But what exactly is evaporation? We now know this process involves a key phase change whose huge energy requirements are primarily powered by the sun. That is, high-energy photons impact and excite water molecules so that some of them achieve a high enough velocity to escape the hydrogen bonds that usually more closely bind them to their neighbors; this is a physical process, not a chemical one, as the water molecules retain their identity across the air-water interface. Evaporation is a relatively invisible process, requiring a set of subtle concepts (conservation of molecular species, atomic theory, diffusion and transport, relative humidity, and temperature effects) or measurement techniques to master.

Certainly measurement of ocean evaporation is not a trivial challenge, even ignoring its spatial and temporal complexity. How many undergrads could propose a viable and reasonable device to measure ocean evaporation? How do you come to grips with a vastly spatially distributed invisible process? Without knowing "lots about a great deal" the whole process feels like the product of "an infinity of space" with a "vanishing of depth." But, as we gradually came to discover over many years, a zero times infinity gives an indeterminate answer, one that might come out to almost anything depending on the details of the limiting process. But it is exactly in the details that the problems lie. Taken together, it is not surprising that our current understanding was achieved slowly and painstakingly, with many false steps. If one imagines a modern undergrad being transported, equipped with a modern hydrological explanation, to the past, they'd be more likely to be met with ridicule and laughter than ready acceptance! And for them to prove the modern explanation in an ancient context, without practical and conceptual support, would not be easy.

Yet we can't stop our considerations here. The hydrologic cycle is no less complex when it occurs at the local level of a watershed, even though here it is more on the scale that permits direct perception and experience. But consider that the precipitation falling upon a watershed may be partially intercepted by vegetation or built structures and thus ultimately be lost to evaporation. Precipitation that reaches the ground can be infiltrated into the soil, some of which is transpired to the atmosphere, while the remainder is stored or slowly percolates in the subsurface. This groundwater constitutes the supply of base flow to rivers and streams. Ponding of surface water will occur when the rate of precipitation exceeds the rate of evaporation and infiltration. As depressions are filled, water will begin to flow overland. This surface runoff is much quicker than the subsurface runoff and usually forms the majority of streamflow during a rainfall event. Streams eventually find their way to bodies of water where evaporation returns water to the atmosphere, but at each stage complications, delays, adjustments or hidden (e.g., ground water) exchanges can occur.

Not surprisingly, the discovery of the hydrologic cycle was a slow and difficult process. Hypotheses were proposed on this subject since the early and classical ages. Development in this area was constrained until the mid-16th century when Bernard Palissy successfully integrated the various components of the hydrologic cycle into theory. Further progress required researchers to develop: (a) a sense of conservation - water molecules change phase, but most remain as water; (b) a sense of magnitude or quantification - to evaluate the relative contribution of terms; and (c) a sense of time -virtually all the processes are unsteady, changing rapidly or slow in time.

The conservation of water perhaps seems trivial today however this concept was not evident to observers of the past. Quantification requires careful and sustained measurements and unsteady processes are inevitably more complex to evaluate than steady ones. Consider the now obvious fact that streamflow ultimately originates from precipitation. Yet there is clearly not a one-to-one relationship between rainfall and runoff. Two common observations obscure the concept of conservation: (a) The volume of streamflow is less than the volume of precipitation - so we must learn how to compute a complex set of losses or abstractions, terms that feel to many students like a poorly fitting patch on a bad job and (b) streams continue to flow even without recent rainfall - thus, much of the water that does run off is not associated with the current rain, but with slow and mostly invisible subsurface processes. This reality requires more patches and more arm waving, otherwise known as "baseflow separation techniques." In fact, even today, it is not trivial to quantify or precisely separate surface from subsurface contributions to stream flow. Thus, apparently obscure and difficult theories of evaporation losses and baseflow are necessary to complete the concept of conservation of water, even at the watershed scale. As humans, we tend to mistrust such long chains of cause and effect, wanting simpler and more emotionally satisfying explanations.

A sense of magnitude was also important to the development of hydrology. The contribution of infiltration to groundwater flow and groundwater flow to baseflow was long ignored because their role seemed insignificant. However infiltration over a large catchment can provide a significant volume of water to the subsurface; another computation tending to "zero-infinity" indeterminacy. Yet, quantification must be instrumental to establish a concept like conservation. Ideas that appear fanciful today flourished without measuring apparatus to disprove them. Modern understanding gained acceptance when verified thorough experimentation (Adams, 1938). Thus development in hydrology owes a lot to the development of time-keeping devices that made possible the precise measurement of time-dependant parameters, not to mention subtle probes and devices to pick up subtle changes.

Palissy's work helped clear up conceptual blocks discussed above. Subsequent experimentation has led to (excuse the expression) a flood of material concerning the topic of the hydrologic cycle. Yet although relatively well understood, the hydrologic cycle continues to challenge scientists and to mystify students, at least at the level of engineering modeling and prediction. As an example of these challenges, even though there may be a degree of scientific consensus about climate change, the implications of temperature changes for the hydrological cycle certainly remain extremely vexing and controversial.

Difficulties in Discovering the Hydrologic Cycle

Early and classical ages

One of the earliest civilizations that dealt with the notion of the hydrologic cycle was the Chinese. The role of precipitation was discussed in several literary works from approximately the 9th century B.C., while the dynamic concept of the hydrologic processes was recognized by the late 4th century or so (Chow, 1976). Yet the most common explanation even up to the Middle Ages in Europe was based on the belief that all rivers and streams issued from one or more subsurface caves or lakes. The first known written proof of this opinion was found in Book XXI of Homer's *Iliad* that refers to 'the mighty deep-circling Oceanus, stream from whom all seas and rivers rise, all springs and bottomless wells' (Homer, 1977: 429).

Later, the Ionic philosopher Anaximenes (585-525 B.C.) studied the meteorological phenomena and presented reasonable explanations for the formation of clouds, hail and snow, and the cause of winds and rainbow. In the 5th century B.C., the Pythagorean philosopher Hippon recognized that all waters originate from the sea (Koutsogiannis and Angelakis, 2003: 2). At the same time, Anaxagoras (500-428 B.C.) and Plato (429-347 B.C.) were based on Homer's poetical view and developed erroneous theories, claiming that a huge cavern inside the earth supplied all fluvial water.

Aristotle (384-323 B.C.), by contrast, correctly articulated the idea that there must be a continuous process. In *Meteorologica* Aristotle rejects the assumption of one large reservoir arguing that, if this were the case, it would have to be 'larger than the earth, or, at any rate, not much smaller' (Aristotle, 1984: 570). He was one of the earliest writers who provided the notion of cycle for the hydrologic processes, by observing natural processes such as the sun rise and recognizing the connections between water, air and the sun, as well as the resulting phenomena, such as rainfall, evaporation and condensation, which he explained in a simplified yet innovative for the time way.

> *So we get a circular process that follows the course of the sun. For according as the sun moves to this side or that, the moisture in this process rises or falls. We must think of it as a river flowing up and down in a circle and made up partly of air, partly of water.* (Aristotle, 1984: 566).

He hypothesized that waters of springs and rivers take their origin from three different sources, from which only the first is still accepted nowadays (Adams, 1938: 429-430): (a) Rain that has been formed by the condensation of air into water in the high atmosphere falls upon the earth's surface and sinks into the earth that then retains it like a sponge; (b) condensation of air to form water that entered the earth's crust from the external atmosphere; and (c) condensate vapors which rose from a source not stated in the text. Yet, although his explanations were sometimes reasonable, he found it impossible to believe that it was rain alone that fed the springs and supplied the rivers and he struggled with the difficult question of how streams can continue to flow for many weeks in the absence of rain (Deming, 2005).

The general understanding during the Roman Age could be summarized by the philosopher and dramatist Seneca (3 B.C.-65 A.D.), who also considered rainfall inadequate to supply all rivers and springs.

Rainfall may cause a torrent, but it cannot maintain the steady, constant flow of a full river. Rains cannot produce; they can only enlarge and quicken a river. (Adams, 1938: 431).

Seneca recognized the significant role of evaporation and believed that the co-existence of air and water is the main force that directs water to flow out of the earth and form springs and rivers. Marcus Vitruvius (1st century B.C.), a crucially important Roman writer, scientist and engineer, in his book *De Architectura* provided a scientific explanation of precipitation and the processes that led to the formation of springs in the mountains based on evaporation mechanisms and landscape, which is much closer to what is accepted today.

Middle ages and Renaissance

Between the 1st and the 17th century A.D. most sciences remained inactive. Therefore little attention was directed to the subject of the hydrologic cycle and the first theory of the large subterranean reservoirs was prominent. However, the coming of the Middle Ages brought the subject again to the surface and new approaches were gradually developed. Historically, the strongest intellectual influence of that time was the teaching of the Christian Church. The Bible was the main, if not the only, reference for almost all scientific publications. According to the book of Ecclesiastes the ocean was the source of all moving bodies of water, such as rivers and springs.

All rivers run into the sea, yet the sea is not full: unto the place from which the rivers come, thither they return again. (Adams, 1938: 432).

The conceptual model was built (correctly) on a cyclic understanding of the hydrologic cycle; however, the interpretation of the Biblical text contained an incorrect assumption that the cyclic process was facilitated through holes at the bottom of the sea. It was believed that the flowing water traveled from the assumed holes up to the mountain summit through subterranean passages and then back down the mountain as springs and rivers. Since most writers and scholars were somehow connected with the Church, this belief was quoted with tiresome reiteration throughout the medieval period (Adams, 1938: 432).

One of the most famous scholars of that age is the German Jesuit Athanasius Kircher (1602-1680), who dealt with the hydrologic cycle in his 1664 book, *Mundus Subterraneus*. Kircher rejected Aristotle's view of evaporation and condensation in underground caverns, since he argues this process could not supply the rivers with sufficient amounts of water. He supported and extended the explanation provided in the book of Eccleciastes, considering the sea as the source of all springs and rivers. According to his analysis, the earth's interior is crossed by numerous subterranean passages that lead water into great reservoirs within the mountains and then supply it to the surface in the form of springs. *Mundus Subterraneus* is indicative of the medieval difficulty of perceiving the temporal discontinuity between rainfall and river flow, which is the main reason why precipitation was not recognized as sufficient to supply rivers with all their water.

(...) nor would a perpetual flow be secured by the accession to it of supplies of water from rain and melting snow, for such contributions would be intermittent and the flow supply of water to the rivers would be irregular. (Adams, 1938: 436).

Another explanation for the hydrologic cycle was provided by the theory of Alembics, which was first set forth J.J. Becher's (1635 - 1682) book *Chemisches Laboratorium*. According to his observations, the earth resembles a giant alembic or distillation apparatus. The seawater that penetrates from the ocean bottom into the earth is heated by the underground fire and is vaporized. On its way to the surface, it easily enters the cavernous interior of the mountains. Since the mountains are covered with snow the temperature is significantly lower and therefore the vapor condenses to water, which forms springs that run down the mountain slopes and end again in the sea. Furthermore, there were two significant contradictions that show the shortcomings of the theories of that time and that caused discussion and motivated research regarding the explanation of the hydrologic cycle: (a) The assumption that water rises up from the sea level to the mountains is against its nature, since it normally follows the reverse route, moving from high to low elevations and (b) if the ocean is connected with the mountains, then the fact that the water of the sea is salty, while the water of the rivers and the springs is fresh is a contradiction. All efforts to answer those two questions were a mixture of arbitrary hypotheses, speculations and religious beliefs, generally lacking any scientific basis. For example, several theories were developed claiming that the surface of the Ocean is higher than the Land, and therefore the movement of water to the mountains is reasonable, or that the water's reverse movement is in obedience to the word of God or that fire from the earth's interior heats the groundwater and causes its evaporation to the surface. With respect to the concern about water salinity, it was widely accepted that water was filtered during its movement from the sea to the mountains through geological layers of very low porosity that removed the salt.

The early Modern ages and the correct understanding of the hydrologic cycle

One of the first correct approaches to the true explanation of the hydrologic cycle was proposed by the Italian polymath Leonardo da Vinci (1452-1520), who recognized the role of pervious hydrogeological structures, especially those having a great slope and lying on impervious layers. Rain and melting snow from the top of mountain ranges can be infiltrated by the pervious beds, carried for long distances below the earth surface and either flow out again as springs or end into the sea.

However, the person who managed to set forth an integrated theory for the hydrologic cycle and explain the process in a scientific way was the French Bernard Palissy (*ca.* 1510-1590). In his 1580 book *Admirable Discourses*, Palissy rejected all previous theories using convincing and sound arguments and first stated that rain and melting snow were the only source from which springs and rivers derived their waters.

> *When I had long and closely examined the source of the springs of natural fountains, and the place whence they could come, I finally understood that they could not come from or be produced by anything but rains*. (Palissy, 1957: 48).

In more detail, Palissy thoroughly defines the cyclical route of water, describing processes such as precipitation, evaporation and condensation, infiltration, surface run-off as well as groundwater storage and discharge. Another interesting aspect of Palissy's work, indicative of his deep and broad understanding of nature, is the fact that he provided a sound explanation of the temporal discontinuity between rainfall and river flow, with which all scholars from Aristotle to Kircher, had struggled.

> *(…) rain water that falls on mountains, lands, and all places that slope toward rivers or fountains, do not get to them so very quickly. For if it were so, all fountains would go dry in summer: but because the waters that fell on the land in winter cannot flow quickly, but sink little by little until they have found the ground floored by something, and when they have found rock they follow its slope, going into the rivers. From this it follows that under these rivers there are many continual springs, and in this way, not being able to flow except little by little, all springs are fed from the end of one winter to the next*. (Palissy, 1957: 68).

In the following years, when Science had already started moving towards another level of understanding, numerous scholars examined the topic in depth. In 1674, Pierre Perrault presented the results of his efforts to experimentally quantify the hydrologic cycle. In his book *De l' Origine des Fontaines*, he considered a certain catchment area, calculated the average rainfall which fell upon the area using a rain gauge and then measured the amount of water carried off the area by measuring the volume that passed through a certain canal. According to his findings, the ratio of the volume of rain to that of river flow was 6 to 1, giving sound proof that rainfall is more than adequate to supply springs and rivers; in fact, more processes than precipitation and run-off were required to complete the hydrologic budget. A similar experiment carried out a few years later by the French physicist and priest Edme Mariotte (*ca.* 1620-1684) provided an even greater ratio of approximately 8 to 1 (Adams, 1938).

One significant step further was achieved by the research of the Italian medical scientist and naturalist Antonio Vallisnieri (1661-1730), who spent long periods in the Alps in order to examine the natural mechanisms that created springs and rivers. His greatest finding is the notion of infiltration. He observed that although the snowfields of Monte S. Pellegrino were extensive, the rivers near Modena were small and weak. A careful observation revealed that water produced by melting snow was flowing down from pervious layers below the earth surface and followed an invisible underground route for a long distance beneath Modena towards Bologna. As a result, the subterranean passages that were discussed during the Middle Ages existed, but their role was not to carry seawater from the ocean upwards to the mountain tops, nor fire, but simply and quietly to transfer water from one area to another (Adams, 1938). Thus, it was really only by 1715 or so when it could be said that humanity finally managed to form a complete picture of the hydrologic cycle.

In the decades that followed, the correct theory regarding the hydrologic cycle gained gradual recognition since the proofs were based on observations, experiments and quantification. Although the traditional explanations, also supported by a strong religious background, still received some support; indeed, numerous scientists, like Vallisnieri, were considered to be heretics. Thus, the true theory was not widely accepted until the middle of the 18th century.

Difficulties in Teaching the Hydrologic Cycle

It is the observations of many academics that teaching the hydrologic cycle to students is quite challenging. Although a minority typically grasps the concepts well, many students struggle with the relationships between hydrologic components, finding concepts of baseflow, abstractions, hydrographs, and cycles of storage and release deeply counter-intuitive and confusing. The difficulty for students to grasp the hydrologic cycle can perhaps partly be explained by recognizing that there are two parallel forms or learning (Vanderburg, 2000): (a) Knowledge Embedded in Experience (KEE) and (b) Knowledge Separated from Experience (KSE).

KEE is the knowledge we gain through daily-life activities. This knowledge is at work when, for instance, a baby learns to speak. Formal grammatical rules are not made explicit but are learned informally by being embodied in the world. KSE in contrast is knowledge that is gained primarily though school-based learning. These two forms of learning remain distinct as can be seen whenever a student in editing an essay recognizes a grammatical mistake without ever knowing the specific grammatical rule broken.

Prior to taking a course in hydrology, a student develops intuitive knowledge about the physical world though daily-life experiences. Rainfall intensity is felt when walking in the rain and an understanding of interception is displayed by running under a tree or some other structure for shelter. The "intuitive physics" a student learns is developed by interacting with the world from the outside in (Vanderburg, 2005). Yet, many modern students have only rudimentary experience with rainfall and with runoff, quite in contrast to what occurred in students with a farming or rural background. And direct experience is not well suited to the challenges of hidden or invisible processes with long time delays.

Upon taking a course in hydrology a student is expected to live within a mathematically abstract world. This artificial world is in contrast to the "real world" because mathematical expressions cannot be experienced (Vanderburg, 2005). Furthermore simplifying assumptions abstract the reality to a point where a student cannot recognize the physical world an equation approximates. Even basic concepts, such as the fact that runoff can continue to increase after a storm, are often surprising and confusing to students who have not experienced this reality, and who perhaps have been overly influence by an instant gratification paradigm. Thus, the KEE and KSE worlds are not just separate as they usually are, but actually often in conflict, with little crossover of ideas or intellectual reassurance.

Further confusion might be experienced when trying to determine when to include and when to exclude certain components of the hydrologic cycle (e.g., ignoring groundwater flow and evaporation losses in the mathematical analysis of a rainfall event). Experience with a backyard garden can guide a student in choosing to water plants a bit more on really sunny days because the plants almost dried out on the last sunny day. However, mathematical expressions divorced from context cannot guide a student in determining when certain terms become important or what kind of accuracy is reasonable to expect.

Dreyfus (1994) gives insight to this problem. Daily experiences develop assumptions of the world that are stored in the metaconscious. These assumptions form the background of perception and help interpret new information and current experiences. The metaconscious makes decision making efficient by focusing the conscious on a narrowed set of relevant choices based on past experiences. On the other hand, mathematical equations, devoid of context, must treat all relationships are possibly relevant (Dreyfus, 1994). Without physical experience to guide and with no direction from equations, students are usually confused and overwhelmed by the information that needs processing.

Links between Historical and Teaching Difficulties

The slow development of the current understanding of the hydrologic cycle and the difficulty of modern students to grasp the concepts is by no means a coincidence. Both problems are linked (literally and metaphorically) by what occurs under the surface.

For ancient civilizations "what occurs under the surface" refers to the fact that the subsurface component remained hidden from human observation. Temporal and spatial variations in the subsurface further removed this component of the hydrological cycle from their experience. The ancients resorted to what Kahneman and Tversky (1982) termed their perceptual best bet. Visual experience of above ground phenomena shaped their expectation of the below ground processes. History is overflowing with examples. Aristotle argued that groundwater formed from the condensation of air to water in the coldness of the earth much like above ground air condensed into water (McCulloch and Robinson, 1993). Athanasius Kircher in the 17th century proposed that the earth was crisscrossed with passageways for water in the same way the human body is composed of a network of veins and arteries (Adams, 1938). These incorrect understandings of the hydrologic cycle are congruent with Vanderburg's analysis of KEE (2005). Such knowledge is limited when what can be experienced does not co-relate well with what is happening and when outcomes are the result of gradual processes.

Since KEE was insufficient to progress the field of hydrology, science and experimentation (KSE) were relied upon to answer the question "what happens when it rains?" This body of knowledge now presents a problem to modern students. Under the surface students are still primarily guided by KEE and their mental maps. Their intuition conflicts with the logic of mathematical expressions. This is one reason why laboratories and practical component of courses are integral to the development of strong students. Practical works allow students to gain visual and physical experience and to correlate "reality" to the context-less abstract world of theory.

Conclusions

This paper primarily examines the connections between the convoluted understanding of the hydrologic cycle throughout history and the challenges that remain even today for teaching these concepts to modern and often urbanized university students. The paper also briefly reflects on the significance this observation might have to broader issues of human learning.

Hydrology and hydraulics are indicative research fields where the enfolding of cultural understanding is quite apparent. The historical review shows how human understanding, influenced to an extent by the conditions of each age, may have been grounded by direct observation of the natural phenomena, but was also strongly influenced by speculation and human creativity, often mixed with mythology, literary and religious considerations. What makes such flights of imagination so understandable is that large components of the cycle that are hidden (e.g., groundwater flow), invisible (e.g., water vapour), spatially distributed over large areas (e.g., infiltration), or significantly delayed in time (e.g., baseflow). The net result is that a full understanding was achieved no earlier than three centuries ago, when humanity finally managed to obtain sufficient background to establish a correct and complete explanation.

An analogous process, yet on a significantly smaller scale and under different circumstances, takes place in a classroom, where students struggle with the various hydrologic concepts and try to obtain a sense of time and magnitude in order to translate experience into knowledge. Systematic knowledge, as the result of a long and often mathematically intensive procedure, needs the contribution of intuition, while at the same time experience on its own could disorient a student, or even a researcher, when it is not framed by both sound scientific tools and a holistic sense of system behaviour.

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Water Purification: From Ancient Civilization to the XXI Century

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Abstract: Ancient civilization valued the vital role of water in human life. As reflected in the literature, environmental awareness led to early water treatments and these are briefly described in this paper. Thus the period prior to 500 B.C. to 1000 D.C. saw the use of naturally occurring materials for water purification, the building of aqueducts, and the introduction of the distillation process. This was followed by a dormant period of five centuries in which hardly any progress was made in water purification methodology. From the 17th to the 19th century, progress was made on filtration processes, the introduction of the microscope. In addition chemical methods for water disinfection by the use of chlorine and ozone were reported. These methods and their combination progressed significantly through the 20th century. However the problems associated with chemical contamination of ground water, from which, drinking water is mainly generated remained practically ignored for about five decades. It was in the late seventies that this was brought to light. Since then technologies for groundwater purification started to emerge but a lot remains to be done in this area of research. The crucial role of suitable analytical tools for any technological development which aims to remove toxic pollutants from water is acknowledged. Thus need of re-visiting old methodology making use of the advantages resulting from the availability of advanced analytical techniques and the possibility of enriching naturally occurring materials by the introduction of selective receptors for water decontamination purposes are emphasized. These are being tested in permeable reactive barrier systems for the removal of pollutants from groundwater.

Keywords Hyppocratic filter; molecular chemistry; natural attenuation; water purification.

Introduction

Water is a chemical substance essential to life to an extent that we cannot live without it. As such, water is closely tied to the history of civilisation. Although scientific achievements have contributed significantly to our present understanding of the role of water in every day life, there is a great deal to be investigated on its unique physico-chemical properties.[1,2]

In the last few decades the concept of Supramolecular Chemistry has been introduced by Lehn.[3,4] Unlike Molecular Chemistry (which involves the interaction between atoms by covalent bonds to give molecules), Supramolecular Chemistry is concerned with the interaction between two or more chemical species to give the ‘supermolecule’ through weaker interactions (electrostatic forces, hydrogen bonding, van der Waals, etc) than those involved in Molecular Chemistry.[5] Within Supramolecular Chemistry the concept of ‘self assembly’ has been extensively discussed[6] in recent years. In fact, water, the most known

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chemical substance, shows self-assembly behaviour. Considering its use, water boils at relatively high temperature while its freezing point is much higher than expected.[1,2] This is attributed to the self-assembly behaviour of water through hydrogen bond formation, regarded by Steed and Atwood as the master key interaction in Supramolecular Chemistry[6] (Fig. 1).

Being water such an essential component of life, the search for clean water was already a subject of priority concern in Ancient Civilisations.[7] This paper aims to give an account on the main developments in water purification from ancient civilizations up to modern times and how chemistry has contributed to these developments.

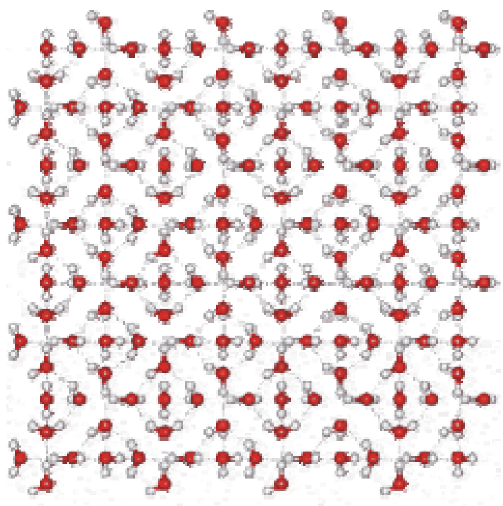

Figure 1 The Structure of Ice.

Historical Developments

For the purposes of this paper, it seems relevant to define the areas covered in Ancient Civilizations. According to the literature Ancient Civilisation of the old World covers parts of Africa, Southern Europe, the Middle East and Asia to India. Thus prior to 500 B.C. there was already concern about the quality of drinking water[8]. Thus the lack of awareness about the fact that toxic and tasteless substances may be present in clear water led ancient civilization to believe that the clarity and taste of water as assessed by visual observation was an indication of its suitability for drinking purposes.

However the use of chemicals to purify water mainly to improve the appearance and taste of water dates back to the 500 B.C. period. Indeed the Egyptians used iron sulphate or aluminium sulphate or a mixture of the two to extract suspended solids from water. These were known in ancient times as Alum and differs from the variety of alums derived from clays, bauxite or Alum from Alunite known today (potassium alum [$K_2SO_4.Al_2(SO_4)_3.24H_2O$]; sodium alum [$Na_2SO_4.Al_2(SO_4)_3.24H_2O$]; chrome alum [$K_2SO_4.Cr_2(SO_4)_3.24H_2O$]; ammonium alum, $NH_4Al(SO_4)_2.12H_2O$]). There are representative examples that coagulants were already used in the early stages of civilisation. These coagulants are still used nowadays. Of course parameters such as doses of coagulants, pH and colloid concentrations are now considered.[9,10]

Water conservation and properties were already a matter of concern in Ancient India. Thus awareness regarding the presence of minerals in drinking water as well as its acid-base pH balance were among the properties required for pure water besides temperature (cold to touch), cleanness and transparency. As far as water purification methods used are those involving naturally occurring substances such as mixtures of herbs,[9,10] including Amla (known today as an antioxidant with the richest source of vitamin C) and Khus (Vetiver, known as oil of tranquillity) among others. These herbs were introduced to water in wells for purification purposes. Others methods used for water purification, based on herbs and naturally occurring products and materials are Nirmali seeds (strycnos potatorum, found now to be, useful in obstetrics), roots of Kanal (lotus/ water lily), rhizomes of algaes and different types of stones such as quartz crystals, garnet and pearls.

Treatment of water with iron or sand (hot) or exposure to sunlight was used. For disinfection, boiling followed by exposure of water to sunlight or the introduction of iron, copper or sand (hot) in water were recommended. It is now well established that copper interferes with the life cycle of bacteria. [11,12] In fact the use of brass containers to store water was already common practice in Indian Ancient Civilization. Achievements in water purification methods in the 500 B.C. to 1500 A.D. period are those by Hyppocrates, a Greek philosopher of the classical period (~ 460-360 B.C.).[7] In his article on Airs, Waters and Places,[13] he emphasized the importance of considering the qualities of water and gave a detailed account through the different parts of his article, on the implications arising from drinking different types of water on the human body and general health. He is acknowledged for introducing the conical water filter known as Hyppocratic filter.

Numerous aqueducts (~ eleven) were built in Ancient Rome in the 312 B.C.-226 A.D. period. These were essentially artificial channels for the transport of water to the city powered by gravity. The fact that the availability of water per inhabitant was around 1 m^3/day gives a clear indication that water scarcity was not a problem at the time for a population of over a million people in the city.

Geber (721-815 A.D.)[13,14] belonged to the current of Alchemists of Ancient Civilization. He declared that '*The first essential in Chemistry is that you should perform practical work and conduct experiments, for he who performs not practical work nor makes experiments will never obtain the least degree of mastery'*. Among his many contributions to Chemistry and Alchemy, he introduced, among many other contributions, the distillation process for water purification.

Avicenna[15] considered boiling as a water purification process by which the impurities are left in the mineral residue[16]. Purification of water by passing it through a wick of sheep's wood was also suggested. However the fall of these civilizations for different reasons interrupted the developments of methodologies for water purification during the 1000-1500 A.D. period. Indeed there are no records of any significant development during this period. It was in the 17th century (1627) that following a compilation of Natural History over ten centuries. Sir Francis Bacon, philosopher and scientist, introduced his thoughts about desalination, an area of research, which is still in progress today. However his idea on that the passage of water trough sand by making a hole close to the sea shore would lead to the removal of salt from water did not work. Other important developments during the 17th century are: (a) the invention of the microscope[17] by the Dutch Antony van Leeuweenhoak (1632-1723) but no importance was given at the time about his observations of organisms. Having stated it, the realization that the placement of lens in a tube leads to the magnification of objects as discovered in 1990 by Z and H. Janssen should be acknowledged. It was on the basis of Janssen's work that van Leeuweenhoak invented the microscope and (b) the design of the multiple filter by the Italian physician Lu Antonio Porzio.

These two developments are undoubtedly essential tools in biology and water analysis and treatment. Indeed it was the microscope which allowed scientists to visualize living organisms in water to the extent that in 1850 (London) it was this instrument and its improved version which allowed the detection of the cholera bacteria while filtration of water through sand filters significantly reduced the outbreak of cholera.[18] In fact, a British scientist John Snow found a link between cholera and poor water quality.

Prior to this incident during the 18th century, concern about the implications of poor quality water on human health grew significantly. This was mainly motivated by philosophers (16th-18th centuries) who were strongly of the view that pure water was one of the rights of the human race. This statement is based on the fact that the French scientist La Hire put forward a proposal by which sand water filters should be installed in all French households. Two patents were granted in the 18th century, the first one to the French man Joseph Army for designing a filter consisting of sponge and sand while a second one was granted to a British architect, James Peacock in 1791 on the design of a three-tank, upward-flow backward filter[7,10,18].

A century later following La Hire's suggestion, the first municipal water treatment plant was installed in Scotland as recorded by Baker and Taras. The aim was to provide filtered water to every household. Filters used were those designed by Thorn and later on by Simpson. However two main drawbacks were encountered in that these filters were slow and their size were too large. Consequently their cleaning was a time consuming exercise. These problems were overcome by the development of fast water sand filters in the USA[18] which were easily cleaned by extensive jet streams of water.

However the ceramic revolution started in 1827[19] when Henry Doulton introduced the ceramic filters to remove bacteria from drinking water using earth and clay materials. In 1835 at the request of Queen Victoria, Doulton produced a water filter which was considered a mixture of art and ceramic technology. Indeed the container was a combination of hand-crafted with ceramic filters technology. This development had a considerable impact on sanitation. Almost simultaneously to Pasteur's discoveries on micro-organisms, Doulton designed in 1862, filters for micro-organisms and subsequently microporous ceramics (diatomaceous earth) capable of removing bacteria with a high degree of efficiency (higher than 99%).[19] These developments had worldwide impact.

The progress made on ensuring water quality in the USA led to the foundation of the American Water Works Company followed by initiatives aiming to standardise bacteriological tests[7]. Filtration methodology expanded significantly in the last two decades of 19th century and thereafter. At present, whole house filtration systems are claimed to be the most up to date water filtration technology. Placed in individual houses, water is filtered as soon as it reaches the house's plumbing system to remove from it, toxic substances.

The effect of the Industrial Revolution was strongly felt. Thus at the end of 19th century chemical methods for tackling water infection were introduced. The aim was to liberate water from harmful bacteria and viruses using either ozone or chlorine for this purpose. The scope and limitations of these two methods as well as other recent approaches for water disinfection have been discussed in the literature.[20]

The Industrial Revolution in the 18th century brought about the exploitation of natural resources and labour with the consequent increase in population and human activities. The developments led to a negative impact on our ecosystem. Chemical contamination started to be a matter of concern. However this concern was mainly centered on surface waters of rivers and lakes. As far as groundwater is concerned, from which drinking water is mainly generated, the issue of chemical pollution remained dormant for about half a century. It was assumed that Nature through the filtration properties of soil offered a suitable purification method to liberate groundwater from chemical pollutants. It was in the 1970s when chemical contamination of groundwater began to be and still is a matter of serious concern. [20]

By then, very well established methods of chemical analysis were available and new methods were appearing. These are essential tools for the detection (qualitative and quantitative) of contaminants in water as well as for the development of new technological approaches for the removal of pollutants from water. Thus the invention of the hollow cathode lamp by Welsh in 1955 has made absorption atomic spectroscopy one of the most popular analytical techniques in water analysis.[21] The introduction of Inductively Coupled Plasma Mass Spectrometry (ICP-MS) in the eighties[22-24]added a very powerful tool for the detection of trace (ppb-ppm) and ultra (ppq-ppb) elemental analysis. Among electrochemical techniques, particular mention should be made voltammetry and potentiometry. The latter has a wide range of applications due to the development of ion selective electrodes, which are currently used for water quality monitoring (ammonium and nitrates in groundwater, cyanide, mercury, cadmium, copper etc).[21, 25]

A wide variety of chemical pollutants can be found in water. Among these are organic compounds (hydrocarbons, oxygenated hydrocarbons, halogenated aliphatic and aromatic compounds, metal cations (cadmium, mercury, copper, lead, chromium). Non-metallic species (arsenic and selenium) and oxy-anions (nitrates and perchlorates)[20] and common anions such as fluoride.[26] As a result several technological approaches have been developed to tackle the problem of ground water contamination by chemicals. Among these are the conventional ones, Natural Attenuation., Free Product Recovery (non-halogenated, semi-volatiles and hydrocarbons), Air Stripping (volatiles), Carbon adsorption (semi-volatiles) and the Slurry Walls (all contaminants).[20, 27] Advantages and disadvantages of these approaches can be found in the literature. Some innovative approaches have been reported. Of particular interest are those using permeable reactive barriers[28-30] which have been successfully used for the removal of halogenated hydrocarbons, aromatic and nitro aromatic compounds as well for inorganic pollutants such as lead, chromium, uranium and arsenic. Among the materials used in the barriers are those of high sorption capacity. To the writer's knowledge highly selective materials based on supramolecular systems have not yet being investigated in these systems. Therefore there is still scope for improving these processes and to further expand their range of applications.[31-33] However the use of naturally occurring materials used in Ancient Civilization such as clays and plants need to be revisited. This statement is based on the progress recently made on the uptake of heavy metals by clays and the enrichment of the latter by grafting selective receptors onto it.

Conclusions

From the above discussion it follows that:

(a) Ancient Civilization has provided the basis for many technological approaches that are in current use. In fact, the ancient treatment of filtering water through sand and charcoal filters has gone a long way to the extent that whole house filtration systems are claimed to be the most efficient technology for the removal of chlorine by- products and organic pollutants.

(b) The idea of using naturally occurring materials for water purification such as clays and plants introduced in early civilisation for water purification is still a research area of considerable interest particularly if these can be enriched by receptors able to interact selectively with heavy metal cations such as mercury speciation, lead. cadmium and many other polluting agents. These still pose a serious threat to the environment and to human health. [34]

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An Overview of the Historical Evolution of the Science of Meteorology

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Introduction

During the last century Meteorology has turned into one of the most significant fields of Physical Sciences, as human activities have expanded. Not only huge steps have been made for the acquisition of meteorological knowledge, but also efforts to alter weather phenomena. The history of meteorology can be roughly divided into three periods. The "Hypothesis Period", which covers a period from the first attempts of man to address weather phenomena up to 1,600 D.C. This period was strongly influenced by Aristotle's work *Meteorologica*. The second period "The birth of scientific meteorology" from 1,600 D.C. up to approximately 1,800 D.C. is characterized by the invention of the basic instruments used in weather observations such as thermometer, barometer and hydrometer. Finally, from 1,800 D.C. up to now, the third period in the history of Meteorology called "Modern Meteorology", in which advances in technology and sciences made possible the distinction of Meteorology from other related physical sciences. Few of the most significant improvements in the science of Meteorology from "birth" up to now can be seen in Figure 1.

The "Hypothesis" Period

It is nearly impossible to determine the exact "beginning" for the science of meteorology, as with most physical sciences. A distinction must be made between meteorology as a science and meteorology as a "branch of knowledge". Progress on meteorology has been achieved by fulfilling two of human's basic needs; the need for utilizing the earth and the environment and the need to discover the physical laws of nature.

The first men on earth were farmers and hunters; therefore they were strongly dependent upon atmospheric conditions for their existence. Although they could not adequately explain many atmospheric phenomena (a problem we still have today), a collection of weather "signs" was accumulated and handed down from generation to generation. In ancient Egypt weather had religious character. Generally, in most ancient civilizations weather phenomena believed that was under God's mood and control. In Babylonian civilization, which flourished between 3,000 and 300 B.C. in the Middle East, weather phenomena were related to celestial bodies. Babylonians were the first that established "astrometeorology". Although weather concerned most civilizations, the ancient Greeks were the first that made regular weather observations and formulated weather theories, thus, the term "meteorology" comes from the Greek words "meteo"… something hanging above us and "orology"… to say about.

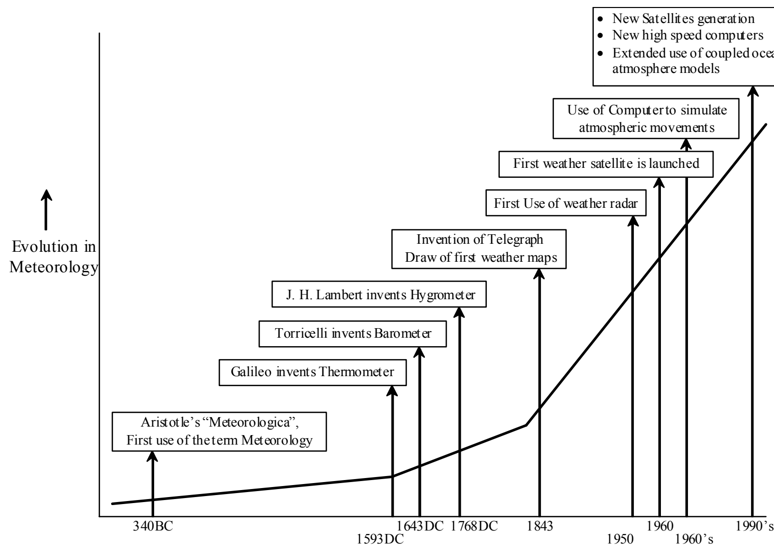

Figure 1 Significant improvements in the science of meteorology.

In the 7th century B.C. Thales of Miletus associated weather with movement of the stars and planets. He considered water to be the basic element of all matter. Anaximander thought that wind was moving air. This idea was later rejected by philosopher Aristotle (Frisinger, 1975). Aristotle was the first that used the term "meteorology" in 340 B.C. when he wrote a book on natural philosophy entitled *Meteorologica*. This work presented the philosophical knowledge of the atmosphere at that time and included topics such as clouds, mist, rain, snow, wind, hail, lightning, thunder, and climatic changes. In addition, several natural sciences such as astronomy, geography and chemistry were also addressed in his work. The manuscript was entitled *Meteorologica* because in those times, any particle which fell from the sky, or was suspended in the atmosphere, called a meteor. Today, we distinguish between "meteors" (extraterrestrial meteoroids) and "hydrometeors" (particles of water or ice in the atmosphere). In *Meteorologica*, Aristotle attempted to explain atmospheric phenomena in a philosophical manner. Several years later,

Theophrastus, a pupil of Aristotle, compiled a book on weather forecasting, called the Book of Signs. His work consisted of ways to foretell the weather by noticing various weather-related indicators, such as a ring around the moon, which is often followed by rain. The work of Aristotle and Theophrastus remained of dominant influence in the study of weather and in weather forecasting for nearly 2,000 years!

During the next 2,000 years, careful observations led to predictions presented in terms of weather folklore. Scientific endeavors declined under Roman rule. Ptolemy (85-165 A.D.), a noted astronomer, stated rules associating the moon's color and clarity with changing weather conditions. Furthermore, Ptolemy constructed a map of the known world and separated it into climatic zones based on the changing length of day at different latitudes and the associated temperature variations. Between 400 and 1,100 A.D., growth in meteorological studies was limited. An Englishman, Bede the Venerable (673-735), expressed a view of meteorology that was remarkably similar to Aristotle's, even though Aristotle's works were not known in Western Europe before the 12th century. Religion played a strong role in the interpretation of meteorological phenomena during that time.

Moslems helped preserve science history and translated many Greek and Hindu works into Arabic. The Moslem physicist Alhaen (965-1039) discussed atmospheric refraction and defined twilight when the sun is 19 degrees below the horizon. This finding led to an estimate of the atmospheric height of about 49 miles. In the Medieval period, scholars relied on translated written works as a basis for truth. This practice began to change in the 12th century, when Roger Bacon commented on Meteorologica and insisted that experimentation and observation were fundamental to good science. Later, Descartes (1596-1650) established the philosophy of scientific method in the 17th century. His philosophy summarized that: Nothing is accepted as truth unless it is proven; personal judgment is not allowed to prejudice conclusions; every difficult problem is solved by considering smaller parts of the problem; and proceed from simple to complex, building on knowledge.

Descartes presented a discourse on meteorology as an example to apply his new scientific method in comparison to Aristotle's work. He emphasized the importance of using mathematics and physics for application to all physical sciences. However, Descartes and all other natural scientists of his time still did not have the instruments needed for quantitative observations in the atmosphere.

The "Birth" of Scientific Meteorology

The birth of meteorology as a legitimate natural science occurred near the end of the 16th century. It had become increasingly evident that the speculations of the natural philosophers were inadequate and that greater knowledge was needed to further our understanding of the atmosphere. In order to do this, instruments were needed to measure the properties of our atmosphere (i.e., temperature, moisture, pressure); instruments which had not yet been invented.

The first of these inventions was the hygrometer. The Greek philosophers seemed to understand the basics of how water circulated through the earth-atmosphere system even without instruments. However, water in its vapour state is invisible; therefore, was the least understood. Questions concerning the properties of this "invisible water" led to the invention of a humidity-measuring instrument by the German mathematician Cardinal Nicholas de Cusa around 1450. Nicholas de Cusa hung out some wool and noticed that was heavier when moisture condensed on it. Around 1593, Galileo was the first to realize that gases and liquids expand when heated, and he invented the first thermometer (Frisinger, 1975).

Throughout the 17th century, different thermometers were developed, but the scales and accuracy of these instruments were questioned. In 1714, Gabriel Daniel Fahrenheit constructed a mercury thermometer which was the first to contain a reliable scale for measuring temperatures as low as the freezing/melting point of water (32°F) and as high as the boiling point of water (212°F). In 1742, the Swedish astronomer, Anders Celsius, proposed a new scale for thermometers. This "centesimal" (meaning 100 divisions) system was much easier to use for scientific work and became the basis for the "Celsius", or "Centigrade", temperature scale. When this scale was developed, Celsius classified the freezing/melting point of water as 100° and the boiling point of water as 0°. The inverse (0°C: freezing; 100°C: boiling) of this scale which we use today was introduced in 1743 by Jean Pierre Christin of Lyons. In 1862, Lord Kelvin, a Scottish mathematician and physicist, proposed an absolute temperature scale. Although many improvements to thermometers were yet to be made (and are still being made today), by the end of the 18th century satisfactory scientific investigations were being conducted about the temperature characteristics of our atmosphere.

Another product of 17th century investigations was the development of an instrument designed to measure atmospheric pressure - the barometer. The invention of the barometer is attributed to Evangelista Torricelli, an Italian mathematician who studied under Galileo. In

1643, Torricelli and a student, Vincenzo Viviani, constructed a vacuum tube and used mercury to measure the weight of the air. The science of meteorology benefited from advances in other sciences, technology, and mathematics. In 1660 Irish-born English scientist Robert Boyle discovered the relationship between pressure and volume of a gas. In 1686, Edmund Halley (the English astronomer who discovered Halley's Comet) proposed that air is heated by the sunrises and winds are caused by air flowing in to replace air that has risen. English meteorologist George Hadley, in 1735, used physics and mathematics to explain how the earth's rotation influences the trade winds in the tropics. In the 1740's, by flying a kite in a thunderstorm, American statesman and scientist Benjamin Franklin demonstrated the electrical nature of lightning and proposed that storms move from place to place. In 1768, John Heinrich Lambert developed the hygrometer (Frisinger, 1975).

French chemist Jacques Charles, in 1787, discovered the relationship between temperature and volume in a gas. The first system of classifying clouds was formulated by French botanist and zoologist Jean-Baptiste Lamarck in 1802. In 1803 Luke Howard, an English naturalist, derived a better system of classifying clouds. In 1806 British Admiral and hydrographer Francis Beaufort invented a wind scale for mariners. In 1830, William Redfield, a Connecticut peddler discovered the circular path of a hurricane. He noticed that after a hurricane, trees in eastern Connecticut fell in one direction, while those in the western part of the state fell in the other direction. In 1835 French physicist Gaspard de Coriolis mathematically demonstrated the effect that the earth's rotation has on atmospheric motions. Moreover, complex equations concerning fluid dynamics were solved, during that period, giving the science of meteorology a step forward in forecasting atmospheric motions.

Before 1814 individuals, typically without adequate instruments or means of communication, were limited to their personal observations or impressions of weather phenomena at the best. Their contribution to meteorological science consisted primarily of their more or less reliable long term record of the climate in their area. Given the instruments needed, the technology to transmit and receive weather observations and advances in chemistry, thermodynamics, and fluid physics, the basic elements were now set for the rapid growth of modern scientific meteorology.

Modern Meteorology

As these meteorological instruments were being developed during the 18th and 19th centuries, other related technological developments impacted our knowledge of the atmosphere. The invention of the telegraph in 1843 allowed for the routine transmission of weather observations to and from observers stationed across the country. This was very important for studying the formation and movement of individual weather systems rather than simply accumulating statistics for climatology. Using this data crude weather maps were drawn and surface wind patterns and storm systems could be identified and studied on much larger time and space scales.

A significant point in the science of meteorology took place around 1920 when a group of Norwegian scientists, led by Vilhelm Bjerknes, and including Tor Bergeron discovered that many weather phenomena result from the meeting and interaction of warm and cold air masses and developed a model explaining the life cycle of a middle latitude storm system. During that time also, Carl Gustaf Rossby (U.S. Weather Service) discovered the jet stream and that it governs the easterly movement of most weather.

Since weather is common and does not have country borders co-operation between different nations have to be established in order to collect and distribute weather observations and track weather systems. Co-operation between nations has been discussed during international conferences in Meteorology in Vienna (1873), Rome (1879), Munich (1891) and Paris (1896). For the international co-operation of all national weather services the International Meteorological Organization (IMO), was founded in 1873. This organization was renamed at 1950 to World Meteorological Organization (WMO) and became the specialized agency of the United Nations for meteorology (weather and climate), operational hydrology and related geophysical sciences in 1951. The WMO has now 187 Member States and Territories.

Weather forecasts based on synoptic charts at that time were empirical and depended on personal experience and judgment of individual meteorologists. At the same time mathematicians and physicists were trying to formulate laws and explain the dynamics of weather systems as well as other atmospheric thermodynamics and motions. That was the time when practical meteorologists realized that knowledge of conditions in the upper atmosphere was essential for a better understanding of weather phenomena and for forecasts. Manned balloons were dangerous, expensive and did not reach a desirable height in the atmosphere; therefore, new techniques had to be invented. That became possible during the 1940's when measurements of upper level meteorological variables became possible. Instruments used to measure temperature; humidity and pressure were placed on balloons and released into the atmosphere. Winds at upper levels were measured by tracking the balloons. This instrument system, that called radiosonde, allowed meteorologists to analyze the atmosphere in three dimensions and greatly improved our understanding of atmospheric processes.

The science of meteorology took a huge step forward in the 1950's with the development of high speed computers. Computer models were developed and the equations which approximated the physical processes of the atmosphere could be solved. These physical relationships are currently used to predict the future behavior of the atmosphere. The computers were also used to analyze and graphically represent the meteorological variables being measured at thousands of weather stations all over the Earth. Starting in the 1950s, numerical experiments with computers became feasible. The first weather forecasts derived this way used barotropic (that means, single-vertical-level) models, and could successfully predict the large-scale movement of midlatitude Rossby waves, that is, the pattern of atmospheric lows and highs. In the 1960s, the chaotic nature of the atmosphere was first understood by Edward Lorenz, founding the field of chaos theory. The mathematical advances achieved here later filtered back to meteorology and made it possible to describe the limits of predictability inherent in atmospheric modelling. This is known as the butterfly effect, because the growth of disturbances over time means that even one as minute as the flapping of a butterfly's wings could much later cause a large disturbance to form somewhere else.

In addition, RA.D.AR was first used in the 1950's as an instrument to detect, from a distance (remotely), where precipitation was occurring. On April 1st, 1960, space age meteorology became reality at Cape Canaveral as the first meteorological satellite launched. This satellite, TIROS I, proved that satellites can observe weather patterns. Subsequent TIROS I improved hurricane-tracking techniques and severe storm warnings, protecting lives and property in coastal areas around the world. TIROS I was the first of at least 70 satellites which have been successfully launched to provide day and night monitoring of world weather and cloud system movements.

Progress that followed those achievements was rapid in all fields. Data from these satellites have been improved as new sophisticated instruments have been placed on new satellite generation. Meanwhile, rapid advances in technology provide improvements in all instruments used to collect weather data such as weather radars. Doppler weather radar is now used for detection of storms. This allows forecasters to see inside storms and to detect wind-driven precipitation. It also helps to give a clear indication of wind rotation and enables meteorologists to detect severe storms such as tornadoes.

Computer models become more complicated as new theories and information are added continuously to improve the models capability of simulating atmospheric movements. Now days three dimensional models that are used, called "coupled atmosphere - ocean models" use information from satellites, weather observations (surface and upper atmosphere), ocean temperature and currents, terrain and with the use of high speed modern computers can derive exact weather forecasts for specific areas up to ten days ahead. New research is focused in long time forecasting (or seasonal forecasts) and in forecasting extreme weather phenomena that cost human lives. Our understanding of how the atmosphere works is constantly improving although variables that are involved in weather creation are far more complex. Given the technology needed our systems of monitoring the weather and simulating atmospheric motions has reached a desirable level for producing forecasts of high accuracy. The future of the science of meteorology lays in technology as new sophisticated instruments and prediction models will increase our capabilities in forecasting the chaotic weather.

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Evolution of Land Treatment Practice for the Management of Wastes

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Abstract: "Land treatment" refers to the application of wastewater to the soil to achieve treatment and to meet irrigation needs of the vegetation. Application of wastewater to the land was the first practice used to protect public health and control environmental pollution and has gone through different stages of development with time. Currently, its application has been expanded for the treatment of various types of wastewaters including dairy, meat, industrial effluents as well as and polluted water sources. It is recognized as the ideal technology for rural communities, clusters of homes and small industrial units due to low energy demands and low operation and maintenance costs. A brief historical overview along with an introduction to the fundamental processes the current trends and the future prospects are provided in this section.

Keywords: History of land treatment; sewage farms; wastewater management; sanitation.

Introduction

Land treatment is defined as "the controlled application of partially treated wastewater onto land to achieve treatment and disposal goals in a cost-effective manner" (Crites *et al*., 2000). Land application is the oldest practice used to manage wastewater and control environmental pollution. Land treatment systems have a long history as evidenced by the elaborate sewerage systems associated with ancient palaces and cities of the Minoan Civilizations. Indications for disposal of wastewater in agricultural land extend back approximately 4500years (Asano and Levine, 1996; Angelakis and Spyridakis, 1996; Angelakis *et al*., 2005). With the progress of the time the land treatment has gone through different stages of development but the basic principles regarding planning, operation and management practices were developed after 1850 when the "sewage farms" were expanded in Europe and USA in an effort to control pollution and protect public health (US. EPA, 1979).

The development of conventional wastewater treatment technologies in the turn of 19th century resulted in a decline of land treatment systems (Reed *et al*., 1995), but the interest was renewed after the passage of Clean Water Act in 1972 (PL 92 500) and particularly the last two decades (Paranychianakis *et al*., 2006). This is mainly due to the low construction, operation and maintenance costs, making this technology suitable for small communities or decentralized clusters of homes, institutions and isolated industrial units (Crites and Tchobanoglous, 1998; Angelakis, 2001). Different types of land treatment systems were developed through the passage of time depending on the rate of applied hydraulic load, the presence or absence of vegetation, the needs for preapplication treatment and the intended level of treatment. These include: a) Slow Rate systems which utilize soil matrix for treatment and the applied load is based on vegetation water requirements; Overland Flow which utilize soil surface and vegetation for treatment and the treated wastewater is collected as runoff; and Rapid Infiltration in which the major difference from slow rate is the lack of vegetation and the higher application rates (Reed *et al*., 1995).

Nowadays, land treatment is recognized as an alternative or supplement to conventional wastewater treatment plants that can be both environmentally sound and economically viable. Land treatment systems have been currently expanded for the treatment of various types of effluents including landfill leachates, dairy effluents, meat processing wastewater, olive oil mill wastewater, agricultural drainage, and contaminated groundwater (Paranychianakis *et al*., 2006 and references there in). Currently, the scientific interest foccuses on the adoption of appropriate operation and management strategies that could increase treatment efficiency and alleviate the potential adverse environmental impacts, understanding the cycling of nutrientsl, the fate of pathogenic organisms and the environmental factors affecting their survival, and the fate of toxic organic compounds.

In this study a brief overview of historical evolution of land treatment concept is discussed with emphasis on the most important technological developments and on the sanitation requirements. Furthermore, the current trends and the future prospects of land treatment concept are presented in terms of management of wastewater and other polluted water sources.

Chronological Development of Land Treatment Systems

The existing literature suggests that ancient Greek civilizations practiced land application of wastewater for irrigation and sanitation purposes, but the development and the expansion of this practice for wastewater management took place after 1840 in three distinct periods. The first period lasted from 1840 to 1905 and the basic principles of operation were developed and the spreading of this technology occurred. The second period lasted until 1972, when the Water Clean Act was enacted and characterized by a sharp drop in the development of these systems. Finally, the third period from 1972 until today, a renewed interest has been observed for the adoption of this practice for the treatment of effluents and polluted waters.

Land treatment systems in the ancient times

Findings from archeological sites in Knossos, Cyclades, Athens and the mainland of Greece reveal that ancient Greeks were aware of the basic hydraulic principles which led to the development of innovative technological achievements for water and wastewater capture, conveyance, storage and treatment (Koutsoyiannis and Angelakis, 2004; Angelakis *et al*., 2005; Cahill, 2003). The most impressive water-related technological achievements occurred during the Minoan civilization (2600 BC). The severe water shortage which was experienced by the ancient Minoans probably led to these developments, the recognition of water value and the need for efficient exploitation of all the available water sources. During that period elaborate sewage and drainage systems were constructed to support both the functional needs of palaces and cities and the requirements of sanitation (Angelakis and Spyridakis, 1996) (Fig. 1a). The use of stormwater for irrigation as well as the beneficial effects of mixing stormwater with wastewater seems to be known to ancient Minoans (Fig. 1b). The "stabilization and sedimentation tanks" found in the palace of Phaistos, in Knossos, in Tyllisos, and in the of Agia Triada villa (Fig. 1c) also indicate that ancient Minoans were aware of the need of treatment to ensure water of appropriate quality. There is substantial historical evidence suggesting that ancient Minoans were among the first have used wastewater for irrigation of agricultural land since 2700 BC. Doxiadis, (1973) reported the existence of sewages through which wastewater was transferred to land treatment sites. Furthermore, since 2600 BC, many ancient Greek civilizations in Athens, Dion, Cyprus, Katerini and Sparti, practiced wastewater irrigation of agricultural crops to ensure sanitation and benefits of the nutrients contained in wastewater for increasing yield (Angelakis *et al.*, 2005).

(a) (b) (c)

Figure 1 Wastewater collection technologies in the Palace of Knossos and Tyllissos: a) Part of sanitary sewerage system; b) Part of sanitary and storm water systems and; c) Cisterns as a part of storm sewarage system in Tylissos.

In the Bible two references are found for wastewater application to the land (Deuteronomy xxiii, 13 and Judges iii, 20). The following years however until 12th century the practice of land treatment disappeared and the concept of sanitation was totally lost. A new concern to health and water issues was given during the Renaissance when cesspools were used as sedimentation tanks and liquid soil infiltration was practiced (Fig. 2).

The first period of land treatment development: 1840-1905

In the more recent history, wastewater effluents were being used in Bunzlau, Germany, for beneficial crop production beginning in 1531 (Gerhard, 1909). In 1650 the "Crargentinny Meadows" project was developed Edinburg (Scotland) where city's sewage was directed to adjacent fields for crop irrigation (Stanbridge, 1976). This project had a significant impact on the later expansion of land treatment as it was clearly indicated the beneficial effects of wastewater application on crop yield. The epidemics of cholera occurred in England during 1830-1850 made urgent the need for sanitation and waste management (Gerhard, 1909). 'Sewage farming' became relatively common as the first attempt to protect public health and to control water pollution. This technology was mainly developed from 1840 to 1890 in England (Folsom, 1876; Stanbridge, 1976), while at 1870s land treatment expanded in the United States, France and Germany (Reed *et al.*, 1995; US. EPA, 1979).

Important technological innovations took place during this period in terms of treatment efficiency and optimization. In 1853 the first spray irrigation sewage farm was established at Rugby, England and some years later (1874), overland flow was applied to grass plots to remove suspended solids and nutrients from applied wastewater (US. EPA, 1979). The development of intermittent filter in 1870 by Sir Edwin Franklin provided the first scientific justification that land application is a purification process rather than disposal. The pioneering experiments and demonstration projects of Denton resulted in the adoption of intermittent filters as wastewater treatment technology in many cities. In addition, the need for adjusting application rates of wastewater to the purifying potential of the land and the prevalence of aerobic conditions became evident (US. EPA, 1979). Concomitantly, it was realized that effluent disposal into fields throughout the year to supply crops with nutrients was not compatible with crop requirements and could cause adverse effects on crops. In 1877 Denton suggested that a combination of intermittent filters and land treatment consisted of the ideal wastewater treatment scheme. This observation in fact made land treatment more flexible for wastewater treatment during adverse climatic conditions and crop harvesting. At that period the first book for land treatment was published which entitled "Sewage, the fertilizer of land, Land the Purifier of Sewage" (Denton, 1871). Some years later, the in depth work of Rafter and co-workers in USA shed light into basic treatment processes occurring in land treatment systems. In 1887, it was shown that organic matter and nitrogen were oxidized by living organisms. Few years later (1894), Rafter and Baker reported the outstanding ability of intermittent filters to remove bacteria (99.9%) from raw wastewater.

By 1876, 35 towns were practiced land treatment in Britain, while in USA and Canada this practice was applied by most of the 143 sewage treatment facilities (US. EPA, 1979). Some land treatment systems established in the early 1900s (Woodland, Bakersfield, Lubbock, and Vineland) have been modified over time and continue to operate successfully until today (Crites *et al.*, 2000). Thereafter, the development of land treatment for wastewater management declined in Europe and USA. The development of conventional treatment processes in the late 1880s and the inability of more sewage plants to expand in order to cover increasing population were considered the principal reasons.

The second period of land treatment development: 1905-1972

During that period conventional wastewater treatment plants, including trickling filters and later activated sludge, were increasingly adopted for wastewater treatment in most municipalities in Europe and USA. Furthermore, a shift was observed in the basic philosophy regarding wastewater management toward the production of partially treated wastewater to be discharged in water bodies. As a consequence, land treatment systems continued to build up at slower rate in the Europe and USA until 1950. It was estimated that by 1939 125 municipalities applied land treatment (Hutchins, 1939), while the number increased to 2,200 by 1964 in USA including treatment of domestic wastewater, food industry effluents and petroleum byproducts (Hill *et al.*, 1964).

The decreasing availability of fresh water sources, especially in the western states of USA and the degradation of their quality due to sea intrusion and eutrophication in the late 1950s renewed again the concern for wastewater application to the land. Emphasis was given at that period to understand the treatment potential of the soil as well as the principal environmental factors affecting the removal of pollutants (Fig. 2). Several studies concentrated on issues regarding pathogen removal in the soil and the potential health risks, the hydraulic loading rates, the fate of nutrients and the needs for preapplication treatment (McGaukey *et al.*, 1966; US. EPA, 1979).

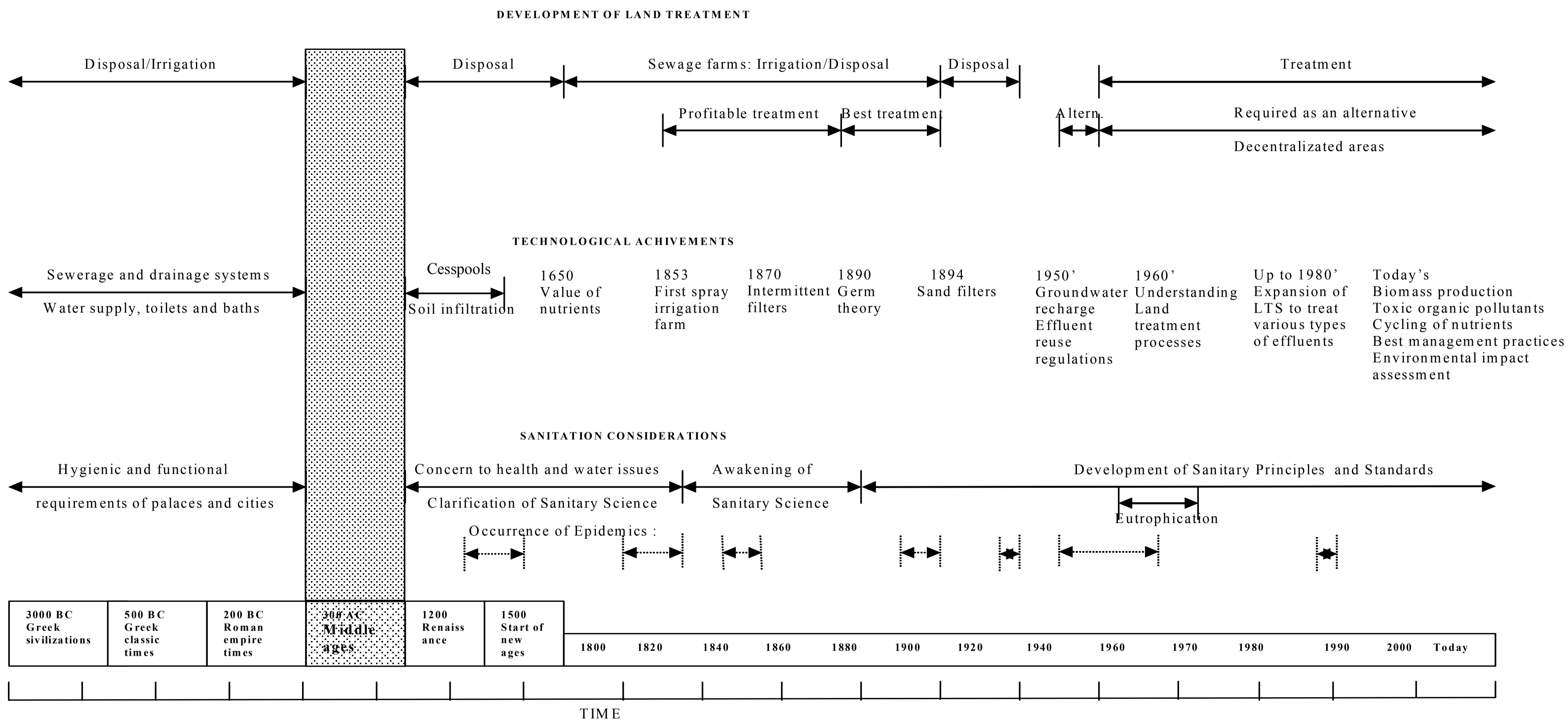

Figure 2 Evolution of land treatment concept through the time.

In addition, a large number of projects of effluent reuse initiated at that period including irrigation of agricultural crops, groundwater recharge and recreational uses. Despite the knowledge accumulated during that period about the potential of soil to remove pollutants a return to land treatment did not occur until 1972 when the Clean Water Act was enacted.

The third period of land treatment development: 1972 until today

A partial return to land treatment systems occurred after the passage of Clean Water Act of 1972, which aimed to the protection of natural waters, the beneficial reuse of treated effluent and the elimination of effluent discharge to waterways. Then, it was realized that land treatment systems could be used to meet the requirements defined by this law (Reed *et al.*, 1995). The number of land treatment systems at this period was estimated to 3,400 and consisted of 10 to 20% of wastewater treatment facilities under operation in USA (US. EPA, 1979) while a further increase up to 50% was expected to occur (Costle, 1977).

During the last two decades, there has been renewed interest in the development of land treatment systems for the treatment and beneficial reuse of wastewater. This interest has mainly been caused by: (a) the inability of centralized wastewater treatment plants to serve clusters of homes, isolated rural communities, or institutions, (b) the high construction, operation, and maintenance costs of conventional plants particularly in small communities (<10,000 e.p.), (c) the need for further treatment for reuse of effluents that have been treated previously in conventional wastewater treatment plants and (d) their efficiency for wastewater treatment in a wide range of climatic conditions. (Paranychianakis *et al.*, 2006). In addition the recognition of the importance of wastewater management in meeting future water demands, preventing environmental degradation, and ensuring sustainable growth is expected to further increase the use of land treatment in the future.

Currently, land treatment systems and particularly slow rate systems are employed in the treatment of various wastewater types including municipal wastewater (Tzanakakis *et al.*, 2005), landfill leachates (Hasselgren, 1998), food processing industry effluents (Sparling *et al.*, 2001), meat processing wastewater (Guo and Sims, 2003), olive oil mill wastewater (Cabrera *et al.*, 1996), agricultural drainage (Rhoades, 1989) and contaminated groundwater (Negri *et al.*, 2003). Particular emphasis has been given the last decade on the production of biomass that can be used for bioenergy and other purposes (Perttu, 1999). Biomass may provide an economic return to municipalities and also contribute in alleviating climate change. Many demonstration and full-scale projects are in operation in northern Europe, Mediterranean Region, Australia and USA.

Ecological and Heath Risk Issues

Greek ancient civilizations and Romans were aware of the benefits of sanitation and developed innovative hydraulic technologies and practices to protect public health, however issues of environmental protection were not considered at all during this period. The following years until in the early 1800s sanitation concept was totally ignored (US. EPA, 1979). A renewed concern about sanitation appeared during Renaissance, while the great epidemics of cholera and typhoid fever in the early 1800s stressed the need for sanitation and the protection of water sources. Although the germ theory had not been developed yet, polluted water sources were associated with the outbreak of diseases. These epidemics motivated the responsible agencies to establish the sanitation requirements by constructing sewerage systems, wastewater treatment units and drinking water treatment and establishing public health protection policies.

In 1865 the "Commission on Towns Sewage Disposal" stated that land application was the only way to avoid river pollution and to make a profit through the higher yields of the irrigated crops. Furthermore, the "Sewage Utilization Acts" of 1865 and 1867 prevented the construction of sewers which discharge directly into rivers and ocean. These laws in fact encouraged the adoption of land treatment by municipalities for wastewater management. In 1872, the first standards for effluent discharge to rivers were established in England and information was provided about land application of wastewater. A second report was published in 1884 by the Royal Commission which also promoted cities to apply land treatment practice. From that period until the beginning of the 20^{th} century many demonstration and full scale projects were initiated in USA and England to investigate the treatment potential of land in order to prevent adverse health effects, and to protect the environment.

The "Royal Commission on Sewage Disposal" adopted standards for effluent discharge in 1912 that included limits of 20 mg/L for BOD and suspended solids (US. EPA, 1979). In 1914, standards for drinking water quality were suggested in USA which formed the basis for the establishment of national standards in 1974. Few years later, the first standards for effluent reuse were adopted by the California State Board of Health (1918) which have continually been revised until today to cover new uses and to meet the increasing ecological and public health requirements. In 1989, WHO published guidelines for the safe use of wastewater in agriculture (WHO, 1989). In the following two decades many environmental agencies established criteria for effluent reuse.

Despite the increasing use of land treatment systems, regulations/guidelines that govern the operation of all types (slow rate, rapid infiltration and overland flow) of these systems have not set yet. It is somewhat surprising since it has been shown by several studies that effluent application to the land may result in significant ecological and public health risks (Bouwer, 2001; Paranychianakis *et al*., 2006). It can be considered however that the concentrations of contaminants in the effluent before its application to the land must not exceed the limits suggested by the existing regulations or guidelines of effluent reuse. Principal factors that affect the requirements of preapplication treatment before effluent application to the land are: (a) the degree of public access to the site; (b) the degree of process control the application area; (c) the end-use of the irrigated crop; and (d) the treatment object (e.g., removal of organic carbon, nitrogen, or pathogens). Thus, primary treatment should be acceptable for isolated sites with restricted public access when irrigating crops are not intended for direct human consumption or when effluent application is implemented by subsurface techniques and the underground part of the irrigated crops is not consumed raw. Biological treatment using lagoons or other processes, and strict control of pathogens should be practiced in locations with public access or for crops to be eaten raw (Paranychianakis *et al*., 2006).

Conclusions

Land application of wastewater known as "sewage farming", has been practiced for centuries as a means to manage wastewater, to control pollution and to eliminate risks for public health. It is an old technique that with prudent management can be compatible with the current high public health and environmental standards adopted by environmental agencies and international organizations and with the sustainable use of land. The use of land-based systems to treat municipal and other types of wastewater is expected to further expand in the future. This expanded use is in response to the high construction and maintenance costs of complex tertiary treatment processes, as well as the need to eliminate disposal of effluents into streams and lakes. Land-based wastewater treatment systems appear to be an ideal practice, particularly in arid or semi-arid regions where effluents can be used efficiently for increasing irrigated areas. Furthermore, land treatment systems, in effect, mimic the water cycle through hydraulic processes and several landmark studies have provided a sound technical basis for the safe implementation of those systems.

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Utilitarian Perspectives and Marvellous Views: Perception Patterns of Water-Power in Medieval Arabic Treatises

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Abstract: The use of water-power to drive machines such as water-mills can be traced in several medieval Arabic treatises of geographical and cosmographical character. The patterns of perceiving water-power range from reports about milling output in terms of day-production of meal or flour up to impressive accounts about marvellous machines with the features of a perpetuum mobile. The presentation proposes explanations for the perception patterns on the basis of the specific socioeconomic context and the dominant literary traditions.

Keywords Arab technology; marvellous devices; water-mills; water-raising machines.

Water-Power and Hydraulic Engineering in the Medieval Arab World

The use of water-power for operating machines has a long tradition in the several regions which came under the dominion of Islam in the medieval times. This heritage includes scientific traditions in the Greco-Roman world, as well as the numerous aspects and technological features of water-powered machines all over the Mediterranean, as well as the Near and Middle East.

The expansion of the Muslim state in the Mediterranean, the Mesopotamia and the Iranian territory during the 7th century A.D. enabled contacts and interactions of several scientific and engineering cultures under the Muslim rule. In the case of water-powered machines and hydraulic technology in general different geomorphological landscapes and climatic conditions acted as a polymorphic background for know-how transfer and further development. Crop irrigation was substantial for the transfer of species like cotton, sugar cane and oranges from East up to the Iberian Peninsula. On the other hand using water-power for milling cereals, oil seeds and sugar cane became increasingly important for the food supply of the rural and urban populations in the several Muslim states which resulted from the Arab expansion. Crucial importance obtained the several types of water-raising machines for both fresh-water supply and irrigation in the Arab-ruled regions which in many cases were characterised by shortage of surface water. Beside their role in every-day technological applications (mostly in rural context as well as in procedures of food processing) water-powered machines were engaged in many marvellous devices conceived and, to a certain extent, presumably realised in environments maintained and supported by princes, rulers and

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distinguished persons. The importance of hydraulic science and engineering in the Muslim states and the Arab contribution to the transmission of previous know-how and to further development have been worked out and analysed by several authors (Hill, 1984/1996: 127-179; Hill, 1986: 860-862; El Faiz, 2005). The purpose of the present study is to demonstrate characteristic patterns of presenting water-power plants in Arabic historical sources and to interpret these perception patterns in the specific political and cultural context.

Sources

Historical references and archaeological evidence concerning water-powered machines in the Greek, Roman and Islamic world are given in the works on history of technology by Forbes (1957), Schiøler (1973), Oleson (1984), Hill (1984/1996; 1986), and El Faiz (2005). In his monumental work on *Science and Civilisation in China*, Needham (1965; 1966) extended the comparative study by considering Chinese evidence. If we focus our study upon *Arabic* primary sources, we encounter mentioning of such machines in travel reports as well as in works of cosmography (i.e., combination of geographical data with cosmological and philosophical doctrines) describing Islamic and non-Islamic countries. Further *genres* are treatises on agriculture, on the rural projects of the State, and finally special treatises concerned with the description of ingenious devices, a kind of marvellous machines conceived on the basis of mechanics and hydraulics. In the following we shall present first some typical references in Arabic geographic texts of the 10th century A.D. We shall then proceed by considering a treatise of the beginning of the 11th century on hydraulic projects of the Muslim state and several texts on agricultural engineering. We shall conclude by referring to several texts concerned with imagery and visions of hydraulic technology as well as with the typical Arabic tradition of hydraulic marvellous machines.

Utilitarian Perspectives

Arab geographers often refer to agricultural production of the countries they describe. A special aspect in such descriptions is the dependency of agriculture on water management. Irrigation systems, dams, as well as water-mills belong to large-scale technology which becomes a positively connoted sign of the landscapes described.

Al-Muqaddasī (d. 1000 A.D.) describes several *dams* in Iran, among which a pre-Islamic dam which provided hydraulic power in Khuzistan and a dam built in the 10th century A.D. on the river Kūr, in the Iranian province Fars, by the Buyid emir ‘Adūd al-Dawla:

> "‘Adūd al-Dawla closed the river between Shiraz and Istakhr by a great wall, strengthened with lead[1]. And the water behind it rose and formed a lake. Upon it the two sides were ten water-wheels like those mentioned in Khuzistan, and below each wheel was a mill, and it is today one of the wonders of Fars"[2].

The positive attitude of Arab and Persian writes towards water power and milling is expressed in the way they estimate water stream according its capacity in powering mills. Referring to Upper Mesopotamia, the granary of Baghdad, Ibn Hawqal (10th century A.D.) underlines the use of Tigris stream for powering *ship-mills*:

> "The ship-mills on the Tigris at Mosul have no equal anywhere, because they are in very fast current, moored to the bank by iron chains. Each [mill] has four stones and each pair

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1 We shall not discuss here the development of the dam construction techniques in the Late Antiquity and the Islamic world. For a survey of the history of dams and further references see Schnitter (1994).

2 Al-Muqaddasī: *Ahsan al-taqāsīm* (*ca*. 990 AD), p. 344; Engl. translation quoted from Hill (1984: 137).

of stones grinds in the day and night 50 donkey-loads. They are made of wood – sometimes of teak"[3].

In 1184 A.D. Ibn Jubayr (1145-1217 A.D.) describes the ship mills across the river Khabur in Upper Mesopotamia with the exalting expression "forming, as it were, a dam"[4].

Even tidal mills are mentioned, e.g., by al-Muqaddasī:

"The ebb-tide is also useful for operating the mills, because they are at the mouths of the rivers, and when the water comes out it turns them"[5].

What is characteristic in all above references is the narrative scheme of the Arab geographers according to which the utilitarian use of water-powered rural machines appears as an indicator for improving the prosperity of the regions described (Hill, 1991: 184). Only few technical details of functioning or construction are mentioned, which implies that the authors had poor knowledge of or no interest in such details. Their main goal was to present these human constructions as something exceptional, as "wonders" which contributed to the image and the prestige of the regions.

Patterns of Prestige and Political Legitimacy

Prestige issues are regularly associated to persons of the political stage (or, more generally, of the public sphere). It is, therefore, understandable that important works related to water – whether providing drinking water, establishing adequate irrigation of fields or constructing water-powered machines – have been honourably attributed to distinguished Muslims. A well-known example is the project to provide the pilgrimage route from Baghdad to Mecca with drinking water. The idea was inherent to the religious duties of the Muslim caliph. It is Zubeida (d. 831 A.D.), one of the wives of the Abbasid caliph Hārūn al-Rashīd (786-809 A.D.), who has associated her name with the project of a canal supposed to carry water from Baghdad all the way down to Mecca. The idea and some financial details of the project are mentioned in the biographical dictionary of Ibn Khallikān (1211-1282 A.D.) (Ibn Khallikān, Vol. I, p. 337); however, no precise information concerning any realised parts is provided, except of the plant for supplying Mecca with water from a spring some 25 miles away. In his journey description Ibn Jubayr (1145-1217 A.D.) gives some aspects of the water supply along the route from Baghdad to Mecca (El Faïz, 2005:111-114).

However, this hydraulic infrastructure is commonly attributed to the caliph al-Ma'mūn (813-833 A.D.) (El Faïz, 2005:113). The imprecise and often contradictory information about the ambitious water-supply projects concerning the Islamic Holy Place[6] underlines the symbolic value of the subject and renders the several versions of the narrative *a pattern of prestige and political legitimacy* rather than a puzzle of historical evidence. Similar narratives of political prestige and power concern prestigious regional rulers or public persons, e.g. the "superintendent of irrigation" of Merv in the 10th century, who was said to have more power than the perfect of the city since he commanded some 10000 workers to build and maintain irrigation canals and dams, and a series of 10 *norias* and attached mills (Ibn Hawqal, 1938: 635-536; Hill, 1984/1996: 25). A report combining description and admiration of administrating irrigation services is included in the *Kitāb al-Hawī* dating to the 2nd quarter of the 11th century A.D. (Cahen, 1949-1951: 117-143). Among fiscal regulations we find detailed data concerning the output of the various water-driven plants: mills, water-

[3] Ibn Hawqal, Arabic text p. 219; Engl. translation quoted from Hill (1984: 137).

[4] Ibn Jubayr, p. 243; Engl. translation quoted from Hill (1984: 137).

[5] Al-Muqaddasī: *Ahsan al-taqāsīm…* (*ca*. 990 AD); Engl. translation quoted from Hill (1984: 138).

[6] Compare the source-orientated presentation by Hitti (1970:302) with the speculative interpretation by El Faïz (2005:111-114).

raising machines etc. Written at the end of the Buyid era it is a typical demonstration of political legitimacy through a discourse based on the *hydraulic network*.

Hydraulic Imagery and Marvellous Machines

The Arabic reports about irrigation plants, dams and water-powered machines formed a cultural construction which could be called *hydraulic imagery*. Quite often patterns of this imagery were associated with individual biographies. The Egyptian historian Ibn al-Qiftī (1172-1248 A.D.) reports about the audacious project of the Basrian scientist Ibn al-Haytham (965-1039 A.D.) who considered to erect a dam on the river Nile near the first cataract in the south of Asswan. The aim of this vision was the effective regulation of the annual overflow of the Nile (Ibn al-Qiftī, 1903: 114-116). After having been officially invited by the Fatimid caliph al-Hākim, Ibn al-Haytham surveyed the region, but apparently gave up his plan. It is reported that he then "simulated" madness in order to escape the wrath of the Fatimid caliph. It is not easy to exclude exaggerations and gigantomany in respect with the biographies of the Fatimid caliph or Ibn al-Haytham; this could be the contribution of the historiography to the formation of hydraulic imagery in the service of glorification of individuals. On the other hand the subject itself is the prototype of an incredible gigantesque project. The name of the Basrian scientist remained inherently associated with his hydraulic utopia and his "collateral madness" as embodied exaltation (El Faïz, 2005:129-137).

Exaltations in reports concerning agricultural technology, particularly hydraulic machines, as well as affinity to the Arabic literary form of the "wonders" (*'ajā'ib*)[7] are typical characteristics of textual sources on travelling and geography of the 12th to the 14th centuries A.D. These aspects are especially prominent in treatises which present both geographical evidence and cosmological models explaining the data on a philosophical and theological basis. In modern terms such treatises are usually called *cosmographies*. In the cosmography of al-Dimashqī (1256-1327 A.D.) such descriptions mostly refer to extraordinary ways of using natural resources (matter, wind or water). In the description of the land of Azerbaijan al-Dimashqī presents the fortified town of Merend (Mehren, 1884: 254-255; Mehren, 1866: 188). The information he gives about this place is concentrated on its remarkable water-mill:

> "In the place named Merend there is a mill which is put in rotation by a still water; and this belongs to the marvels of the world. It is built in the following way: The mill house comprises two stone mills with two water wheels. Each water wheel is put in rotation by its own water [stream]. The upper [mill] stone rotates and grinds the grain. The two water wheels are fixed at the lateral parts of a vault in which the water remains stored with a depth of a man´ s body and a breadth as well as a length of 6 cubits [e.g. ca. 4 m]. In the middle of this vault there is a pillar stretched like a bridge [horizontally] over the breadth of the vault and fixed on both side walls. This pillar bears two reinforced leaden water pipes which hold on each other tightly [unified] and hang over the pillar up to the surface of the water. Both water pipes are open. Inside there is a structure [device?] by means of which the water is sucked up towards a height of half a cubit [e.g. ca. 34 cm]. It is elevated in it [i.e. in the pipes] and kept on in stream until it flows down powerfully through the other pipe, which rises over the surface of the water in a certain distance. Thus the water flows out from this pipe and, as it falls on the water wheel, it revolves the wheel and moves the mill stone. After falling on the wheel scoops the flowing water

[7] A very helpful and concise introduction into the *'ajā'ib* literature is the article of C. E. Dubler in *EI²*, I pp. 203-204. A comprehensive collection of studies on the *'ajā'ib* is given in the Proceedings of a colloquium held by the Collège de France in Paris in march 1974: *L' étrange et le merveilleux dans l'islam médiéval*, Paris 1978.

reaches the same water [of the storing basin], then it is raised up in the other pipe turned to the other side and flows down from there. This pipe is of the same height and breadth [as the first one]. Thus each pipe sucks alternatively the water ejected by the other, so that the water mass neither decreases nor increases nor moves except at the openings of the two pipes where they suck up and pour out again the water."

It is not the purpose of this paper to smooth or modernise the text, in order to make it understandable as far as the *functioning* of the twin water-pipes is concerned. The details provided by the text are not enough to reconstruct the outline of the plant; they do not even elucidate the several possible functions. Even the illustration embedded in the manuscript and referring to the water-mill does not just *illustrate* the text[8]. Moreover, it underlines the apparent goal of the presentation of the water-mill of Merend by al-Dimashqī: the marvel described here is a *perpetuum mobile*. Work (i.e. turning the mill stones) is done without visible input of external power! The textual treatment of hydraulic machines as *marvels* finds its most remarkable expression in the compendia of *ingenious* machines (Arabic: *hiyal*) composed by Banū Mūsā in Abbasid Baghdad (9th century A.D.) and by al-Jazarī in Diyarbakir (1206 A.D.). The *Book of Ingenious Devices* of the brothers Banū Mūsā contains descriptions and illustrations of 100 devices. Al-Jazarī's compedium yields descriptions and construction details for 50 devices[9]. Both treatises refer to design and construction for palace environments – "utilitarian" purposes similar to those of the rural machines described above are not mentioned in the *hiyal* treatises.

Conclusions

In our study we analysed several Arabic textual sources concerning hydraulic machines. The various patterns traced are strongly related to the specific literary forms and the historical-cultural context of the texts. Whereas travellers and geographers of the 10th century A.D. underline utilitarian aspects and insert the hydraulic machines into the specific political and economic landscape, later historians and biographers introduce similar utility patterns as prestige criteria in assessing persons of the public sphere: dealing with hydraulic artefacts enables exalting and distinguishing (in case of failure: discrediting) individual persons. The hydraulic imagery finds a prominent position in the literary form of the "wonders" (*'ajā'ib*), the Arabic *mirabilia*, and in the category of "tricky" devices in palaces and gardens.

The above patterns are expressed through specific *narrative* forms. As a consequence, these forms standardised the manners in which hydraulic know-how and technology are reported. Such reports were undoubtedly inspired by the practical reality; however, it would be an overinterpretation of poor reliability to assert that they depicted social and technological practice. Even if the textual sources in many cases allow the assumption of theoretical scientific insight in the period considered, this is not enough to conclude that "practical realisation of the theory" was just a question of logistics. Technology in the era considered here was not "applied science". The social conditions of technology development might have been quite different from those of literary production, and the motives for using certain narrative forms are not to be found in the literal content of these narratives. Additional historical sources and archaeological evidence are required in order to check audacious hypotheses of "Masters of Water" and "Arab Schools of Hydraulic Engineers"

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8 For a more detailed analysis of the illustration with special reference to the text legends it contains see Canavas (2005), pp. 291-297.

9 For a short presentation of these extraordinary treatises and for further references see the chapters on automata and clocks in Hill (1984/1996:199 ff.).

transmitting their know-how without interruption since the Nabateans and assimilating "quite naturally" the relevant Hellenistic heritage of science and hydraulic technology[10].

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[10] In this sense the arguments of El Faïz (2005) about the transmission and continuity of "hydraulic" knowledge and experience in Near East since the Nabataeans should be considered with the greatest caution. It might me helpful to consider distinct paths of development and transmission for theoretical knowledge and various forms of practical experience - not only in the Arab but also in the Roman-Hellenistic world.

A Toast to our Health: Our Journey toward Safe Water

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Abstract: Human beings have been struggling against epidemics for centuries but the first recorded epidemic in Egypt goes back to 3180 B.C. Historically, it was not recognized that many of these "plagues" were waterborne. Advancements in medicine and microbiological sciences which identified and isolated the pathogens were needed before "Safer" water could be achieved through advances in engineering. Disinfection of drinking water, introduced at the end of 19th century, considerably reduced the spread of cholera and typhoid fever. However, despite these innovations, waterborne disease epidemics continue even in the 20th century. We contend that this is partly because little attention has been paid to sewage practices and these are directly related to our health as the source of contamination, while much attention has been focused on drinking water. We propose that to achieve "Safe Water" and an improvement in global health worldwide in the 21st century, wastewater must be addressed and learning from the past, we must use new advances such as molecular microbiology for pathogen discovery, characterization and control of emerging and re-emerging waterborne diseases.

Keywords Epidemics; plagues; sewage pollution; water microbiology; waterborne disease.

Water and Health

Our life, well being and health are intricately tied to water. Civilization and our communities as we now know them developed and flourished over time as a result of the availability of freshwater supplies. In addition, large cities and populations were possible as a result of the ancient engineers who harnessed and managed water supplies building aqueducts, reservoirs, cisterns and plumbing/ piping. In addition, to being able to transport and bring freshwater into cities, the ability to drain storm waters and control and dispose of wastes was developed. Along with the accumulation of people and concentration of our animals, development of infrastructure and use of the water for city life, agriculture and other purposes, came the inevitable pollution of the same water systems which provided the life-sustaining nourishment of the community and downstream communities. And with this pollution came disease. The first recorded account of a "pestilence" or "plague" as it was often referred to, was in approximately 3180 B.C. in Egypt's First Dynasty. This early description of an epidemic demonstrated the devastation in terms of both morbidity (illness) and mortality (deaths) that occurs within a population as a result of massive widespread disease.

Waterborne disease is defined as the spread of infectious agents (microorganisms) through the direct contact with contaminated water causing illness in humans, transmitted through ingestion of drinking water and exposure to recreational waters. Known as fecal-oral, the bacteria, parasites and viruses that are excreted in the feces of infected individuals are spread through contaminated hands, surfaces, food, and most importantly for a community, water. Intestinal illness (diarrhea) was and is the symptom most often associated with these pathogens. Yet we now know that respiratory, skin, and eye infectious are associated with contaminated water, in addition these agents can cause other health effects such as jaundice, liver and kidney impairment, paralysis, meningitis, and myocarditis. Many different symptoms were often described during the ancient times of pestilence and as with modern day waterborne outbreaks associated with sewage contamination, multiple pathogens and multiple symptoms are recorded.

We would contend that it was the contamination of water in particular with sewage and feces that led to many of the massive "plagues" of ancient times and that this remains today in the 21st century the single largest threat for exposing large numbers of people to serious illness and devastating communities and quality of life in some cases. Thus while there is much attention to drinking water systems, sewage systems are of equal importance but have been neglected throughout history. While individual water systems (wells and cisterns) the ability to carry water into the household allows a single household and family to obtain water, it takes a community effort to address storm waters, sewage and drainage (both in terms of effort and cost) (Crouch, 1993). Important lessons are to be learned from an historical perspective focused on water safety and the convergence of discoveries and advances in microbiology, medicine and engineering which can lead us toward addressing the challenges of today (Fig. 1).

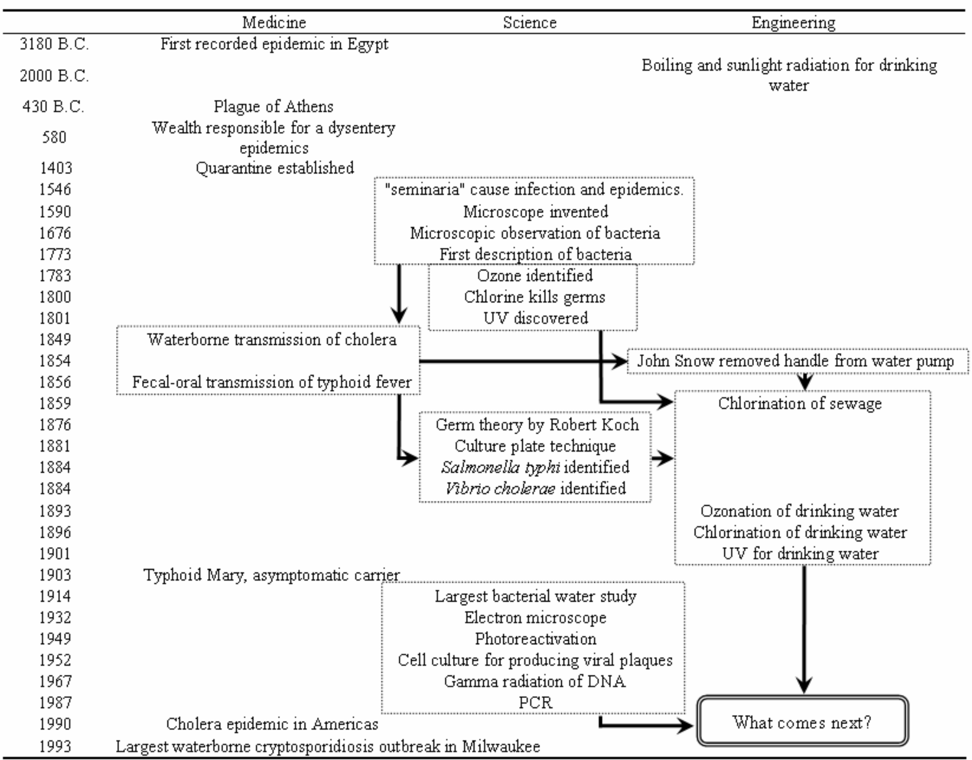

Figure 1 History of key medical, scientific and engineering progress against waterborne diseases (Beck, 2000).

Evolution of the Medicine-Microbe-Environment Connection

It is clear that the chronology of historical events and advances in medicine and microbiology were necessary before environmental health could even begin to shed light on the role of water in the spread of disease (Beck, 2004). Ancient medicine addressed diagnosis of illness via the description of symptoms and the first recorded epidemic took place in *ca.* 3180 B.C. in Egypt. Early diseases were eluded to as "epidemic fevers" which was written in a papyrus *ca.* 1500 B.C. discovered in a tomb in Thebes, Egypt. Early in the history of medicine it was proposed that bad air, putrid waters, and crowding were all associated with disease and it was recognized that these maladies were contagious. "Plagues" were described and in particular associated with the decimation of the Greek Army near the end of the Trojan War (*ca.* 1190 B.C.) and with massive epidemics in Roman history in 790, 710 and 640 B.C. (Sherman, 2006) One of the best described plagues occurred in Athens in 430 B.C. What appeared to be dysentery epidemics (enteric fevers) were described in 580 A.D. However, it was not until the 1500-1700s that advances first in microbiology lead the way for discoveries in medicine which solidified the idea of bacteria and led to the "germ theory", pathogen discovery and the understanding of disease transmission.

The Plague of Athens: An Ancient Waterborne Disease Outbreak?

The epidemic which devastated Athens as reported by the Greek historian Thucydides is often referred to as a medical mystery [Available online at: http://en.wikipedia.org/wiki/Plague_of_Athens; http://www.perseus.tufts.edu/GreekScinence/Thuc.+2.47-55.html]. In 430 to 426 B.C. a massive epidemic was recorded, killing about 30,000 people. Illnesses were identified and described by the symptoms. The "plague of Athens" description included fever, inflammation, blisters on the skin, open sores, nervousness, and severe ulceration and watery diarrhea followed by death. It was noted that it was contagious and that there was some immunity as those that recovered were not attacked twice. Hypotheses have been developed on the etiology including influenza, smallpox, bubonic plague, typhus and *Staphylococcus* (Langmuir *et al.*, 1985). Some have suggested that this is an ancient disease that has since died out (Langmuir *et al.*, 1985). Typhus was suggested yet it was not until 19th century that typhus and typhoid were distinguishable (Corfield, 1902). Many of the symptoms do follow those now known and ascribed to the disease Typhoid. We would propose that one consider that multiple pathogens were the cause of this epidemic with typhoid being the principal disease associated with sewage contamination of the water supply. Recent molecular evidence from bodies exhumed from a mass grave (buried during the epidemic) has supported typhoid fever as a probable cause (Papagrigorakis *et al.*, 2006). In addition, exposure to contaminated water could have also spread viral pathogens associated with respiratory disease and *Staphylococcus*, which has been suggested as the cause of the gangrene (Langmuir *et al.*, 1985).

Water and Wastewater in Athens

Water in Athens was supplied by a series of public fountains, wells and cisterns (Crouch, 1993). Springs as well as engineered and piped water (rock cut tunnels and aqueducts) fed these systems which included rainwater (in the case of the Klepsydra, rainwater drained from the Acropolis). Drainage from storm water and sewage was flushed through drains in the alley or on the side streets between houses. Channels may have run outside the community to areas where the water was reused for crops, having recognized nutrient value as well (Crouch, 1993). Cess pools were also discovered and it is uncertain when these were no longer used in favor of drainage and flushing away from the home. There is also evidence that water pipes were laid and set near or within the drainage channels, or channels with freshwater were adjacent to those carrying wastewater. Combined sewer overflows where both storm water and sewer were mixed and captured were common. As the population increased to about 300,000, along with previous droughts a focus on enhanced water management including approaches used for water storage, collection of rain and runoff, transport, reuse and drainage in the karst terrain and limestone created a situation in which one could envision sewage cross-connections, and transmission of waterborne disease via drinking, bathing and through the irrigated food supply. Historical translations suggested that the disease was seen first in Ethiopia and "Suddenly falling upon Athens, it first attacked the population in Piaraeus, which was the occasion of their saying that the Peloponnesians had poisoned the reservoirs, there being as yet no wells there" (Langmuir *et al.*, 1985).

Cholera and Typhoid, the Icons of Waterborne Disease

The hunt for the cause and cure of diseases began early with a marriage between medicine (including what is now known as epidemiology, study of disease transmission) and microbiology (Beck, 2000). The germ theory had been suggested in 1546 by Girolomo Fracastoro (publishing *De contagione*) and while infectious diseases were being described it was not until the microscope was invented in 1590 and refined in 1668 that bacteria were first seen in 1676 and then fully described in 1773 by Otto Frederik Muller (likely describing *Vibrio*). The "germ theory" was further solidified in 1840 and nine years later John Snow was able to show that Cholera was transmitted through water (1849). Yet the translation of this knowledge to other organisms was slow. It was not until 1856 that it was suggested that Typhoid fever was spread by feces and by then a scientific method to identify "contagious agents" using Robert Koch theories (1876) moved the study of cause-and-effect forward. A significant microbiological advancement was the invent of the culture technique using salts and yeast in 1872 and then a plating technique in 1881 using gelatin. Robert Koch not only addressed these plating techniques, but brought into microbiological practice the use of sterilization (what is now known as the autoclave). Gram stains came along and the *Escherichia coli* as we know and love it, was isolated (1884 and 1885, respectively) but it took 25 more years for the "coliform" to make it's way into applications for assessing water and health risks, addressing fecal contamination. In that same time period (1884), Koch also isolated a pure culture of *Vibrio* and Georg Gaffky isolated the typhoid bacillus.

Typhoid has long been tied to our history and waterborne disease likely played a significant role well before it was appreciated. For US early colonist, in 1607, massive mortality occurred with up to 85% of the individuals dying in Jamestown, Virginia of what is believed to be typhoid brought over by a passenger on a ship from England (Sherman, 2006). Typhoid fever symptoms were described in 1659 but it was not until 1856, that William Budd suggested that Typhoid was contracted through contaminated water, but this did not gain any acceptance until 1873 and was finally proven in 1884 as mentioned above.

In 1909, the US and UK (on behalf of Canada, which became independent in 1931) signed the Boundary Waters Treaty aimed at preventing and resolving disputes between US and Canada over waters forming the boundary between the two countries and which also established a formal binational body, the International Joint Commission (IJC). The treaty was originally intended to protect lake levels and navigability however, this created the capacity for the IJC to get involved in pollution problems in boundary waters (Binder, 1972). There was a huge interest in water quality and the impacts on waterborne disease, primarily Typhoid in the Great Lakes region. Major outbreaks had occurred in Chicago, Detroit and Milwaukee. This instigated one of the most comprehensive bacteriological studies ever conducted. There are several lessons to be learned from the 1914 IJC study. They promoted the use of the most technologically advanced methods; at the time bacteria samples were often grown in gel rather than agar (Durfee and Bagley, 1997) and funded and set up laboratories for testing. Recommendations from the study which focused on coliform bacteria included the protection of the Lakes from wastewater discharges.

Studies on waterborne typhoid in the US and Canada between 1920 and 1930 reported 242 outbreaks, with 9367 cases, even more surprising 84,345 cases of dysentery (of an unknown etiology) were associated with these outbreaks (Wolman and Gorman, 1931); in Canada, there were 40 outbreaks and 2836 cases of typhoid. The high mortality finally precipitated drinking water treatment (both filtration and disinfection). But more importantly changed the way wastewater was handled. In 1833, about 150 people lived in the Chicago area, by 1880 more than ½ million people lived and disposed of their waste into the water supply, Lake Michigan. Begun in 1900 it was not until 1922 that the Chicago Drainage canal was completed taking all wastewater down stream into the Chicago River and to the Mississippi (Capano, 2003). During this time period, Typhoid dramatically decreased and the disease was finally eliminated.

Cholera-like diseases were described early in China and Asia and certainly in Greece by 400 B.C. (Sherman, 2006). Massive outbreaks killing as many at 60,000 occurred in India in 1768, and these spread across Europe, reaching all the way to England. By 1832, the disease had reached NY, erupted in 1873 particularly in port cities (New Orleans and NY). Thus John Snow's advancement on the transmission via water played a significant role in moderating the disease spread and by 1854 the *Vibrio cholerae* bacterium was described. This organism spread quickly and is the first to be described in terms of a "pandemic", which is the spread of disease throughout the globe. Cities such as New York City and other coastal communities were able to discharge wastes to the ocean, thus once disinfection began for drinking water, the cholera was readily eliminated in the developed world. It is curious that cholera was eliminated long before Typhoid. This may be due to a number of reasons: (a) Infectivity (*Salmonella typhi* has greater infectivity at low doses than *V. cholerae*); (b) survival in fresh water and wastewater (*Salmonella* survives better, as *Vibrio* prefers saline waters); and (c) carrier states for Typhoid that contribute bacteria consistently to the sewage.

These diseases continue to ravage populations and communities. The current disease burden of typhoid is estimated at 17 million per year and 600,000 deaths [Available online at: http://www.who.int/ vaccine_research/diseases/typhoid/en/]; while cholera is reportable and the numbers range from 100,000 to 250,000 cases per year with about 2000-3000 deaths [Available online at: http://www.who.int/ wer/2005/wer8031.pdf]. We have to ask ourselves why the advances in our knowledge in medicine, microbiology and engineering have not controlled these diseases world-wide. It is our contention that lack of effort placed on community infrastructure and particularly sewage treatment that is of most immediate concern. Drinking water safety can be directed at the household level however storm waters, sewage and drainage as well as treatment must have community support (Crouch, 1993).

Other Waterborne Diseases of Modern Times

There is now a growing list of waterborne diseases of concern. Some are those which come from animals and humans, are zoonotic and can be transmitted across species barriers

(*Cryptosporidium* and *Giardia*, *Campylobacter*, *Salmonella*). Thus animal waste in addition to human waste will need to be addressed. There are those associated with respiratory disease, cancer and neurological problems (*Legionella*, *Helicobacter*, polyomaviruses, and coxsackieviruses). Thus better disease surveillance and full understanding of the disease dynamics and transmission are warranted. And finally, there are possibilities of those which are rare and full of oddity that must be examined (SARS virus, Influenza and Anthrax). Our understanding of the diseases through advances in medicine/epidemiology and advances in microbiology will allow us to examine the transmission and waterborne disease potential thus focusing on the necessary engineering advances for community health and protection.

Engineering Advances and Water Safety

In ancient time, there were almost no provisions for protecting against waterborne epidemics, as the etiological agents were not known, the diseases nor their transmission were not understood. Aesthetics played a primary role in the need to separate wastes from drinking water. Early on, controls were also attempted based on assumptions at the time on why sickness had occurred. During an epidemic of dysentery in France in 580, King Chilperic burned all the tax lists, believing that wealth was responsible for the epidemic (Beck, 2000). Other measures were more successful based on limiting exposures. In 1377, a 30-day isolation called "trentina" was officially imposed for ships entering the port of Ragusa (now Dubrovnik, Croatia) to protect its citizens from a plague epidemic (Gensini *et al.*, 2004). This isolation was then fixed at 40 days for land travelers, from which derived our current word "quarantine".

A major turning point in protection of community health and epidemics came in the mid-19th century. During a pandemic of the disease which had broken out in India in 1846, John Snow observed that cholera was transmitted through drinking water. He was then able to test his theory using one of the first engineering controls, by simply removing handle from a water pump, which he suspected as the cause of the outbreak in a district in London (Vinten-Johansen *et al.*, 2003). His achievement was enforced by the isolation of *Vibrio cholerae*, the bacteria that cause the disease in 1884 by Robert Koch (Beck, 2000). In the same period, a similar theory was suggested by William Budd on typhoid fever. The isolation of typhoid bacillus, now named as *Salmonella typhi*, by Georg Gaffky in 1884, supported his hypothesis (Beck, 2000). Both of these scientists proposed eliminating the exposure to the contaminated water supply and this initiated a search for an approach to disinfect or sanitize as was being done then in hospitals.

The discovery of water-borne transmission of these pathogens produced a drastic change for water and the ability to cope with these disease epidemics. Disinfection of drinking water to render or prevent spread of diseases was then started around the turn of that century. Chlorine was widely accepted as the measure because of its ease and cost-effectiveness in treatment. The first use of chlorine for sanitation of drinking water was by William Cruikshank in 1800 (Beck, 2000), almost 100 years prior to the medical discoveries mentioned above. While he suggested that chlorine could kill germs in water, the germ theory had yet to be substantiated and there was little wide-spread support of his ideas. However, the purification of "putrid waters" with chlorine gained some acceptance. It was not until 1896, that hypochlorite was first used temporarily as a disinfectant of drinking water during a typhoid epidemic in Austria-Hungary naval base of Pola (Baker, 1930). In the next year, "bleach solution" was used as a temporary measure to disinfect drinking water in Maidstone, England following a typhoid outbreak (Leal, 1909). These attempts proved that chlorine was effective as a disinfectant of drinking water and could be used to abate epidemics. Then this was followed by the first continuous chlorination of a water supply in Middelkerke, Belgium in 1902 (Whipple, 1906). Thereafter, chlorination of drinking water was accepted as a primary measure throughout the world and is still protecting our health from water-borne disease epidemics in the 21st century.

Other disinfection techniques were also introduced in the same period. Ultraviolet light, which was discovered by Johann Ritter in 1801, was first used for municipal drinking water in Marseille, France in 1901 (Beck, 2000). However, this technique was not widely used because of the high cost of UV lamps and the rapid spread of an easier technique, chlorination. Ozone was also introduced to water treatment in Oudshoorn, Netherlands in 1893, initially to deodorize water (Baker, 1930).

Some attempts were also made to disinfect sewage, particularly aimed at urbanized area. The first chlorination of sewage was conducted during the pandemic of cholera in the 1850s. The Royal Sewage Commission added chloride of lime to deodorize sewage in London, because odor was considered as the cause of water-borne diseases at that time (White, 1999). In 1893, chlorine was used as a disinfectant of sewage effluent in Hamburg, Germany (White, 1999). However, chlorination of sewage was not as widely implemented as it had been for drinking water, partly because the treatment of wastewater was not considered as important as the treatment of drinking water. Already available, septic tank and disposal to the subsurface was thought not to pose a risk and trickling sand filter technologies were being used in some areas to stabilize the wastes.

Health-Related Water Microbiology: The Future

In the 21st Century, other diseases have changed the landscape of medicine. AIDS now infects millions of people worldwide and up to 30% of the populations in Africa. Waterborne diseases will be particular devastating to these individuals and as already mentioned, there is a growing list of potential waterborne agents. Yet recent microbiological advances which include polymerase chain reaction (PCR) provide the tools necessary for monitoring any new agent of interest. Thus we must follow in the footsteps of Koch and Snow and continue to study and isolate the microorganisms of concern from water ways. The era of pathogen discovery is not over. We should be prepared to use all the microbiological advances to continue to understand the transmission of diseases through water. This must then be coupled with our knowledge in engineering to determine how to maintain and develop our infrastructure. The ancient Greeks knew that geology, hydrology and engineering were all important to a health, economics and well-being of a community. They knew that water was important to health. With the advances made in medicine, microbiology and engineering we can add to this body of knowledge to continue our journey toward “Safe Water” on a global scale. We would recommend that currently the most significant areas to pursue are the following: (a) New advances should be applied to wastewater streams for pathogen discovery and for characterization of disease in our populations; (b) these data should be used to further an analysis of water quality and health status; (c) the assessment and recognition of community approaches and action should be focused on sewage, drainage and treatment; and (d) an analysis of household versus community based water and waste water systems and choices should be undertaken.

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The Water as a Source of Life: An Archaeological Approach

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Abstract: In this paper we essay to present the cultural role of water in the daily life of persons from the antiquity until our days. We realise the importance of water as purgative and therapeutic “resource” in the cultural environment not only of the Greco-roman and Byzantine civilisation, but also in the modern world.

Key words Acheloos; attic vase painting; Baptism; Constantinople; Korpi; saint Barbarian; Weltanschauung.

Proemion

The prehistoric man lived in wooden lakeside or riverside settlements because the water was the basic element for his survival. In the historical times the big cities of the Near East, Ctesiphon, Baghdad, Babylon, Antioch, Alexandria, developed their urban layout round a big river as for example the rivers of Tiger, Euphrates, Orontis, Nile. In the ancient Hellenic area the bigger rivers of Attica, Kefjssos and Ilissos, constituted the aquatic benchmark of Athens. The corresponding river in Sparta, Peloponnese, was Eurotas.

In his early existence the human being deified the seas, the lakes and the rivers and lay emphasis on the incalculable importance and value of these aquatic elements of nature in society, culture and life. We will report a characteristic example of this religious perception. In Greece, but also in Europe, are particularly exposed in archaeological museums and are included in private collections statues and carved compositions representing the river Acheloos, which for thousands years crosses the regions of Epiros and Evrytania, the plain of Aetolia and debouches in Ionian Sea, in the south-western of the region of Aetolia, creating in his estuaries an important biotope. Apart from the sculptural works in which the personification of Acheloos is portrayed, representations of the God-Acheloos still exist in attic vase painting.

Sculptural and Vase Painting Representations

We intend to remind two representations that emanate respectively from sculpture and vase painting.Regarding the first, in the archaeological Museum of Piraeus is kept a carved panel from ancient Kalydon, capital of the ancient Aetolia. The city has been excavated in the decade 1920-1930 by the Greek archaeologist K. Romaios (Cf. his classic works in international bibliography: 1. Excavations of Kalydon, Tiles of Kalydon, 3. Maids of Aetolia). In the carved panel is represented the river Acheloos, portrayed old and bearded, to

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which the god of forests Pan leads three elegant and lissom girls touched hand to hand. The three women symbolize three Aetolian cities: Kalydon, Pleuron, Oeniades. All the more three cities were in direct dependence from the river Acheloos. The later, because of his abundant waters and the affluence given to the earth, was be lauded by the historian Thucydides.

However, frequently the Acheloos river happened to be found uncontrollable-the God of fury in ancient times. Then, in extreme meteorological conditions the Acheloos river flooded and destroyed not only the agricultural production of the region, but also villages and settlements were drowned by his incredible vehemence and many people were engulfed. For this natural phenomenon mythology invented an enchanting fable. The demigod-hero Hercules came to Aetolia, fought to the death with the terrible Acheloos and managed to break down him. Lots of depictions in attic vase painting represent the heroic feat of Hercules. The most beautiful of all saws Hercules fighting with an enormous snake having a head of a bull with horns. The hero has touched the snake-Acheloos from the horns, fights wildly against him and finally overcomes. Behind the fable is hidden the explanation of the construction by the Aetolians of inhibitory flood-preventing works aiming at the protection of their lives and their fortunes from the rage of the river. The symbolic composition depicting Hercules fighting down the snake-Acheloos constitutes the emblem of the present city of Agrinio, Aitoloakarnania, a modern city which continues to be supplied with water by the river Acheloos.

It deserves here we underline that the region of Aitoloakarnania, with its plains and its massifs, allocates the privilege of aquatic treasures: four natural lakes (Trichonis, Lysimachja, Ozeros and Amvrakia) and four artificial lakes-hydroelectric dams (Kremasta and Kastraki in the Acheloos and the lakes Megdova and Eyinou by which Athens is supplied with potable water). The ancient perception for the value of water as source of life includes the innate characteristic of "awe" in the face of the natural forces. For this reason natural phenomena and elements were deified.

Baths and Baptism

After the intromission of humanity into the spiritual world of Christianism, the ancient adorations and ceremonies connected with water acquired a different content, exceeded the pagan data and got dressed the new holy cloak of "blessed water". The former became the basic constitutive element in the human mystic ceremonies of the Christian adoration, including the Holy Mysteries of Baptism and Eucharist.

Since the antiquity the use of Baths (warm-cold) was considered as not only invigorating the bodies, but also giving to the human being mental cheerfulness. Homer, for example, mentions frequently that his heroes, after a laborious trekking or after a fighting that they needed to give all their forces, tired out and storm-tossed, found alleviation in the bath. Those who have read the Odyssey will surely remember that Nafsika with her servant girls were taking their bath in the river and that respectively Helen used taking her bath in the Eurotas river, Sparta.

In the historical years were organised more systematically the so-called *Valaneia*, the public baths that usually functioned, for understandable reasons, near the public buildings as Gymnasium, Paleastra, Hostelry. Romans organised in a more systematic manner the public Baths, the use of which was propagated and they acquired a high reputation. Then the Byzantines, being the inheritors of that roman tradition, attached great importance to the use of water through the public and the private baths in all the big cities of the empire.

It should firstly be marked that Constantinople during 1100 years (330-1453) as the capital of the Byzantine empire was supplied of water from a large network of open and closed reservoirs that were constructed in carefully chosen places of her seven hills. Moreover, the big monasteries inside Constantinople had their own cistern-reservoir for water supply. Famous was the reservoir of the Myrelaion monastery (Bodrum Camii), Constantinople. It has a circular form with seventy columns bearing its roof. Impressive, as for its size, was the devastated today cistern of the Studios monastery. It was in shape a vaulted reservoir based on 23 columns.

The historian Euagrios in *his Ecclesiastical History* describes the luxury of the public baths of Antioch. An interesting report has been recorded. During the reign of the emperor Theodosius II, at the 5th century, are testified in Constantinople eight large scale public Baths and hundred fifty three private (Cf. Skarlatos Vyzantios, Constantinople, vol. I, p. 119-120). Certainly, private baths were in use in the mansions of riche people and of the aristocrats of the courtyard of the emperor, while in these were also included also the baths of the monasteries. In the big cloistral complexes of Constantinople, Antioch, Alexandria, Thessalonica, but also in the smaller regions (e.g., Osios Loukas, Beotie), the Baths constituted independent buildings with a particular domed construction, an underground hypocaust from which the burning-hot water, by the use of special water pipes, was distributed to the rooms of the Bath.

For a long period had prevailed the idea of the monks "unwashed" condition during the Byzantine period, a phenomenon that was inscribed in certain exaggerations by some austere anchorites or in some extreme sermon of abbots and bishops. The truth however is found in the *Typika* of many monasteries, which fix the time (once the week or every Saturday or bi-monthly-the ill more often) at which the monk should take a bath in the public Baths or in the Baths of the monastery. About the cleanness of Byzantines and their relation with water characteristic is the cute anecdote that reports the historian Sokrates (*Ecclesiastical History*, 6, 22) for the patriarch of Constantinople Sisinos I. When he was asked why he was taking a bath twice the day in the public Baths he replied quipping: "Be gob, because I cannot three times".

From what has been exposed above we understand the extra value, but also the fundamental aged-old role that plays the affair of water for the individuals and the societies, for the nations and the populations. Particularly nowadays, period of mismanagement of aquatic resources that condemns to thirst one third of the population of the planet, the programmed and acceptable from all the social and political institutions rational use of the big treasure that is the water, but also the equitably structured modern city which protects her residents from the floods and the natural destructions, both these constitute important priorities not only in a local level but also in an international one.

Another parameter related with our subject concerns the devotional content of water. The philosophers, the theologians, the archaeologists, the sociologists and the anthropologists know that the water, the adoration of which is documented in all the ancient civilisations, is considered a primeval element of the visible world according to the *Weltanschauung* of the Christian religion (Cf. Old testament, *Genesis*, 1, 2: "*και πνεύμα επεφέρετο επάνω του ύδατος*"). The worldwide faith accepts the merciful release of water.

Particularly, the Christian religion recognized the primordial role of water in many of its basic religious rituals. We mention certain characteristic uses of water: a. In the churchyards, to the west side of the churches, next to the narthex, already from the early pale Christian period, "fountains" were built, which later, especially to the monasteries of the Holy Mountain, became an open-air cisterns covered with a dome where is taken place the benediction of the waters. b. Water is considered the basic element of the Baptism in

Orthodox Church. The sacrament of Baptism is also named "bath of regeneration" and constitutes for the baptized a source and a force of life. c. Every year, as a memory to Christ's Baptism to the river Jordan, the orthodox church celebrates the benedictions of the waters. We must equally consider that the ceremony of the blessing of the waters take place the first day of the month or during the origination of a project or to mark the begging of an important fact. In many regions of the Near East, Palestine, Syria, Egypt, Sina, Constantinople, in both the continental and the insular Greece, exist, in congruity with churches and monasteries, water sources from which springs holy water. The medicinal baths and the drinking of holy water is credited with the reinforcement of the believer, bodily and mental.

Renowned are the independent buildings constructed over holy water sources as those of the Source of Life in Balikli and of the Virgin Mary in Vlachernes, both in Constantinople. In the continental Greece is well considered for its curative effect the holy water of the monastery of Kaisariani, Athens. A corresponding example from the insular Greece is the holy water of Saint Paraskevi in the village of Charakas of Asterousia, Crete. The elegant church of the 14th century is built over a water source from which springs the holy water. The former is offered by a small opening to the believer as a remedy against bodily and mental affections. Another case may be unique in the continental Greece. It concerns a devastated Byzantine church in the mountains of Xiromero, Aetolia, where was buried an ex pirate who has been sainted, the saint Barbarian. From the church-martyrdom of the saint Barbarian springs the famous medicinal water of Korpi. The specialists report that the water of Korpi has many therapeutical properties. For that reason the homonym company undertook the bottling and the promotion of the Korpi water not only in the domestic but also in the international market. Finally, the Blessing ceremony of the holy water is connected symbolically with the growth of nature. The use of this holy water for the sprinkle of the trees aims to the regeneration of nature after the long “brumal depression".

Conclusion

Lastly it becomes explicit the objective of this note: to show the multiple uses of water, to explain his important role in the daily life of persons, to underline the common ascertainment that the water is a source of life that strengthens the person bodily and mental, to answer in the question of its classification from the Othodox Church between the four more important elements of life and nature (wheat, wine, oil, water) and to recognize the anxiety of modern people who have connected their present and their future with a more rational management of water.

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Water and Health in Ancient Civilizations

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Abstract: Roughly 10,000 years ago a revolutionary change began to shape people's living. During the following millennia most people on earth became sedentary agriculturists. This created a brand new relation between humans and water. Pathogens transmitted by contaminated water became a very serious health risk for the sedentary agriculturists. The first urbanization in Europe occurred during antiquity (*ca.* 500 B.C. - 500 A.D.) around the Mediterranean region. The urban population reached some 10-20% in the centuries around the birth of Christ. The realization of the importance of pure water for the health of people is evident in the myths of ancient people. Religious cleanness and water were important in various ancient cults. Alcmaeon of Croton (floruit *ca*. 470 B.C.) was the first Greek doctor to state that the quality of water may influence the health of people. The purpose of this presentation is to examine the influence of water on public health during antiquity. The material for the study consists of the works of ancient Greek and Roman medical authors and several Roman authors outside medicine proper such as Vitruvius, Pliny the Elder and Frontinus. Special archaeological studies relevant for understanding public health during antiquity are also used.

Keywords Antiquity; medicine; public health; sanitation; water.

Introduction

Roughly 10,000 years ago a revolutionary change began to shape people's living. During the following millennia most people on earth became sedentary agriculturists. This created a brand new relation between humans and water. Pathogens transmitted by contaminated water became a very serious health risk for the sedentary agriculturists. This was a world in which guaranteeing pure water for people became a prerequisite for successful urbanization and state formation. In the Bronze Age city of Mohenjo-Daro in modern Pakistan, there are still to be seen ancient wells, water pipes and toilets. The first evidence of the purposeful construction of the water supply, bathrooms, toilets and drainage in Europe comes from Bronze Age Minoan (and Mycenaean) Crete in the second millennium B.C.

However, the first urbanization in Europe occurred during antiquity (*ca.* 500 B.C. - 500 A.D.) around the Mediterranean region. The urban population reached some 10-20 % in the centuries around the birth of Christ. The majority of townspeople lived in quite modest-sized towns (5,000-10,000 people). The most urbanized areas were the Eastern Mediterranean, Egypt, North Africa (modern Tunisia), the Apennine Peninsula (modern Italy), and the southern part of the Iberian Peninsula, most of which were areas of quite modest rainfall. In this period the archaeological and written sources become richer, and consequently improve our possibilities to study the relationship between water and health of people. The realization

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of the importance of pure water for the health of people is evident in the myths of ancient people. Religious cleanness and water were important in various ancient cults. Alcmaeon of Croton (floruit *ca*. 470 B.C.) was the first Greek doctor to state that the quality of water may influence the health of people: *"Disease may come about from external causes, from the quality of water, local environment or toil or torture."* (Aëtius, *On the opinions of the philosophers* V.30.1)

The purpose of this study is to examine the influence of water on public health during antiquity (*ca.* 500 B.C. - 500 A.D.) (Vuorinen, 2006). The material for the study consists of the works of ancient Greek and Roman medical authors (e.g. the so-called Hippocratic writings, mostly written around 400 B.C.), and several Roman authors outside medicine proper such as Vitruvius, Pliny the Elder and Frontinus. Special archaeological studies relevant for understanding public health during antiquity are also used.

Water and Health According to Ancient Greek and Roman Authors

Hippocratic treatise *Airs, Waters, Places* (around 400 B.C.) deals with the different sources, qualities and health effects of water in length.

> *"He* (the itinerant doctor) *must also consider the properties of waters; for as these differ in taste and in weight, so the property of each is far different from that of any other.* […] *He must consider with the greatest care both these things and how the natives are off for water, whether they use marshy, soft waters, or such as are hard and come from rocky heights, or brackish and harsh.* […]" (*Airs, Waters, Places*. 1).

> *"I wish now to treat of waters, those that bring disease or very good health, and of the ill or good that is likely to arise from water. For the influence of water upon health is very great. Such as are marshy, standing and stagnant must in summer be hot, thick and stinking, because there is no outflow; and as fresh rain-water is always flowing in and the sun heats them, they must be of bad colour, unhealthy, bilious. In winter they must be frosty, cold and turbid through the snow and frosts, so as to be very conducive to phlegm and sore throats. Those who drink it have always large, stiff spleens, and hard, thin, hot stomachs, while their shoulders, collar-bones and faces are emaciated;* […] *This malady is endemic both in summer and in winter. In addition the dropsies that occur are very numerous and very fatal. For in the summer there are epidemics of dysentery, diarrhoea and long quartan fever, which disease when prolonged cause constitutions such as I have described to develop dropsies that result in death. These are their maladies in summer.* […] *Such waters I hold to be absolutely bad. The next worst will be those whose springs are from rocks - for they must be hard - or from earth where there are hot waters, or iron to be found, or copper, or silver, or gold, or sulphur, or alum, or bitumen, or soda. For all these result from the violence of heat. So from such earth good waters cannot come, but hard, heating waters, difficult to pass and causing constipation. The best are those that flow from high places and earthy hills.* […] *They would naturally be so coming from very deep springs.* […] *Spring waters should be used thus. A man in health and strength can drink any water that is at hand without distinction,* […]"(*Airs, Waters, Places.* 7).

> *"Rain waters are the lightest, sweetest, finest and clearest.* […] *Such waters are naturally the best. But they need to be boiled and purified from foulness* […] *Waters from snow and ice are all bad.* […] *I am of opinion that such waters derived from snow or ice, and waters similar to these, are the worst for all purpose"* (*Airs, Waters, Places*. 8).

"Stone, kidney disease, strangury and sciatica are very apt to attack people, and ruptures occur, when they drink water of very many different kinds, or from large rivers, into which other rivers flow, or from a lake fed by many streams of various sorts, and whenever they use foreign waters coming from a great, not a short, distance. […] *Such waters then must leave a sediment of mud and sand in the vessels, and drinking them causes the diseases mentioned before.* […]*"* (*Airs, Waters, Places.* 9).

Various other Hippocratic treatises contain short comments on the influence of water on the health of people (*Internal Affections*. 6, 21, 23, 26, 34, 45, 47; *Diseases I*. 24; *Epidemics II*. 2.11; *Epidemics VI*. 4.8, 4.17; *Aphorisms.* 5.26; *Humours.* 12; *Regimen IV or Dreams*. 93). The author of the Hippocratic treatise, called *Humours* warned against marshy waters: "*Some [diseases] spring from the smells of mud or marshes, others from waters, stone, for example, and diseases of the spleen; of this kind are waters because of winds good or bad*." (*Humours.* 12) The author of *Internal Affections* had the same warning against stagnant and marshy waters: *"The next dropsy arises in the following way: if, in summer, a person on a long journey happens upon some stagnant rain water, and drinks a large amount of it at one draught,* […]*"., and "Another ileus: this one occurs mainly in summer, in swampy areas; in most cases, it comes on as result of drinking water,* […]*"* (*Internal Affections*. 26, 45).

According to the late first century B.C. Viruvius, marshy areas must be avoided when the site of a city is chosen:

"*First, the choice of the most healthy site. Now this will be high and free from clouds and hoar frost, with an aspect neither hot nor cold but temperate. Besides, in this way a marshy neighbourhood shall be avoided. For when the morning breezes come with the rising sun to a town, and clouds rising from these shall be conjoined, and, with their blast, shall sprinkle on the bodies of the inhabitants the poisoned breaths of marsh animals, they will make the site pestilential*" (*De Architectura*. I.iv.1).

Pliny the Elder in the first century A.D. had in his works a long section concerning the different opinions on what kind of water is the best:

"It is a question debated by the physicians what kinds of water are most beneficial. They rightly condemn stagnant and sluggish waters, holding that running water is more beneficial, as it is made finer and more healthy by the mere agitation of the current. For this reason I am surprised that some physicians recommend highly water from cisterns. […] *Rain-water, it is agreed, becomes putrid very quickly, and it is the worst water to stand a voyage.* […] *But cistern water even physicians admit is harmful to the bowels and throat because of its hardness, and no other water contains more slime or disgusting insects. Yet it must be admitted, they hold, that river water is not ipso facto the most wholesome, nor yet that of any torrent whatsoever, while there are very many lakes that are wholesome. What water then, and of what kind, is the best? It varies with the locality.* […] *Slime in water is bad.* […] *From what source then shall we obtain the most commendable water? From wells surely, as I see they are generally used in towns, but they should be those the water of which by frequent withdrawals is kept in constant motion, and those where due thinness is obtained by filtering through the earth.* […] *One point above all must be observed - and this is also important for a continuous flow - well water should issue from the bottom, not the sides"* (Plinius *NH*, XXXI, xxi-xxiii).

Galen (2nd century A.D.) summarises the preferable qualities of water in his *De Sanitate Tuenda*:

"I do not consider, as some do, that such children should be wholly enjoined from cold beverage; but I permit its use mostly after meals and in the hottest seasons, when they incline to cold, especially, if possible, from a fresh spring which has no acquired harmful quality; […] *But one should be on guard against stagnant, muddy, malodorous, and salty*

pools, and in short those which display any unpalatable quality. For the purest water should seem to them the best, not only to the taste but also to the smell" (Galen. *De Sanitate Tuenda*. I.xi).

The ancient Greeks and Romans were also quite aware of the dangers of water coming from hills and mountains where mining was carried out as evidenced by Hippocratic author of *Airs, Waters, Places* (quoted above) and Vitruvius:

"But when gold, silver, iron, copper, lead and the like are mined, abundant springs are found, but mostly impure. They have the impurities of hot springs, sulphur, alum, bitumen; and when the water is taken into the body and, flowing through the vessels, reaches the muscles and joints, it hardens them by expansion. Therefore the muscles swelling with expansion are contracted in length. In this way men suffer from cramp or gout, because they have the pores of the vessels saturated with hard, thick and cold particles" (*De Architectura*. VIII,iii,5).

The quality of the water was examined by the senses: taste, smell, appearance and temperature. Also the health of the people and animals using a water source was considered (Vitruvius *De Architectura*. I,iv,9,10; VIII, iv,1,2). Throughout antiquity tasty or tasteless, cool, odourless and colourless water was considered the best, and stagnant, marshy water was avoided. These ideas were held until the end of antiquity as expressed by the fifth century author Palladius (*Opus Agriculturae*. I, 4). Paulus Aeginata in the 7th century A.D. referred to Hippocrates, and favoured rainwater and considered best water that is limpid, cool, odourless and tasteless (Paulus Aeginata I.50).

Water and Public Health

The ancient authors have thus made some comments about the influence of different kinds of water on the health of people, but had these comments any influence on the health of people is hard to infer. The archaeological evidence is also quite meagre on the connection between the health of people and their water supply. Thus, because of the inadequacy of sources, it is practically impossible to evaluate the health of ancient populations and the role of water in it. It is, however, quite safe to conclude that despite the impressive measures used to obtain pure potable water, urban centres had serious public health problems. In the words of V. Nutton: *"(A)ncient society had neither the power nor the administrative structures to deal adequately with matters of public health"* (Nutton, 2005: 26)

The Greeks and Romans used different methods to improve the quality of the water if it did not satisfy their quality requirements. From written sources and archaeological excavations, we know that using settling tanks, sieves, filters and the boiling of water were methods used during antiquity. At least boiling of water, which was widely recommended by the medical authors during antiquity, would have diminished the biological risks of poor quality water. Unfortunately the available sources do not permit the estimation of how often boiling or other methods were used or how effectively they improved the quality of the water. As a consequence, it is not possible to evaluate the effects of these methods on public health. Although the boiling of water might have been feasible from a hygienic point of view, it was ecologically and economically not feasible in extensive use since firewood and other combustibles would sooner or later have become a scarce resource around the Mediterranean.

The poor level of waste management, including wastewater, most probably involved a major risk for public health during antiquity. For instance, toilet hygiene must have been quite poor. The abundance of water that was conducted to the bath could also be used to flush a public toilet. The Romans, however, lacked our toilet paper. They probably commonly used sponges or moss or something similar, which was moistened in the conduit in front of the seat and then used to rinse their bottoms. In public toilets facilities were common to all; they were cramped, without any privacy, and had no decent way to wash one's hands. The private toilets most likely usually lacked running water and they were commonly located near the kitchens. All this created an excellent opportunity for the spreading of intestinal pathogens.

Water-borne infections must have been among the main causes of death. Dysentery and different kinds of diarrhoeas must have played havoc with the populations. Although the ancient medical writers described different kinds of intestinal diseases, the retrospective diagnoses are difficult and the causative agents cannot be identified. Summer and early autumn, when water resources were meagre in the Mediterranean world, must have been a time when drinking water was easily contaminated, and intestinal diseases were rife as presented in several passages in the Hippocratic writings (e.g. *Airs, Waters, Places*. 7; A*phorisms*. III, 11, 21, 22; *Internal Affections*, 26, 45). The mortality of children, especially recently weaned, must have been high, which is probably echoed in the following passage of a Hippocratic author: *"It is mostly children of five years that die from this disease* (dysenteries)*, and also older ones up to ten years; other ages less"* (*Prorrhetic II*. 22).

It should also be kept in mind that the salubriousness of the water supply must have differed markedly in accordance with the social status of people in the Roman towns. The rich had running water in their homes; the poor had to fetch their water from public fountains. The rich had their own baths and toilets, the poor had to use public toilets and baths. All this must have caused differences in the health of rich and poor people.

A lot of the water in a Roman town was consumed in bath(s) connected to the aqueduct(s). Ideally shining marble walls and limpid water were considered a feature of a bath in Rome, the cleanliness of which was watched over by aediles (Seneca. *Ad Lucilium epistulae morales*. 86). Baths were probably also beneficial for public health in towns where there was an abundance and rapid turnover of water. However, in towns where water was in short supply, cisterns had to be used and the turnover of water was slow, the role of baths was probably negative for public health.

The relatively extensive urbanization during antiquity may to a significant extent be attributable to the importance assigned to the transportation of sufficient amounts of good quality water to the towns. However, during antiquity the indirect effects of water on public health might have been greater than the direct effects. Agriculture depended on the proper amount of available water. Too much or too little were bad things. Droughts and floods led to food shortages and famines. Two important diseases caused by parasites were intimately connected with water and the ways water was managed during antiquity: malaria and schistosomiasis.

The breeding of mosquitoes depended on water and mosquitoes spread malaria, which was a serious and widespread health problem around the Mediterranean during antiquity (Sallares, 1991: 271-281, 467-469; Sallares, 2002; Grmek, 1989: 275-283). Malaria was well documented by Greek and Roman medical authors from the Hippocratic writings onwards. Among the cases in *Epidemics I* and *III*, a serious complication of chronic malaria, blackwater fever, has been identified by M.D. Grmek at least in one patient, Philiscus, but probably also in another, Pythion (*Epidemics I*, fourteen cases, case 1; *Epidemics III*, sixteen cases, case 3; Grmek, 1989: 295-304). A fine description of malarial cachexia (quoted above) is to be found in *Airs, Waters, Places*, (*Airs, Waters, Places,* 7; Grmek, 1989: 281).

Not only did the Romans lead water into the towns by aqueducts, but they also drained water out of towns. Most of the drainage (e.g., lakes and marshes) occurred, however in rural areas. Drainage in antiquity, as in later times, was a complicated business. It has even been argued that many drainage schemes in antiquity were failures (Sallares, 2002: 75). Sometimes the efforts to drain a lake or marsh might have favoured the spread of malaria in the area.

Schistosomiasis (bilharzias) has been for millennia a scourge in Egypt. The parasite (blood-vessel inhabiting worms) has an intricate relationship between the human host and a snail intermediate host. The disease must have been very common in villages of the Nile Delta and other areas where humans had constant contact with fresh water. The type of agriculture (irrigation, flooding of the Nile) must have spread the disease. Although the evidence from ancient Egyptian medical papyri remains hard to interpret, there is strong paleopathological evidence of schistosomiasis in human remains from ancient Egypt (Sandison and Tapp, 1998, 39-40; Millet *et al.*, 1998, 99-101; Nunn and Tapp, 2000).

Water had an important indirect effect on the health of people through water transportation, which played a definite role during antiquity in the spread of disease. Like food and people, also pathogens were easily transported by water during antiquity. Maritime trade was especially vigorous around the Mediterranean in the period 200 B.C.- 200 A.D. This meant that the Mediterranean world became more or less a common pool of infectious diseases (McNeill, 1979: 78-140).

The contamination of water by lead has been a topic in the discussions concerning the health of people in Roman times. Roman authors expressed doubts concerning the use of lead pipes and recommended the use of ceramic pipes (Vitruvius. *De Architectura.* 8.6.10-11; Palladius. *Opus Agriculturae.* 9.11; Columella. *Rei Rusticae* 1.5.2; Plinius. *NH.* XXXI.31.57). However, in practice it seems that although ceramic pipes were used, water was in many situations routinely distributed by lead pipes, as revealed by both written sources (Vitruvius *De Architectura*. 8.6.1, 4-6; Frontinus, 25.2, 27.3, 29.1, 30.1, 39-63, 105.5, 106.3, 115.3, 118.4, 129.4-6) and archaeological remains (Bruun, 1991: 124-127; Hodge, 1992: 307-315). So in theory there was a possibility for lead poisoning to occur through the water. Yet, there are two reasons to believe that exposure through water was quite minimal, as pointed out by A.T. Hodge (Hodge, 1981; 1992: 308). Firstly, as a consequence of the quality of the water, a calcium carbonate coating separated the lead and the water in most cases. Secondly, because of the constant flow, the contact time of water in the pipe was too short for contamination by lead.

Frontinus expressed clearly that a water system needed constant maintenance to function efficiently (Frontinus, 116-123). For instance, calcium carbonate incrustation that formed inside the conduits needed constant removal, otherwise the flow of water would eventually stop (Hodge, 1992: 227-232). In Italy aqueducts and baths seem to have been maintained even after other monumental buildings in the towns, with the exception of town walls and palaces, fell into disuse in late antiquity (Ward-Perkins, 1984: 31, 128). In Antioch and other Near Eastern towns, at least part of the ancient water system was maintained into the Byzantine period and possibly up to the Era of Islam (Kennedy, 1992). Although there were continuities from antiquity to the Middle Ages, the water supply was more limited and the Christian water patronage replaced the classical one: it was a move from luxuria to necessitas (Ward-Perkins, 1984: 152).

Conclusions

Written sources indicate that the idea of the salubrity of water is connected to the general “scientific” level of the society. The quality of the water was examined by the senses: taste, smell, appearance and temperature. Also the health of the people and animals using a water source was considered. Tasty, cool, odourless and colourless water was considered the best.

Stagnant, marshy water and water coming from mining area was avoided. Settling tanks, sieves, filters and the boiling of water were methods used to improve the quality of water during antiquity. The available sources do not permit the estimation of the public health effects of these methods.

Taking care of transporting a sufficient amount of good quality water to a town might have been the fact that made it possible to reach a relatively high level of urbanization during antiquity. The role of baths was probably positive for the public health in towns where an abundant amount of water was available. The poor quality of waste management (including wastewater) was most probably a major danger for public health during antiquity. Consequently, waterborne infections must have been one of the main causes of death during antiquity. In ancient towns there were vast social differences in the salubrity of the water supply and sanitation. The indirect public health effects of water might have been greater than the direct effects during antiquity. Malaria was widespread around the Mediterranean and schistosomiasis was common in Egypt. Droughts and floods led to food shortages and famines. Food, people and pathogens moved most easily by water during antiquity.

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Water as Power; Early Christian and Byzantine Watermills in Greece: Typology and Distribution

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Abstract: In this study the use of waterpower in productive technology from the 4th to the 15th century A.D. is examined, and the typology and geographic and chronological distribution of the Early Christian and Byzantine watermills, which have been unearthed in Greece, are presented.

Keywords Water tank; water tower; watermill; waterpower; waterwheel.

Introduction in Watermills

The utilization of the waterpower -the mechanic power, which is produced by waterflow- comprises a hallmark in the evolution of the productive technology, as for the first time natural power was exploited by man for the operation of light motive machinery. As it becomes evident by written sources, waterpower, as motive power for mills, was in use in the Mediterranean from the Late Hellenistic and Early Roman period (Anthologia Graeca IX.418.3-6. Plinius, Naturalis Historia, XVIII.xxiii.97). The so called *υδραλέτης* (*hudraletes*, water-grinder) (Strabo, XII.3.30), which was the precursor of the water-driven workshops of the Late Antiquity and the Mediaeval world was a structurally simple machine, which was constructed with a rotate mandrel, on the bottom point of which a wooden wheel with hollow blades was appended (Forbes, 1956: 593). The wooden mandrel of the waterwheel penetrated the bottom immovable stone of a stone mill, through a hole in the middle of the millstone and was joined with wooden or metal junction in a socket of the upper movable millstone, forcing the mill to resume the rotation of the waterwheel. The friction of the grindstones, which was caused by the rotation of the common mandrel of the waterwheel and the movable millstone, had as a result the grinding of the cereal products placed within (Fig. 1a). The operation of this primordial watermill required the continuous water-flow of a stream, in which the waterwheel was sunken, without artificial hydraulic system for the regulation of the water supply (Forbes, 1956: 593; Nomikos, 2000: 3). This early watermill type was more a collateral element of the rural life rather than a form of energy source suitable for organized light industries. Even though natural power was used for machine operation, as far as the energy level is concerned, the water-flow simply replaced the muscular or the animal power, without the potentiality to increase the quantity of the produced energy, in order to reduce the needed labor-time and increase the production (Raptis, 2001: 234).

The transformation of the water-driven machinery of the watermills resulted in the introduction and the domination of a new technological type of watermill, which was characterized by a vertical waterwheel, rotated around a horizontal mandrel. Technical description of this type of waterwheel is included in the tenth book "De architectura" by Vitruvius (Vitruvius, De architectura, X.IV-V). For the modification of the direction and for the transmission of the movement from the vertical waterwheel to the horizontal millstone the intercession of a simple motion mechanism, was requisite, which was comprised by subsequent wooden gearwheels (Fig. 1b). In particular a vertical gearwheel was appended at the one end of the horizontal mandrel of the waterwheel, and zapped the motion to a similar horizontal gear, the vertical mandrel of which caused the rotary movement of the upper movable grindstone of the mill. The main advantage of the operation of the vertical waterwheel, comparing with that of the horizontal, was that, due to the transmission of movement through gearwheels of decrescent diameter, one rotation of the waterwheel implied multiple rotations of the millstone (Forbes, 1956: 595-596).

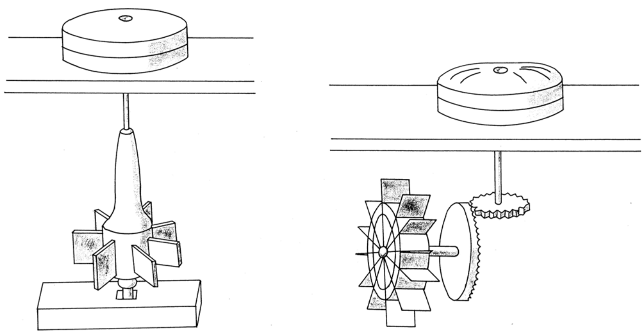

Figure 1 Watermill systems: (a) with horizontal waterwheel and (b) with vertical waterwheel.

On the basis of the position of the waterwheel in the water-supply canal, two sub-types of watermills with vertical waterwheel are detected during the antiquity. Proceeding chronologically is the simpler waterwheel with vertical *undershot* waterwheel. This type was located in a continuum stream of water, which drifted the underwater blades of the waterwheel and caused its rotation. In the second sub-type belongs the watermill with vertical *overshot* waterwheel, in which the water, driven by waterspout of continuum flow, fell from small height and stroke the waterwheel on its upper part, rotating it.

Early Christian and Byzantine Watermills in Greece

By the Early Christian and mostly during the Byzantine and Post-Byzantine period the waterpower, as it is shown by both the archaeological findings and the references of watermills in written texts, was widespread in Greece.The name of the water-driven workshops are known from contemporaneous texts, in which the vocables *υδρόμυλοι* (*hydromiloi*, watermills) or *υδρόμυλα* (*hydromila*, watermills) are mentioned, while the term *υδρομυλικόν εργαστήριον* (*hydromilikon ergasterion*, water-driven workshop) is also referred once. In the same texts the appellation of the owners of watermills is given: the so-called *μυλινάριοι* (*milinarioi*, millers) or *μυλωναρίοι* (*milonarioi*, millers), who operated a group of subsequent watermills, known as *μυλώνες* (*milones*, groups of watermills). The water-driven mills are referred as *μονόφθαλμοι* (*monophthalmoi*, one-eyed) or *διόφθαλμοι* (*diophthalmoi*, two-eyed), in proportion to the number -one or two- of the millstone pairs being in operation (Koukoules, 1948: 204). In written sources of the period the information about the operation of water-driven workshops, are mostly referred in restrictions related to the water-supply of the watermills. A number of laws, dated from 4th to 6th century, banned the use of water from aquaducts for the operation of water-driven light industries (Codex Theodosianus XV.2.6. Corpus Juris Civilis, Codex Justinani, XI.43.10 ; Karayannopoulos, 1987: 124, 149-150), while posterior laws enforced whoever ravaged a watermill, or even a water-tank, or a water-canal, which was related with the operation of a watermill, to repair the damages within thirty days (Forbes, 1956: 601).

As far as the proprietary status and the trustees of the water-driven workshops are concerned, the texts of the era give indirect references. According to the Roman law all the water-driven workshops were recognized as state estates (Mouzakis, 2000: 5). This status changed during the early Christian period, as in contemporaneous statutes the possibility of watermills to be owned by civilians is implied. According to legalisms of the Farmers Law, in the context of a free rural community, the farmers had unconditional and heritable dominance of their estates, where fields, vineyards, gardens and watermills were included (Ashburner, 1910: 97-108; Ashburner, 1912: 87-95; Zepos and Zepos, 1936: 63-71). Synchronously the possibility of the utilization of private watermills is arranged and the remainders of estates, involving watermills, are instituted to be arranged through the preferences of the neighbor landholders. From the 10th century these statutes were used for the accumulation of the land and the formation of large private cultivable grounds, the so-called *στάσεις* (*staseis*), in which watermills were included. During the late Byzantine period, the watermills were seized to officers and monasteries by imperial donations. Watermills organized in subsequent groups are referred in written sources of the period as *δεσποτικοί μυλώνες* (*despotikoi milones*, monastic watermills) or *μυλικά εργαστήρια υδροκίνητα* (*milika ergasteria hydrokineta*, water-driven grinding workshops) and belong either to monasteries or to the local church (Mouzakis, 2000: 5).

In spite of the great significance of the waterpower for the productive technology of the period, there are few architectural remains of Early Christian and Byzantine watermills found in Greece. On the basis of the type of the waterwheel and its connection with the water-supply system as well as with the grindstones of the workshop, during that period two technological types of watermills are in use: a. the so called “roman” watermill, which is characterized by artificial water-supply system with open water-canal of continuum flow, vertical waterwheel rotated inside a long water-tank and b. the “Hellenic” watermill, which is characterized by the existence of a large system of water-collecting open cisterns, horizontal waterwheel and vertical water-tower in order hydrostatic pressure to be produced by waterfall.

Roman Watermills with Vertical Waterwheel

The main technological evolution of the watermill with vertical waterwheel, seems to be conduced during the Late Roman or Early Christian period. Water-driven workshops, which were found in the Mediterranean countries, dated from the early 4th to 5th century have the same morphological and technological characteristics and, despite their fragmentary maintenance, witness a general technological evolution of the watermill with vertical waterwheel. It concerns a water-driven grinding light industry with eight millstone pairs in Barbegal, near Arles in south France (Forbes, 1956: 598-599), a watermill in Eleusina (Archaeologikon Deltion, 31, 1976, B΄1: 55-57; Raptis, 2001: 99-100, no 115), and a group of three watermills with the same waterwheel type excavated in the Athenian Agora (Parsons, 1936: 70-90; Thompson, 1960: 349; Spain, 1987: 335-353; Frantz, 1988: 80-82; Raptis, 2001: 100-102, no 116). Their alteration, compared to watermills of the previous period, is consisted in the transition of the undershot waterwheel into overshot and in the modification of the water-supply system of the mill, as from that period the water-supply was exclusively achieved by artificial means. The water was deviated from the stream and through stone-built water-canals of continuous flow was conducted on the waterwheel. As the water fell from the water-supply canal on the waterwheel's blades, the level of the waterpower increased by the gravity, caused by the artificial waterfall (Forbes, 1956: 593, 596).

As, both the waterwheel and the mechanism, which transmits the movement to the mill, were constructed by wood, and neither of them is today traceable, basic evidence for the identification of Early Christian watermills are primarily the built water-tank, inside of which the rotation of the waterwheel took place and secondly the necessary for the utilization of the watermill artificial water-supply canal (Fig. 2). The artificial water-supply canal was usually stone-built and founded, as it is concluded by the Athenian examples (Parsons, 1936: 82; Thompson, 1960: 349; Spain, 1987: 336-339) on a wall, which has smoothen the terrain and given to the watercourse of the canal the appropriate declination to the waterwheel tank. For the ejaculation of the water to the upper part of the waterwheel and the reduction of the waterfall height a movable part of water pipe, of decreasing lumen, was added at the end of the water-supply canal. That pipe was used as spout in order to increase the water pressure. Thus, the water was headed momentum to the upper part of the waterwheel, rotating it with swiftness around its horizontal mandrel. To terminate the waterwheel's rotation and interrupt the watermill's operation it was sufficient to remove or change the declination of the movable spout, in order the water to be poured in the water-tank without hitting the blades of the waterwheel (Spain, 1987: 336-339).

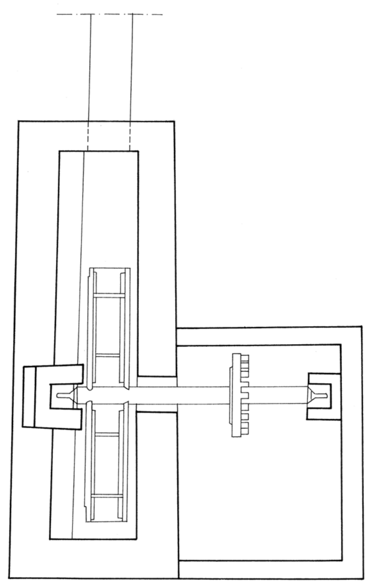

Figure 2 Watermill with water-tank and vertical waterwheel (plan).

The water-tank, inside of which the vertical waterwheel of the mill was installed, was a longitudinal trench, of large dimensions, with built walls, which were coated with hydraulic plaster in order to reassure the watertightness of the construction. The water fell inside the tank from the overhead built water-supply canal and outflew from the tank through wastewater canal, which was opened to the bottom level of the opposite narrow side of the tank (Fig. 2). The horizontal mandrel of the waterwheel was supported either by vertical stone pillars, used as gimbals, which stood inside the water-tanks, as in the Eleusinian example, either by special modulated sockets, enwalled in the masonry longitudinal sides of the waterwheel's tank, as in the Athenian watermills. In the masonry of the water-tank of the best preserved Athenian watermill, a conch was constructed, on the floor of which was enwalled the socket of the one ending of the waterwheel's horizontal mandrel. On the same level of the opposite masonry of the tank, there was a rectangular opening, through which the mandrel of the waterwheel passed to the side workroom, transmitting its rotation to the motive machinery of the mill. The grinding millstones were installed on a small wooden floor above the underground workroom of the wooden machinery of the mill (Parsons, 1936: 77).

The motive machinery (Fig. 3) of the Early Christian watermills of that type can be graphically restored on the basis of the description of the vitruvian watermill (Vitruvii, De architectura, X.V.2). The water falling from small height to the blades or into wooden buckets, placed on the periphery of the waterwheel, caused its rotation inside the longitudinal water-tank. The waterwheels' motion entailed the rotation of its wooden horizontal mandrel, which passing through the walls of the tank, wheeled its motion to the vertical gear-wheel, placed on the other ending of the waterwheel's mandrel inside the adjacent room, where the motive machinery of the mill was installed. That vertical gearwheel gave motion to a second, horizontal gear, of decreasing diameter, the vertical mandrel of which passed through the immovable grindstone and was conjoint with wooden or metal junction with the upper movable millstone, causing its rotation. The multiplication of the motive power, caused by the reduction of the horizontal gear-wheel's diameter, had as a result the increase of the grinding capability of the watermills, because only one rotation of the waterwheel implied multiple rotations of the millstone (Raptis, 2001: 249).

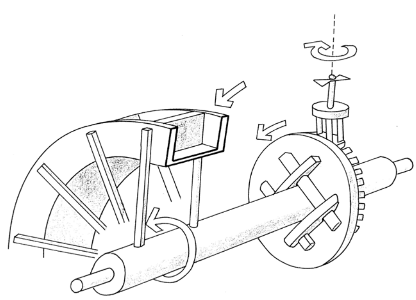

Figure 3 Motive mechanism of watermill with vertical waterwheel (axonometric).

Contemporaneously with the technological domination of the vertical overshot waterwheel, the use of the simpler undershot waterwheel was continued. Though the only known example of Early Christian watermill with undershot waterwheel was fount outside Greece -it's a water-driven workshop in Venafro, near Naples in Southern Italy (Forbes, 1956: 597-598)- undershot waterwheel is depicted on a mosaic floor from the Great Palace in Constantinople, dated in the 5th century. This unique depiction of a water-driven workshop in Byzantine art, presents a watermill with vertical waterwheel with eight rungs, which is semi-sunken in a water stream and is rotated by waterflow (Brett *et al.*, 1947: 83, tab. 41). The presence of the older technological type of waterwheel in the 5th century mosaic floor from the capital of the Empire proves that the undershot waterwheel was also in use at the East part of the Empire during the Early Christian period. The fact, that watermill with undershot waterwheels have not been detected by excavations, is due to the difficulty of discovering their architectural remains. As for the operation of the undershot waterwheels it is not essential to construct water-tanks and water-supply canals, elements that are of main importance for the identification of the sites (Raptis, 2001: 241).

From the end of the Early Christian period, when the Athenian watermills are destroyed, and until the 10th century a gap in the study of the water-driven workshops is observed, as there aren't any excavated watermills of any type, the construction or the utilization of which can be dated in the transitional period (7th -9th century). Though we have to assume that the watermills of that period, were of the same type with the known Early Christian examples, at least till 10th century when the utilization of the only late example of the type is dated. It is a watermill, which was excavated in Thebes, which was in use from 10th to late 11th century. The architectural remains and the site organization of the Middle Byzantine watermill are similar to these of the Early Christian workshops. The water fell from a higher artificial water canal on the vertical waterwheel, which was rotated inside a longitudinal underground water-tank, and outflew from an efflux hole opened on the opposite narrow side of the construction. The wooden motive machinery of the mill was located in an underground adjacent room while the grindstones of the workshop were presumably installed on a higher wooden floor (Archaeologikon Deltion, 52, 1997, B: 116-118; Koilakou, 1999: 57-59; Koilakou, 2004: 229-230). In spite of the advantages of the vertical waterwheel, as far as the quantity of production is concerned, and the knowledge of the significance of the waterpower as motive power for large scale light industries, the use of the vertical waterwheel wasn't generalized in the Mediterranean, but was restricted in a few urban productive centers till 10th century.

Hellenic Watermills with Horizontal Waterwheel

During the 10th century, a new type of watermill was imported from the eastern provinces of the empire and was spread in Greece and the Balkans. Introducer of this new type is considered by tradition St. Athanase the Athonite, as in the narration of his life (Petit, 1906), the construction of a watermill with vertical water-tower and horizontal waterwheel, is mentioned, which would be the dominant type of water-driven workshops throughout the Byzantine and Post-Byzantine period. During the Byzantine and Post-Byzantine period the water-driven workshops, as it is shown by relevant references in written texts, were widespread in Greece. Byzantine watermills gathered in groups operated near streams and torrents of Macedonia, Thessaly and Peloponnese, in Crete, but also on islands of the Aegean Sea, such as Chios and Lesbos, where in spite of the seasonal rainlessness the operation of watermills was possible through open water-collecting cisterns (Raptis, 2001: 251). However, the studied architectural remains of Byzantine watermills are restricted in a few watermill groups, operated near streams of the suburban area of Thessaloniki (Siaxampani, 1985: 86; Siaxampani, 1992:116-120; Siaxampani, 1997: 338-341; Raptis, 2001: 94-97, no 109-111), by the lake Volvi (Archaeologikon Deltion, 38, 1983, B΄2: 289; Papangelos, 1995: 187; Raptis, 2001: 97-98, no 112) and on the uplands of Chalkidiki (Archaeologikon Deltion, 34, 1979, B΄2: 298; Raptis, 2001: 98-99, no 113-114).

The Byzantine watermills were usually constructed on sites selected on the basis of water-supply capability, and operated in organized groups developed on the slopes of large streams, which offered the necessary quantities of water for the operation of the water-driven machinery, as well as the appropriate declination of the ground for the construction of the vertical water-tower in order to achieve hydrostatic pressure (Siaxampani, 1997: 338; Raptis, 2001: 251). By the study of their architectural remains it is concluded that the Byzantine watermills belong to the so called "Hellenic" type, with artificial system of water-collecting, vertical water-tower and horizontal waterwheel and appear typological relation and common morphological characteristics, mainly as the organization of the site and the construction of the water-tower are concerned. These watermills had large open cisterns for water-collection, triangular in plan water-supply canal and vertical water-tower with amplifying pilasters supporting the façade and vertical well-like water-canal for the production of waterfall and the development of hydrostatic pressure. The water with open water-canals was driven from the natural source and was collected in earthen or built open cisterns of large dimensions. Through a horizontal water-canal of triangular plan, the shape of which increased the water-pressure, the water was driven from the open cistern to the upper opening of a vertical well-like water-canal, which was opened inside a tower-like construction (Figs. 4 and 5). From horizontal rectangular efflux hole-jet opened on the masonry of the water-tower on the level of the waterwheel, the water ejaculated with pressure, caused by the waterfall inside the vertical well-like water-canal and hit the wooden blades of the horizontal waterwheel, causing its rotation.

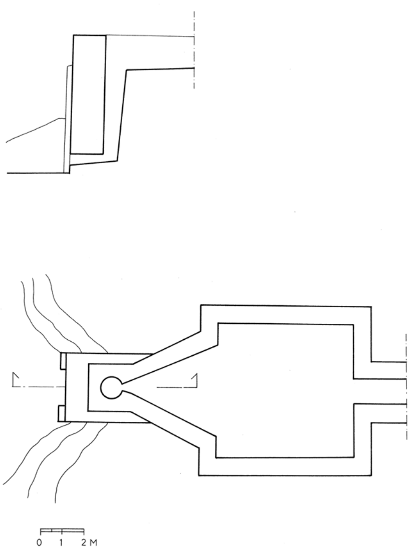

Figure 4 Watermill with vertical water-tower and horizontal waterwheel (section, plan).

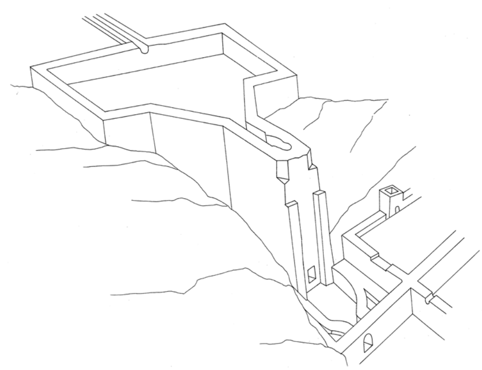

Figure 5 Watermill with vertical water-tower (axonometric).

Basic elements for the identification of the sites are the discovery of the water-tower, the length of which was turned by the declination of the slope of the stream, while its height, which in some examples is as high as 9-10m. (Siaxampani, 1997: 341), was bounded by the morphology of the ground, the height of the banksides, and the hypsometric contrast between the level of the waterwheel and the level of the water-collecting cistern or the natural water-supply source. The masonry of the water-towers was built with stones, plinths and hydraulic mortar in order for the construction to be waterproof, and is often characterized by a common Byzantine building system with small horizontal plinths built in the vertical mortar joints between the stones. The vertical water-canal with circular lumen of decreasing from the upper to the lower part diameter, which was opened inside the masonry thickness of the water-tower, was coated with hydraulic mortar and often bared small scales for the cleaning and the conservation of the construction (Raptis, 2001: 255-256).

Even though the organized watermills of the period are characterized by special treatment and forethought, as far as the planning of the site and the construction of the hydraulic system are concerned, the motion mechanism of the water-driven machinery of the "Hellenic" watermill with horizontal waterwheel was very simplified, compared to the mechanism of the "Roman" watermills with vertical overshot waterwheel, which was in common use during the previous period. It was consisted of the wooden horizontal waterwheel, installed in a small workroom in front of the efflux hole on the basis of the water-tower, and the grinding machinery comprised by one or more pairs of large millstones, installed on the workroom's wooden floor, over the waterwheel room. The waterwheel and the stone mill were connected by a single common vertical mandrel, which transmitted the rotation from the waterwheel to the grindstone.

In all the studied Byzantine watermills, the motive machinery is restored, because of the low stud of the waterwheels' room, with horizontal waterwheel (Raptis, 2001: 256-257). Though, in spite of the many advantages of the "Hellenic" watermill, as far as the water economy is concerned, as it was possible to operate a watermill of that type with small or seasonal water concentrations, in the same time the fact, that every rotation of the waterwheel implied only one rotation of the millstone, was the main disadvantage of its operation as the grinding sufficiency of the workshop was in the same labor-time much smaller than the productive capacity of the watermill with vertical waterwheel (Forbes, 1956: 593-594).

After the 10th century and during the Byzantine period, the application of the vertical waterwheel is very limited in Greece, and is restricted in the overshot sub-type. The only studied Late Byzantine example, which operated with vertical waterwheel, was the watermill of a light industry for sugar production, excavated recently in the area *Ζαχαρόμυλος* (*Zacharomilos*, Sugar-mill) in Charaki on Rhodes. The organization of the site and the construction of the plant, in spite of the late building techniques applied in the masonries of the workshop, are similar to those of earlier watermills with vertical overshot waterwheel, rotating inside an underground longitudinal water-tank and transmitting the produced motive power through a motion machinery consisted of gear-wheels to the large millstones of the grinding workshop, which were installed in a workroom adjacent to the water-tank (Kollias and Michaelidou, 2004: 18-21). The operation of the water-driven sugar-mill constitutes the induction of a western technological element in Frankish dominated Rhodes, as that type of hydrokinetic machinery, which needed large quantities of water and advanced technological knowledge, was in common use in Mediaeval Western Europe, where the intense geophysical terrain and the existence of natural water sources of continuous flow facilitated the operation of the vertical waterwheel (Forbes, 1956: 602, 608-614).

In spite the fact that divergence of the production's quantity per time unit, is significant, except of the Rhodian example there are no other watermills with vertical waterwheel, operating in Greece during the Late Byzantine or the Post-Byzantine period. During the Post-Byzantine period, for which there is more evidence than for the previous years, the construction and the operation of watermills were widespread in Greece, both in the mainland and the islands, provided that there was, even seasonally, water in the area. The watermills of the period, often in use till the World War II, are characterized by artificial water-supply systems with water-canals or open water-collecting cisterns, and water-towers with scalable façade. As far as the type of the waterwheel is concerned, the Post-Byzantine watermills continued the Byzantine tradition and operated with horizontal waterwheel.

Though during the late Post-Byzantine or the early Pre-Industrial period there are references of water-driven workshops with external vertical overshot waterwheels (Raptis, 2001: 258).

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Rainwater Harvesting in Ancient Civilizations in Jordan

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Abstract: It has always been thought of that location of settlements through history depended on the existence of a nearby permanent water source. But Lars Wåhlin supports that anthropologist and geographers seem to have missed that residents in many parts of the Middle East have been able to provide themselves a water supply, where nature was not kind enough to create a river or a spring, long time ago. Jordan is a country where this is statement prevails. Despite of an arid to a semi arid climate conditions, several civilizations have started and flourished with these conditions. This paper aims at investigating the major techniques that people have used through history to survive and create their own civilization in this part of the world. The paper starts by presenting the civilization at Jawa, which was built in northern Jordan at the Bronze Age, 3,000 B.C., with an extensive hydraulic system. Then it presents how people in Um El Jimal, a city built at the Bezantine era, built their deflection dams, canals and reservoirs. Afterwards it demonstrates some of the work of the Neabatean engineers who have excelled in water management and their cut-stone reservoirs of the Nabatean city of Petra, in a civilization that flourished more than 2,500 years ago in the southern desert of Jordan. Later, it gives some insight into the underground cisterns found in the country's Umayyad desert palaces of the Islamic era, located in different parts of the country. Looking into these practices and how water resources were managed through time may help inspiring new ideas in facing the challenges of today.

Keywords Ancient civilizations; Nabatean; rain water harvesting; water management.

Introduction

Jordan is currently one of the ten poorest countries in the world with regard to its water resources. Rainfall ranges between 50 mm in the eastern and southern desert regions to 600 mm in the northern highlands. However, over 90% of the country receives rainfall less than 200 mm/yr. As an arid to semi arid country, with limited surface water resources, Jordan is facing great challenges with managing its water sector. Looking in the history might help thinking how people have managed to survive and civilizations to flourish. One technique that has been extensively used was obviously rain water harvesting. A standing example on that is the famous "Moabite Stone" where King Mesha of Moab commemorated proudly around 850 B.C.:

'I made two reservoirs in the midst of [Qerkhah]. Now there was no cistern in the city, so I said to all the people, Make you every man a cistern in his house'.

This may be the first time that water cisterns are mentioned in a text, but obviously the technique has been used earlier. According to an Archaeological Encyclopedia of the Holy

Land, “The first cisterns were dug in the Middle and Late Bronze Age (2,200-1,200 B.C.; LW). The rainwater that collected in them during the short rainy season would be enough for at least one dry season. In some parts of Palestine cisterns were the main (sometimes even the only) source of drinking water in peace time as well as in war time. In the early Iron Age (1,200-1,000 B.C.; LW) the sides of cisterns began to be covered with watertight plaster, which considerably prolonged the time for which water could be stored. It was this important innovation that made it possible to extend the areas of settlement into the mountainous parts of the country (Wåhlin, 1997). The dating of the first cisterns to Middle Bronze may be too late, however. At Jawa in the black lava desert of north-eastern Jordan a sophisticated water-collecting system was planned and built already before 3,000 B.C.

However, cisterns would not be constructed in large numbers before the Iron Age. At Hesban, already in the Iron I (1,200-1,150 B.C.), we encounter a significant water management complex consisting of at least one, and probably many (had our excavations been more extensive) cisterns, and an overflow tank, which possibly also served as a channel for leading water to a yet-to-be-discovered reservoir", as (Wåhlin, 1997) describes. Through the following Hellenistic Roman and Byzantine Period, Construction of wells and cisterns increased and continued (Abujaber, 1995).

This paper aims at investigating major water harvesting schemes that existed in the country. Those schemes were constructed at different ages and by different ancient civilizations that have flourished in this part of the world.

Jawa

Jawa ruins dates back the Bronze Age, i.e., about 5,000 years ago. The climate conditions in the area where Jawa ruins were found are characterized by intensive rainfall for few days during the year and dry weather with high temperatures for the rest of the year. The hydro-technology in Jawa which dates to almost 5,000 years is so simple and above the ground that even today is measurable. Jawa is a truly good example in the history of urbanization that has nevertheless preserved a potential recognition of prehistoric scientific ideas (Helms, 1981). Jawa is a typical example of how from the early ages people in arid regions relied on surface waters resulting from winter rains which was collected and stored in man made reservoirs or cisterns.

The water supply of Jawa depended mainly upon a large macro-catchment and a number of micro-catchments. Wadi Rajil was the major supplier of water for the town and judging from its size it can be imagined how difficult it was for the people of Jawa to control such a Wadi. It has been estimated that currently an average of 2 Mm^3 of water is discharged every year. Therefore it is safe to assume that a similar volume of water could have been discharged in the ancient times (Helms, 1981). Although it seems unrealistic but floods in this part of the desert are a very common thing and in this particular case they are the only source of water for the habitats of the town. From this huge amount of water that is discharged the amount that passed through the town’s system was only 3% (around 70,000 m^3) (Helms, 1981).

Water was retained at Jawa by deflection and not by total damming. The construction of such dams directed only a small part of water from the big valley to the canals leading to the storage areas (Helms, 1981). This required a good knowledge of weather patterns as well as hydrodynamics, surveying and earth mechanics but above all required the understanding of basic science in terms of observation, recording, evaluation and prediction (Helms, 1981). The water system in Jawa can be subdivided into three sub-systems to ease understanding. These three sub-systems also represent the three catchment's areas that the city depended on:

(a) Sub-system No1 consisted of a canal that lead water from a deflection dam through a number of irrigable fields to an outflow gate where a proportion entered an underground reservoir. The main canal continued to another overflow where it divided in order to fill three water reservoirs utilized for drinking purposes. The second branch of the main canal bypassed the storage area, passed through fields and reached an animal watering point (Helms, 1981). All the excess water was returned back to wadi Rajil. Additional run-off was captured with three linked micro-catchments through a deflection wall, which lead the water either along the bypass canal, or to the three reservoirs.
(b) System No2 consisted from a second deflection dam opposite the eastern quarter of the lower town and raised water along the steep eastern shore of wadi Rajil (Helms, 1981). The canal transferred water to an outflow gate from where it was stored in two pools. As in system No1, a micro catchment was added and thus increased the area by a long canal. The run-off from the micro passed through- a number of fields to a pool.
(c) System No3 was also based on a deflection dam and collected water from a gravity canal to a number of outflow gates (Helms, 1981).

This is the general organization of the most comprehensive urban water system yet discovered anywhere for such an early date (Helms, 1981). Dams in Jawa mainly consisted from a stone water face and stone reinforcement downstream with an earth fill in the middle. These middle cores were made up from hard clay, silt and packed with layers of ashes (Helms, 1981). The base of the waterface was constructed from a stone paved surface. The purpose of such a construction was to protect the dam from any wave action that may have affected its structure (Alkhaddar *et al.*, 2005). Figure 1 represents a reconstruction of the dam. The use of ash as a water-resistant material has proven to be very effective. Compressed ash is better than compressed silt or clay. So ash was used for the outside layers of the core and the remainder consisted from silt and clay (Alkhaddar *et al.*, 2005).

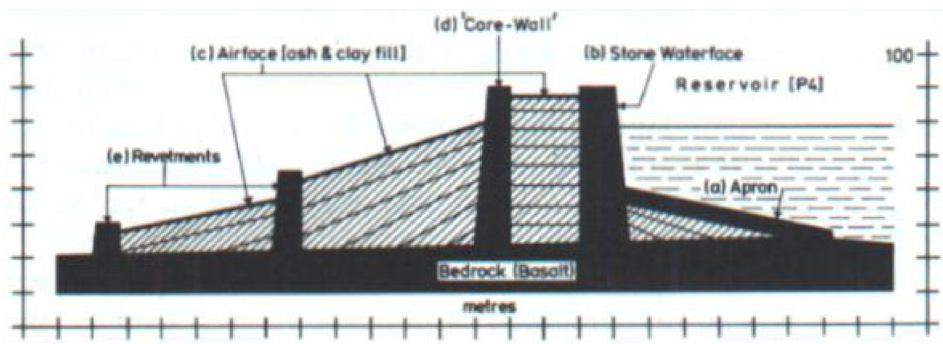

Figure 1 Reconstruction of a dam (Helms, 1981).

The structure of the dams at the time was very similar to modern dams. Except from the water face the downstream revetments had a function similar to the drainage blanket of recent embankment dams (Helms, 1981). The silting of the reservoirs used to serve multiple purposes. First it would fill any gaps between the basalt rocks to prevent any leakage and secondly when it was removed it was used for house building (Alkhaddar *et al.*, 2005). The same technique that was used to build the dams was used to build the pools. Jawa's water harvesting system had very good management techniques. The people of Jawa knew how to predict the weather and the raining patterns of their territory. Jawa is a bright example for the future of water harvesting in the area as it seems to be the oldest water resource the people of Jordan had at the time and they succeeded in managing it efficiently.

Umm El-Jimal Water Harvesting System

Umm el-Jimal is an extensive rural settlement constructed of black basalt in the lava lands 20 km east of Mafraq, Jordan. It is located on the edge of a series of volcanic basalt flows that slope down from the Jebel Druze, a mountain 50 km to the northeast. This sloping black bedrock provided ancient Umm el-Jimal with two basic resources: stone for construction of sturdy houses, and water for drinking and agriculture (de Vries, 1997). The city was founded in the Early Roman period when it enjoyed considerable Nabataean influence, flourished as a frontier city of the Roman and Byzantine Empires, and continued to prosper in the Umayyad period, perhaps because of its proximity to the Desert Castles and the Pilgrim Route. Umm el-Jimal was destroyed by an earthquake at the end of this period and not rebuilt because the region of the Hauran lost its preeminence when the seat of government shifted to Baghdad under the Abbasid Caliphs (de Vries, 1981).

A sophisticated hydraulic system was constructed in Um Al Jimal to supply both town and countryside. The two main canals, which supplied the reservoirs of the town, were constructed in the late Roman period (Bert de Vries, 1993). The water supply system was constructed in order to utilize the intensive rainfall during the end of February and the beginning of March. After that period of rain the average rainfall dropped to a very low value which forced the habitats of the town to develop a water harvesting system to deal with the all year round drought (Alkhaddar *et al.*, 2005).

The water system of this ancient town is a combination of dams, channels and underground reservoirs. The dams were used in the higher parts of the mountains is order to collect and divert the water to the channels and then to the reservoirs (Alkhaddar *et al.*, 2005). The amount of water reaching the area proves that there is enough water for the town if it is collected and stored properly. The way that the water drops in the form of rain is very intense. A typical example is the 92 ml of rain that fell in one hour in April of 1982 and the 113 ml of rain that fell in an hour and twenty minutes (Khoera, 1990).

However, the area has a very long summer with very high temperatures that can reach up to 50^0 resulting in high evaporation rate. Rainy days do not exceed 30-40 d/yr. These extreme conditions of heat and rain forced the people at the time to develop the adequate technology in order to deal with these weather conditions (Alkhaddar *et al.*, 2005). Three dams were built from rocks and had no moving parts except for one which had something like a release valve which was triggered manually in case of flooding in the area. The purpose of these diversion dams was not only to store water but also to hold the water for some time until it reaches the canals and the reservoirs. They are designed to delay the water and then guide it (Alkhaddar *et al.*, 2005). The 3 dams were connected with the city with a network of surface canals that carried the water inside the walls of the town. The length of the main canal connecting the town with the dams was around 4 km and it was built entirely out of stones. The width and the depth of the canal varied according to the topography and the slope of the ground. Outside the town the dimensions of the canals were between 30 cm and 60 cm in width and 20 cm and 60 cm in depth. Inside the town the canals had different dimensions. The dimensions varied between 120 cm and 80 cm in width and between 60 cm and 50 cm in depth (Alkhaddar *et al.*, 2005). The various sizes of the canals served a number of purposes. It was necessary for the water to reach the town fast in order minimise evaporation. However it was also important for the water to travel at a relatively slow speed to avoid any damage to canal (Alkhaddar *et al.*, 2005).

In addition, the town of Umm el-Jimal had ten totally covered reservoirs inside the town's walls and a number of open ponds inside and outside the town. Once the reservoirs are all filled up the water is diverted to these secondary ponds. This water was mainly used for irrigation or watering the animals. The water was stored underground not only to prevent evaporation, but also to protect the public and animals from falling in since most of the reservoirs where inside the town limits. The roofs of the reservoirs needed a certain type of design. This was based on spanning the reservoir (or cistern) with traverse arches, which were then leveled with the help of filler blocks in order to support the slabs. On top the slabs soil was deposited, approximately to a depth of 1.5 m, so the water was completely protected from evaporation and people could actually walk on the reservoirs (Alkhaddar *et al.*, 2005).

The main reservoir was a great deal larger than any other reservoir built in other towns in the same period. The main reservoir of the town was rectangular with a length of 39.7 m, a width of 29.9 m and a depth of 4.3 m making the total capacity 5,144.229 m^3 (Khoera, 1990). The size of this reservoir leads to the suggestion that it was not entirely artificial but may have been a natural one. It was difficult to understand how this reservoir was covered. After its original inhabitants abandoned the reservoir and the town the Bedouins took over and utilized the reservoir until the present day. So the changes that took place do not allow us to know how it was covered. The town also had 28 ponds, which were built in order to be utilized during the construction of the town. Afterwards they were used to store the excess water from the overflowing cisterns and run-off.

Even though it was not common at that time, water was treated in Umm el-Jimal. The system that was used was a very simple but effective system for removing the suspended solids in the water. Other types of pollution weren't present at the time so no further treatment was required. Water treatment 2,000 years ago is considered to be a very pioneering development. The method used was based on a small settling tank with three different compartments before the main reservoir as can be seen in Figure 2. The tank had a total capacity of 40,836 m^3 and each one of the three compartments had a capacity of 13,612 m^3. The depth of the tank was 2.05 m. Water was allowed to enter the settling tank and solids were removed as it flowed through the three compartments. After the final stage of settling in the third compartment of the tank the water finally was allowed to enter the main reservoir. The cleaning of the filter was probably achieved manually at the end of the raining period by someone entering the tank and removing all the sludge deposited. This very simple method of water treatment enabled the people of Umm el-Jimal to remove any particles that might have entered the water during its journey to the reservoirs. This simple technique is still used today in wastewater treatment (Alkhaddar *et al.*, 2005).

Figure 2 The settling tank (Alkhaddar *et al.*, 2005).

In conclusion, the town of Umm el-Jimal is a very good example of the water management techniques the people of Jordan have developed almost two thousand years ago. They managed to adapt to the hostile environment of the Northern Eastern Desert of their country and flourish without harming the environment in long-term. It is an example of sustainable development in a time that there wasn't any need for it. The techniques used in Umm el-Jimal can be adapted in current water management strategies in order to improve their efficiency.

Nabateans

The Nabtateans civilization had emerged in southern Jordan more than 2,500 years ago. Originally a nomadic tribe known as the Nabateans began migrating gradually from Arabia during the sixth century B.C. to and gradually overtime they abandoned their nomadic ways and settled in a number of places in southern Jordan. Their capital is the historic city of Petra. The Nabatean carved grandiose buildings, temples and tombs out of solid sandstone rock. They also constructed a wall to fortify the city, although Petra was almost naturally defended by the surrounding sandstone mountains [Available online at: www.KingHussein.gov.jo/history.html].

Building an empire in the arid desert also forced the Nabateans to excel in water manage met. They were highly skilled water engineers, and irrigated their land with an extensive system of dams, canals and reservoirs. As the Nabatens gained more wealth and prospered, their increase standards of living and settlements needed more water. To meet the needs they increased the use of traditional water harvesting techniques of the area. They also started using new techniques learned from their contact, noticeably the Hellenistic world (Oleson, 1995).

Forder (1923) wrote for Petra that huge cisterns were hewn in the rocks into which the rain water was run through surface channels. These cisterns were high up in the side of the rock, so as to prevent defilement. The interior was divided by rock partitions into reservoirs, oft-times many in number, and so arranged that when one was full it would overflow into another. In these rock-hewn reservoirs millions of gallons of water could be stored and be always cool, clean, and available. Figure 3 is a photo of Jabal Garoun: High point in Petra, 1,265 m, overlooking Wadi Araba, it was used as a military area during the Nabateans time-with many water cisterns and channels, the water harvesting system was at this point.

Figure 3 A water harvesting system in Petra.

Oleson (1995) has written quite extensively about the Nabatean water supply system and how they evolved. Of the traditional water harvesting techniques, the terracing of the hell sides is perhaps the most noticeable The paper will present here two examples of rainwater harvesting schemes at two settlements of Nabatean.

Humeina

Humeina, site of ancient Auara, was the major Nabatean central in the Hisma, Jordan's southern desert. The average rainfall in the area is about 80 mm/yr. A survey conducted in 1986 focused on the settlements catchments area: about 240 km². 61 sites were recorded outside the settlement centre and divided into the following groups: 51 cistern, 4 springs, 1 aqueduct, 1 dam, 2 sets of wadi barriers and 6 sets of terraces or stone piles (Nydahl, 2002). Some of those cisterns were unroofed, roofed with stone slabs, or roofed with undisturbed stratum of bedrocks. 14 out of them are roofed in the typically Nabatean fashion using transverse arches (Oleson, 1992). A survey conducted in 1987 on the water supply system inside the settlement documented 16 structures: 11 cisterns, 2 reservoirs, 2 sets of conduits or drains and 1 bath building.

Cisterns

Two cisterns known as cistern No, 67 and 68 are two good examples. One has a capacity of 445 m³ and the other a capacity of 486 m³. Both are rectangular, narrow and roofed with stone slabs carried by sixteen transverse arches. They were built to harvest water from a large run-off field that covers approximately 100 ha north of the settlement. The area was protected from habitation throughout the history of the settlement. Cistern 67 has a 25 m long intake channel. Cistern 68 intake channel (width 0.64 and depth 0.35) was built of large, heavy slabs of stone and deep settling tank with a length of 3.18, width of 2.58 m and depth of 1.6 m and was roofed with a slab carried with 2 transverse arches. Major parts of the roof are still supported by the 14 remaining arches. The stones were carefully cut and placed and were waterproofed with a hard sandy plaster containing pebbles (Oleson, 1988). Figure 4 represents a reconstructed perspective view of the cistern. Since these two cisterns size, interrelationship, quality and location, Oleson (1988) suggests that a municipal authority has built them for public use.

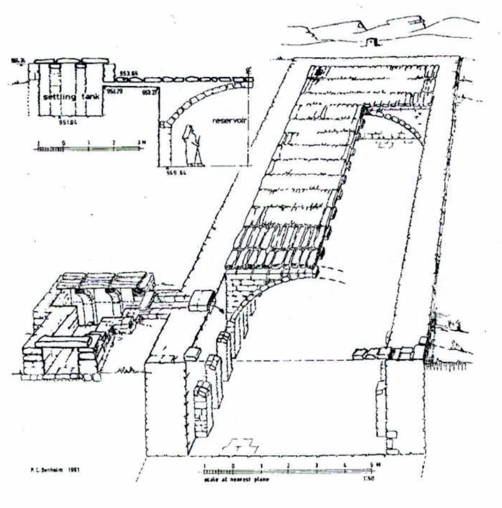

Figure 4 Cistern no. 68 at Hummeima. Reconstructed preview view (Oleson, 1995: 712)

The other nine cisterns found in the centre of the settlement are built of blocks. All but one of the nine cisterns are circular is shape and of much smaller size. Oleson (1988) concludes that the smaller size and the fact that they are usually buried in structural remains suggest they were built for private use and are built by individual families. Figure 5 is a reconstructed preview of the cistern No. 54.

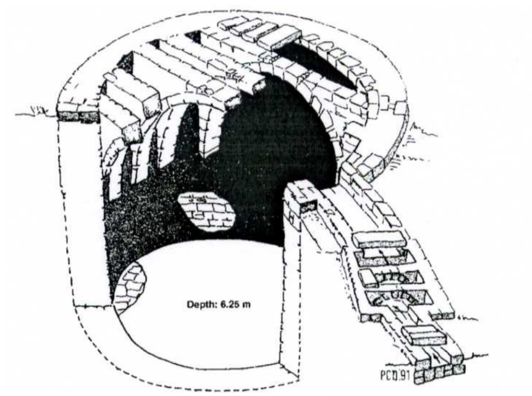

Figure 5 Cistern No. 54 at Humeina, Reconstructed perspective view (Oleson, 1995: 712)

Nakhl

Nakhl is one of the larger antiquities sites on al Karak Platateau. It is situated at the heart of three wadis with rainfall higher than Humeima, about 300 mm/yr and falling in winter months. The Nabateans (and later Roman and Byzantine population) at Nakhl used the headwaters at Wadi Nakhl and built low-placed dams to store water, usually filling the highest dam first, and then allowing to fill the next dam down stream. Cisterns were used to store water surface runoff from streets and buildings. Wells were constructed to allow inflow as well as overland flow for replenishment.

In the catchments area, there are preserved lateral walls that were constructed to retain moisture for crops and animal use. The total catchments area is 52,000 m², while the constructed walls span an area of 34,000 m². Walls were built of unquarried stones lying in the area. Furthermore, there are two low walls dividing the areas between the walls into smaller spaces that the walls may have been pools or reservoirs (Nydahl, 2002).

Ummayyad Desert Palaces

Ummayyad Desert Castles mark the flourishing beginnings of the Arab civilization. They were built mostly under the Ummayads (A.D. 661-750), when Muslim Arabs had succeeded in transforming the fringes of the Deserts into settlements with their water management systems. Desert Castles are mainly clustered to the east and south of Amman. The following are some examples of those castles and there water management systems (Jordan Tourism Board Publications).

Qasr al Hallabat

Qasr al Hallabat site comprises a conglomeration of separate and widely spaced units. These include a qasr, a mosque, a huge reservoir, eight cisterns dug into the western slopes, and an irregularly shaped cultural enclosure with an elaborate system of sluices and a cluster of houses which extend to the northwest of the reservoir.

Hamam Al Sarah

This Desert Castle consists mainly of three principle elements: (a) The audience Hall; (b) the bath complex; and (c) the hydraulic Structure. However, this monument suffered from damage in the 1950's, when building was pilfered for its stones.

Qasr Haraneh

Qasr Al Haraneh is situated about 65 km east of Amman. It consists of 61 rooms arranged into two levels surrounded by a central court yard. This Desert Castle has a small water tank standing in the middle of the courtyard to collect rainwater from roof tops. Additional water was obtained from seep-holes dug in the adjacent wadi bed.

Al Qastal

Al Qastal lies 25 km south of Amman. Unfortunately, the site has been built on and a large portion of the main building has been submerged by a modern house. More than 100 cisterns and substantial barrage, 400 m long and 4.25 m wide have been identified. Plans are underway to restore the qasr and the ancient water system. Figure 6 below presents a water harvesting system built in Amman Citadel which was also built in Ummayyad times.

Figure 6 A historical example of water harvesting at the Amman Citadel. Water collected from the roof is directed through channels towards water storage areas.

Conclusion

In the third Millennium, when we say we strive for sustainability and good husbandry with the earth's resources, people sometimes appear to know less (or, worse, care less) about such matters than did people who lived centuries and even millennia ago. One field in which this is obvious is water management and conservation (Wåhlin, 1997). Lessons learned from old civilizations surviving and flourishing in arid zones, including their solutions to water supply, such as water harvesting might be inspiring for new solutions for today. A number of historical examples that incorporate effective water harvesting systems have survived in the country. This paper has tried to present some of these systems through which people have lived and survived in this part of the world. This is of special importance to Jordan, with the water crisis as one of the major challenges that it faces today. Looking into those practices and how water resources were managed in past may help with new ideas in facing the challenges of the management of water resources of today.

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Some Reflections on the Ambush of Achilles against Troilus: Tarquinia, Tomb of the Bulls and its Connection with Water

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Abstract: The representation of the ambush laid by Achilles to kill Troilus is one of the most popular in Greek imagery of the Archaic period, and one which found its way into Etruscan imagery as well. We notice a shift in the content of the myth expressed by Etruscan iconography versus the original Greek imagery. The myth offers several layers of interpretation, which testify its complexity: scholarly analysis and interpretations focused on several aspects of the story, such as the presence of a sacrificial element in it. The focus of this paper is instead the connection of this myth with water and the symbolic power of water. The symbolic connection of this myth with water appears to be the most significant element of the story. It is also the one which mostly interested the Etruscan artists and the patrons who decided to choose this particular myth for the decoration of the Tomb of the Bulls in Tarquinia. Its owner, Arath Spuriana, was part of one of the most important aristocratic families at Tarquinia.

Keywords Greek and Etruscan Fountain Buildings; Tomb of Bulls; Troilus; water as Symbol.

Introduction

According to the sources (Kereny, 1951; Kossatz- Deissmann, 1981), the destruction of Troy would have not been completed until the youngest of Priamus' sons was alive. Therefore, Achilles decided to set an ambush to kill Troilus, who, since Troy was under siege and deprived of regular water supplies, used to water his horses and draw water at the sacred fountain of Apollo Thymbreus together with his sister Polyxena. The episode found its way early in the 6th century B.C. on Greek Black-figure vases from Attic, Laconia and Chalcidic, as well as in relief.

Later on we find it on South-Italian vases, twice on the so called Pontic vases and finally in the monumental fresco of the Tomb of the Bulls in Tarquinia. This tomb is among the most ancient burial places in Tarquinia, dating around the third-fourth quarter of the 6th century B.C. The tomb consists of an entrance hall, in the end wall two doorways lead to two funeral chambers. The main decoration of the tomb is the fresco painted in the area between the doorways. The painter divided the wall in two roughly rectangular areas, the lower panel is decorated with a series of plants and bushes, above it the Troilus myth is painted (Fig. 1).

The Tomb of the Bulls is unique because here we find the first and almost unique mythological narrative in Etruscan frescoes; furthermore it is a monumental tomb which belonged to a member of the Spuriana's family: Arath Spuriana, whose name is written in the pediment just above the fresco. Scholars have noticed the iconographic connection between the Tarquinian fresco, Pontic vases and Black-figure Etruscan vases in general terms.

However, it seems that a deeper analysis of the iconography of the fountain, one of the key elements in the iconography of the myth, might shed some new light.

Figure 1 Ambush of Achilles against Troilus, Tomb of the Bulls, Tarquinia.

Interpretations of the Myth

The myth of Troilus, as already mentioned in the introduction, takes place in the temple of Apollo Thymbreus and has been codified in Greek art at the beginning of the 6th century B.C. through a recurrence of fixed iconographical elements: the protagonists, Achilles and Troilus, the fountain. In Greek vases from Corinth and Athens early in the 6th century B.C., a large number of representations of fountains together with the myth of Troilus start to appear. The frequency in the appearance of fountains and the myth of Troilus is directly associated with the period of the tyrants both in Corinth and Athens (Periander, Cypselus, the Peisistratids) and their policy of public works, especially fountains and water supplies for the towns (Dunkley, 1935-36). Numerous Attic vases, especially the tyrrenic amphorae with representations of water supplies and the myth of Troilus reached Etruria and were used to make known and boost Athenian power (Giuliano, 1969).

Correspondingly, in Etruria before the end of the 6th century B.C. the kings of the Southern Etruscan towns and Rome realized important public works to enhance their public image in which they show a particular interest in water supplies related works (Cloaca Maxima; swamp drainage in Velabrum Forum and Valle Murcia; tunnels and drains) (Torelli, 1991). All these elements concur to suggest that the choice of the representation of the myth of Troilus in such a monumental tomb was not incidental. Nevertheless, authoritative scholarly studies until the 1960's emphasized the lack of artistic skills of the Tarquinian painter and a general lack of interest of the painter towards the myth itself: almost all the main scholars agree in talking about an embarrassment of the painter towards the myth and Etruscan "banalization" of Greek myths (Banti, 1955-56; Camporeale, 1969; Giuliano, 1969).

In the last decades new studies (Simon, 1973; Krauskopf, 1974; Oleson, 1975; Prayon, 1977; Cerchiai, 1980; Colonna, 1984; D'Agostino, 1985; Cambitoglou, 1985; Gaultier, 1986; Cristofani 1988, Torelli 1991) suggested new readings of the fresco which would imply a clear intention of the painter to emphasize important elements of the myth, some of them related to the original Greek tradition, some others added by the Etruscans. These studies suggest a complexity of meanings which were earlier underestimated.

A focus on the war-like elements and the existence of a homosexual relationship between the protagonists were part of the Greek tradition both in art and literary sources. According to the latest studies, the Etruscan Tarquinian fresco and the Etruscan iconography introduce an emphasis on some additional elements: for example D'Agostino (1985) and Cerchiai (1990) underline that Etruscan iconography focuses on the sacrifical aspect of the story, identifying the sword of Achilles as a special kind of knife used for sacrifice (máchaira). E. Simon, following the identification of painted plants as laurum sacred to Apollo, believes that the conceptual centre of the Tarquinian fresco is the connection with the god Apollo and the importance of his cult in Etruria. Another interesting interpretation looks closer to the secondary representations in the pediment space in the Tomb of the Bulls, where it is possible to see sea-horses (Fig. 2). A young man riding on a sea-horse who is going over the sea towards an island is a unique image in this Tomb. However, representations of sea-horses recur in other tombs (Tombs of the Tritons, Bartoccini, Stefana, Little Mouse, Painted Vases) and on Black-Figure Etruscan amphorae from funerary contexts, and appear to symbolize the journey to the Underworld.

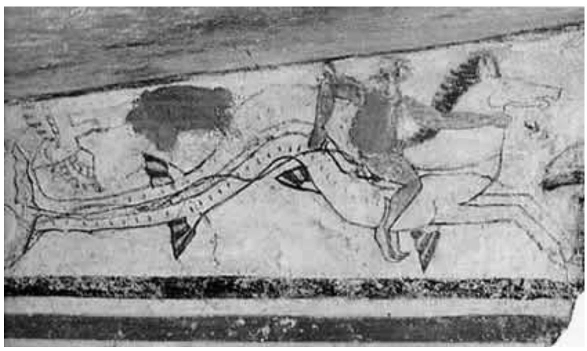

Figure 2 Sea-horse, Tomb of the Bulls, Tarquinia.

Water, Myth and the Iconography of the Fountain

If we take a fresh look at the fresco of the Tomb of the Bulls, we have the impression that the emphasis and the focus of the painter is on nature. What seems to dominate in the fresco is not man, but nature. The eye is not impressed with the image of the "victim", Troilus, whose figure vanishes on the back of a huge horse, even less with the slaughterer, Achilles, whose size is even smaller than his victim. A flourishing nature is celebrated; see the palm tree and the vegetation in and around the scene (pomegranates' cornices, and plants in the area below). An interesting suggestion recognizes the representation of agricultural rites of fertilization, grafting, and rites to guard fields against hail, which were common among ancient South-Eastern Mediterranean civilizations, in the secondary scenes painted in the tomb (Seppilli, 1990). Nature can be fertilized only by water, symbolized by the large fountain building which man set up in sacred land.

The setting is in fact very significant in itself: the temple of Apollo Thymbreus was a sacred area and neutral territory for both Greeks and Trojans during the Trojan War. Within the temenos area, no war could take place and this was related to the temple's peculiar characteristic: a fountain which was the only place where the people of Troy could draw water, since the town was under siege. Nevertheless the temple was the theatre of the death of many heroes of the Trojan saga, and it is the place where Achilles itself will be killed later on. Although Achilles does not appear to be the focus of the Tarquinian fresco, the hero's connection with water is reknowned: he was born from the nymph Tetis, and the name of his father Peleus is connected with the names of liminal river gods. When Achilles was born, he underwent a kind of initiation ritual throughout the immersion in the Stix to make him invulnerable. For Achilles, water is a medium in between life and death, with an initiation value. Achilles's association with water, helps him to face the wrath of the Scamandrus in the XXI book in the Ilias (Seppilli, 1971; Faranda, 2003). As Achilles kills Troilus at the sacred fountain nearby the Temple of Apollo Thymbreus, he will kill Hector in front of two fountains, one with hot water and the other with cold water, from which springs the Scamandrus, and located outside the Shean Gates of Troy. The sacrificial aspect evoked by this story, in Tarquinia seems more connected to water than to the blood of the victim. The painter's main focus is the fountain, the means to draw water, as it emerges from its dimensions and peculiar profile. Therefore, it makes sense that half the scene is dominated by the fountain and the other half by Troilus on the horse. Troilus, or his sister Polixena, is the one who has the important task to draw water. Furthermore, we might imagine that the fact that Troilus is threatened by Achilles, who in any case will be killed in the same temple, is an allusion to the fact that one of the most precious resources for the town, water, and water supply systems, might be in peril. The presence of the fountain building in the tomb of the Bulls appears prominent among the various iconographical components of the entire scene, due to its impressive dimensions and decoration. This observation encouraged us to take a closer look at the iconography of the fountain, which appeared to be quite peculiar and different from the Greek Attic tradition.

These and the previous considerations seem to suggest that the key element in this fresco and the reason why this myth was chosen among various possible mythical stories is water. In the Tarquinian fresco the fountain is a monumental solid building, with masonry wall with a coloured surface, surmounted by two reclining felines, probably lions, which imposes itself in the center of the scene. The water flows on the right side from the mouth of a lion onto a basin. The fountain building stands on a basis formed by three elements, the lower one has a perpendicular profile, the other two show a convex torus-like profile. The masonry wall has roughly square blocks, and the painter reserved for several of them the most precious green-blue color (perhaps an allusion to water). Monumental dimensions do not belong to the Greek Attic iconographic tradition for fountains as they are usually reduced to a thin pillar with a prominent lion's head functioning as spout. Otherwise, when Attic vase painters want to show a monumental fountain building, it has columns on the front. The only Greek vase showing a fountain similar to that of the fresco is a Laconian dish, in which a large wall is shown, although never as big as to override Achilles, whose figure is always prominent (Zancani-Montuoro, 1954).

The Etruscan vase paintings show fountain buildings with large dimensions, and the shape of a solid cubic building, nevertheless they are never bigger than Achilles, which seems evidence that the Etruscan painters maintained the mythological relevance of the hero to the story. Some scholars, claimed that Etruscan imagery combined the representation of the fountain with that of an altar, in order to emphasize the sacrificial side of the story. However, the fountain of the fresco is topped by two reclining lions as we already noticed, which is a peculiarly Etruscan trait. Therefore, the presence of these lions occupying all the space on top of the building would make it hard to consider it as an altar. Another peculiar element in the iconography of the fountain of the Tomb of the Bulls pertains its profile: the fresco's fountain has a convex profile which points at a round building. This might suggest a different kind of building such as a well or a cistern (Meer, 1995). On the contrary, in Etruscan vase paintings, we find big fountain buildings with isodomic masonry similar to that on the tomb, but their profile is always perpendicular. Therefore, it seems that although scholars have underlined how the fresco's painter relates to Etruscan vase paintings, the fresco of the Tomb of the Bulls presents itself as unique, especially in the iconography of the fountain. For example we can look at the so called Pontic vases, in particular, the amphora in the Louvre, by the Paris Painter (Fig. 3).

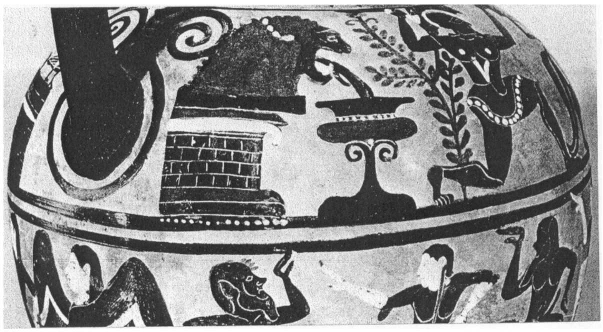

Figure 3 Pontic Amphora – Paris Painter, Musée du Louvre, Paris.

Here, the Troilus myth is represented and a relatively small fountain building is topped by a huge and monstrous lion's head, which seems to hint to the presence of demons to guard the Apollo's fountain, an Etruscan addition to the original myth (Prayon, 1977). The fountain's shape reminds of the fresco's type only in general terms, but it is as far from Greek imagery as from the Tarquinian fresco's as well. The Etruscan Astarita Black-Figure amphora with the myth of Troilos (Fig. 4) on the other hand has a fountain building quite similar to the one on the tomb. However even in this case, there are differences: the profile is perpendicular, and the spout is a conventional lion's head on the side. Furthermore, the demon with wolf's head on top of it, reminds of different meanings compared to the fresco. The so called Reading Amphora from the University of Reading (Fig. 5) is usually considered as the closest comparison for the fresco's myth and fountain.

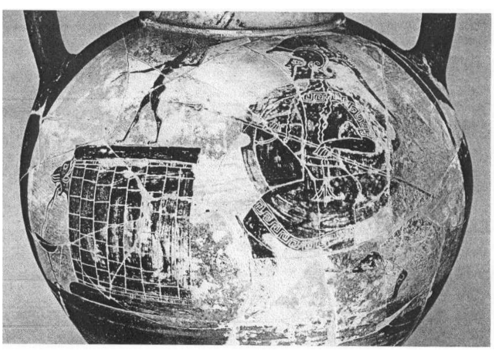

Figure 4 Amphora Astarita, Vatican Museum, Rome.

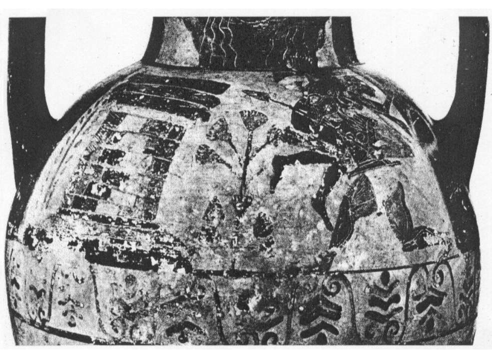

Figure 5 Reading Amphora, Reading University.

The common elements are: the partition of the space in two halves by means of a palm tree, although in the vase is a short plant; the fountain's shape with a similar base with three elements. However, the fountain of the vase is not surmounted by lions. And as far as the narrative, the vase seems to focus on the war-like element, since it represents Achilles with the body of Troilus on the shoulders. Even later Etruscan media, such as the Cistae from Praeneste, although do not show the myth of Troilus, when representing fountains, they are never monumental.

Conclusion

The analysis of the monuments relevant to the Etruscan representation of the myth of Troilus seems to show that the main element in the fresco of the Tomb of the Bulls is water. The Etruscan representation presents a complex stratification of meanings emphasized by the peculiarity of the iconography which, far from being incidental or dominated by lack of understanding; seem to indicate a specific interest in choosing a myth particularly connected with water. The iconographical analysis also offers some evidence that the Etruscan skills in water related technologies were given a symbolic meaning as means to substantiate powers by aristocratic families. The importance of water as shown by the peculiarity in the iconography of the fountain, together with the general Etruscan skilfulness in hydraulic works, might refer to some important building's construction related to the deceased. The elements of the myth, namely Achilles, Troilus, the setting in the Temple of Apollo Thymbreus, seem to be used as means to celebrate water and nature nurtured by water. In particular, the protagonists of the myth do not seem to have much prominence. Nevertheless, both Achilles and Troilus, for different reasons, have a special association with water, which the fresco might make allusion to.

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Logical and Illogical Exegeses of Hydrometeorological Phenomena in Ancient Greece

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Abstract: Technological applications aiming at the exploitation of the natural sources appear in all ancient civilizations. The unique phenomenon in the ancient Greek civilization is that technological needs triggered physical explanations of the natural phenomena and behaviours, thus enabling the foundation of philosophy and science. Among these, the study of hydrometeorological phenomena had a major role. This study begins with the Ionian philosophers in the seventh century B.C., continues in classical Athens in the fifth and fourth centuries B.C., and advances and expands through the entire Greek world up to the end of Hellenistic period, when Romans conquered Greece. Many of the theories developed in the course of ancient Greek civilization are erroneous according to modern views. However, many elements in Greek exegeses and interpretations of various hydrometeorological processes, such as the evaporation and condensation of vapour, the creation of clouds, hail, snow and rainfall and the evolution of hydrological cycle, are impressive even today.

Keywords Ancient Greece; hydrology; meteorology; science; technology.

Introduction

In all ancient civilizations the exploitation of the natural sources, such as sun, wind and water, was a major activity triggering cultural progress through inventions and technological advances. These achievements helped ancient communities to manage the wind for sailing, to exploit the water for drinking and irrigation and to take advantages of the solar energy by appropriate orientation of buildings. Such technological applications certainly imply some understanding of the nature and the behaviour of these natural elements. However, at the first stages this understanding was primitive and the related explanations were hyperphysical, i.e. mythological.

In ancient Greece, the eternal struggle of humans to control the natural powers has been imprinted in a rich mythology which was survived in texts as well as in artefacts. For example several myths related to Hercules (Heracles), the polymorphic and diachronic hero of ancient Greeks, symbolize the struggle against the destructive power of water. The myth depicted in Figure 1 is related to the duel between Achelous (or Acheloos) and Hercules. Achelous, the greatest (in discharge) river of Greece, in mythology was deified as the son of Poseidon, the god of the sea. Achelous was eventually defeated by Hercules (surrendered after Hercules cracked his horn). As demystified later by the historian Diodoros Siculus (IV 35) and the geographer Strabo (X 458-459), the meaning of the victory is related to the channel excavation and the construction of dikes to confine the shifting bed of Achelous.

With the advancement of technology, a new need arose, the physical exegesis of hydrometeorological phenomena that govern the natural sources (wind, rain, sun). In ancient Greece, several theories were proposed in an environment that lasted for more than six centuries (roughly from Archaic to Roman Period), in which mental activities flourished. This environment has been credited as the birthplace of philosophy and science as both appeared there for first time in history (Krutwig Sagredo, 2006).

Reviewing the original texts of this period, the researcher meets a great variety of theories that extended from mythological explanations based on epics (Homer, Hesiodus), to scientific views. Inside this prosperity, the modern investigator can perceive mythical, poetical, religious, symbolical, philosophical and scientific views. Interestingly, the mythological and symbolical views have been popular even in the late stages of this period, even thought scientific theories had already been developed. This is depicted for instance in the Wind Tower, a monument built in Athens in the 2nd or 1st century B.C., where the winds are shown as deities (Fig. 2).

Figure 1 Attic red figure vase, 6th century B.C. depicting the battle of Hercules against Achelous (British Museum).

Figure 2 Detail of the Wind Tower in Athens showing Kaikias, the northeast wind holding a shield with hail-stones [Available online at: www.stoa.org/athens/sites/romagora/source/p06059.html].

Today even the scientific views of ancient Greeks are not useful for the explanation of the hydrometeorological phenomena. The modern scientific basis is very solid (even though several phenomena are not fully understood until today) and seems to be totally independent of the ancient Greek scientific views. However the study of the ancient science is still useful because it reveals that thinking and reasoning, which were the main tools of ancient philosophers (in contrast to modern modelling tools and computers), can establish consistent views of the world, whose precision in some cases is admirable even today (even though in some other cases the views are illogical according to modern knowledge). And also because it enlightens the continuity of the development of science as it is known that the ancient Greek ideas had a major contribution in the beginnings of modern science (during the Renaissance).

Although the modern world inherited many original texts of the ancient Greek civilization, the majority of them have been lost. The next sections focus on the views on hydrometeorological phenomena that come mainly from original texts and cover three phases of the ancient Greek philosophy: the scientific views of the Ionian philosophers, those developed in classical Athens, with emphasis to Aristotle's influential perception of the universe, and the advanced developments of the Hellenistic period, with emphasis on the theories of Epicurus.

Ionian Philosophers

Although the technological application in water resources started before 2,000 B.C., in the Minoan civilization, and continued later in the Mycenaean civilization (Koutsoyiannis and Angelakis, 2003), the first scientific views of phenomena were formulated only around 600 B.C. Greek philosophers from the Ionia region (at the east coast of the Aegean Sea), rejected the prevailing hyperphysical approaches of that period that were reflected in epic poems (mostly in Homer's Iliad and Odyssey), and explained many physical phenomena in a scientific manner.

Thales of Miletus (640-594 B.C.), one of the Seven Sages of Greece, was the founder of the Ionic philosophy (and according to many, the father of philosophy and of science). Interestingly, his record includes also some engineering achievements thus emphasising the link of technology and philosophy in the genesis of the latter. According to the historian Herodotus (480-430 B.C.; Histories, Cleo, 75) he accomplished the diversion of Ales river in order to help the army of Croesus (king of Lydia) in a conflict against the army of Cyrus (king of Persia). Thales and other Ionian philosophers formulated the theory that the water is the fundamental substance of the world.

Anaximenes (585-525 B.C.), another philosopher from Miletus, devised logical explanations for the formation of clouds, rain and hail (Koutsoyiannis and Xanthopoulos, 1999). According to him

> *"hail is produced when precipitating water from clouds freezes; snow is produced when the water in the clouds freezes"*

Also, of particular importance is the explanation of Anaximenis for the creation of winds:

> *"they are caused when the air density is decreased, so the air becomes light and then starts to move"*

Finally, he gave an explanation for the formation of the rainbow (iris) and attempted to explain lightning (Georgoulis, 1957b).

The philosopher Anaxagoras of Clazomenae (500-428 B.C.) has been very influential; as he lived mostly in Athens, he transplanted the ideas of Ionian philosophers to Athenians including the great politician Pericles, who was his student, the famous dramatists Euripides and Sophocles, and the historian Herodotus. As a natural philosopher and founder of experimental research, he clarified the concept of the hydrologic cycle and studied various meteorological phenomena (winds, storms) generally accepting and completing the explanations of Anaximenes. Specifically, he considered that the differences in the air density, caused by the solar heat, were responsible for the creation of winds (Georgoulis, 1957a). Also, he explained the rainbow (iris):

> *"iris is the reflection of the solar light incident to the clouds"*

Finally, he tried to explain a popular hydrological "paradox" of this period, the floods of the Nile River. The fact that the Nile floods occur at the summertime when rainfall in Egypt is minimal, puzzled the ancient philosophers. Anaxagoras's explanation was that the snow melting in the mountains of Ethiopia in spring, causes summer floods in the regions of Delta of the Nile, with time delay. This explanation is related by Herodotus (Histories, Euterpe), from whom we also know that it was accepted by Euripides and Aeschylus. Herodotus also presents two additional explanations, a mythical one, based on Homer (the floods are produced as the Nile originates from the Ocean, a mythical river located in the Sky) and a more physical, attributed to Thales. According to the latter, the main cause of the floods was the northern wind that prevails in the region in wintertime and does not permit the river to flood. During summertime, because of the attenuation of the winds, the river outflows. Obviously, none of these explanations is correct; the ancient Greek philosophers were not aware of the tropical storms in summertime. But what is more important than a correct explanation is the fact that the question is put and studied. Herodotus himself does not adopt any of these explanations. In addition, he appears to understand the processes of hydrologic cycle, such as the evaporation under the influence of heat, the condensation of water vapour and the formation of rainfall.

Philosophers in Classical Athens

As mentioned above, Anaxagoras is regarded as the link between the Ionian philosophers and Athens. However, the founder of Athenian philosophy is regarded to be Socrates (*ca.* 470-399 B.C.), who is also widely credited for laying the foundation for Western philosophy. Socrates did not write anything himself; however, his student Plato (*ca.* 427-*ca.* 347 B.C.) has conveyed some of his teacher's views in his Dialogues, in which Socrates is often a character.

Plato was one of the most influential philosophers and the founder of the Academy in Athens. Despite the great importance of Plato's views in metaphysics, epistemology, politics and ethics, his contribution in natural philosophy is disputable. He is responsible for an erroneous view of the hydrologic cycle, influenced by Homer's epics. For example, in his dialogue Phaedo, he expresses the following view which he attributes to Socrates:

> *"One of the chasms of the earth is greater than the rest, and is bored right through the whole earth; this is the one which Homer means when he says 'Far off, the lowest abyss beneath the earth' and which elsewhere he and many other poets have called Tartarus. For all the rivers flow together into this chasm and flow out of it again, and they have each the nature of the earth through which they flow. And the reason why all the streams flow in and out here is that this liquid matter has no bottom or foundation. [...] And when the water retires to the region which we call the lower, it flows into the rivers there and fills them up, as if it were pumped into them; and when it leaves that region and comes back to this side, it fills the rivers here; [...] Thence they go down again under the earth [...] and flow again into Tartarus". Phaedo (14.112)*

Interestinly, this, indeed erroneous, view was adopted by many thinkers and scientists from Seneca (*ca.* 4 B.C.-65 A.D.) to Descartes (1596-1650).

Aristotle (384-328 B.C.) was a student of Plato but the theories he developed are far different from those of his teacher. Aristotle was influenced by Ionian philosophers to develop his own view of the world. His famous treatise 'Meteorologica' is a great contribution to the explanation of hydrometeorogical phenomena. According to Aristotle, there are four principles (hot, cold, dry and liquid), that are combined in order to create the four basic elementals (bodies) of perceptible world. These are the Earth, the Air, the Fire and the Water. These four elementals are the combinations of dry and cold, hot and humid, hot and dry and liquid and cold, respectively. The arrangement of the four basic elementals is spherical (Fig. 3). The Earth is the internal sphere, encapsulated by the spheres of Water, Air and Fire; but the distinction of the elementals is not rigid because they are mixed, in order to produce all substances and phenomena of perceptible world. Roughly, the four concentric spheres correspond to what we call today lithosphere, hydrosphere, atmosphere, and outer space, respectively. The Earth is motionless and only Uranus is moving, affecting natural phenomena. The creation of meteorological phenomena is due to the existence of exhalation. The Earth, while heated by the sun, produces two types of exhalation, the smoke and the vapour. The smoke is hot and dry and originates from the Earth, and the vapour is humid and cold and originates from the water. The smoke is the cause of the creation of winds, while the vapour is the cause of creation of precipitation.

According to Aristotle, the genesis and the direction of winds are related to the dry exhalation (smoke) that emerges from the heat of Sun. Despite that dry exhalation (smoke) rises vertically to the surface of ground, the winds blow at inclined directions. This happens because they follow the circular movement of Uranus that surrounds air. Consequently, while the cause of creation of winds is found on the earth, the cause of their movement is owed to Uranus.

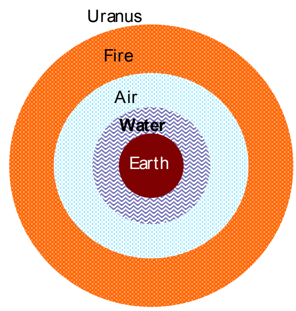

Figure 3 The basic elementals of the world according to Aristotle.

Most of these views are erroneous according to modern knowledge and had already disputed in the Greek antiquity, for instance by the astronomer Aristarchus of Samos (310-230 B.C.) who formulated the heliocentric model of the solar system. However, they contain some pieces of truth; for example the recognition of the spherical Earth. In addition, Aristotle formulated correctly the hydrologic cycle (in contrast to Plato). He understood the phase change of water and the energy exchange required for this:

"... the sun causes the moisture to rise; this is similar to what happens when water is heated by fire" (Meteorologica, II.2, 355a 15)

"... the vapour that is cooled, because of lack of heat in the area where it lies, condenses and turns from air into water; and after the water has formed in this way it falls down again to the earth. The exhalation of water is vapour; air condensing into water is cloud." (ibid., I.9, 346b 30)

He also recognized the principle of mass conservation within hydrological cycle:

"Thus, the sea will never dry up; for the water that has gone up beforehand will return to it; and if this has happened once we must admit its recurrence." (ibid., II.3, 356b 26)

"Even if the same amount does not come back every year or in a given place, yet in a certain period all quantity that has been abstracted is returned." (ibid., II.2, 355a 26)

An impressive perception for the world transformation is also included in Aristotle's texts. Specifically, he puts the question whether the extent of land is decreased, compared with that of the sea. Aristotle discusses this question in light of three basic philosophical theses of ancient Greek philosophers. The first is that universe is eternal (Hesiodos, Plato), the second is that is deteriorated (Democritus) and the third is that there is an alternating process (Heraclitus). Aristotle appears to agree with the third opinion. He believes that on large time scales all changes:

"The same parts of the earth are not always wet or dry, but they change depending on the formation or the disappearance of rivers. And so the relation of land to sea changes and a place does not always remain land or sea throughout all time, but where there was dry

land there comes to be sea, and where there is now sea, there one day comes to be dry land. But we must suppose these changes to follow some order and periodicity." (ibid., I.14, 351a 19)

"... neither the Tanais [the ancient name for the River Don in Russia] nor the Nile has always been flowing, but the region in which they flow now was once dry: for their life has a bound, but time has not. And this will be equally true of all other rivers. But if rivers are formed and disappear and the same places were not always covered by water, the sea must change correspondingly. And if the sea is receding in one place and advancing in another it is clear that the same parts of the whole earth are not always either sea or land, but that all changes in course of time. (ibid., I.14, 353a 16)

The successor of Aristotle in his Peripatetic school, the philosopher Theophrastus (372-287 B.C.), adopted and advanced his teacher's theories on the formation of precipitation from condensation and freezing of water vapour. He also understood the relation of winds and cloud formation and the role of the orography on the latter. His contribution in the understanding of the relation between wind and evaporation is widely recognized (Brutsaert, 1982, p. 16).

The above examples indicate the importance of the understanding of meteorological and hydrological processes in classical Athens. We can imagine that the discussions of these issues would be strong and that the acceptance of the new scientific ideas by the public would not be easy because of superstition. These are vividly expressed in the theatre play Clouds (Nefelae) by the comic dramatist Aristophanes (*ca.* 448 - *ca.* 385 B.C.). The central character of the play, Strepsiades, a citizen of Athens (whose name means "Twister"), decides to become a student of Socrates to learn rhetoric so he can talk his way out of having to pay his debts. The following passage, a dialogue between Socrates and Strepsiades, is characteristic:

Soc.: *What Jupiter? Do not trifle. There is no Jupiter.*

Strep.: *What do you say? Who rains then? For first of all explain this to me.*

Soc.: *These to be sure. I will teach you it by powerful evidence. Come, where have you ever seen him raining at any time without Clouds? And yet he ought to rain in fine weather, and these be absent.*

Strep.: *By Apollo, of a truth you have rightly confirmed this by your present argument. And yet, before this, I really thought that Jupiter caused the rain. But tell me who is it that thunders. This makes me tremble.*

Soc.: *These, as they roll, thunder.*

Strep.: *In what way? you all-daring man!*

Soc. : *When they are full of much water, and are compelled to be borne along, being necessarily precipitated when full of rain, then they fall heavily upon each other and burst and clap.*

Strep.: *Who is it that compels them to borne along? Is it not Jupiter?*

Soc.: *By no means, but aethereal Vortex.*

Strep.: *Vortex? It had escaped my notice that Jupiter did not exist, and that Vortex now reigned in his stead. But you have taught me nothing as yet concerning the clap and the thunder.*

Soc.: *Have you not heard me, that I said that the Clouds, when full of moisture, dash against each other and clap by reason of their density? (Clouds, 356, English ed. by William James Hickie):*

Philosophers of the Hellenistic Period

In the Hellenistic period (as the period after the death of Alexander the Great is called), many different schools of thought were developed in the Greek world, among which the most notable were the Sceptics, Stoics and Epicureans. The latter school, which for the first time admitted women and slaves into it, was the one that mostly explored nature and natural phenomena. Its founder Epicurus (341-270 B.C.) represented a departure from the other major Greek thinkers of this and earlier periods. However, he kept several ideas of earlier philosophers. Like Leucippus (first half of 5th century B.C.) and Democritus (*ca.* 450 - *ca.* 370 B.C.), he was an atomist, believing that the fundamental constituents of the world are atoms flying through empty space (void) and colliding, rebounding, and becoming entangled with one another. These movements he considered random rather than ordered (linear), thus expressing a view different from the determinism of Leucippus and Democritus and more consistent with the indeterminism of Heraclitus (*ca.* 535 - 475 B.C.). This view allowed the development of notion of free will; according to Epicurus, Gods exist but they do not intervene in natural phenomena or human affairs. His advanced ideas were subsequently (and are even today) misunderstood by many; the most characteristic example is his idea of hedonism, which today has a negative meaning different from that taught by Epicurus. For he explicitly warned against overindulgence because it often leads to pain, whereas the real meaning of hedonism is the absence of physical and mental pain. His epistemological views are remarkable and could stand in a modern discussion, as shown for instance in the following passage (cf. the modern notion of the Theory of Everything):

> *"It is not good to desire what is impossible, and to endeavour to enunciate a uniform theory about everything; accordingly, we ought not here to adopt the method, which we have followed in our researches into ethics, or in the solution of problems of natural philosophy. [...] We cannot act in the same way with respect to the heavenly phenomena; these productions may depend upon several different causes, and we may give many different explanations on this subject, equally agreeing with the impression of the senses. Besides, it is not here a question about reasoning on new principles, and of laying down, a priori, rules for the interpretation of nature; the only guides for us to follow are the appearances themselves." (Letter to Pythocles, reproduced by Diogenes Laertius, English translation by C.D. Yonge)*

Some of his views on the hydrometeorological phenomena and presented in his letter to Pythocles:

> *"The clouds may be formed either by the air condensed under the pressure of the winds, or by the agency of atoms set apart for the end, or by emanations from the earth and waters, or by other causes. For there are a great number which are all equally able to produce this effect. When the clouds clash with one another, or undergo any transformation, they produce showers; and the long rains are caused by the motion of the clouds when moved from places suitable to them through the air, when a more violent inundation than usual takes place, from collections of some masses calculated to produce these effects." (ibid.)*

He also studied, and attempted to explain hurricanes, hail, snow, dew, hoarfrost, rainbow, lightning and thunder; for the time lag between the last two he says:

> *"... perhaps, the two phenomena being simultaneous, the lightning arrives among us more rapidly than the noise of the thunder-bolt, as is in fact remarked in other cases when we see at an instance the clash of two objects." (ibid.)*

From the school of stoics, the philosopher who is known to have studied meteorological phenomena is Posidonius (*ca.* 135 - 51 B.C.) who taught in Rhodes, Athens and Rome.

Among his writings, all of which are lost except a few fragments, are the treatises "On meteorology" and "On meteors". It is known that he gave explanations on clouds, mist, wind, rain frost, hail, rainbow and lightning, closely following the teachings of Aristotle.

The Hellenistic period signifies the transformation of science to a more rigorous basis, closer to its modern sense. Thus, in this period one can trace the foundation of modern mathematics by Euclid (*ca.* 325 - 265 B.C.), Archimedes (287 - 212 B.C.) and Apollonius (*ca.* 262 - *ca.* 190 B.C.), and the modern astronomy by Aristarchus of Samos (already mentioned above) and Eratosthenes (276 B.C. - 194 B.C.). Archimedes is also considered as a physicist and engineer and the founder hydrostatics. He introduced the principle, named after him, that a body immersed in a fluid is subject to an upward force (buoyancy) equal in magnitude to the weight of fluid it displaces.

Another famous mathematician, physicist and engineer of the late Hellenistic period is Hero (Heron) of Alexandria (he lived around 150 B.C. [Available online at: http://www.history.rochester.edu/steam/hero/translators.html] or, according to other references, during 10-70 A.D.; note that the Greek ruled in Egypt up to 30 A.D. when the Roman emperor Augustus conquered it from Queen Cleopatra). In his treatise Pneumatica he founded several physical concepts with their modern meanings such as pressure (air pressure, water pressure, and the connection of the two), flow velocity and discharge. His views are impressing and his experimental method very modern, as revealed from the following passage:

> *"Vessels which seem to most men empty are not empty, as they suppose, but full of air. Now the air, as those who have treated of physics are agreed, is composed of particles minute and light, and for the most part invisible. If, then, we pour water into an apparently empty vessel, air will leave the vessel proportioned in quantity to the water which enters it. This may be seen from the following experiment. Let the vessel which seems to be empty be inverted, and, being carefully kept upright, pressed down into water; the water will not enter it even though it, it be entirely immersed: so that it is manifest that the air, being matter, and having itself filled all the space in the vessel, does not allow the water to enter. Now, if we bore the bottom of the vessel, the water will enter through the mouth, but the air will escape through the hole. [...] Hence it must be assumed that the air is matter. The air when set in motion becomes wind (for wind is nothing else but air in motion), and if, when the bottom of the vessel has been pierced and the water is entering, we place the hand over the hole, we shall feel the wind escaping from the vessel; and this is nothing else but the air which is being driven out by the water. It is not then to be supposed that there exists in nature a distinct and continuous vacuum, but that it is distributed in small measures through air and liquid and all other bodies. [...]Winds are produced from excessive exhalation, whereby the air is disturbed and rarefied, and sets in motion the air in immediate contact with it. This movement of the air, however, is not everywhere of uniform velocity: it is more violent in the neighbourhood of the exhalation, where the motion began." (Pneumatica, Treatise, English translation by Bennet Woodcroft)*

Hero was able to convert his theoretical knowledge into technological inventions. Thus, in his writings he describes numerous devices and mechanisms he invented, among which the simplest is the siphon and the most famous is the steam engine or steam turbine (aeolipile; Fig. 4), the first recorded engine exploiting the power of steam, which was created almost two millennia before the industrial revolution.

Figure 4 Hero's steam engine.

Conclusion

Technological applications aiming at the exploitation of the natural sources appear in all ancient civilizations. The unique phenomenon in the ancient Greek civilization is that technological needs triggered physical explanations of the natural phenomena and behaviours, thus enabling the foundation of philosophy and science. Among these, the study of hydrometeorological phenomena had a major role.

Many of the theories developed in the course of ancient Greek civilization are erroneous according to modern views. However, there are many impressive elements in Greek exegeses and interpretations of various hydrometeorological processes, such as the evaporation and condensation of vapour, the creation of clouds, hail, snow and rainfall and the evolution of hydrological cycle. Naturally, at the latest stage of this civilization, the Hellenistic period, the theories developed were more advanced, closer to the modern sense of scientific theories, and reveal better understanding of physics. The latter theoretical advances enabled a significant technological progress, which however soon after was discontinued, its potential only to be realized during or after the Renaissance.

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The Road not Taken: How Traditional Excreta and Greywater Management may Point the Way to a Sustainable Future

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Abstract: This paper argues that modern, end-of-pipe sanitation systems are not the pinnacle of centuries of wastewater technology development, and may actually prove to be a technological dead-end - expensive to build, operate and maintain, and out of step with traditional wastewater management philosophy. A brief examination of a series of excreta and wastewater management systems from around the world and throughout history clearly shows that viewing faeces, urine and grey water as a worthless waste to be disposed of is only a modern concept, which ignores the realities of limited resource availability, and the obvious benefits to be had from closed-loop systems - as was clearly recognised in the past. While currently, expensive, technically complicated end-of-pipe sanitation systems are dominant, several modern systems have been developed specifically to ensure an efficient resource recovery and reuse. Reconsidering and researching historical approaches to wastewater management and applying modern technologies to improve their functionality may contribute to the solution of many of today's sanitary and environmental problems.

Keywords Agriculture; excreta and greywater reuse; sanitation philosophy; wastewater management systems.

Introduction

The advent of agriculture around 10,000 B.C. enabled larger human populations to settle in a fixed location for longer periods than had been previously possible among hunter-gatherers. With this settlement, people were faced for the first time with the problem of what to do with the large volumes of excreta and used water that accumulated as a result of a sedentary lifestyle. Many old, traditional agricultural societies approached this in a logical and pragmatic manner that recognised the nutrient and organic value of excreta by practising the recovery and use of "night-soil" (faeces and excreta). This enabled them to live for centuries in closed loop systems, where nutrients and organic matter from liquid and solid household wastes were returned to the soil from whence they came. In China, where this is still widely practised, they have been able to maintain soil fertility over millennia, despite the high population density. This knowledge however was not based on scientific research, but was rather culturally codified and traditional practical knowledge. In general, historical descriptions on this theme are sparse.

Over the last century or so traditional reuse practices have been abandoned, and replaced by "end-of-pipe" wastewater disposal systems. Today, in view of the construction and operation and maintenance costs of these systems, the degrading quality and fertility of our soils, the limited availability of mineral phosphorous reserves, the high energy consumption of fertiliser production, and the need to protect our freshwater reserves, the resource value of excreta and greywater needs once more to be recognised and systematically implemented, using modern technological and operational solutions, and ensuring maximum health protection.

To be able to apply such closed loop approaches in a modern and hygienically safe manner historical research is needed, as is an improved cooperation between scientific disciplines. The motivation for this paper was therefore to look to the past to provide a direction for the future.

A Brief History of Excreta and Greywater Use

In a very broad sense the recovery and use of urine and faeces has been practiced over millennia by almost all cultures. The uses to which they were put were not limited to agricultural production (although for modern application this is of course of most relevance), and indeed covered a wide variety of practices. The Celts had many uses for urine, one of particularly practical importance being its use in dyeing and washing cloth, although they also used it in personal hygiene and had various ritual uses. In India, ancient Sanskrit texts outlined the medicinal use of urine through *shivambu* (auto-urine therapy), which was practiced throughout India and Asia, and still has a popular following today.

Like the Celts, the Romans were well aware of the cleaning power of urine and also used it for washing clothing, developing in some towns and cities the logistics to collect larger volumes of urine. Fullers, who worked in laundries, would install amphoras in streets and alleys of towns to serve as public urinals, and would pass regularly to collect the urine, transporting it back to the laundry for washing. Of course, for those involved, washing with urine was a rather smelly business, but also an extremely lucrative one, which led to Vespasians famous quote “pecunia non olet”. Throughout Europe fullers continued to work in this way right through to the Middle Ages, using urine to remove the fat from raw wool and to soften it.

From these few examples it is clear that throughout history attitudes to excreta have not always been as negative as they are today, and that excreta was seen as a resource. However, this can most clearly be seen when one considers the use to which both excreta and greywater have been put in agriculture throughout the ages. The most widely renowned example of the diligent collection and use of human excreta in agriculture is of course that of China. It is reported that the Chinese were aware of the benefits of using excreta in crop production before the 500 B.C., enabling them to sustain “more people at a higher density than any other system of agriculture” (Brown, 2003). The value of “nightsoil” as a fertiliser was clearly recognised with well developed systems in place to enable the collection of excreta from cities and its transportation to fields. Like the work of the fuller, this was a lucrative enterprise. Contractors first had to pay for a license before collecting the excreta and selling it on to farmers, and larger towns were often zoned so that those living nearer the fields paid less for their collection than those living in the centre. In Scott (1952) the annual market price of the excreta output of the entire population was estimated at “between 50 and 80 million pounds sterling at 1924 market prices.”

The Japanese too practiced a disciplined use of excreta in agriculture, being applied at rates of up to 4 t/ha on fields in an environment that was considerably more urbanised than that of China. King (1911) reported seeing nightsoil transported out of Yokohama and Tokyo “carried on the shoulders of men and on the backs of animals, but most commonly on strong carts drawn by men bearing six to ten tightly covered wooden containers holding forty, sixty or more pounds each" (Brown, 2003). Statistics from the Japanese Bureau of Agriculture for 1908 state that 23 950 295 tons of excreta had been used on around 13.5 million hectares of arable land (King, 1911). Like the Romans, the Japanese provided public toilets with the express aim of collecting excreta for use. The Japanese regarded urine as a particularly useful fertiliser and this would be collected separately for direct use (Matsui, 1997). However; the reuse of excreta not only was limited to China and Japan, but was and continues to be practiced right across Asia.

Apart from collecting urine separately for laundry purposes, the ancient Romans also practiced the use of excreta in agriculture, a practise which they may have adopted from the ancient Greeks. Texts exist from both ancient Roman and Greek authors praising the virtues of its use in agriculture. The Romans also practiced the consequent reuse of greywater - huge volumes of which were produced as a result of the Roman bath culture. Daily per capita water consumption has been estimated at up to 600 L for the upper classes, whereas slaves and soldiers may have used around 200 L/inh·d (Guhl, 2004). As the use of excreta for agriculture was the rule in Roman times, the wastewater from most settlements was in the main greywater only. This was often lead outside of the settlement and used to irrigate agricultural areas, as for example was the case at Barbegal in Provence, France. Here, greywater coming from the settlement which had an estimated population of around 500, was mixed with the water passing through the largest grain mills in the Roman Empire and used to irrigate an agricultural area of around 22 ha.

Ancient Arab cultures also incorporated the collection and use of excreta into their agricultural systems, a practice that continued for very many centuries. In the 12^{th} and 13^{th} century, Ibn al-Awam, an Arab living in southern Spain wrote of composting techniques incorporating human excreta, and of its benefits in curing illnesses in plants such as bananas, apple trees, peach trees, citrus trees, figs, grapes, palms, cedars and wheat. Elaborate systems were developed in the urban centres of Yemen that enabled the separation of urine and excreta even in multi-storey buildings. Faeces were collected from toilets via vertical drop shafts, while urine did not enter the shaft but passed instead along a channel leading through the wall to the outside where it evaporated. Here, the faeces were not used in agriculture but were dried and burnt as fuel. This was common practice for many centuries resulting in a sanitation system, which required very little water. In modern times this traditional sanitation system has been changed with the introduction of water-flush toilets, which appeared to offer a more convenient and "modern" solution. However this has lead to water shortages and a dramatically falling water table in the area of the Yemeni capital city of Sana'a, and to structural damages of the existing multi-storey clay-buildings (Winblad and Simpson-Hébert, 2004). In Mexico and Peru, both the great Aztec and Inca cultures collected human excreta for agricultural use. In Peru, the Incas had a high regard for excreta as a fertiliser and would store it, dried and pulverised to be used when planting maize.

After the fall of the Roman Empire, many of the centralised structures and systems put in place during that period began to dissolve. However not all of their knowledge was lost. Indeed the collection and reuse of excreta continued. Monasteries, which served as repositories for information and learning throughout Europe at this time continued to apply the recovery of nutrients from excreta and greywater. For example near Milan, the Cistercians introduced the use of city refuse and sewer water on their land in around 1150 C.E. The Cistercians had also developed sophisticated washing systems, and used the greywater from wash houses to either directly irrigate gardens or, as at their monastery at Silvacane, near Marseille, mixed it with wastewater from buildings and fresh water to feed fish ponds (Guhl, 2004).

In the Middle Ages, the use of excreta and greywater was well established. European cities were rapidly urbanising and sanitation was becoming an increasingly serious problem, whilst at the same time the cities themselves were becoming an increasingly more important source of agricultural nutrients. In Flanders, for example, the sale of excreta and animal dung was a booming business. By the 16th century up to 60% of farmers expenditure was on fertiliser (excreta and dung). By then near Antwerp farm rents were soaring, with farmers able to ensure a high enough production to pay them thanks to their relatively easy access to the cities nutrients (Brown, 2003).

In Freiburg, Germany, meadows were irrigated with nutrient rich wastewater coming from the town, with this practice first officially recorded in 1220 C.E. The meadows were mostly located in areas with permeable soils along rivers. The installation of agriculture on these meadows ensured plant growth in dry periods and extended the vegetation period by washing away the snow in spring or winter. The irrigation also served to reduce the incidence of plant pests (a phenomena reported from other areas where either excreta or greywater was used), and contributed to ensuring a stable nutrient balance in the meadows. The water used for irrigation had passed through settlements and had been used several times, and was therefore enriched with nutrients and suspended matter. Thus the nutrient loss caused by the removal of crops from the meadow was compensated. Irrigation of the meadows reached its heyday in the early 19th century, although the practice itself only stopped in the 1960s.

The practice of using the nutrients in excreta for agriculture therefore clearly continued in Europe into the middle of the 19th century, and the marketing of fertiliser derived from excreta and organic waste continued to be a thriving business. There were “great stores of manure on the Schelde between St Amand and Baasrode…whence the excrement from Dutch towns was transported by barge” (Brown, 2003). Farmers were eager to get these fertilisers to increase their yields, the value of excreta was clearly recognised, and urban sanitation benefited. There are countless similar examples from these times of the use and potential of the excreta coming from urban areas. In Paris for example, in 1850 urban agriculture was practised on 15% of the city area and Paris was exporting vegetables, compost and fertiliser from pits to the surrounding regions (Illich, 1987; Lange 2002).

As the industrial revolution progressed it was becoming increasingly possible to develop more complex approaches to collect excreta for reuse. In 1865, Prince Heinrich der Niederlande had asked T. Charles Lienur to remove the sewage from Castle Luxembourg without polluting the River Elz and without using wagons (The introduction of sewer systems in the second half of the 19th century - see below - provoked hefty discussions on their pros and cons, as treatment plants were non-existent and they were causing serious pollution of surface water bodies). Lienur’s system consisted of two pipes. One carried rainwater, greywater, and industrial water, while the other was what could be considered the predecessor of modern vacuum sanitation systems (as found on planes and high speed trains), and was used to transport blackwater and water from stables and slaughter houses. The vacuum toilets required very little flushing water and the blackwater collected was used to produce “poudrette” (a dried natural fertiliser). At that time the industrial production of mineral fertiliser had not yet started (the first factories were built in 1870) and the price for fertiliser was high enough to allow the production and successful marketing of “poudrette”.

In developing areas of Amsterdam in 1906 more than 4,500 vacuum toilets where connected to a Lienur-system. Soon however the production of poudrette was seen as being too costly as prices for industrial mineral fertiliser decreased. Although some information on Lienurs system is available, a thorough investigation of why the system could not compete with central sewer systems in urban areas, particularly under the specific and very difficult conditions in a city like Amsterdam, has not been carried out (Lange and Otterpohl, 2000; Lange 2002).

Why did this All Change?

However, whilst the recovery of nutrients and organic matter from excreta and greywater was addressing the sanitation problems of settlements and contributing to securing and increasing agricultural productivity - one Spanish author in the 18th century describing yields from excreta fertilised crops as being “monstrously large” - the practice was not destined to become the dominant approach to sanitation in the 20th century. There were four main driving factors that lead to the demise in the recovery and use of excreta and greywater from cities.

Firstly, urban settlements continue to grow dramatically in size over the centuries. The cities attracted people eager to try their luck there, with each new arrival producing excreta and wastewater. However, the logistical challenge of removing the faeces of a booming population from densely packed city centres to bring to agricultural areas many miles away proved too great. The sanitary conditions in major European cities degraded rapidly. In 19th century Britain an average of 26% of children died before the age of 5, whereas in the cities the average was double that at around 50% (Brown, 2003), and cholera was the scourge of the country. In addition to this the collection, handling and use of partially or untreated waste was having extreme impacts on public health - particularly as there lacked any knowledge of modes of transmission of faeco-oral diseases. Considering once more the example of China, a study looking at agriculture and health there in the 1930s revealed alarming statistics (Scott, 1952). Life expectancy was 34 years, compared to 60 years in Britain at that time, with 42% of all deaths occurring amongst children under 10. In Tinghsien, south-west of Beijing, 18.5% of all deaths were from gastro-intestinal illnesses.

Secondly, up until the end of the 19th century the dominant theory on the spread of illness was the miasma theory. This long established theory, which had its roots in classical times, basically held that illness was caused by volatile substances that were inhaled. As bad smells were thought more likely to contain illness, everything that smelled had to be gotten rid of. To some degree the miasma theory contributed to containing some disease, but did not allow for a suitable approach to safe excreta reuse to be adopted. Excreta smelled bad and was therefore to be gotten rid of.

Thirdly, the arrival of piped domestic water supplies in the 19th century made water flushed sewerage system finally possible. The water flushed system, often using existing stormwater drains, was the answer to many people’s prayers at the time. Governments had attempted to legislate to improve sanitation but this was proving difficult to implement, and physician and hygienists were caught in a losing battle. Water flushed systems dramatically transformed this situation, with sewage being flushed away from homes and the hearts of cities into nearby rivers. Water flushing of course greatly increased the volume of sewage, whilst at the same time diluted the nutrients in it, making it virtually impossible for nutrient to be recovered and reused as they we previously.

And fourthly, as was seen in the case of Lienur’s poudrette, the nutrient demand of farmers was eventually met by cheap chemical fertilisers, making any efforts to recover and reuse the nutrients and organic material from the large volumes of sewage completely obsolete. The evidence was clear. Sewered cities became cleaner, healthier places to live, city pollution became river pollution, downstream communities suffered and the concept of the water-borne sewer system became the standard approach to solve the sanitation problems in urban areas of industrialised countries during the second half of the 19th century and into the 20th (van Zon, 1986; Lange and Otterpohl, 2000; Lange, 2002).

The End of the Pipe at the End of the Line?

Of course for 19th century engineers there was already a precedent for water flushed systems systems, from the times of the mighty Roman Empire. The Roman Cloaca Maxima, built by Tarquinius Priscus (616-578 B.C.), was originally a system of channels draining rainwater from Rome, particularly the area around the Forum. It later became the main Roman sewerage canal carrying wastewater and storm water out of the city, and discharging it downstream into the Tiber, thus protecting at least to a small degree the water quality of the Tiber within the city catchment. However, despite this water quality "protection measure", the Tiber was still unsuitable to be used as a water source, requiring fresh drinking water to be brought to the city via aqueducts. Today for many it remains a mystery as to why the achievements of this forerunner of modern centralised wastewater systems, and this form of wastewater "disposal" was completely forgotten until the 19th century. What however is less often recognised is that the Cloaca Maxima was practically an emergency "solution" to deal with the vast quantities of wastewater generated in the capitol that could not be dealt with in any other way. It is by no means proven that the Cloaca Maxima served to transport excreta out of the city. Indeed this would have been surprising as recovery and reuse of excreta was common place in the time of the emperors.

In many ways, the sewage systems of the 19th century were a similar emergency solution to a social health crisis, and for 150 years engineers have continued to try and perfect this emergency solution. Instead of fixing the hole in the dyke, we have continued to ensure that the boy's fingers just about fill the crack. In order to improve the abysmal sanitary state of cities it was initially considered acceptable to discharge effluent (raw sewage) to surface water bodies, spending large sums of money to install vast sewerage networks throughout cities to do so. Later, when the effects of the severe river pollution this caused became obvious, mechanical treatment of wastewater was introduced (the first German treatment plant being built in 1887 in Frankfurt-Niederrad), followed in time by biological treatment for the degradation of organic substances, and tertiary treatment for the removal of nutrients and reduction of eutrophication of the receiving water bodies. These three steps now represent the present state-of-the-art in wastewater treatment.

Although these conventional sewer systems have improved the public health situation in towns, cities and countries that can afford the massive installation, operation and maintenance cost, they have also drained economies, polluted and squandered fresh water resources, broken nutrient cycles and impoverished soils. For almost half of the world's population, the estimated 2.6 billion people who do not have access to adequate sanitation today (WHO/UNICEF JMP, 2005), "end-of-pipe" systems remain both unaffordable and inappropriate. The centralised end-of-pipe paradigm has let billions of people down. As millions are spent perfecting these expensively wasteful systems, an estimated 2.2 million people, most of them children under the age of five, die every year as a result of illnesses caused by contaminated drinking water and poor sanitation and hygiene in developing countries. 80 % of all diseases and 25 % of all deaths in developing countries are caused by polluted water (UN, 1992). At the same time soils are impoverished and nutrients lost to water bodies as the "end-of-pipe" paradigm discourages recovery and reuse. In Africa, 85% of arable land is losing an average of 30 kg of nutrients per hectare per year (Morin, 2006).

However it is not only in the developing world that end-of-pipe systems are at the end of the line. In wealthy Europe for example, of 540 major cities, only 79 have advanced tertiary sewage treatment, 223 have secondary treatment, 72 have incomplete primary treatment and 168 cities have no or an unknown form of treatment of their wastewater (EcoSanRes, 2002). The conventional sewer system was developed at a time, in regions, and under environmental conditions where the priority was mainly to remove liquid wastes and dilute excreta from cities. Today with increased population pressure, changes in consumer habits and increasing pressure on freshwater and other resources, this human waste disposal system is no longer able to meet the pressing global needs. In the light of dwindling natural resources there is a need to reassess the functioning of conventional sewage collection and treatment stems. The motivation and inspiration behind end-of-pipe systems needs to be reassessed from a historical perspective and in the light of technological advances. Around the globe the reflections have begun and a range of systems have been developed, based on the recycling principals of the past and using modern technological and systems approaches.

Closing the Loop Once More

In Sweden, near a nature reserve in a suburb of Stockholm, the Gebers collective housing project can be found, initiated by a network of friends and neighbours, who converted a deserted and vandalized building complex into 32 apartments with a total of 80 inhabitants. With the installation of a closed-loop system for toilet and organic waste, the project contributes to the environmental protection of the reserve (GTZ -project data sheets, 2006).

Toilets designed to separately collect faeces and urine were installed, with each fraction being treated before reuse. The urine is flushed with water and piped to polypropylene collection tanks whilst the faeces are collected without flushing water, falling straight into individual plastic bins, with both the tanks and the bins located in the cellar of the complex. The plastic bins are housed in a special compartment which is constantly under negative pressure through ventilation, improving dehydration of the faeces and preventing odours from entering the homes. The urine tanks are emptied about twice a year by a tanker truck and the treated urine is used as fertiliser in agriculture. The faeces are composted together with other organic household wastes. The resulting compost has a soil-like appearance, and will be used as a soil conditioner in agriculture to produce horse feed.

On the other side of the globe, Erdos is a cluster of cities in a coal mining belt of Inner Mongolia, where a new town is being developed in a suburban area a few kilometres from the city centre of Dong Sheng. Housing for 7,000 people in the town is being equipped with modern porcelain dry toilets which enable urine to be collected separately. The toilets and related equipment and fixtures are being developed and manufactured in China (Zhu, 2006).

Similar to Gebers, the faeces will be collected in dry form in containers in the cellar, which will be regularly emptied. The faeces will then be composted together with household organic wastes and used as a soil conditioner. Urine will be collected on-site in tanks and used in local agriculture. Greywater will be collected and treated on site in small aeration and filtration treatment facilities. Organic and other solid wastes will be sorted and collected in eco-stations. Storm water will be collected separately using drains. The project will undergo a period of development and testing prior to its full-scale implementation. Once in operation the model town will be the object of further performance studies by water and sanitation specialists, urban planners, urban agriculturalists and others.

The village of Haran Al-Awamied is located south east of Damascus, Syria. The villagers are poor in this village, with farming the main source of income. Untreated wastewater from the existing gravity sewers was, until recently, commonly used for irrigation, resulting in a high incidence of disease. A new combined public sewer system was therefore recently installed to collect and transport rain and wastewater to a new wastewater treatment plant.

The plant consists of bar screens and a sedimentation tank as a pre-treatment, two reed beds to treat the wastewater, and one reed bed for the soilification of the sludge. The treated water is collected in a tank for storage, and is pumped from the collection tank to irrigate the fields near the plant when needed, with the distribution being organised by the farmers.

The improved availability of irrigation water with a high nutrient content has reduced the farmer's expenditure on commercial mineral fertilisers. It has contributed to higher yields in crop production, and increased the number of harvests from one to several per year. The reed plants of the constructed wetland are used for wicker and roofing materials and the treated sludge is used as a soil conditioner. As the farmers clearly benefit from the constructed wetland, they have provided a great deal of support to ensure its correct functioning (GTZ - project data sheets, 2006)

A further example of how closed-lop systems are being implemented can be seen at the headquarters of the German Technical Cooperation (GTZ) in Eschborn, near Frankfurt. During the renovation of the main office building, a modern, ecologically sustainable concept for the management of the wastewater from the toilets has been installed. The main building is equipped with waterless urinals and water flushed urine diversion toilets. Through the separate, undiluted collection of urine, the water demand for flushing toilets is expected to be significantly reduced. With this concept, the GTZ will not only saves 900 m^3 of water per year, but also significantly reduce the load of nutrients and other substances from the urine on the water treatment facilities (GTZ -project data sheets, 2006). After treatment the urine will be used in agricultural tests carried out as part of a research project. The information collected from the project aims to improve agricultural production with urine based fertiliser. When finished, the system will serve as a model for similar facilities, also in countries where water is scarce and fertiliser is needed in local agriculture. As the building receives thousands of overseas visitors per year from developing countries, a large public relations impact is expected.

For the treatment and reuse of the brownwater (i.e., faeces and flush water originating from the toilets) an additional research component is foreseen. Treatment with an activated sludge reactor, followed by membrane filtration, is currently being discussed as one possible technological option.

Conclusion: The Past may Contain the Path to a Sustainable Future

A brief examination of excreta and wastewater management systems from around the world and throughout history clearly shows that viewing faeces, urine and grey water as a worthless waste to be disposed of is only a modern concept, which ignores the realities of limited resource availability, and the obvious benefits to be had from closed-loop systems - as was clearly recognised in the past. 150 years ago this changed dramatically and unsustainable, end-of-pipe, wastewater disposal systems were developed as a way out of a sanitation crisis in wealthy, water rich cities, where they successfully contributed to improving the hygienic situation there. With a century and a half of research and development behind them end-of-pipe systems have become the state of the art in waste water management. The unreflected export of this end-of-pipe philosophy, even to water scarce, poor regions of the South, has however also contributed to the alarming sanitation statistics there, with 4,000 children under 5 dying daily from the effects of contaminated water. Historical research is therefore needed to help clearly establish how we have arrived at this situation and to highlight alternatives to the current dominant approach.

In attempting to understand the road that has been taken in sanitation it is important to understand the context of the time. Clearly this includes the technological, economic and environmental context, but the cultural context in which sanitation developments have taken place is also of rime importance. For example the influence of the ultimately erroneous Miasma Theory on the development of cultural attitudes to excreta in Europe can help explain to a degree the "faecophobic" thinking behind end-of-pipe systems. Socio-cultural considerations are also important for new developments in sanitation. Research on history and traditions of sanitation-related socio-cultural aspects can therefore greatly contribute to the socio-cultural sustainability of sanitation systems.

Historical research on the urbanisation of 19th century Europe has already shed some light on the driving forces behind sewered, water-borne sanitation, and end-of-pipe treatment systems in Europe. The historical research of Lange (2002) and some earlier work of van Zon (1986) are useful to help us understand the alternatives that have been discussed and tested, and to gain some preliminary insight as to why these were ultimately rejected or accepted in their day.

In order to effectively address the current global sanitation crisis, and to lobby for a paradigm change towards closed-loop, socially, economically and environmentally sustainable systems it is important to have a clear understanding of the history of sanitation. This field has to date not been given sufficient attention, and the future of sanitation would clearly benefit from an examination of the past. Historical research questions could include:

(a) Which sanitation systems were developed in different periods and cultures?
(b) How were these systems culturally, economically, technically and environmentally embedded in the given social context?
(c) Why has the end-of-pipe sewer system become so dominant today?
(d) How can previous, historical experience and philosophy of sanitation be collected and made useful and relevant in a modern context?
(e) What traditionally codified social knowledge, values and habits may prove to be of use when introducing innovative sanitation systems? Which taboos, reservations and social boundary conditions need to be considered?

Historical research is therefore being called upon to examine the route we have taken in addressing our sanitation problems and in so doing to provide inspiration for the road we may take into the future.

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Styx Water, Myth and Reality: An Interpretation of its Corrosiveness Based on Pausanias’ Text

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Abstract: In Pausanias’ book (*ca.*174 A.D.) “Description Of Greece” and in particular in the *ARCADICS* (Book VIII) there is an excerpt, in which the “miraculous” properties of Styx water are described, which springs from a rock of today’s mountain of Aroania (Helmos) and keeps supplying a small river, named “Crathis” in antiquity. A technological interpretation of the text, on the basis of greek mythological substratum of “Styx” (Oath of Gods, River of the Underworld) is attempted. Especially the corrosiveness of the Styx water mainly to metallic materials and its additional property to crack inorganic materials (pottery, ceramics, stones etc) are explained. It is concluded that Pausanias’ text is a blend of different sources, containing mythological and real elements. The property of causing cracks is probably related to the underworld origin of Styx and referred to metallic melts, which in some cases break the crucibles or the molds, in which they are carried. The corrosiveness of the Styx water to the metals can probably be attributed to the formation of an acidic sulfuric solution, produced by biological corrosion of sulfide minerals via thiooxidant bacilli.

Keywords Ancient; biological; corrosiveness; metals.

Introduction

The major importance of water, as a basic element of the Mediterranean basin civilizations, included the hellenic world from antiquity up to the Byzantine Era, can be proved in the archeological field, through numerous witnesses of aqueducts, springs, sewers and other artifacts, related to the utilization of the natural water.

The Myth of Styx

Etymology-Styx water in Pausanias’ Arcadics

The wide- known natural water of Styx, of which many references in ancient texts can be detected, is the main object of this article. Searching the etymology of Styx, the river of the Underworld, we find the verb *«στυγέω-ω»,* meaning “to be afraid of”, “to be fearful” (Fragoulis, 2002). Interpreting the same verb as lemma according to Suida (2002) we find: “*μισει*”, or “*φοβειται*”…*Από της Στυγός, ήτις εστί πηγή εν άδου*»”, meaning: “to hate or to be afraid of, derives from Styx, which is a spring in Ades”. Many references are found about this name in ancient literature, whether Styx is presented as an Oath River, or as an Oceanid. All of them are aspects that strengthen its mythological basis. Thus, Styx is called “The Hateful”, because she is the embodiment of Water in the Underworld, over which the souls of the dead are carried by Charon and by which the Immortals swear their most solemn oaths.

The main description of Styx Water, that seems to overpass the myth and appears to have reasonable elements, is presented in Pausanias (XVIII), on which our interpretation is primarily based. He was born around 110 A.D. in Minor Asia. He traveled to Greece, Egypt, Rome, Syria and elsewhere. He wrote "*Ελλάδος Περιήγησις*", "*Description of Greece*", in which he attaches explanatory material, related to political historical facts, mythological elements, and also to the topography of the areas he had visited. Especially, *Arcadics*, the eighth book of "Description of Greece", concerning Peloponnesus, is the main historical source, from which an exhausted description of Styx is presented. Its writing must have finished around 174 A.D., during the period of Marcus Aurelius (161-180 A.D.) (Easterling and Knox, 2000). The river Styx is in the northern part of Arcadia, which includes the mountain Aroania (nowadays Helmos). About the topography of the area the following lines are indicative: *"...Το δε ύδωρ το από του κρημνου του παρά την Νώνακριν στάζον εσπίπτει μεν πρωτον ες πέτραν υψηλήν, διεξελθόν δε διά της πέτρας ες τον Κραθιν ποταμόν κάτεισι...*", translated as: "The water trickling down the cliff by the side of Nonacris falls first to a high rock through which it passes and then descends into the river Crathis" (Fig. 1; Jones and Ormerod, 1918).

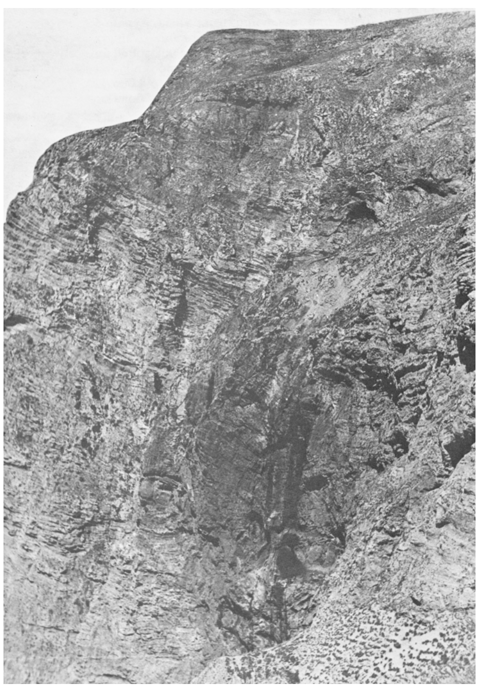

Figure 1 Styx water by the side of ancient Nonacris.

Besides his own text Pausanias is referred to Hesiod's book about Styx, (Tsaknakis, 2006). On the following lines of his text Pausanias proceeds to inform the readers about the toxicity of Styx water on human and animals: *"...θάνατον δε το ύδωρ φέρει τουτο και ανθρώπω και άλλω ζώω παντί. Λέγεται δε ότι γένοιτό ποτε όλεθρος απ' αυτου και αιξίν, αι του ύδατος έπιον πρωτον*", translated as: "Its water brings death to all, man and beast alike. It is said too that it once brought death even upon goats, which drank of the water first; later on all the wonderful properties of the water learnt and…".

Styx water in ancient Greek literature

Before proceeding to the description of the water properties, the most representative lines of ancient Greek literature concerning Styx are about to be referred. The earliest and most exhausted report of Styx can be studied in Hesiod's *Theogony,* a didactic epos full of genealogies. Hesiod, the first Greek poet who tried to represent all the elements of the world, living and soulless, personified them, and classified the divine beings through a systematic genealogy, places Styx among the Okeanides. She is the daughter of Tethys and Ocean, wife of Pallas, who was offspring of Titans. Styx gave birth to Nike-*Νίκη* (Victory), Zelos-*Ζήλος* (Rivalry), Via-*Βία* (Force) and Kratos-*Κράτος* (Power). Taking in consider the role of Styx in the Titan-War-*Τιτανομαχία,* namely her help to Zeus, we assume that she assists the values of Good, Balance, Harmony and Order, that Zeus represented.

Styx- as an Okeanid (one of the 3,000 Okeanids) and as an embodiment of The Oath River appears in *Theogony*, Genesis. For instance: «*και Στύξ, η δή σφεων προφερεστάτη εστίν απασέων*»… "…and Styx, who is the most preeminent of all" (Lines 361-362, as translated by Hugh G. Evelyn- White). The role of Styx as an Oath and her close relation to Zeus commitment to punish every god who would break the oath appears in *Theogony,* for instance: « *τοιον άρ' όρκον έθεντο θεοί Στυγός άφθιτον ύδωρ, ωγύγιον· το δ' ίησι καταστυφέλου διά χώρου.*»…"Such an oath, then, did the gods appoint the eternal and primeval water of Styx to be: and it spouts through a rugged place (…)" (Lines 805-806). Related to the mythological elements of the Trojan War is the effort of Thetis to achieve the Immortalization of her son Achilles. The mother tried to make the infant Achilles invulnerable by dipping it in the waters of the Styx (Fig. 2).

Figure 2 Donato Creti (1671-1748) "Achilles dipping in Styx" (Paipetis, 2005).

However, the heel by which she held him –also mentioned as *Achilles' Tendon*- was not protected by the Styx's waters. In the story of Achilles in the Trojan War in the Iliad, Homer does not mention this weakness of Achilles' heel although in the *Iliad* by Homer, about 800 B.C., the name Styx is mentioned four times. References can be read also in the *Odyssey* (Homer), for instance, when Calypso swears to Odysseus on the water of Styx that she will allow him to leave her island... Also in Book 10 and 11 "…at the entrance of the Underworld beyond the Ocean is limited by the river Acheron, Pyriphlegethon and Kokyttos, the river of cry, a branch of Styx…".

The Properties of Styx Water in Pausanias' Text

The main information, concerning those properties of the water, which could be scientifically discussed and are to be explained, is found in the subsequent Pausanias' passage. It is an exhaustive description of the harmful effects of Styx water on inorganic materials,organic materials and metals: «*…Ύαλος μέν γε και κρύσταλλος και μόρρια και όσα εστίν ανθρώποις άλλα λίθου ποιούμενα και των σκευων τά κεραμεα, τα μεν υπό της Στυγός του ύδατος ρήγνυται…*» "...For glass, crystal, murrhine vessels, other articles men make of stone and pottery all broken by the water of the Styx…", «*…κεράτινα δε και οστέινα σίδηρός τε και χαλκός, έτι δε μόλυβδος τε και κασσίτερος και άργυρος και το ήλεκτρον υπό τούτου σήπεται του ύδατος...», "*...while things of horn or of bone, with iron, bronze,lead, tin, silver and electrum, are all corroded by this water...", «*…το δε αυτό [εν] μετάλλοις τοις πασι και ο χρυσός πέπονθε...*»,"...Gold too suffers just like the other metals...",«*...καίτοι γε καθαρεύειν [γε] τον χρυσόν από του ιου ή τε ποιήτρια μάρτυς εστίν η Λεσβία και αυτός ο χρυσός επιδείκνυσιν...*», "...and yet gold is immune to rust, as the Lesbian poetess bears witness is shown by the metal itself...", «*...έδωκε δε άρα ο θεός τοις μάλιστα αεριμμένοις κρατειν των υπερηρκότων τη δόξη. τούτο μέν γάρ τά μάργαρα απόλλυσθαι πέφυκεν υπό του όξους, τουτο δε τον αδάμαντα λίθων όντα ισχυρότατον του τράγου κατατήκει το αιμα· Και δή και το ύδωρ ου δύναται της Στυγός οπλήν ίππου βιάσασθαι μόνην, αλλά εμβληθέν κατέχεται τε υπ' αυτης και ου διεργάζεται την οπλήν...*», "So heaven has assigned to the most lowly things the mastery over things far more esteemed than they. For pearls are dissolved by vinegar, while diamonds, the hardest stones, are melted by the blood of the he-goat. The only thing that can resist the water of the Styx is a horse's hoof", «*...ει δε και Αλεξάνδρου του Φιλίππου συνέβη την τελευτήν διά του φαρμάκου γενέσθαι τούτου, σαφως μέν ουκ οίδα λεγόμενον δε οιδα...»,* "...When poured into it the water is retained, and does not break up the hoof. Whether Alexander, the son of Philip, met his end by this poison I do not know for certain, but I do know that there is a story to this effect…".The reader who wishes to search behind Pausanias' words and explain the chemical properties of the Styx water, should carefully take that text in consider.

Text's Explanation-Comments

Studying the structure of the text it is strongly considered to be a blend of different information, containing mythological and real elements. It seems that the writer's method was to accumulate without a systematic methodology knowledge, ideas and opinions from various sources. According to our aspect, three parts can be detected in that context.

Thus, the first part concerns the property of breaking or cracking. The word "ρήγνυται", meaning "breaks" or "cracks" should not interpreted as a property of water, but as a mechanical process. The breaking or cracking concerns not objects themselves but crucibles or moulds of stones, ceramics, pottery in which metallic melts are carried (Conophagos, 1980). Destruction of these materials is usually caused by thermal shocks. Thus, the Styx water could be a metallic melt or a magma instead of water. This is also compatible with the identification of Styx as chthonian existence, as a river of the Underworld.

In the second part the destruction of materials like metallic alloys is considered to be interpreted in terms of corrosion science. Styx water is probably a corrosive acidic solution. A possible explanation could be the presence of hydrogen sulphuric anions or /and sulphuric anions in Styx water. The formation of these anions is possible by biological (bacterial) corrosion of sulphide minerals like copper sulphide via thiooxidants bacilli (bacteria).Aerobic sulphur oxidizing bacteria (thiooxidans thiobacillus)) are capable of oxidizing elemental sulphur or sulphur -bearing compounds to sulphuric acid (H_2SO_4.) It is reported that these organisms can produce localized sulphuric concentrations up to 5% by weight. Thus, the creation of extremely corrosive conditions are possible (Fontana, 1976) Thiobacilli are found frequently in sulphur fields, in oil fields, and in and about sewage disposal piping that contains sulphur -bearing organic waste products. Damages of walls of sewers have been reported due to sulphuric acid produced by oxidation of hydrogen sulphide (Koutsogiannis, 1993). Although such bacilli are known since 1924, their practical use is mentioned in literature after approx. 40 years (Yfantis, 2003) By bacterial leaching of sulfide copper minerals is produced an acidic sulfate solution of cupric and ferric/ferrous ions (Mueller, 1975) Then in a next step metallic copper is produced (USA, Canada and Germany). Another reference concerns the formation of sulfate copper ores via the same mechanism in Cyprus. Due to this process the copper minerals of Cyprus were wide famous and extremely wanted (Constantinou, 2005). Furthermore, anaerobic bacilli exist that are capable to reduce sulfates to sulfide (Yfantis, 2003). These sulfate reducing bacilli are found in soil and can accelerate corrosion rate of steel structures buried in soil (Yfantis *et al.*, 1998). A scheme showing the chemical reactions of both processes (oxidation-reduction) is presented below:

S, H_2S, $CuFeS_2$

$$S^{2-} \underset{\text{Sulfate reducing anaerobic}}{\overset{\text{Thiooxidant aerobic}}{\rightleftarrows}} SO_4^{2-}$$

Elemental sulfur (S), hydrogen sulfide (H_2S).or copper pyrite ($CuFeS_2$) are oxidized to sulfate(SO_4^{2-}) or hydrogen sulfate ions (HSO_4^{-}) through aerobic thioooxidant bacilli. Sulfates are reduced to sulfide via anaerobic bacilli (desulfovibrio desulfuricans).

The reference concerning gold should not surprise the reader. Pausanias mentioned that Styx's water can also cause corrosion to gold. It is known that gold is fully dissolved only by a mixture of nitric- hydrochloric acid. (1: 3), known as '*aqua regia*'. Such a solution is not possible to be created in the environment.Gold in this part of the text could be explained as an alloy of gold or a gold-looking metal, the term "gold" refers to materials such as copper's alloys (mainly bronze and brass). Studying the vessel of Derveni we are in front of a typical case of confusion caused by its gold-looking color. It was considered as gold but the chemical analysis showed that there was no portion of gold. Thus, the gold looking surface was a result of tin as alloying metal (about 14%) (Varoufakis, 1996) (Fig. 3).

The report in text about electrum is correct. The word is Latinised fom the Greek « ήλεκτρον » The same word is also used for the substance amber.But in fact, electrum is a gold-silver alloy and not amber, which is a yellow-looking fossil resin.Due to this confusion in meaning, in some translations the word "electrum" has been replaced by "amber (Yfantis, 2006). This explanation seems to be convenient enough, because Pausanias, as a traveller recorded –through oral narrations-rumours,experiences and local mythological events of individuals. Styx water as an dilute sulphuric acid is a poison and can cause death..In the last lines of Pausanias text,death of Alexander, son of Philip, is attributed to Styx water. In book VII of Arrian (Flavius Arrianus, 95-180 AD) "Αλεξανδρου Ανάβασις" is mentioned that Alexander (the Great) drunk a poison sent by Antipater from Macedonia in a horse's hoof" (Arrian, 2004).

Figure 3 Vessel of Derveni (4th century B.C., Archaeological Museum of Thessaloniki).

Conclusion

From this study the following conclusions can be drawn:

(a) It is useful -maybe even necessary- to turn to ancient texts via an interdisciplinary approach.

(b) Pausanias text is probably a blend of different knowledge and-or- observations from various sources.

(c) In the first part cracking of crucibles or moulds due to metallic melt could be an explication for the destruction of materials like stones, pottery, etc.

(d) An acidic sulfate solution corrodes probably metals or alloys like iron, bronze, lead, tin, silver and electrum, etc.

(e) The acidic sulphate solution is probably produced by biological corrosion of sulphide minerals via thiooxidants bacilli.

(f) the creation of extremely corrosive conditions are possible due to oxidation of sulphur – bearing compounds to sulphates.

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Is the "Labyrinth" a Water Catchment Technology? A Preliminary Approach

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Abstract: Water supply was a crucial substance in prehistoric Crete difficult, to acquire. As a result, firm techniques to locate, convey and store water were needed. Minoan "palaces" are representative of varying water supply techniques. Varying forms of water supply and sewerage systems have been found in all "palaces". Furthermore, these techniques are eloquent of statements concerning social status and prestige in the context of the palatial agenda. It is argued that the control of techniques concerning the management of water gave prestige to the elite and the prehistoric mastercraftsmen involved in the construction of hydraulic features of the "palaces". The complicated water supply and sewerage systems of Minoan "palaces" were greatly admired by people from other areas and/or from later periods, while sometimes they were also misunderstood. As the most sophisticated and elaborate of these features are attested to "palaces" and to domains of palatial influence their content was not viable by everybody and especially in the centuries following. It can be argued that this is one of the factors that led to the conception of the complicated of the "labyrinth" mentioned in the Greek myths of later periods.

Keywords Administration; architecture; Crete; prehistory; society; water resources.

Introduction

A great variety of remarkable developments have been marked in several stages of the Minoan culture, a culture that flourished during the Bronze Age in Crete. Many scholars have seen Minoan "palaces" of the 2nd *millennium* B.C. very differently according to time, nationality or academic background. The term Palace itself is conventional and thus allusive. With the discovery of the Minoan "palaces" in the very early 20th century it has been put forward that the "labyrinth" mentioned in ancient texts were actually the "palaces" and especially that at Knossos due to its complicated structure.

Although sometimes used as a synonym for "maze", the word "labyrinth" is mainly used today for a thing that is highly intricate or convoluted in character, composition, or construction. The "labyrinth" has been thought to hold spiritual and religious meanings in different cultures while metaphorically signifies In prehistoric Crete the iconography testifies to a vast number of mazes depicted on seals, sealings and on a fresco from the Palace at Knossos but the connection with the mythical dimensions and connotation of the "labyrinth" in prehistoric people is quite problematic and often related to religion. However, for the ancient Greek mythology it was a structure of a great number of corridors crossing one another, where a hybrid monster of a man and a bull called *Minotaur* was kept, a sort of dungeon. Sometimes the "labyrinth" was conceived as having the shape of a sea snail. Both conceptions have as a common feature the complicated system of dark galleries with no way out for those who entered. The conception of ancient Greeks of the shape of the "labyrinth" is well illustrated in several Greek coins from Crete (Fig. 1), especially from Knossos (Svoronos, 1890). Diodorus (I, 96) refers to the Labyrinth as a tomb well admired and difficult to imitate. The latter enforces the previously discussed characteristics and should be probably taken to mean that the "labyrinth" was an underground or at least hidden structure.

Figure 1 Ancient Greek coin from Knossos with the "labyrinth (Svoronos, 1890).

As mythology provides vague information about the "labyrinth", its features could suggest a use concerning the management of water and wastewater. The "labyrinth" is described as a man made complicated structure, hidden, complicated, dark (underground?), moisty and inappropriate for people. It resembles of a sewerage system and/ or drainage more than anything else. Sewerage systems and drainage systems have been found in all Minoan "palaces" in different forms, though the earliest example comes from the middle of the 3rd *millennium* (Early Minoan IIa) in a house under the west court of the Palace at Knossos (Evans, 1972; Wilson, 1985). They constitute a significant feature of the Minoan architecture and sometimes they were big enough for a person to enter (Evans, 1930).

Mythology informs us about the great engineer and inventor *Daedalus*, who built the Cretan Labyrinth for king Minos. However, the origin of the structure was thought to be from Egypt. Herodotus (II,148) describes the pyramid complex at Hawara in Lower Egypt as a work "beyond human labour", a "labyrinth" with more than 3.000 chambers, half of them underground. According to Diodorus of Sicily (I, 61), *Daedalus* made the Cretan Labyrinth after having seen the Hawara Labyrinth. The Hawara Labyrinth is probably dated to the reign of Middle Kingdom King Amenemhat III (1844 to 1797 B.C.) of the 12th Dynasty. The attribution of major achievements to Egyptians was very common to the Greeks as they admired and respected the Egyptian culture, while they often legitimised their own achievements through it. Surprisingly, the Hawara area is related to a major artificial lake for irrigation purposes by water conveyed into the Faiyum Depression. This hydraulic project is likely to have began under King Senusert II (1897 to 1879 B.C.) and continued until the reign of King Amenemhat III (Hassan, 2005). Egypt along with Mesopotamia had a long experience in water management and thus, the belief of the Egyptian origin of the "labyrinth" can illustrate an influx of technology from Egypt to Crete. Several Egyptian and Egyptian-like artefacts were found in Crete from the middle of the 3rd *millennium* B.C. (Early Minoan II period) in tombs at Messara and in the settlements at Palaikastro and Mochlos. The contacts with Egypt intensified from the period of the first "palaces" (*ca*. 1900-1700 B.C.) onwards. This is right after the first intermediate period in ancient Egypt (*ca*. 2040 B.C.), a period of economic demise that may have forced people to move in other areas such as Crete (F. Hassan, pers. comm.). This suggests a possible influx of technology related to water resources in this specific period, a suggestion that coincides with the advanced and sophisticated water and wastewater techniques applied in this particular period. The scope of this article is to propose a different view of the Minoan “palaces” and of the people acting in them.

Water Management in the Bronze Age

The systematic evolution of water management in ancient Greece begins in Crete with the rise of significant settlements during the Early Bronze Age*, i.e.* the Early Minoan period (*ca.* 3500-2150 B.C., dates after Myers *et al.*, 1992). This included various scientific fields of water resources such as wells, aqueducts, cisterns, water distribution, construction and use of fountains, and even recreational uses of water. Therefore, a specific group of mastercraftsmen living in Bronze Age Crete were aware, of some basic principles of what we call today water and environmental engineering. It should be stated that these techniques concerning the water supply were only supplementary and precautionary to the traditional transportation with the use of labour.

In the Minoan “palaces” and settlements, water supply was differentiated according to the local conditions, concerning climate -mainly precipitation-, the water table and the terrain. As a result, different practices were followed. The attitude towards water supply in Minoan settlements was different between those set on highlands like Early Minoan III settlement at Trypiti on the Asteroussia Mountains and Late Minoan Ia settlement at Zominthos set on 1200m on Psilorites Mountain that were depended on springs and occasionally on snow and those on lowlands.

Natural features such as rivers and springs provided people living in Prehistoric Crete with water. From the beginning of the Bronze Age (*ca*. 3500 B.C.) and especially from the Early Minoan II period (*ca*. 2900-2300 B.C.) onwards, water supply was also obtained by a variety of means such as wells, cisterns and aqueducts. Nevertheless, Minoan architecture was formed in ways that could exploit the potentials offered. Flat rooftops, light-wells and open courts are three of the main and distinctive features of Minoan palatial architecture (Preziosi, 1983). All of these features were playing an important role in water catchment.

Climate and the environmental Agenda

The climate in Crete is typical of the Mediterranean area with cool winters and hot summers. Information from the investigation of pollen cores in Crete shows a change of climate from cold and humid to warmer and dryer in the turn from the 4^{th} to the 3^{rd} *millennium* B.C.. From the 3^{rd} *millennium* onwards no major differences have been attested (Blitzer, 1993; McCoy, 1980), although recent studies propose a significant increase of water resources from 1900 to 1200 B.C. in Crete (Moody, 2001). Successive periods of warm and dry and colder and damper periods have been suggested for the eastern Mediterranean (Issar, 1996) but the differences from the present climate in Crete are considered also minor.

The rainfall on the island of Crete is temporally and regionally uneven. It increases to the west, while snowfall is common most of the winter above an altitude of 1600 m. In addition to this, the eastern part of Crete is drier and semi-arid where as the western is more humid and green (Rachham and Moody, 1996). Moreover, there is an increase in temperature from northwest to southeast with a respective effect on the vegetation. The nature of the rainfall itself is uneven distributed. 75% of the total annual precipitation occurs from December to February with significant periods of aridity. The latter means that the rainfall, though annually confined, is torrential. The last characteristic is one of the factours along with deforestation and animal grazing that led to soil erosion (Zangger, 1992). Hence, only the

25% of the precipitation assists the groundwater recharge with 10% consisting a surface runoff to the sea, while 65% is lost by the evapotranspiration especially during summer months.

The geology of Crete is rich in limestone that allows the water to penetrate creating major karstic formations. Crete stands on the verge of the tectonic trough of the Mediterranean and the Aegean volcanic bow that cause important phenomena that set Crete in a perpetual motion. Geoarchaeological information argue for major earthquakes in the past that changed or influenced the landscape, the architecture, the culture and perhaps the social attitude towards what is generally known as religion (Driessen and MacDonald, 1997; Stiros and Papageogriou, 2001). A series of major tectonic events may have also affected the groundwater supplies causing abandonment of settlements (Gorokhovich, 2005) especially in areas depending on groundwater like Zakros and Palaikatsro.

From the above it can be argued that climatic and geological conditions imposed special approaches concerning the management of water resources. The water supply is a crucial factor for the establishment and continued existence of settlements. Ancient scholars emphasized the role of water supply. Vitruvius (I.IV.9-10) argues for the importance of water in the selection of the appropriate location of settlements. Laws were also applied to protect water supply and to secure the fair and reasonable use of water (Plutarch, 23.5); However, it is notable that areas of the Greek mainland and the Aegean islands including Crete, with low water resources availability hosted considerable cultures in the absence of great rivers like Tigris, Euphrates or the Nile. Despite these disadvantages, people living in prehistoric Greece did not only survive but also played and important role in the eastern Mediterranean. Hence, an *agenda* was needed for the supply and disposal of water and wastewater for the survival of the settlements.

To conclude, special climatic, geological, social and economic factors in Crete had as a result to apply a distinctive, individual and pioneering *agenda* in the water management. However, specific environmental and socio-economic conditions are decisive for the application of an individual and distinctive *agenda* for the collection and proper use of water. Such creative and distinctive *agendas* resulting innovative technologies can be traced in different areas, times and in several activities like in the sophisticated irrigation techniques of terraced agriculture in pre-Columbian Peru or the construction of fire-fences by aboriginal people of Australia.

Water catchment

The problematic groundwater recharge troubled by the intense seismic activity and the eroded and uneven landscape made people living in Crete to develop sophisticated water catchment techniques applied until recently all over the island. From the investigation of the main “palaces” found at Knossos, Phaistos, Malia, Zakros, as well as those at Petras and Galatas it has been noted that a sort of plan must have been applied as they share a number of characteristics. Among them are the open courts that are divided into centrals around which the “palaces” were clustered and peripherals usually on the west. The presence of a central court or open area is a characteristic that derives from the period before the emergence of Minoan “palaces” in the cases of Chamaizi and Agia Photia. At the house complex found at a hill near the modern village Chamaizi –its main phase belonging to the Middle Minoan Ia period (*ca*. 2150-1900 B.C.)- a cistern collected the waters from the rooftops and from the surrounding open area (Davaras, 1972). The cistern like in the case of the central courts of the “palaces” is in the centre of the house complex (Fig. 2a). It is interesting to notice that the cistern is situated in the most protected area, in the centre of the house complex. This is a connotation of the importance of water for the natural survival and cultural continuity of a settlement. Another house complex belonging to the same period was found at the site of Kouphota near the modern village of Agia Photia (Tsipopoulou, 1988). The complex is clustered around a rectangular court comparable to these found later at "palaces" though undersized (Fig. 2b). Here, the presence of the court could operate as a water catchment device in a hostile environment as the site is in a low hill a stone's throw from the sea of eastern Crete.

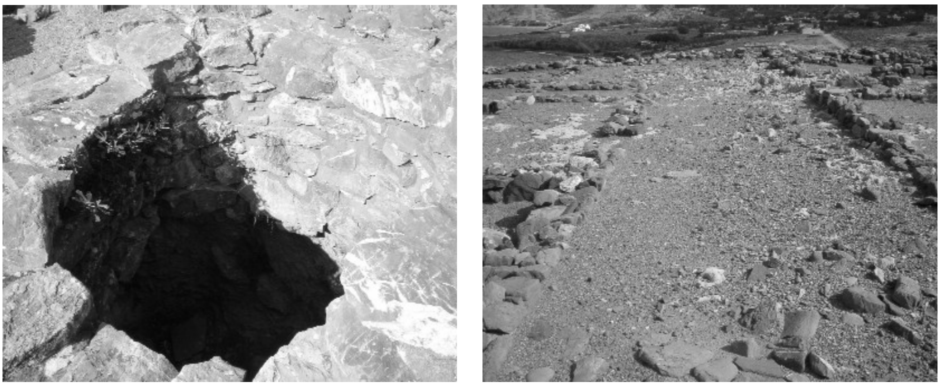

Figure 2 Prepalatial settlements: (a) Cistern in the centre of the house complex at Chamaizi and (b) central court from Agia Photia.

In the "palaces", the function of rectangular central courts concerning matters of water catchment is more salient. All of the central courts were paved except that from the Palace at Zakros. Having the side on the north to south axis it can be put forward that this arrangement accommodates among others the direction of precipitation usually coming from the north. Courts and open areas across the entire structure of the "palaces" played a significant role in collecting and conveying water. At the Palace of Phaistos, where no wells or springs have been indicated within the Palace, the water supply system was considerably dependent on precipitation. The rainwater was collected in cisterns from rooftops and open courts (Fig. 3a). Special care would have been given to secure the purity of water with the use of filters (Fig. 3b).

Figure 3 Water catchment in the palace of Phaistos: (a) Paved court and (b) sandy filter system from later period.

Flat rooftops constitute another feature of Minoan architecture. Features from the Minoan iconography, and miniature terracotta houses unearthed signify for flat roofs in lowlands (Evans, 1921; Lebesi, 1976). Like in the case of traditional architecture of the Cyclades, flat rooftops were used to collect water. Such a system has been traced in several "palaces" with carved stone ducts (Fig. 4a) and terracotta pipes (Fig. 4b) or a combination of both techniques like in the case of the drainage system of the "Court of Stone Spout" (Evans, 1930; McDonald and Driessen, 1990).

Figure 4 Drainage systems: (a) Carved duct and (b) terracotta pipes. Some of these pipes were used for the water supply as well as for the drainage of the "palaces".

Moreover, the drainage systems in the Palace at Phaistos were in some cases conveyed into terracotta vessels interred near light-wells, acting as water collectors (Shaw, 1973). That water was used in wide range of activities, while in case of shortage it could have been used to drink.

In addition to that, as in the case of artefacts, architectural features can have multiple parallel uses and functions. Accordingly, it can be suggested a primary use and secular function for the causeways like those found in the west court of the Palace at Knossos, Phaistos and Malia along with the ceremonial proposed. Raised causeways (Fig. 5a) can be viewed as a way to convey runoff and to protect those passing through from getting wet. Similarly, the indented façades of palatial architecture (Fig. 5b) serves apart from aesthetic reasons the increase of the surface resulting an additional increase in the amount of water collected through courts and other open areas to cisterns.

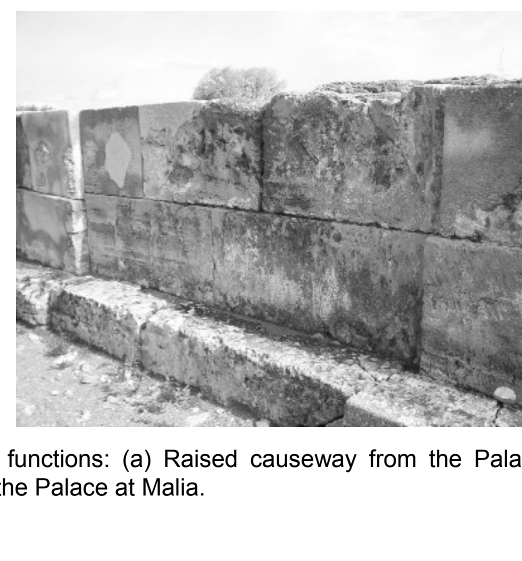

Figure 5 Palatial features of multiple functions: (a) Raised causeway from the Palace at Knossos and (b) indented façade from the Palace at Malia.

"Palaces" and Water, Wastewater and Storm Water Applied Technologies

As discussed above special care was given to the management of water and wastewater in Minoan palatial architecture. Sometimes in spite of the cost in terms of labour and energy expenditure special solutions were applied. The use of parabolic curves in the side of a staircase (Fig. 6a), and a raceway carefully carved following the outline of a low wall in an open-air area both from Knossos (Fig. 6b), show not only a sophisticated conception of lifestyle but also a carefully scheduled *agenda* concerning water and an accumulated knowledge on hydraulics in the domains of the Palace.

In water supply, aqueducts of gravity flow and pressured piped systems were designed in the Palace of Knossos, at the Minoan settlements at Tylissos, and Gournia, while terracotta pipes have also traced in Phaistos, Palaikastro and Zakros (Evans, 1927; Shaw, 1973). The use of terracotta pipes consists one of the earliest application of hydrostatic law of the communication vessels. At Tylissos and Hagia Triadha, the presence of sedimentation tanks signifies for a deep knowledge of water science principles (Fig. 6c).

Figure 6 Some sophisticated Bronze Age technologies: (a) Use of parabolic curve in the Palace at Knossos, (b) raceway following the course of the wall, and (c) sedimentation tank from Tylissos.

These finds suggest that people living in Bronze Age Crete commanded considerable knowledge of water management techniques. The structure of the "palaces" facilitated water collection by embracing different techniques of water catchment and abstraction. However, Minoan "palaces" can be seen, not only as actual water catchment mechanisms but also as a setting for the centralized control of water in terms of <u>knowledge</u> and <u>use</u>. The fact that almost all the sophisticated features were found in "palaces" or in areas of palatial influence and palatial architecture is indicative of a palatial supervision by an *elite* within Minoan society. This reminds the myth according to which *Daedalus* built the Cretan Labyrinth under the orders of King Minos.

It is no chance that the first known example of sewerage in Crete comes from Knossos in Early Minoan IIa (Wilson, 1985) before the rise of the first Palace, signifying a sophisticated illustration of social storage that led to the foundation of the Palace at Knossos. Moreover, from the palatial era, a Middle Minoan terracotta collar of a well found at House A in the "Little Palace" at Knossos –at short distance from the Palace- bears an impression in Linear A (Evans, 1930). This is suggestive of a palatial control and planning. This is indicative of the accumulated knowledge and social storage that forced sophisticated applications in order to deal with specific environmental conditions.

As a result, the palatial *agenda* for water management and applicable knowledge was encumbered or rather favoured a special group of individuals like the *masons* mentioned in Linear B (Chadwick, 1976). This group of mastercraftsmen must have been related to the *elite* like the prehistoric scribes. Similarly, stored terracotta pipes found in the Minoan settlement of Gournia for possible repairs (Boyd Hawes *et al.*1908) signify the existence of an *agenda* and hence for a possible group of mastercraftsmen. To the same direction points the considerably large number terracotta pipes in several sites that show a wide and planned production for a specific purpose. Nevertheless, an *elite* through a specific group of individuals (mastercraftsmen) imposed the application of such sophisticated knowledge in the Minoan era, like major preceding hydraulic works in Mesopotamia and Ancient Egypt. These qualities and the prestige of these early mastercraftsmen gave them legendary and mythical proportions like *Imhotep*, the architect that made the first pyramid and that was considered to be a god and *Daedalus* the man that built the Cretan Labyrinth both in the verge of myth and reality.

However, as already mentioned, the "palaces" were in control not only of knowledge but of use of water as well. As they were responsible for the construction of hydraulic works, the "palaces" may be seen as having played an administrative role in the use of water. Irrigation works have not been discovered in Bronze Age Crete. However, several sites have been proposed like that close to the Palace at Phaistos (Angelakis and Spyridakis, 1996). As one of the main region of agricultural production area at that time was the Messara plain in south-central Crete, irrigation projects would have been developed to boost the production, especially near the rich in groundwater and surface water area of Agios Ioannis village southwest of the Palace. These irrigation works were also important for the cultivation of new domesticated species and thus, may have been applied in some sort. If yes, the Palace would have been in charge of the construction and most importantly the control of the irrigation procedure.

The management of urban waters, on the other hand, is well represented in the archaeological record. The varying activities taken place in the palatial context made water a commodity with economic proportions. Apart from its biologic role and domestic use water had an important part in Minoan economy in activities concerning the production of metals, textiles and of several crafts related to the "palaces". The cistern in the "Hall of the Cistern" at the Palace in Zakros can be seen in this context of water calculation and control (Fig. 7). There are many theories regarding the function of the cistern (Platon, 1974). However, a device for the estimation of water supply in order to define the proper use of water in the different activities of the Palace and perhaps to calculate the agricultural contribution to the storage areas of the Palace is suggested, reminding the Egyptian Nilometers. Moreover, the excavator of the Zakros Palace considers very likely that the *throne* was also in the particular room. This reminds of the house complex at Chamaizi were the cistern was in the middle of it. The place of the cistern in the middle of the room like in the case of that found at Chamaizi underscores the socioeconomic significance of water and the need for control.

What is more, the complex of Caravanserai found at close distance in the south of the Palace at Knossos can be viewed as a remarkable area of water actual control. The water from at least two springs is passing through a complex of buildings, including several basins and a variety of stone and clay conduits including a possible shrine in the "Fountain Chamber". Although it has been traditionally proposed as guesthouse (Evans, 1927) receiving people coming from the south it can be rather argued to be an area for the control over quality, flow, and use of water. The existence of a possible shrine dedicated most likely to a divinity related to water -that reminds comparable shrines of later periods dedicated to the Nymphs- underpins the importance of water.

Figure 7 The “Hall of the Cistern” in the Palace at Zakros.

In the Early Minoan II (*ca*. 2600-2170 B.C.) settlement of Myrtos Fournou Korifis, in close distance from Hierapetra in eastern Crete, the earliest Minoan domestic shrine has been proposed. In the shrine a female figurine was found among offerings. The figurine holds a jug and according to the excavator “had a domestic character, including the protection of the water supply, so vital for life on the Myrtos hilltop” where the settlement was founded (Warren, 1973). Hence, the consumption of water with its wide applications was in need of an *agenda* considering matters of supply and proper use and reuse.

In the management of water and wastewater, “palaces” also included features of a specific character. Toilets and hygienic installations found in several sites in Crete (Palyvou, 1997) are representative of an *agenda* concerned with conspicuous consumption of water. In the same way can be seen the zoomorphic waterspouts found at the Palace of Zakros (Platon, 1995) as well as the *jet d’eau* fresco from the “House of Frescoes” in the Palace at Knossos (Evans, 1930), which is most likely a representation of an actual fountain/ jet placed in the garden suggested in Minoan “palaces”. All these features mentioned above are indicative not only of the technological sophistication, taste and level of water management but also of the prestige acquired from conspicuous consumption of an important economic and biological element (Shoep, 2004). Those that were privileged to use these features were people living and/or acting in the *palatial environment* and at the same time had access in the specific areas.

Conclusions

Minoan culture that flourished in the Middle and first phases of Late Bronze Crete gave birth to building complexes known as Minoan “palaces”. Although their function remains somewhat obscure, one of their characteristic are the varying features of water management. A series of finds related to water and wastewater management highlight the emphasis given to the treatment of water and wastewater by people living in Bronze Age Crete. These features have been attested in the first large settlements of the Early Minoan period in the midst of the 3rd *millennium* including mainly cisterns, wells and sewers. However, sophisticated methods have been applied from the early 2nd *millennium* B.C. with the foundation of the “palaces” with the additional construction of sewerage systems, open and closed (piped) aqueduct systems and sedimentation tanks. Recreational uses of water were also considered and applied in the Minoan gardens with the use of fountains and jets while purgatory installation such as “toilets” have also been found. These features and especially those hidden under the “palaces” may have contributed to the formation of the myth of the

Cretan Labyrinth in antiquity. Sewers that sometimes were big enough for a man the enter, communicating cisterns and other features, may have led people of later periods to question their function attributing their construction to the great mythical engineer and inventor *Daedalus*. The myth of the Cretan Labyrinth could have been a fragmented *memoir* of sophisticated water and wastewater management or even the confused explanation of the varying features related to hydraulics found by later people.

Scholars, on the other hand, have seen "palaces", very differently. Several functions have been proposed from an economic or social perspective, viewing "palaces" as devises for the redistribution of goods, temples, or as the actual palace of a *priest-king*. However, the mere architectural plan and the "palaces" and specific features like the flat rooftops, the light-wells and the open areas and courts facilitate a role of water catchment. All the Minoan "palaces" must have functioned as water catchment mechanisms in order to overcome both problems of water supply storm water drainage. In addition to that, different applications of water supply were used according to local conditions, resulting thus a "regionalism" in the treatment of water management. The Palace of Phaistos was primarily depended on precipitation, that at Knossos on springs and the one at Zakros on groundwater abstraction (Angelakis and Spyridakis, 1996). Every different treatment was combined with water catchment providing a viable and efficient solution in the need of water.

It can be argued that the management of water in Minoan Crete was the result of a specific *agenda* imposed by an *elite* acting in the "palaces" and applied by a group of people that possessed the practical knowledge controlled by the *elite* in that same way with prehistoric scribes. Apart from the knowledge over water management the *elite* was also responsible for the administration of water use. This binary control of water in terms of knowledge and use by an *elite* was conditioned by environmental and socioeconomic reasons and was established through a specific *agenda*. A sort of plan should have existed to overcome problems related to matters of proper use and consumption of water and to successive destructions of aqueducts, wells, cisterns etc. due to earthquakes or fire. This *agenda* is suggested to be applied by an *elite* that performed a coordinating and controlling role in terms of knowledge and division of labour. Consequently, the binary control of water and its conspicuous consumption gave prestige to the parts involved and primarily to the *elite*.

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The Water of Memory, the Water of Life: Reflections in/of/on Water in Ancient Greek and Near Eastern Thought

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Abstract: Water as the ultimate source of all life is a conception that permeates the cosmogonic thought of Greece and the Near East. This primeval Water of Life also holds the promise of immortality in these cultures, from the Egyptian Field of Reeds, where the gods give cool water to the deified dead, to the Greek Orphic afterlife, where the soul must gain access to a guarded spring to drink of the Water of Memory. The Greek poetic tradition finds a more secure means of achieving immortality in the lasting glory bestowed by praise-songs, and water is the primary symbol of the song of praise. The poet's waters of memory are epitomized in the sacred spring of Thebes, said by the archaic Greek poet Pindar to have been created by the Muses, the daughters of Memory. It is this Water of Memory-'Dirke's sacred water'-which Pindar claims as the source of his poetic inspiration and which he offers to those he honours with his immortal and immortalizing 'drink of song'.

Keywords Cosmogony; glory; immortality; memory; Pindar.

Introduction

Water as the ultimate source of all life is a conception that permeates the cosmogonic thought of Greece and the Near East. For the Egyptians, Nun was the primordial water, where Atum, the 'self-created', in turn created the sun-god Re. The Sumerian water-goddess Nammu is called mother of Heaven and Earth, and the great Babylonian water-deities Apsu and Tiamat are echoed in the Homeric Oceanus and Tethys. In later Greek thought, Orphic cosmogony continues the tradition of a primeval watery abyss, which gives birth to the eternal creator, the winged serpent Chronos (Time), whose female counterpart is Ananke (Necessity), and the Pre-Socratic Thales posited water as the first principle of all creation.

The Water of Life

The Enûma Elish, the Babylonian creation epic, dating from the early second millennium B.C., is the prototype (Pritchard, 1969):

When on high the heaven had not been named, firm ground below had not been called by name,
Nothing but primordial Apsu, their begetter, and Mummu-Tiamat, she who bore them all,
Their waters commingling as in a single body; no reed hut had been matted,
no marsh land had appeared, when no gods whatever had been brought into being,

Uncalled by names, their destinies undetermined-then it was that the gods were formed within them.

In Homer's Iliad Oceanus and Tethys are the primeval parents, said to have been long estranged from each other because of a quarrel. West notes that: '*Behind this Olympian gossip there may lie a cosmogonic myth, for the separation of primeval parents who were originally united is a familiar cosmogonic motif. Usually they are Earth and Heaven. But in the Babylonian Enuma Elish they are…the aquatic figures Apsu and Tiamat-a suggestive parallel to Oceanus and Tethys.*' (West, 1983: 120-121).

In both the Babylonian accounts and the Greek accounts what we have is cosmogonic mythology but, as Jonathan Barnes says of Hesiod's (Near Eastern-influenced) cosmogony, 'This is not science; but it is, as it were, a scientific story: many of [the] gods and goddesses are…personifications of natural features or phenomena, and in telling the birth of 'the gods' [the mythographer-cosmogonist] is telling, in picturesque form, the origins of the universe' (Barnes, 2001, 4).

The Pre-Socratic philosophers, who were or intended themselves to be scientists, were interested in first principles. For Thales this was water. Aristotle's account includes the following comments: '*Most of the first philosophers thought that material principles alone were principles of all things. ...There must be some nature -either one or more than one- from which, being preserved itself, the other things come into being. Thales, the founder of this kind of philosophy, says that it is water (that is why he asserted that the earth rests on water). He perhaps came to acquire this belief from seeing that the nourishment of everything is moist and that all hot things come from water and live by water (for that from which anything comes into being is its principle) – he came to his belief both for this reason and because the seeds of all thing have a moist nature, and water is the natural principle of moist things.*' (Aristotle, *Metaphysics* 983b6-11, 17-27)

Barnes points out that if it seems insane to claim that both a cucumber and the sands of the Sahara are nothing but water, we should 'think how utterly different diamonds are from coal-and then recall that they are merely two different forms of the same stuff, carbon.' 'Thales' suggestion', Barnes says, 'is false in fact; but it is not foolish-on the contrary, it is thoroughly scientific in spirit' (Barnes, 2001, xxii-xxiii).

Other early Greek cosmogonies are reported to have found the origin of all things in water and the mud which formed from it: '*For water was…the origin of everything, and from the water mud formed, and from the pair of them a living creature was generated…*', '*There was water...and mud, from which the earth solidified…the third principle after the two was engendered by these…its name was Unaging Time and also Heracles.*'(Athenagoras and Damascius: West, 1983: 183)

The Stoic philosopher Zeno is reported to have said that 'Hesiod's "Chaos" is water, from the settlement of which mud comes into being, and when that solidifies the earth is established' (West, 1983: 184). West notes further that 'in the text of Athenagoras…the Homeric verse "Oceanus, who is the genesis of them all" (*Il.* 14.246) is attributed to Orpheus and closely linked with the primeval water' (West, 1983: 184).

The Water of Immortality

Not only is water the source of life in a cosmogonic conception but in eschatological thought it is also the source of renewed life and therefore of immortality for individual human beings. In many cultures the dead are thought of as parched with thirst, a conception that is evidently based on both the physical phenomenon of the dying often becoming very thirsty and also the observed fate of the body after death as epitomized in the aphorism 'dust to dust'.

Associated with the water of life is the tree of life, which stands in or near a source of water-a lake, a river, a spring. The tree of life grows in the Persian primeval lake Vourukasa, the source of all the world's rivers, and the evil lizard created by Ahriman lurks beneath it, trying to reach the fruit of the tree that confers immortality. The tree of life grows, too, in the Egyptian Field of Reeds; the gods eat from the fruit of the tree and give the fruit to the dead who have joined them in the realm of eternity, along with cool water to quench their thirst. Egyptian motifs-tree, water, and the challenge to the soul of the deceased to identify itself: 'Who art thou?'-occur also in the Greek Orphic texts, where the soul, newly arrived in the world of the afterlife, must answer this question to gain access to the Water of Memory that springs up below a cypress tree and holds the promise of renewed life and immortality: 'I am a child of Earth and Heaven, and of heavenly birth, you know it yourselves. But I am parched with thirst, I perish: give me quickly to drink of the unfailing spring on the right by the cypress-tree.' When the soul is permitted to drink from this water, it is admitted to paradise, to the 'holy meadows and groves of Phersephoneia' (West, 1971: 65). As Edmonds observes, in the Myth of Er in the *Republic*, Plato is 'clearly playing with the same elements from the mythic tradition that are found in the [Orphic] tablets-magic water, memory and life, a choice dependent upon previous experiences' (Edmonds, 2004: 51). The 6th century B.C. Greek cosmogonist Pherecydes shows these Near Eastern elements (that occur also in Greek Orphic thought) in his vision of the tree of life, with its associated spring of ambrosia on which the gods feed, and an outflow, apparently from the base of the tree-trunk, perhaps the same as the gods' ambrosial spring, which gives new life to the dead (West, 1971: 58).

The Water of Memory

The longing for immortality takes another path as well, in the streams of song. In the Greek poetic tradition the glory bestowed by praise-songs is seen as a more secure means of achieving immortality by ensuring the continuation of the laudandus' fame in the memory of his family and community. This is an aristocratic tradition, a continuation of the praise poetry of epic, with its fundamental concept of *kleos aphthiton*, 'imperishable fame', which is generated by the laudandus' deeds and perpetuated by the correspondingly famous and imperishable song of the poet, which serves as the vehicle for the continuation of the fame of the person praised within the context of his family, his clan, and his community. As such, it is a socially-based, communal concern, diametrically opposed to the quest for immortality of the individual soul urged by Orphic belief. Of the latter Edmonds writes:

'The deceased, however, does not hope that by drinking the water of Mnemosyne she will live on in the memories of those still living. The draught of the waters of Memory permits the deceased to remember her true origins and identity. This type of memory provides a kind of immortality very different from the *kleos aphthiton* of the hero who is honored by his city, his clan, and his family; this focus, through memory, on the individual identity apart from the different lives places value on the self that exists outside of the mortal world, on an immortal part whose proper place lies outside the hierarchies and boundaries of the earthly, political, material world. In one sense, it is the body that is devalued in comparison to the soul; in another sense, it is the present time that is devalued in comparison to the time when the individual is in the proper place, in the community of the immortals. Memory serves to recall the individual from the mortal world and the normal order back to the world of the immortals. The idea, moreover, that memory provides not the immortal glory of epic but a personal immortality through the recollection of the self may appeal to those, such as women and nonaristocratic men, who are unlikely to be immortalized by epic *kleos*.' (Edmonds, 2004: 53-4)

The Greek tradition of praise-song, epitomized in its application to individual living men, as opposed to the legendary heroes of epic, by the archaic Theban poet Pindar, stands in direct contradistinction to the Orphic emphasis on the status of the soul after death, and yet water is the primary symbol of the song of praise. Streams of water, cooling, soothing, pure and life-restoring: this is the image Pindar chooses to convey the effect of his songs of praise, which bring, he says, true fame to the man he honours. The waters of memory reflect human excellence as in a mirror, and under the fresh dew of the poet's praise-song, human excellence-*aretê*-grows, Pindar says, like a well-watered tree raised to the liquid heaven. Remembered and glorified by the poet, great deeds are not, ultimately, ephemeral but timeless, immortal: they last and flourish in the song. The primeval tree of life has become the poet's tree of immortality, nourished by the waters of memory, symbolized in turn by Dirke's sacred water, the sacred spring of Thebes, created, Pindar says, by the Muses, the daughters of Memory. It is this Water of Memory-Dirke's 'lovely water'-which Pindar claims as the source of his poetic inspiration and which he offers to those he honours with his immortal and immortalizing 'drink of song'. As Deborah Steiner writes of the power of the Pindaric epinician:

'Poetry in its life-promoting role frequently appears in the shape of water, the cardinal symbol of fertility and regeneration. Again, song stands in direct contrast to Hades which, like death itself, is dry. …dead creatures sometimes seek to replace the liquids they have lost by means of the offerings they drink down, and the tradition of the thirsty dead prevails in many cultures. Other thirsty men are the Pindaric athletes and heroes who stand in need of celebration in song, parched of that additional source of moisture which continues on even after the individual has spilt his life substance on the field of battle, or lies dry and withering in the grave. The poet, bringing his songs of praise to men, carries drink to the dry. …The waters of song which Pindar provides are a far surer means of achieving immortality, and foster the life not only of the individual, but of his family and community.' (Steiner, 1986: 129).

Pindar's justly famous *Seventh Olympian*, in praise of Diagoras of Rhodes, victor in the boxing competition at Olympia in the year 464 B.C., opens with the image of the golden bowl, the *phiale pankhrusos*:

As when a man takes from his rich hand a bowl, foaming inside with dew of the vine and presents it
to his young son-in-law with a toast from one home to another-an all-golden bowl, crown of possessions-
as he honors the joy of the symposium and his own alliance, and thereby with his friends
present makes him envied for his harmonious marriage, so I too, by sending the poured nectar, gift of the Muses and sweet fruit of the mind, to men who win prizes, gain the favour of victors at Olympia and Pytho.
Fortunate is the man who is held in good repute. Charis, who makes life blossom, looks with favor
now upon one man, now another, often with sweetlysinging lyre and pipes, instruments of every voice.
And now, to the accompaniment of both, I have disembarked with Diagoras, singing a hymn
to Rhodes of the sea, the child of Aphrodite and bride of Helios, so that I may praise, in recompense for his boxing, that straight-fighting man of prodigious power, who won a crown by the Alpheos
and at Kastalia, and may praise his father, Damagetos, who is favored by Justice;

they dwell on the island with its three cities near to the jutting coast of broad Asia among Argive spearmen (O.7.1-19) (Race, 1997).

Just as the golden bowl is the crown of a man's possessions, so too is the victory hymn a crown of possessions, a glorious and gracious gift which makes a man equal in fortune to kings. Just as from the bowl is poured forth the wine of libation and of celebration, gift of Dionysos and sweet fruit of the vine, so from the song is poured forth the nectar of praise, gift of the Muses and sweet fruit of the mind (*O*.7.8).

The golden bowl is an especially appropriate image to bring to Rhodes, steeped as she is in gold from her birth from golden Aphrodite and marriage to Helios, father of piercing sunbeams and master of fire-breathing horses (*O*.7.70-1), and drenched with Zeus' golden rain at the birth of Athena (*O*.7.49-50)-Rhodes, where this very ode was reportedly inscribed in golden letters and dedicated in the temple of Athena on the acropolis of Lindos.

The song of praise as nectar poured from a golden bowl is part of an intricate complex of metaphor, figuring song, the praise it conveys, and the inspiration it embodies, as liquids of various sorts, especially water and honey. In the *Tenth Olympian*, which tells how Herakles named Kronos' Hill and founded the games with the first Olympiad (*O*.10.49-50,58-9), Pindar speaks of his song of praise as drenching with honey the victor's city of brave men (*O*.10.98-9). And he begins the *Third Nemean* with an invocation of the Muse and a reference to his own task as a builder of honey-sounding revels (*N*.3.1-5). The song exalts the victor's ancestors, Herakles, Peleus, and Telemon, and it tells of the great deeds of Achilles even as a child at play. The song itself Pindar describes in this way, as he takes his leave of the friend he praises: 'Farewell, friend. This I send to you, this honey mixed with white milk, crowned with whipped foam, a drink of song' (*N*.3.76-9).

The *First Olympian* famously opens with the unqualified assertion that ‘water is best’; water here takes pride of place alongside gold, the sun, and the games at Olympia, each preeminent in their respective spheres. Water is a powerful symbol for Pindar; water is the image he chooses in the *Seventh Nemean* to convey the effect of his songs of praise, which bring, he says, true fame to the man who is his friend: streams of water, cooling, soothing, pure and life-restoring. In the *Sixth Isthmian* Pindar offers the victor he praises a drink of Dirke’s sacred water, which, he says, the deep-bosomed daughters of golden-robed Memory made to surge by the well-walled gates of Kadmos-Dirke, the spring at Thebes which Pindar claims as the source of his poetic inspiration: Dirke, ‘whose lovely water I shall drink’, he says in the *Sixth Olympian*, ‘as I weave for spearmen my varied hymn’. ‘Inspiration’, Steiner observes, ‘as the term suggests, demands that the poet take in some power from without, and that he carry within him the force of the divine which makes him truly *entheos*, god-possessed. The media which the Muses, Nymphs and Graces cohabit furnish natural symbols for the forces which the poet must accommodate; their presence is implied within water, the liquid substance which the singer often swallows. …The varied images of light and water and the Muses come together in the extended metaphor [in the *Seventh Nemean*] where Pindar describes the complex relationship between poetry and the achievement it celebrates. Here, by virtue of the Muses and of Memory, the poet overcomes darkness and holds up a mirror to the deed the ode recalls. The symbol of the mirror’s polished surface evokes the water which reflects back an image, and sends out light from its face. Possessed of the forces of illumination, growth and nurture, poetry moves with its own impetus and enjoys an independent life. Once articulated, it is an autonomous thing, capable of future growth and self renewal, unquenchable in the rays which it sends out through time and space’ (Steiner, 1986: 44-8).

That libations of water, as of milk and honey, were made to the dead in the Archaic period allows Pindar to extend the imagery of liquid song to the hope that even the victor's dead ancestors may hear beneath the earth of his great achievements sprinkled with soft dew beneath the outpourings of revel songs (*P*.5.98-101). The water and honey of praise-songs at once purify, preserve and nourish the fleeting achievements of mortal men. Under the fresh dew of praise-songs, excellence, virtue-*aretê*-grows like a well-watered tree when it is raised by wise and just men to the liquid heaven (*N*.8.40-2). Remembered and glorified by the poet, great deeds are not, ultimately, ephemeral but timeless, immortal; they last and flourish in the song (Teffeteller, 2005).

Conclusions

Water, regarded as the origin of all life in the creation myths of ancient Greece and the Near East, also holds the promise of immortality in these cultures. The soul of the deceased gains access to immortal life in paradise by drinking cool water provided by the gods or by guardians of a holy spring. A different kind of immortality is found in the Greek tradition of praise-song, where the fame of the laudandus, amplified and guaranteed by the poet's song, keeps his memory alive among his family and fellow-citizens. Here too the symbol and metaphor of life, of immortality, of memory is cooling, soothing, life-giving water.

From cosmogonic first principle to eschatological promise of immortality to poetic guarantee of undying fame, water serves as the powerful and preeminent symbol of life everlasting.

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Water in Ancient Civilizations: The Case of Ancient Arkadia in Crete, Greece

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Abstract: This article, on one hand, studies the literature and the archaeological finds which refer to ancient Arkadia of Crete, and, on the other, examines the etymology of toponyms in the area, in order to support the hypothesis that water was intrinsically connected to the inhabitants of Arkadia in ancient Crete.

Keywords Ancient Crete; Arkadia; cistern; springs; water.

Introduction

Water in ancient Greece was considered a gift from the gods and thus sacred. This is explained through the etymology of the Greek word *ὕδωρ*, which derives from the first syllables of the two words *ὑγρόν δῶρον* (*hygron dōron*)[1]. The ancient Greeks believed that rain was caused by the male Zeus, who was thence called *Hyetios* (=the one who grants *hyetos*, i.e. rain)[2]; on the other hand, the water of springs was related to the Nymphs and came from the female Earth[3].

In antiquity water springs (*πηγαί*) were turned into fountains (*κρῆναι*), following certain architectural modification[4]. A fountain usually consisted of an aqueduct, through which water was transferred from a spring to a cistern; then, from a cistern water flowed through orifices, to which a spout, often of a lion-head shape, was possibly adjusted. The fountain's façade was often complemented with basins for water collection and sometimes with some sort of cover, as seen at the Kastalia fountain in Delfi or at the Onithe fountain in Goudeliana, Crete[5]. Descriptions of springs and fountains occur in Pausanias, an ancient Greek traveler and writer (2nd century A.D.)[6].

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1 S. Guettel Cole, 1998, "The Uses of Water in Greek Sanctuaries", in: R. Hägg, N. Marinatos and G.C. Nordquist (eds.), *Early Greek Cult Practice* (Stockholm), 161.
2 A. Tziropoulou-Efstathiou, 2006, *Ο εν τη λέξει λόγος* (*O en tē leksei logos),* (*About words*), (Athens), 275 and 633.
3 Guettel Cole, *ibid.*, 161.
4 Guettel Cole, *ibid.*
5 K. Psaroudakis, 2004, «Ονιθέ Γουλεδιανών: νέα ματιά στα ίχνη μιας αρχαίας κρητικής πόλης», ("Onithe Goudelianon: a new look at the traces of an ancient Cretan city"), *Kretikē Estia* 10: 27, 28 and note 72.
6 Paus. *Description of Greece*, 2.3.5.8 and 2.3.6.3 (*krēnai*), 2.25.3.3, 3.22.7.4, 3.22.8.5, 4.20.2.1, 4.31.4.2, 5.7.2.1 and 8.13.5.4 (*pēgai*).

Water was connected to a number of ancient Greek deities, like Apollo, Demeter, Artemis, Asclepius and Poseidon[7]. Furthermore, ancient sanctuaries were located in sites, where running water existed. The water installations in a sanctuary had a double function: to quench the visitors' thirst, on one hand, and to cover the ritual needs of the sanctuaries, on the other. Such installations were cisterns, water pipes, channels, drains, springs, fountains, bathtubs. Although most of them were found outside of buildings, yet water in a building was frequently used for ritual purposes[8].

The Evidence

The present paper, based on the available archaeological finds, as well as on literary sources, examines the relation between water and the ancient Cretan city Arkadia or Arkades[9] (identified with the ethnic name of the inhabitants). A view of the ancient city of Arkadia is shown in Figure 1.

Figure 1 View of ancient Arkadia. On top of the hill, on the right, the small church of Prophet Elias can be seen.

The center of the ancient city was recognized to be the area northwest of the modern village Aphrati in Pediada district, after excavations were performed by the Italian Archaeological School[10]. In antiquity there existed tens of cities in Crete[11]. Yet, the case of ancient Arkadia in Crete has attracted the particular attention of the authors of the present article, due to three pieces of evidence, which allow for two assumptions: (a) there must have existed plenty of water in Arkadia in antiquity and (b) water and the people of Arkadia appear closely interconnected. The evidence is the following: (a) Ancient Greek and Roman

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7 Poseidon was also called "king", meaning king of water; he was also granted the epithet "νυμφαγέτης" (*nymphagetēs*), i.e., "leader of the water nymphs". For this, see A. Tziropoulou-Efstathiou, 2006, *ibid.*, 636-637.

8 Guettel Cole, *ibid.*, 161.

9 On the existence of the city in ancient Crete, see the fragment of the *Cretan History* written by Xenion, a hellenistic Cretan historian, which is preserved by Steph. Byz., s.v. *Ἀρκάδες*. For the collection of fragments, see F. Jacoby,1950-54, *Die Fragmente der Griechischen Historiker*, III B (Leiden: E.J. Brill), No. 460F3. For a discussion of the toponym "Arkadia" and the ethnic name "Arkades", see A. Strataridaki, 1988-1989, "The Historians of Ancient Crete: A Study in Regional Historiography", *Kretika Chronika* 28-29: 161-162.

10 D. Levi, "Arkades", *Annuario della R. Scuola Archeologica Italiana di Atene e delle Missioni Italiane in Oriente*, vol. X-XII (1927-1929), Bargamo (Istituto Italiano di' Arti Grafiche 1931), and especially chapt. V: "La Necropoli di Arkades".

11 Crete is known as hekatompolis in Homer *Il.*2.649.

literary sources, which refer to the drying out of water springs in Arkadia of Crete; (b) etymology, mythology, and toponyms relating to Arkadia; and (c) archaeological finds.

Discussion and Interpretation of the Evidence

Ancient Greek and Roman literary sources

Regarding the first evidence, it can be stated that three writers, i.e., Theophrastus (4th century B.C.), Seneca the Younger (1st century B.C.), and Pliny (1st century A.D.), mainly focused their attention on the destruction of ancient Arkadia by the Romans and on the consequences of that destruction, i.e., the drying out of the water springs. Specifically, Pliny emphatically says that, after the destruction of Arkadia, many existing springs and rivers in the area dried out, and only six years later, when the city was rebuilt and land cultivation began, the springs started flowing again[12]. Pliny's emphasis on the drying out of springs for six years may signify the degree of the city's destruction, on one hand, and the sufficient water quantity, on the other. Pliny attempts an interpretation for the drying out of springs by saying that the destruction of the city included the loss of trees and bushes, which used to reduce flooding and increased the ground water before.

A similar explanation is offered by Theophrastus[13], who states that springs and rivers ceased to exist, exactly because land was not cultivated. But, as soon as it started to be cultivated again, new springs reappeared. In other words, Theophrastus says that due to the destruction of the city, the soil became hard, and as it was not cultivated, it could not reduce flooding and increase the ground water[14]. Seneca does not agree upon Theophrastus' interpretation and notes that in many areas which are barren and, thus, not cultivated, there are many water springs. Furthermore, he adds that before people proceed to cultivate any land, they usually search for water first, since water is what will assure them a good crop.

The evidence above has attracted the attention of the authors of the present article, who saw a direct connection between the existence of water in ancient Arkadia and Arkades, its inhabitants; the impression one gets from the sources is that the Arkades' lives were particularly connected with water. Although no water fountains have been excavated in the area, oral folk tradition speaks of the existence in the past of a large number of fountains[15]. Perhaps, this may explain the emphasis given by ancient authors on the drying out of springs; the absence of water fountains in the excavations may also comprise a strong indication of the destruction of the city and its fountains by people as well as by natural phenomena. Along these lines, we could surmise that the ancient sources do not simply refer to the drying out of the springs and fountains, but they probably allude to the destruction of the fountains, where the spring water ended up. This assumption may appear convincing (if compared to the one about the drying out of springs and fountains), as it is in agreement with the destruction of Arkadia by the Romans, a fact which may naturally have led to the destruction of all water supply installations. It could also be added that in antiquity it was probable that fountains existed on the hill of "Prophitis Elias" (Prophet Elias), where today most

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12 Pliny, *Naturalis Historiae* [*N.H.*], 31,53.
13 Theophrastus' account is preserved by Seneca, *Naturales Quaestiones* [*N.Q.*], 3,11,5-6.
14 Seneca, *N.Q.*, 3,11,5-6.
15 E.G. Chalkiadakis, 2000, «Τα τοπωνύμια των χωριών Αφρατίου Πεδιάδος και Αρχοντικού Μονοφατσίου του Νομού Ηρακλείου» ("The toponyms of the villages Aphrati in Pediada and Archontiko in Monofatsi in Herkalion nome"), *Ta Kretika Toponymia.* Proceedings: A Two-Day Scientific Conference, Rethymnon, 6-7 November 1998, Rethymnon: Historike kai Laographike Hetaireia Rethymnou, 406.

researchers place the center of ancient Arkadia[16]. The location of fountains on high places in ancient times may be relevant to Aristotle's remark *αἱ κρῆναι αἱ πλεῖσται ὄρεσιν καὶ τόποις ὑψηλοῖς γειτνιῶσιν* [Aristot. *Meteor*., A 13.350a4-5].

Etymology, mythology and toponyms relating to Arkadia

The second evidence is based on linguistic connections made between the inhabitants of Arkadia and water through etymology and mythology. First, the etymology: the pre-hellenic root *ar-* of the word "Arkades" refers to water[17]. Second, the mythology: the mythological tradition of the Arkades of the Peloponnesus wants them to be definitely connected to water, as will be shown below. It was the Peloponnesian Arkades who settled in Arkadia in ancient Crete[18]. According to the scholiast of Dionysius of Periegetes (2nd century A.D.), the Arkades of the Peloponnesus were also called "Apidanēes"[19], and their land, Arkadia, was also named "Azenis"[20]. "Azenis" means "dry land". One can appreciate this meaning, if considering the scholiast's remarks, i.e., in the beginning there was no water in Arkadia of the Peloponnesus ("…there were neither fountains nor water in the beginning…"[21]); but later, in Azenis, there was plenty of water due to the existence of many rivers in the area[22]. Thus, the originally dry land, "Azania", was transformed into a land rich in water by the mythical hero Apis, who came from Naupaktia and settled in Arkadia, Peloponnesus (known also as Apia)[23]. Considering this myth, the reader of the scholia can assume that "Apidanēes", the synonym of Arkades, could possibly mean "the ones who repel dryness or lack of water".

The second evidence is also supported by the toponyms found in the Aphrati region today, which reflect water existence in the area. Some indicative toponyms are the following: "In Ayíando Leivadi": referring to a place, where there is a water spring; "Kalami" ("The Reed"): the name refers to reeds, the existence of which also implies the presence of water;

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[16] Levi, 1927-1929, "Arkades", *Annuario della R. Scuola Archeologica Italiana di Atene e delle Missioni Italiane in Oriente*, vol. X-XII, *ibid.*, N. Xifaras, 1998, «Η κατάληψη του χώρου στην Πρωτογεωμετρική και Γεωμετρική Κρήτη» ("The occupation of the area in Proto-geometric and Geometric Crete"), *Rithymna* 2, Rethymnon, 34-36, A. Lebessi, 1969, "Aphrati", *Archaiologikon Deltion* [*A.D.*] 24 (Part B' - Chronika), 415-416.

[17] For the root *ar-*, see other toponyms, like Archanes, in Y. Sakellarakis & E. Sapouna-Sakellaraki, 1991, *Κρήτη – Αρχάνες* (*Krēte – Archanes)*, Athens: Ekdotikē Athenōn, 18; P. Faure, 1983-1984, "Hydronymes Crétois", *Κρητολογία* 16-19 (*Kretologia*), 30-61; Κ. Παπαδάκης, 1998, «Τοπωνύμια της επαρχίας Αγ. Βασιλείου Ρεθύμνης με αρχαία ελληνική προέλευση» ("Ancient Greek toponyms of the district of Agios Vassilios in Rethymno"), *Ta Kretika Toponymia*, B', Proceedings: A Two-Day Scientific Conference, Rethymno, 6-7 November 1998, Rethymnon: Historike kai Laographike Hetaireia Rethymnou, 17-79, especially 21-22.

[18] Chalkiadakis, 2000, «Τα τοπωνύμια των χωριών Αφρατίου Πεδιάδος και Αρχοντικού Μονοφατσίου του Νομού Ηρακλείου» ("The toponyms of the villages Aphrati in Pediada and Archontiko in Monofatsi in Herkalion nome"), *Ta Kretika Toponymia.* Proceedings: A Two-Day Scientific Conference, *ibid.*, 405.

[19] Scholia in Dionysii periegetae orbis descriptionem Vita – Verse of *Orbis descriptio*, line 415.

[20] Kallimachos granted the name "Azenis" to Arkadia, as noted in Scholia in Dionysii periegetae orbis descriptionem Vita – Verse of *Orbis descriptio*, line 415. See also, H.G. Liddell, R. Scott & H.S. Jones, [*LSJ*], 1968, *A Greek – English Lexikon*, Oxford Clarendon Press, s.v. Αζάνες. Αζανία "land of Ζάν or Ζεύς, i.e. Arcadia, St. Byz." See also, s.v. αζαίνω "dry". Hence, Αζανία is "dry land".

[21] Scholia in Dionysii periegetae orbis descriptionem Vita – Verse of *Orbis descriptio*, line 415 ff. See also, M. Glezos, 2001 [*Ύδωρ, Αύρα, Νερό*, (*Hydor, Avra, Water*), Athens: Kastaniotis, 270], who states that the word "pidakas" refers to a fountain, from which water springs out; the word has been preserved with the same meaning until today since the Homeric times.

[22] Scholia in Dionysii periegetae orbis descriptionem Vita – Verse of *Orbis descriptio*, line 415. This can be understood especially if one considers that Αζηνίς is the land of Zeus, the chief Greek god, as well as the god of rain (Hyetios). See *LSJ* (above n. 20). Nevertheless, it is interesting to observe that "Αζηνίς", meaning "dry land", is not compatible with rainwater, which is closely related to Zeus, the god of rain. For the epithet of Zeus as *Hyetios*, see above n. 2.

[23] Scholia in Dionysii periegetae orbis descriptionem Vita – Verse of *Orbis descriptio*, line 415.

"Linarés": the name of a place, where people used water for working out flax; "Limē" ("Small lake"): a hollow ground depression, where rainwater collects; "Papadyia's ryaki": a toponym indicating that there existed a water stream (ryaki); "Potistika": the name refers to fields, where water for irrigation existed; "Papas' kolybos": a place-name referring to a natural or artificial hollow ground depression filled with water (this place does not exist today)[24]. Except for these toponyms, other place-names which reflect large quantities of water are also found in the broader region of Arkadia in Crete, which became known in the 6th century A.D. by the ecclesiastic term "The Diocese of Arkadia"[25].

The water-related toponyms in the Diocese of Arkadia are "Megali Vryssi" ("Great Fountain"), "Pigaydakia" ("Small Wells"), and "Sternes" ("Cisterns"); all three refer to modern villages, which are located near the Monastery of Apezanes, and reflect water presence there. Taking into account these place-names, it is interesting to underline a possible semantic relation between the name Apezanes[26] and Apidanēes, another name of the ethnic Arkades[27]. If the two names, i.e., Apezanes and Apidanēes, are semantically cognate,

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[24] See Etaireia Kretikon Istorikon Meleton, 1953, *Πίναξ τοπωνυμίων της περιοχής του χωρίου Αφρατίου. Συνταχθείς υπό Σταύρου Μουσουράκη, διδασκάλου*, Αφρατί, 20 Απριλίου 1953. ("A Table of toponyms in the region of Aphrati, composed by Stavros Mousourakis, Elementary School Teacher"), Aphrati, 20 April 1953. See also, Chalkiadakis, 2000, *ibid.*, 407-410, M. I. Pitykakis, 2001, *Το Γλωσσικό Ιδίωμα της Ανατολικής Κρήτης*, τ. Α΄, Α-Λ (*The Linguistic Idiolect of Eastern Crete*, v. A', A-Λ), Neapoli, Crete, 465-466: s.v. «κόλυμπος».

[25] The Bishop of the Diocese had his seat in a settlement located 3 km west of Arkalohori, and named "Mikre Episkope" (Small Dioces), but it is not possible to refer with certainty to the borders of the Diocese. It is known that the Diocese of Arkadia included the ecclesiastic region of Messara. The seat of the Diocese was located first in Agioi Deka, and in 1946 it was moved to Moires of Kainourgio district, where it exists today. (Th. E. Detorakis, 1990, *Ιστορία της Κρήτης* [*History of Crete*], Heraklion, 436.) The Diocese was renamed as the Diocese of Gortys in 1961. (Ancient Gortys was a city, which, according to a view, was founded by Arkades coming from the Peloponnesus. Specifically, Pausanias mentions that the city was built by inhabitants of Tegea [Paus. VII, 53], and refers to the mythical Gortys, a son of Tegeatēs. The sons of Tegeatēs, i.e., Kydon, Arkadios, and Gortys, perhaps suggest a) possible settlements of Arkadian tribes in Crete, and b) toponyms that derive from those names. For more information, see St. G. Spanakis, 3 1984, *Κρήτη [Κεντρική – Ανατολική, Ν. Ηρακλείου και Λασιθίου], Τουρισμός-Ιστορία –Αρχαιολογία*, τ. Α΄ [*Crete (Central-Eastern, Nomes of Heraklion and Lasithi), Tourism-History-Archaeology*, v. I], Heraklion, 168; I. Th. Kakridis [ed.], 1986, *Ελληνική Μυθολογία, οι τοπικές παραδόσεις*, τ. 3ος [*Hellenic Mythology, the Local Traditions*], vol. 3, Athens: Ekdotikē Athenōn, 284.) In 1962 the Diocese of Arkadia was named as "Metropolis of Gortys and Arkadia". For this, see Detorakis, 1990, *ibid.*, and Spanakis, 3 1984, *ibid.*, 142.

[26] There is a view, according to which the name of the Monastery may have come from the plural genitive of the family name "Apezanos". For this, see C. Z. Tsikritsi-Katsanaki, 1975, «Συμβολή στη μελέτη των τοπωνυμίων της Κρήτης: τοπωνύμια από οικογενειακά ονόματα» ("A Contribution to the Study of the Cretan Toponyms: Toponyms from Family Names"), *Amaltheia* (Agios Nikolaos, Crete) 22-23: 25-59, especially 30.

[27] See above n. 18. See Tziropoulou-Efstathiou, 2006, *ibid.*, 269, s.v. "άζω" (=ξηραίνω). It is worth mentioning, besides the literal meaning of the name "Apezanes", which refers to the Monastery, the symbolic meaning of it. The Monastery was a center for Education and Letters for the broader region around it. According to literary evidence, the area of the Asterousia mountains, where the Monastery is located, was a land defending Orthodoxy against the vigorous propaganda of Catholic Church already since the 14th c. (See N. Psilakis, 2 1994, *Μοναστήρια και Ερημητήρια της Κρήτης* [*Monasteries and Hermitages of Crete]*, Heraklion, 245.) Taking into account the attempt of the Monastery to preserve this spiritual tradition during the Venetian occupation of the island, it is reasonable to assume that the name "Apezanes" was selected for reflecting the struggle of an educational center against a propaganda, which might cause "spiritual dryness" in Orthodoxy. It is significant to mention that in the Monastery a school functioned, in which ancient Greek literature was taught. Perhaps, then, the name of the Monastery had been carefully selected by the teachers of the ancient Greek authors in the Monastery, just to pass the symbolic meaning. For the function of the Monastery as an educational center, see Th. Detorakis, 1982, «Τα μοναστήρια στη Βενετοκρατούμενη Κρήτη» ("The Monasteries in Crete during the Venetian Occupation"), *Parakletos* 37 (Rethymnon), 21. Regarding the etymology of "Apezanes" as the name of the Monastery (the exact date of the Monastery's foundation is not known), there is one interpretation, according to which the name of thw Monastery came from the verb

it might be reasonable to extend the earlier hypothesis (relation between Apidanēes and water) to the connection between Apezanes and water.

Archaeological finds

The third piece of evidence provided here, in order to establish the relation of water and the Arkades of Crete, comes from archaeology. Before stating the connections between water and the Arkades, on the basis of the finds, it is necessary to briefly mention the major archaeological discoveries in the area.

Excavations done in the beginning of the 20th century, as well as more recent research, have revealed that on the hill of "Prophitis Elias" northwest of the modern village Aphrati, and specifically around its top -where there is a small church dedicated to Prophet Elias- lie the ruins of an ancient city, and specifically those of a necropolis with some vaulted tombs and many chamber room tombs[28]. These ruins have been identified with the ancient city of Arkadia, as excavations done chiefly by the Italian Archaeological School have shown[29]. The mission by Doro Levi was performed in 1924, and brought to light many finds, like vases, coins, jewellery, weapons -bronze and iron- and other finds, as well as inscriptions, all discovered in vaulted tombs[30]. These objects were dated from the Late Minoan Age until the Classical and Hellenistic Periods. More recent excavations in the same region by the archaeologist Angeliki Lebessi have unearthed new archaeological finds[31].

The ancient city of Arkadia was probably colonized by Arkades from the Peloponnesus[32]. The ancient Cretans had enacted a law which concerned foreigners and prescribed to them the specific regions in Crete, where they were allowed to reside. Other regions and cities, except for the prescribed locations, were prohibited to non-Cretans for residence. One of the specified regions for foreigners was ancient Arkadia[33]. As those areas were settled by

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πεζέφνω=αφιππεύω, and in fact from the aorist of the verb, i.e., απέζεψε, ξεπέζεψε, meaning "climbing down/off a horse". The Monks who carried the icon of St. Antonius stopped at the point where they built the Monastery, and selected for it a name that derives from the above verb. This interpretation is not likely, to the opinion of the authors of this article. For further information about the above oral tradition, see E. P. Lekkos, 1998, *Τα μοναστήρια του Ελληνισμού, Ιστορία – Παράδοση – Τέχνη, τ. Β΄, Πελοπόννησος, νησιωτική Ελλάδα,* (*The Monasteries of Hellenism, History – Tradition – Art, v. B', Peloponnessus, Greek Islands*), Peiraeus: Ichnilatis, 221. See also, Spanakis, [3]1984, *ibid*., 136-137; St. G. Spanakis, 1991, *Πόλεις και χωριά της Κρήτης στο πέρασμα των αιώνων (μητρώον των οικισμών),* (*Towns and Villages of Crete through the Centuries*), Heraklion: Detorakis, 119. For general information about the Monastery of Apezanes, see also Psilakis, *ibid*., 239-259.

28 Xifaras, *ibid.,* 35.

29 The excavations were performed initially by F. Halbherr ("Ruins of unknown cities at Hagios Ilias and Prinia", *AJA* 5: 1901: 393-403) and continued mainly by Doro Levi (see above note 10).

30 Levi, 1931, *ibid*. See also, M. Prent, 2005, *Cretan Sanctuaries and Cults. Continuity and change from Late Minoan IIIC to the Archaic Period, Religions in the Graeco- Roman World*, vol. 154, Boston – Leiden: Brill, 278-279.

31 A. Lebessi, 1969, "Aphrati", *Archaiologikon Deltion* [*A.D.*] 24 (Part II - Chronika), 415-416.

32 On the relation between the Arkades of the Peloponnessos and those of Crete, see Strataridaki, 1988-1989, *ibid.*, 161-162; Chalkiadakis, 2000, *ibid*., 405 f.

33 By the end of the 6th c. B.C. the Cretan cities enacted laws about the controlled residence of foreigners in specified areas of the island, so that all foreigners were governed by certain legal sanctions. The law of Gortys represents a collection of earlier legal provisions of the Cretan cities. See M. Guarducci, 1950, *IC*, IV, 72, Roma; R.F. Willetts, 1982, "Cretan Laws and Society", in: J. Boardaman & N.G.L. Hammond, "The Expansion of the World, Eighth-Sixth Centuries B.C.", Cambridge Ancient History III, 3, 235-248; R.F. Willetts, 1967, "The Law Code of Gortyn", *Kadmos* (Suppl. I), Berlin: W. de Gruyter; D. Skiadas, 1999, *Η Δωδεκάδελτος Επιγραφή της Γόρτυνας* (*The Twelve-Table Inscription of Gortys*), 19; St. Spanakis, 1957, «Ανέκδοτος Κατάλογος των 100 πόλεων της Κρήτης» ("Unpublished Catalogue of the 100 Cities of Crete"), *Kretika Chronika*, 11: 277-301, especially 281-282. Spanakis, [3]1984, *ibid.,* 142: «…η Αρκαδία είχε οριστεί, όπως κι άλλες πόλεις, ως τόπος εγκατάστασης των ξένων» (Arkadia, like other cities, had been defined as a place for the foreigners' inhabitance). That Arkadia was a

foreigners coming from various parts of Greece, the new communities were named after the ethnic name of the new settlers (for instance, Arkades) or the name of their land of origin (i.e., Arkadia). This seems to be the reason why the name of the settlement appears in some writers in the plural form "Arkades" (referring collectively to inhabitants) and in others in the singular form "Arkadia"[34].

Regarding the location of ancient Arkadia in Crete, there is no agreement among researchers. Paul Faure holds that the ancient city probably existed where the modern village Ini of Monofatsi is located today[35]. Some researchers identify Arkadia with the village St. Thomas in the Tetrachorion Municipality; another group locates the city near Kastelli of Mylopotamos[36] in the Rethymnon region, whereas others propose that the city probably existed at the site of modern Arkalochori[37]. Other scholars hold that the settlements of the Arkades were spread out at the sites of the modern villages Damania, Kephala, Melissochori or Melidochori, and Arkadi[38].

Nevertheless, the excavations by Doro Levi in the broader region of Aphrati, and the discovery of the necropolis on the "Prophitis Elias" hill provide a strong indication for the assumption that the Arkades' city must have existed, at least in the beginning, in an extended region, which included, on one hand, the hill of "Prophitis Elias" as its center, and, on the other, a broader region comprising the villages near this community. It is known from the ancient literature that the Arkades inhabited their city "kata komas"[39] (meaning "in autonomous agricultural and cattle-raising communities"); in a few words, the city of the Arkades perhaps consisted of many such communities, which progressively created an administrative center, and which, according to many modern scholars[40], was located very close to the modern village of Aphrati.

To make a connection between water and ancient Arkadia it is worth referring to the archaeological ruins on the hill of "Prophitis Elias" in Aphrati. Among the ruins most

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community for foreigners is preserved in the Latin catalogue *Centum antiquae urbes insulae Cretae quarum nomina apud Stephanum Byzantium and apud Ptolemeum extant*, no. 14: Arcadia sive Arkades hospitium exterorum. See also, E. Nikoloudaki, 1980, «Περιγραφή και κατάλογοι των 100 πόλεων της Κρήτης» ("Description and catalogues of the 100 cities of Crete"), *Amaltheia*, (Agios Nikolaos, Crete) 41, 42, 43-44 & 45: 363-370, 37-54, 143-154, 233-249, respectively, in which the Italian Catalogue by Fr. Barozzi (*Descrizione dell' Isola di Creta*) is also included.

34 Specifically, writers like Polybius (4.53.6) and Xenion, who is preserved by Stephanus of Byzantium (see above n. 9), use the ethnic name "Arkades" to denote the city, whereas Theophrastus, who is preserved by Seneca (*N.Q.* 3.11.5.) and Pliny (*N.H.* 31.53) cite the name "Arkadia". See also G. I. Papadakis, 2002, *Βιάνος. Διαχρονική πορεία από τα βάθη των αιώνων μέχρι σήμερα* (*Vianos. History through the Ages*), Athens: Smyrniotakis, 86; and Chalkiadakis, 2000, *ibid*., 405.

35 M. Guarducci, *Inscriptiones Creticae*, [*IC*], I (Roma 1935), Arkades, 6; P. Faure, "La Crete aux centes villes", *Kretika Chronika* 13 (1959), 171-217, esp. 194; Spanakis, [3]1984, *ibid*., 142; Papadakis, 2002, *ibid*., 86-87; E. G. Chalkiadakis, 2005, «Δημοτικό Διαμέρισμα Αφρατίου Πεδιάδος, Αρχαία Αρκαδία: ιστορική, κοινωνική και ονοματολογική προσέγγιση», *Πρώτο Παμβιαννίτικο Συνέδριο (πρακτικά συνεδρίου,)* τ. Β΄ ("Municipality of Aphrati in Pediada: Ancient Arkadia: a historical, social and etymological approach", *First All-Viannos Conference (Proceedings)*, v. I), Ano Viannos, Heraklion, 7.

36 Spanakis, 1957, *ibid*., 277-301, esp. 281, n. 16; Papadakis, 2002, *ibid*., 86-87.

37 Chalkiadakis, 2005, *ibid*., 6.

38 See F.W. Sieber, 1994,*Ταξιδεύοντας στη Νήσο Κρήτη το 1817* (*Travelling in Crete in 1817*), Athens: Istoritis, 154. See also, Guarducci, 1935, I, *ibid.*

39 That the settlements of the inhabitants Arkades were more than one perhaps is related to the name of the city, which was called not only Arkadia (singular) but also Arkades (plural). For the settlements of Arkades «κατά κώμας», see also Prent, 2005, *ibid*., 279.

40 Levi, 1931, *ibid*.; M. Guarducci, 1935, I, *ibid*.; N. Xifaras, 1998, «Η κατάληψη του χώρου στην πρωτογεωμετρική και γεωμετρική Κρήτη» ("The occupation of space in Proto-geometric and geometric Crete"), *Rithymna* 2, Rethymnon, 34-36; B. L. Erikson, 2002, "Aphrati and Kato Syme. Historical Implications", *Hesperia* 71: 77-79.

prevalent are a settlement, a cemetery and a sanctuary, whereas on top of the hill there are the ruins of a trapezoidal fort[41] and of a cistern near the fort.

The cistern, unearthed by Doro Levi, was described in detail by him as a deep and closed cistern, which was plastered with red mortar on the bottom. The shape of the cistern was trapezoidal, and one of its sides was parallel to the fort. A rock rising steeply plays the role of the fourth side. At this point it should be noted that in Crete, during antiquity and even later, it was a common practice in the construction of buildings to carve rocks and include them as parts of the buildings[42].

Regarding the cistern in Arkadia, it should be pointed out that the construction is so mutilated, that it is not possible to form a full picture of the building. What is certain, however, is that the fort was attached to the cistern. On the long side of the cistern a window-like opening[43] exists, which, when the cistern was in use, would have allowed the besieged to look through it and check the water level. It seems that at some point in time when the fort was not used, the cistern must have ceased to function as such. This is indicated by the various kinds of debris (e.g., broken pottery)[44] found in the cistern.

In reference to the use of the cistern, it is reasonable to ask how it was filled with water. To answer the question one could only make assumptions, as the archaeological evidence does not suffice, though it is reasonable to assume that there must have been some kind of water channel letting water into the cistern[45]. Aristotle notes that the existence of water reservoirs presupposed the building of water supply channels, which were often underground, and collected water, as the latter gushed up from the higher parts of the earth[46]. The cistern in Arkadia, one could say, may have been filled with water from a nearby spring[47]. This could have occurred, if there was a spring on top of the hill, but until today no

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[41] According to N. Xifaras (1998, *ibid.*, 34), the dating of the fort cannot be estimated. See also, Prent, 2005, *ibid.*, 278-279. Prent states that the archaeological finds are dated from the Classical and Hellenistic periods (*ibid.*, 278).

[42] Psaroudakis, 2004, *ibid.*, 26, n. 65. This practice is met even in earlier periods. A characteristic example is the carved cistern in the northern slope of the hill of Paliochora, which was constructed in the Late Minoan III period (14th-11th c. B.C.) for the needs of the local sanctuary. For this, see Prent, 2005, *ibid.*, B.60. Amnisos.

[43] The opening is 0.60 m wide at the top and narrower at the bottom of the horizontal covering stone.

[44] Levi, 1931, *ibid.*, 35-36.

[45] At the time it was common for people to collect water from fountains or wells. A fountain comprises a natural water source, through which the water is channeled, through proper modification, to pass through; a well, on the other hand, is an artificial source, from which water is pumped up. The first evidence for *φρέαρ* appears in Homer, *Il.* 21.196-197: *ἐξ οὗ [Ὠκεανοῦ] πάντες ποταμοὶ καὶ πᾶσα θάλασσα πᾶσαι κρῆναι καὶ φρείατα μακρὰ νάουσι*. People also used to build aqueducts. For this, see Glezos, 2001, *ibid.*, 40, 134, 158.

[46] Aristot. *Meteor.* A 350a1: *οἱ γὰρ τὰς ὑδραγωγίας ποιοῦντες ὑπονόμοις καὶ διώρυξι συνάγουσιν, ὥσπερ ἂν ἰδιούσης τῆς γῆς ἀπὸ τῶν ὑψηλῶν.*

[47] Generally, on the construction and use of cisterns in antiquity, information is offered by ancient Greek writers, like Herodotus, Plato, and Aristotle. Herodotus says that cisterns were buildings constructed and used by man for keeping water (Herod., 6.119.14: …*ἀντλέει καὶ ἔπειτα ἐγχέει ἐς δεξαμενήν*…). In his dialogue *Kritias* (Plat. *Krit.*, 117a-b) Plato, referring to the Acropolis of the mythical Atlantis, leads to the conclusion that water should be traced first, before cisterns are built near it. The same idea holds true even today. Not long ago, in the 19th century, construction techniques of wells and cisterns prescribed that a water spring would have had to be located higher than a cistern, so that the water could have flowed down to it through a closed-up aqueduct, in order to protect water quality. For this, see I. E. Tsouderos, 1995, « Πώς οι Κρητικοί του Ρεθύμνου επεσήμαναν την ύπαρξη υπόγειας φλέβας νερού και πως έφτιαχαν ένα πηγάδι και μία στέρνα για πόσιμο νερό το 19ο αιώνα και ως το 1865. Σύγκριση με πηγάδια και στέρνες πόσιμου νερού της Μινωικής, Ελληνιστικής, Ρωμαϊκής και Βενετσιάνικης περιόδου της Κρήτης», *Πεπραγμένα του Ζ΄ Διεθνούς Κρητολογικού Συνεδρίου*, τ. Γ2, τμ. Νεωτέρων Χρόνων, ("How the Cretans of Rethymnon found the existence of underground water flow and how they were building a well and a cistern for potable water in the 19th c. until 1865."), *Proceedings of the 7th International Cretological Conference*, v. III2, Rethymnon: Municipality of

signs of such a spring or fountain have been traced there[48]. It is rather likely, then, that the cistern must have been filled with rainwater.

Specifically, Aristotle speaks of cisterns as reservoirs of rainwater. He refers to a cistern on the Acropolis of Athens (510-480 B.C.) as a characteristic example of such a case; that is, a cistern was built there for the collection of rainwater, which was channeled into it after flowing all over the surface of the rock. For this reason, an aqueduct was carved in the natural rock, and in the form of a belt. Thus, rainwater was led into the cistern through this belt-like aqueduct[49]. Here, Aristotle points out the significance and the utility of the cistern being filled with rainwater[50] and, through this example, he appears to advise the inhabitants of all cities to proceed in building similar cisterns, so that they have plenty of water in cases of siege. Aristotle's reference to the cistern in Athens reminds one of the cistern adjacent to the fort of the "Prophitis Elias" hill. As mentioned earlier, this cistern had an opening, which would have been used by the people inside the fort to check the water level in the cistern[51].

Returning to the connection of Arkadia with water, this relation can also be emphasized through the existence of a sanctuary among the ruins of the city. One of the most significant archaeological finds in Arkadia is the "house-sanctuary", which was excavated by Angeliki Lebessi in the northeastern slope of the "Prophitis Elias" hill and specifically in Katzilakis' land[52]. The excavation revealed three building phases of the sanctuary between the 9th and the 7th centuries B.C., when the sanctuary took its final form[53]. The presence of the sanctuary suggests the existence of a water source nearby in the form of a fountain or a well for ritual purposes and for the needs of the worshipers. Although no fountain has been excavated in the area, yet the existence of some type of fountain in antiquity is reasonable to assume. During the excavations in the region in 1968, a channel used for the drainage of water off the roof was discovered. There was also found a clay bathtub (length: 1.15 m, maximum preserved width: 0.75 m, height: 0.45 m). Its shape is similar to that of a bathtub found in "Palaia Smyrne" (i.e., ancient Smyrne) the painted decoration of its flat rim with two rows of continuous spirals is often found on pithoi of the early half of the 7th century B.C. (700-650 B.C.)[54]. Bathtubs, in general, apart from being house objects, constituted offerings to temples by wealthy worshipers, as during antiquity they had a symbolic function linked to ritual purification. Therefore, the clay bathtub from Aphrati could have been such an offering of wealthy dedicators, who had participated in rituals honoring a warlike goddess (probably Athena)[55].

Among the movable finds which were discovered 100 m away from the sanctuary, and which can also be connected with water use, are: a basin (vessel) of white stone, which was discovered together with broken pottery dated from late archaic and early classical years; a

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Rethymnon –Istorikē kai Laografikē Etaireia Rethymnis, Rethnymnon), 609-657, especially 631 and 651.

48 Although there are no finds of fountain or spring on top of the hill, there must have been water at the foot of the hill in antiquity. Today there is still a water spring called "Ayiando Leivadi". For this, see Chalkiadakis, 2000, ibid., 407-408.

49 T. Tanoulas, 1992, "The Premnesiclean Cistern on the Athenian Acropolis", *Athenischen Mitteilungen* 107: 129-160.

50 *Polit*. 1330b6: *…διὰ τοῦ κατασκευάζειν ὑποδοχὰς ὀμβρίοις ὕδασιν ἀφθόνους καὶ μεγάλας.*

51 Tsouderos, 1995, *ibid.*, 631. Levi, 1931, *ibid.*, 35-36.

52 A. Lebessi, 1970, Chronika: "Aphrati", *Archaiologikon Delti*on 25: 455-460.

53 Xifaras, 1998, *ibid.*, 35-36.

54 A. Lebessi, 1969, Chronika: "Aphrati", *Archaiologikon Delti*on 24: 415-418; R. V. Nicholls, 1958-59, "Old Smyrna: The Iron Age Fortifications, etc.", *BSA* 53-54: 36-137,especially 75, n. 182.

55 Lebessi, 1969, *ibid.,* 418. J.-N. Svoronos, 1890, *Numismatique de la Crète ancienne, premiere partie, Description des Monnaies, Histoire de Geographie*, 25-27. The depiction of goddess Athena on the coins of Arkades leads to the assumption that the war deity was probably Athena.

spouted jar; an hydria; 11 black-slip cups; 3 basins, the type of which belongs to archaic basins, and which came from the cemetery of Arkades; a conical cup; a small crater and a three-leaved spouted jar, which, on the basis of two lamps, were dated from the 5th century B.C.[56]. Although there are no archaeological finds to manifest existence of aqueducts in ancient Arkadia, the toponyms mentioned earlier from the broader region of the Aphrati village today are etymologically connected to water[57].

Conclusion

In conclusion, it can be stated that even though there is lack of hard data that would prove the existence of water supply installations in ancient Arkadia, the available evidence as presented above reveals strong indications for a relation between the Arkades of ancient Crete and water. Needless to say, further research is awaited to be done, in view of many still unanswered questions about ancient Arkadia.

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[56] Lebessi, 1970, *ibid.*, 458-460.

[57] See above n. 21. G. Kornarakis suggests that the name of Aphrati derives from Phrati (Phrati relates to *φρεάτιον* [= "well"]) after *apokope* (*elision*) of the ending *-ον* [H. W. Smyth, 1976, *Greek Grammar*, Cambridge, Mass.: Harvard University Press, 23§70, 71], and with *hyphaeresis* (*omission*) of *ε* before α (*φρεάτιον -ου → φρατί*), [H. W. Smyth, 1976, *Greek Grammar, ibid*., 18§44a], while the prefix α (*alpha privative*) is added [H. W. Smyth, 1976, *Greek Grammar, ibid*., 249§885.1; the derived form "aphrati" means "land with no wells" (i.e., without water). This view is not accepted by the authors of this article. If one takes into account that the original name of the village was Phrati rather than Aphrati, then α was probably added for *euphony*. For this, see Chalkiadakis, 2005, *ibid.*, 4-5.

Water Resources Management in the Ancient World

Water Management in Bronze Age: Greece and Anatolia

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Abstract: While the water management systems of Minoan Crete are legendary, water management on the Greek mainland in the Mycenaean period also shows a high degree of technological sophistication. Projects considered in this paper include the draining of the Kopais Lake, generally agreed to be one of the greatest engineering achievements of early antiquity; the cistern at Mycenae with its corbelled access tunnel cut deep into the bedrock of the citadel; the twin springs at Tiryns, with their underground passageways approached through the massive 'cyclopean' walls; and the North Fountain on the Mycenaean Acropolis of Athens. These Mycenaean systems are compared with the remarkable underground water supply system at Troy uncovered by the recent excavations led by Manfred Korfmann, a structure which may date to the beginning of the 3rd millennium and which appears to be invoked among the deities of Wilusa (Troy) in the early-13th century treaty between Muwattalli II of Hatti and Alaksandu of Wilusa (and which may be a precursor of the famous Persian qanats).

Keywords Kopais; Mycenae; Persia; Tiryns; Troy.

Introduction

The water management systems of Minoan Crete in the 2nd millennium B.C. are legendary: the water supply system, the management of wastewater and the sewerage system, all these were technologically advanced to a level that would be the envy of many societies today. But there was also a high degree of technological competence and vision in water management projects on the Greek mainland during the period immediately following the Mycenaean ascendancy over Minoan Crete. These include the draining of the Kopais Lake, generally agreed to be one of the greatest engineering achievements of early antiquity; the cistern at Mycenae with its corbelled access tunnel cut deep into the bedrock of the citadel; the twin springs at Tiryns, with their underground passageways approached through the massive 'cyclopean' walls; and the North Fountain on the Acropolis of Athens. These Mycenaean systems may be compared with the water management systems found at Troy, particularly the remarkable underground water supply system uncovered by the recent excavations led by Manfred Korfmann, a structure which may date to the beginning of the 3rd millennium and which appears to be invoked among the deities of Wilusa in the early-13th century treaty between Muwattali II of Hatti and Alaksandu of Wilusa, and which may be a precursor of the famous Persian *qanats*, known from the 1st millennium and still in use today.

The Kopais Lake Drainage Project

The draining of the Kopais Lake in Boeotia in the 14th century B.C. is the earliest drainage project in European history. Said by ancient writers to have been the work of the Minyans of Orchomenus, a rich and powerful Mycenaean kingdom on the western side of the Kopais basin, the project involved the construction of an elaborate system of canals leading to a central canal that drew off the water of the lake and emptied it into the sea at Larymna. The lake was fed by the Kephissus river and by streams from Mt. Helicon, and was surrounded by limestone mountains. A network of drains (*katavothrai*) in the stone, both natural and manmade, drained water from the basin into the northern part of the Euboean Gulf. The area was a shallow marsh in summer, with portions, particularly in the western part (the Kephisis), often dry enough to allow cultivation of the land. But the lake flooded periodically, to some extent annually, and apparently extensively on a more or less regular nine-year cycle.

The point of convergence of the Mycenaean drainage dykes with the artificial canal and the natural outlets (*katavothrai*) was near the location of Gla, the large Mycenaen site which was apparently not a palatial centre such as Thebes, Orchomenos, Mycenae, etc., but rather an administrative outpost which served both as protection for the area and as a depository for the produce of the fertile plain that surrounded it and that was available for cultivation while the Mycenaean drainage system was operational (Fig. 1). The site of Gla itself was evidently "incorporated into the complex of drainage works and fortifications that surrounded it in antiquity, and was apparently the key point of the whole system", its "main function [being] to protect the installations by which the lake was drained" (Iakovidis, 1983).

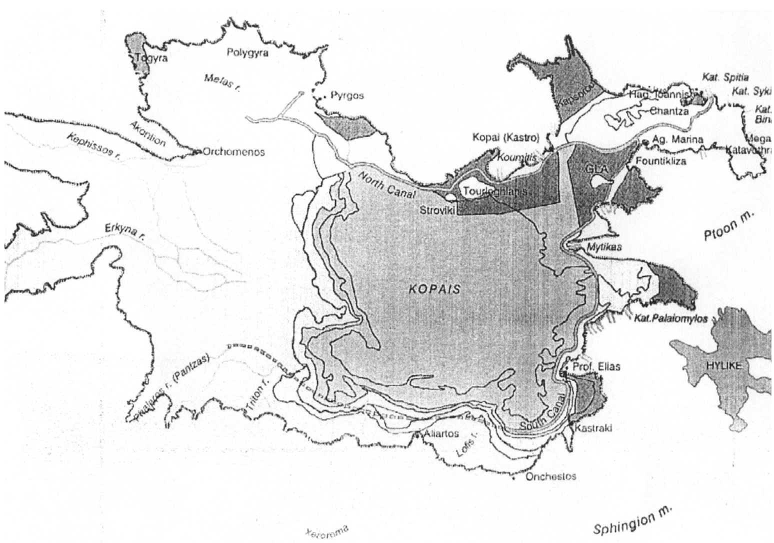

Figure 1 The Mycenaean drainage system (Iakovidis, 2003).

When the lake was drained again in 1886 it was over three m deep in the area around Gla, which was consequently a true island, as the site would have been in the Mycenaean period prior to the drainage project. The method used in the 19th century drainage project reflected that of the second millennium B.C.: A system of dykes was constructed to hold back the waters running into the basin from the surrounding rivers, while the drainage outlets carried the lake water underground to empty into the sea.

The Underground Cistern at Mycenae

In the third and final building phase at Mycenae in the late 13th century, the fortification walls were extended to protect the water supply for the citadel in case of siege. An underground cistern collected water from the Perseia Spring near the Lion Gate, conveyed by an underground conduit consisting of clay pipes. The problem of bringing this conduit inside the fortification wall, where it would be accessible only from within the citadel was solved by the Mycenaean engineers in what is considered to be “one of the most impressive technical achievements of the Mycenaeans” (Iakovidis, 1983), “an outstanding example of [their] architectural ingenuity and building skill” (Scoufopoulos, 1971). An underground cistern was constructed about 18 m below ground level and a roofed staircase was built leading down to it, protected by the new extension of the wall. The staircase is in three sections, with changes of direction and intervening landings (Fig. 2). The first section has a corbelled ceiling, as does the remainder in part, alternating with a saddle roof. In total the staircase extends to about 40 m and includes 83 steps (Scoufopoulos, 1971). The well-shaft itself is 3.50 m deep and the level of the water it held fluctuated with the seasons and the supply from the spring. The well-shaft and the lower courses are lined with two layers of stucco for waterproofing. A row of stones acted as a filter at the point where the conduit emptied into the cistern (for fuller description, with references, see Scoufopoulos, 1971; Iakovidis, 1983).

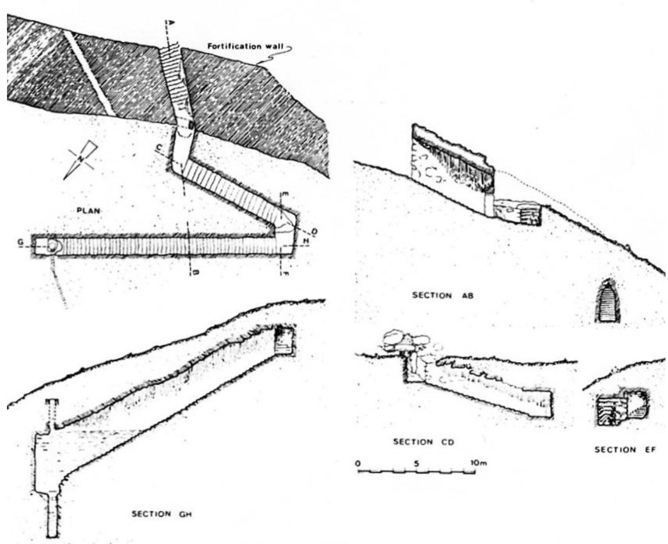

Figure 2 Underground cistern at Mycenae (Iakovidis, 1983).

The Subterranean Galleries of Tiryns

Paralleling that at Mycenae, a third and final building phase was undertaken at Tiryns toward the end of the 13th century, which doubled the total area enclosed within the fortification walls, massively increased the amount of available storage space, and, once again, guaranteed the water supply in case of siege. During the course of restoration work in 1962, two openings were found in the north-west wall, which led to two subterranean galleries

(Fig. 3). These were parallel to each other and extended about 20 m to the west, converging from 9 m apart inside the wall to 2.60 m apart just beyond the wall. The passageways were well built of large Cyclopean blocks and, like the descent to the underground cistern at Mycenae, they were roofed with corbel vaults, and had steps cut into the rock, along with (presumably) wooden steps, which were not preserved. Scoufopoulos (1971) has recorded that "the thick wall of the southern entrance had a cross-wall forming two rooms beyond it [which] may have served as small guard-rooms protecting the entrance", and the north entrance has what was apparently a small retaining wall, below which "ran a section of an elaborate drainage system which passed diagonally across the reservoir entrance and kept that area free and clear of water running from the higher area in the center of the Lower Citadel". Water from the surrounding hills collected in the area west of the citadel, where there was a spring with water seeping through the rock, and the galleries drew upon this supply, functioning as cisterns. As Iakovidis (1983) observes of their state on discovery in 1962, even "32 centuries after they were constructed, there was enough water at the bottom of them to leave no doubt whatsoever as to their original purpose".

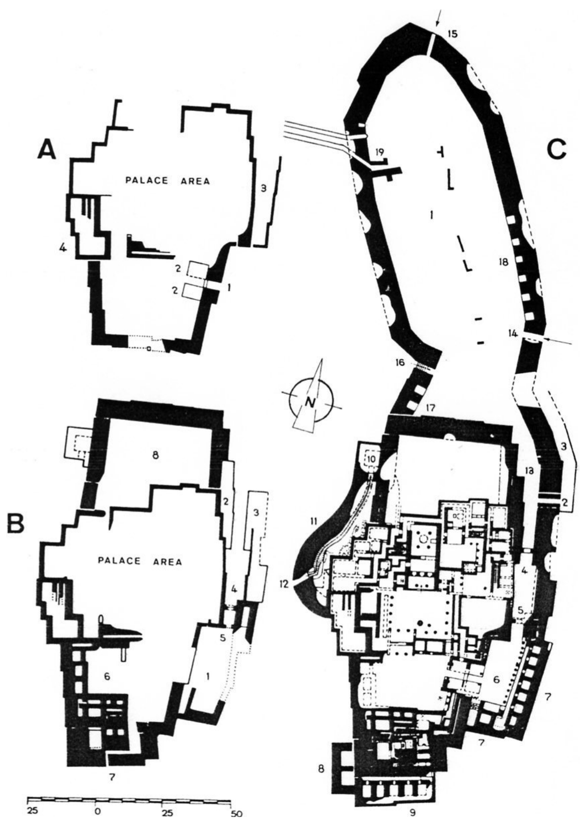

Figure 3 Tiryns Citadel (Iakovidis, 1983).

The North Fountain at Athens

A large cleft in the rock on the north side of the Acropolis functioned as a natural reservoir, which was accessible only from the summit of the hill. The Mycenaean engineers dug into this cleft, which varies in width from 1-3 m, to a depth of 34.50 m and constructed an underground fountain, 4 m in diameter, reached by eight flights of stairs (Fig. 4). A settling-pit in the middle of the reservoir acted as a filter to collect mud and other impurities. Iakovidis reports that “even in summer the water level was high enough for it to be drawn, by means of a bucket tied to rope, from the bottom step of the staircase” (Iakovidis, 1983). The descent opens underneath the fortification wall and is thought to have consisted of a corbelled gallery of the sort found also in the access passageways to the secured water supply at Mycenae and Tiryns. The first two flights of stairs ended at a “natural opening in the cleft which leads outside, to the cave of Aglauros” (but cf. Dontas 1983 on the location of the Aglaurion). According to Broneer (1939), the fountain was in use for only about a quarter century, when presumably the threat that led to the securing of an enclosed water supply, along with strengthening of the fortifications in the latter half of the 13th century, was no longer felt to require such precautions. Athens is the only major Mycenaean citadel which did not suffer destruction at the end of the Bronze Age, and the construction and subsequent abandonment of the North Fountain might be thought to indicate a concern for increased security at the time of widespread destruction elsewhere, which in the end was not required for the defence of the Acropolis.

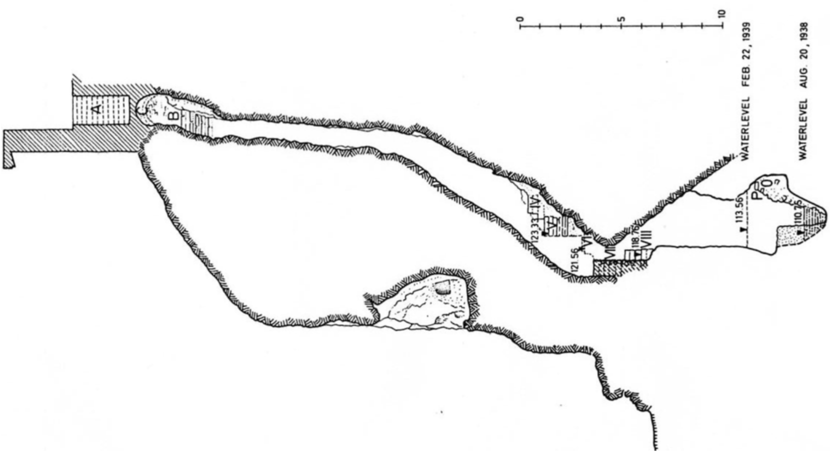

Figure 4 Athens: North Fountain, vertical section (Iakovidis, 1983).

The Underground Water Supply System at Troy

During the recent excavations at Troy, led by the late Manfred Korfmann, a particularly exciting discovery was made in the 1997 and 1998 seasons. In the lower town a deep cave was found, cut into the hill, with (as described by Latacz, 2004) “one broad main arm 13 m long and three narrow channels branching off it, one of them over 100 m long” (Fig. 5). This was originally a small subterranean reservoir, built perhaps as early as the beginning of the third millennium B.C.; even today up to 1,400 L/d still flow through this system. Most remarkably, in a 13th century treaty between the Great King of the Hittites and Alakšandu of Wilusa (Troy), among the gods of Wilusa invoked to guarantee the treaty is included the ‘Underground Watercourse of the Land of Wilusa’, evidently referring to this very installation. The plan of this subterranean system, with extended arms branching off to sources from which water is brought via underground conduits to a central reservoir may be a precursor of the Persian *qanat* sytem, known from the first millennium B.C.

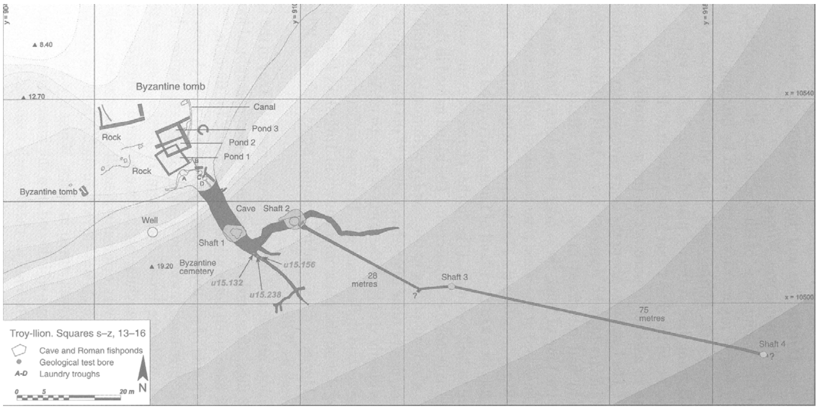

Figure 5 The water supply system uncovered in Wilusa/Troy in 1997 (Latacz, 2004).

The Persian Qanats

It is reported that in 714 B.C. Sargon II of Assyria discovered in the kingdom of Urartu, just north of the Zagros Mountains, a system of underground conduits that had been constructed to channel snowmelt. He is said to have admired and imitated these irrigation channels and two centuries later, Cyrus the Great had this type of system used throughout his empire. Eventually the system was expanded to cover 250,000 square miles on the Iranian plateau alone, producing ten million gallons of water a minute. The French geologist Henri Goblot regarded it as “one of the greatest civil engineering projects in the history of the world” (Khansari *et al.*, 1998). The system is still in use today, although its use is increasingly diminishing due to the drop in the level of the water table caused by extensive construction of dams and wells.

These underground channels, or *qanats*, while simple in concept, are extremely labour-intensive, both to build and to maintain. As shown in the diagrams (Figs. 6 and 7), a master shaft is sunk to the water source, typically at the base of mountains to tap the snow-fed subterranean water. A tunnel then runs on an incline from the source to the destination, which may be many miles away; where necessary the tunnel is lined with ceramic rings.

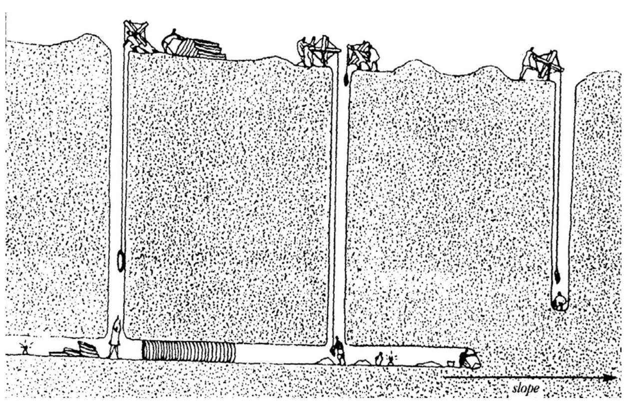

Figure 6 Method used to construct a qanat and its access shafts (Khansari *et al.*, 1998).

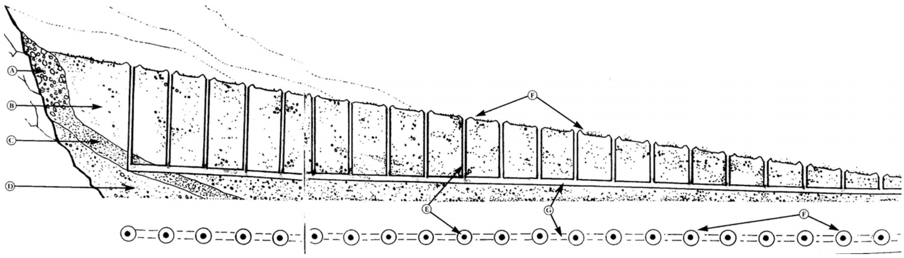

Figure 7 Cross section of a qanat (Khansari *et al.*, 1998).

At intervals of from 15 to 60 feet additional shafts are sunk to allow for removal of the excavated dirt and the provision of air for the workers; on completion these shafts provide access for ongoing maintenance work. As Khansari *et al.* (1998) point out, the Iranian desert is “laced with lines of these shafts”, which look from the air like giant molehills (Fig. 8). From its original homeland in Persia, the technique of qanat construction spread to Oman and Egypt, and subsequently to Europe and other parts of Africa and eventually to the Americas and other parts of Asia (Fig. 9).

Figure 8 Aerial view of a qanat near Yazd (Khansari *et al.*, 1998).

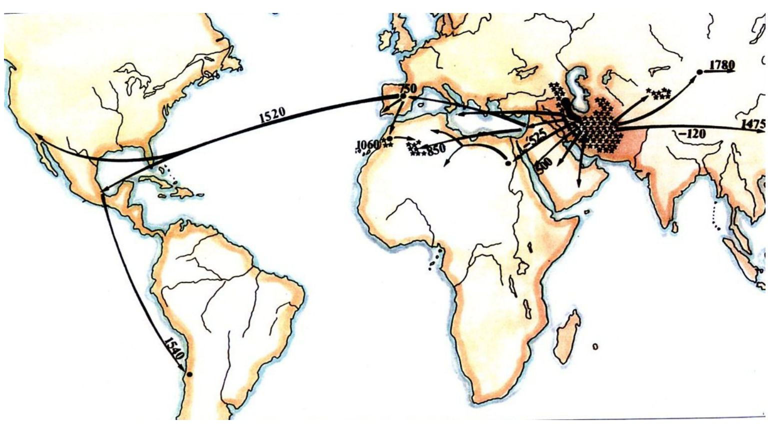

Figure 9 Spread of the technique of the qanat system (Khansari *et al.*, 1998).

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Traditional Water Management and Sustainability: Toward an Integrated Dynamic Ecosystem Model

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Abstract: This contribution provides a conceptual model for the sustainable development of traditional water management systems. The model is based on the dynamic interaction of the ecological and cultural variables that influence water supply and demand.

Keywords Traditional water management, sustainable development, dynamic modeling, ecosystems, water resources.

Introduction

For millennia, traditional water harvesting systems in arid lands provided a means of sustaining human populations in areas that are otherwise barren. Such systems reveal a great deal of ingenuity in maximizing water capture from a variety of water sources ranging from air humidity to torrential flow in wadis. These traditional water systems, evolving over many generations under different historical settings were sustainable and resilient because they worked within the bounds of ecological variability and in the context of a social and ideological system that minimized long-term disruption of fragile desert ecosystems. Today, the introduction of pumping and deep well water extraction have led to the overexploitation of groundwater resources and a dramatic drop the level of groundwater tables. In addition, changes in the ecology of catchment areas due to landscape degradation as a result of intense human activities, and in some areas overgrazing has affected the hydrological regimes, desertification, and potential impact of climate change.

In addition, traditional water harvesting and management systems are rapidly vanishing due to market economics and shift of economic activities, emigration in response to falling revenues from traditional subsistence systems and developing opportunities for wage earnings elsewhere. This has led to a dramatic disappearance of experts and expert knowledge. The combination of socioeconomic changes and technological developments are thus rapidly undermining the sustainability of human populations in arid and semiarid regions. Short-term benefits requiring high input from non-renewable energy sources, capital financial resources, advanced technology, and extra-local managerial control cannot be sustained indefinitely with the probable consequences of creating uninhabitable areas in many parts of the world.

Sustainability

Sustainability is used here to refer to the long-term maintenance of a viable water management system which depends on eliminating activities that harm the ecological integrity of the region and the catchment area and the social fabric that allows the system to function, without compromising the historical and cultural values of the built environment. Such a system, however, cannot be sustained without economic solvency. Long-term continuity (sustainability) of the system also depends on the ability of the system to recover from occasional perturbations (resilience). A resilient system is robust and has built-in mechanisms to override or militate against occasional setbacks. A great deal of resilience depends on the ability to monitor and anticipate harmful consequences of certain actions (e.g. lowering water table) or otherwise unforeseen events (e.g., climate change or new marketing opportunities), the ability to innovate to eliminate harmful developments and improve performance (e.g., use of solar energy, change crops, water recycling).

The Water Management System

This consists of the following interactive components (Fig.1): (a) Water harvesting; (b) water transport and distribution; (c) storage; (d) water treatment; (e) water lifting; (f) water utilization; and (g) elimination and drainage.

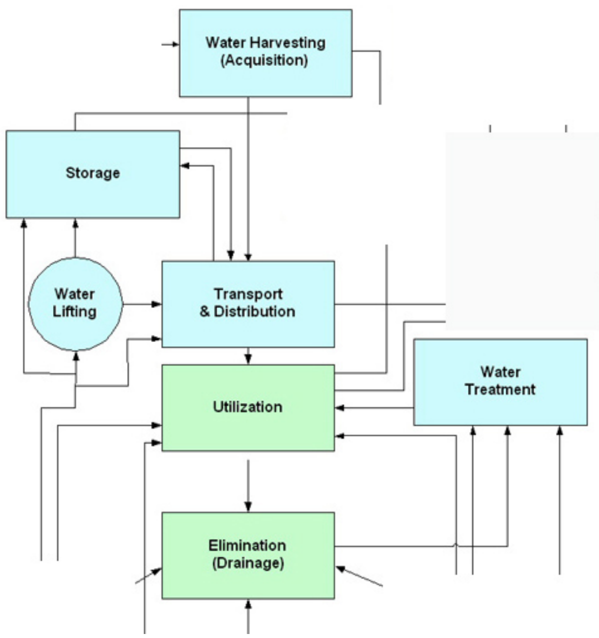

Figure 1 Components of water management systems: a segment of the graphic model shown on Figure 4.

Water harvesting

Traditional water harvesting systems in North African and Southwest Asia include some of the oldest sustainable methods of water harvesting in arid lands. An understanding of these systems, which have lasted for millennia, is crucial for current efforts to combat desertification and rehabilitate degraded desert habitats at a time when climate change is compounding the threat to many areas in North Africa and Southwest Asia that are extremely vulnerable to shifts in climatic conditions.

ICARDA issued a monograph by Oweis *et al.* (2004), with case studies from Tunisia, Jordan, Morocco, Syria, Libya, Iraq, Egypt, and Yemen. In an introductory chapter Oweis *et al.* (2001) present a classification system. Another classification was suggested by Prinz (1996; 2000). From these classifications, the following categories of water harvesting may be recognized:

(a) Rainwater Harvesting. Rainwater harvesting techniques collect the rainfall before it enters the soil, i.e., as surface runoff. The collection and concentration of rainfall and its use for the irrigation of crops, pastures, trees, for livestock consumption and household purposes is called rainwater harvesting.

(b) Runoff (micorcatchmen) Water Harvesting**.** This group of techniques depends on the harvesting of surface runoff water from a small catchment area ranging from a few square meters to around 1000 m^2. Runoff refers to water movement from rainfall downslope.

(c) Wadi Floodwater Harvesting. This system depends on harvesting water from wadis. Water flow in the wadis is seasonal, erratic, and occasionally torrential. Several methods are used to harvest water from the wadi which depends on slowing water flow during peak discharge to allow water infiltration and divert water flow to fields or cisterns.

(d) Groundwater Harvesting. These methods depend on collecting water from grounwater sources such as springs, seepage water, or even dripping water in a cave.

Transport and Distribution of water resources

This involves making water available where it is needed when it is needed and allocating water to different users in a community for various purposes.

Water Lifting

This refers to the use of devices to lift water from one level to another. This may involve the use of pulleys, buckets, baskets, the shaduf, the saqqyia, the Archimedean screw, or water pumps. It may used at any stage of water management.

Water Storage

This involves the storage of water for use at any stage in the water management system. They range from large reservoirs in wadis or upper reaches of catchment areas, small cisterns to harvest and store water runoff, to storage jars at home to store water for domestic uses.

Utilization

This refers to the different uses of water in a community such as drinking, ablution, agriculture, domestic use, industrial use, recreational use.

Water treatment

This refers to the treatment of water to render it suitable for use, re-use or discharge into the environment. Depending on the objectives of water treatment, the process involves the removal by mechanical and chemical methods of pollutants, solid impurities, bacteria, algae, fungi, and germs. The treatment can range from simple ponds to filter solid particles to chemical treatment to kill germs (purification) and range in scale from residential to industrial.

Elimination

This refers to the removal of water before or after use from area where the presence of water is not desirable. Elimination of water for reclamation by draining land, removal of waste water from homes and factories, as well as removal of water after irrigation from fields are different aspects of this process. Drainage of water from agricultural land after irrigation is essential for growing crops, but rise in water table in depressions where drainage water accumulates may lead to the rise of water table and the salinization of soil.

Water Management Parameters

We may classify the parameters that influence traditional water management systems into (a) ecological and (b) cultural.

Ecological parameters

The integrity and viability of water harvesting systems depends on climatic parameters, sources of water, the catchment area from which water is harvested, and the characteristics of the landscape that influence the hydrological processes and the health of the community.

(a) Climate. Mean, seasonal, and monthly rainfall, evaporation, temperature and other climatic parameters related to extreme events, cloud cover, inter-annual variability, and dust storms.
(b) Catchment: area, extent, distance from extraction area, ration of catchment area to extraction area, the impact of historical processes on the parameters that influence the recharge of groundwater and surface runoff and stream flow (e.g., degradation of vegetation cover, droughts and other climatic factors, digging deep wells, other modes of water abstraction, pollution).
(c) Aquifer: area, volume, bedrock, recharges rates, water quality, and potential extraction rates.
(d) Surface hydrology: surface runoff, surface storage, subsurface storage, infiltration, evaporation, channeled runoff, rivers, lakes, springs.
(e) Landscape:
    (i) Geology, geomorphology and pedology: Relief, topography, superficial deposits, bedrock, geological structure, karst features, soils (soil processes, erosion, weathering, transportation).
    (ii) Natural vegetation and wildlife: types, spatial distribution, pattern, density, condition, resilience (succession, resilience seasonality, evapotranspiration, soil moisture, frost, soil conditions).
    (iii) Cultural landscape: farmland, pastures, urban areas, industry, recreational activities (farming, pastoralism, urbanization, industry, recreation, population growth, migration, economic conditions, belief systems, knowledge systems).

Cultural parameters

Culture involves norms, paradigms, and schemata of thinking, communicating, and acting in the world. Culture is transmitted from one generation to the next in a number of related societies through oral, written, performative and other media of communication and socialization and enculturation. Material manifestations of social activities reinforce and substantiate cultural traditions. In everyday life, cultural norms, ways of thinking, and world views are preserved, modified, or eliminated by individuals situated within communities. Innovations as well as traditional norms are preserved, modified or eliminated through social processes of negotiation, selection, and rejection. The survival of traditional water management systems depends ultimately on how traditional systems are perceived by the current generation of users and other stake holders. Individuals within societies have always had access to information from other individuals within the same or different cultural domain. At the moment, the interests of different stake holders are based on ideological considerations, social factors, and economic parameters. There is no simple mathematical way of judging the magnitude of influence of any of these variables. However, the weakness and strength of certain parameters may be gauged on the basis of ethnographic observations, current practices, and interviews:

(a) Ideological and social parameters, such as (Fig.2):
  (i) Ideology, ethics, rights and legal issues;
  (ii) Motivation, risk-taking attitudes, psychological factors, and expectations;
  (iii) Social organization;
  (iv) Governance and policies;
  (v) Population: Size, distribution, density, growth rates, composition, emigration, labor force, dependency ratio);
  (vi) Knowledge-base and education;
  (vii) Communication: modes and efficiency;
  (viii) Consumption patterns; and
  (ix) Historical and architectural values. This refers both to tangible and intangible aspects of traditional water systems, e.g., architecture, tools, songs, stories, spatial layout, time-keeping. The values include appreciation of aesthetics of landscape, waterworks or tools, religious values and symbolic significance, as well as social institutions and traditions cemented by certain water management strategies.

Figure 2 The ideological and social parameters.

(b) Subsistence and economics (Fig. 3). This mainly refers to the balance of income to expenses. The viability of the system is based on a long-term continuity in producing enough income to meet the expenses of maintaining the system and providing enough income to meet the needs of the community, and at best surplus resources to invest in improvements of the systems and or living conditions, including education and capacity building. Capital may bee needed at times to restore the system or for overhauling the economic structure. This may have to be secured through government or international subsidies, loans, and grants. It may involve the private sector and new economic practices (e.g., eco-tourism). Economic development in a sustainable scenario must not be at the expense of the integrity and viability of the social and ecological components of the system. It should enhance rather than destroy or undermine the historical/architectural heritage of the region. Some of the factors involved here are subsistence activities, craft industries, ownership, trade and exchanges, financial institutions, capital, pricing, and patterns of economic transactions, transport, and labor force.

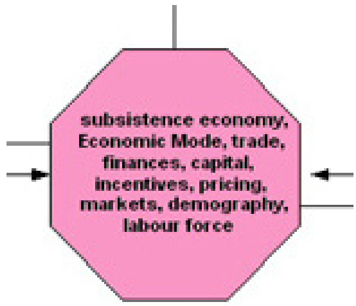

Figure 3 Subsistence and economics.

(c) Energy and technology. Some of the parameters involved here are:
 (i) Type of energy: human, draft animals, fossil fuels, electricity, etc.;
 (ii) Rates of consumption and availability;
 (iii) Environmental impact;
 (iv) Water-lifting devices;
 (v) Water-transport and storage systems;
 (vi) Water treatment, recycling and purification systems;
 (vii) Tools;
 (viii) Materials;
 (ix) Techniques and skills;
 (x) Training; and
 (xi) Innovations and development.

The Dynamics of Water Management Systems and Sustainability

The water management system is bound with ecological and cultural parameters in a systematic way (Fig. 4); i.e., a change in one parameter often leads to a change in one or more other factors sometimes with a chain reaction in other factors. Some factors are more critical than others. A change in one of those factors can lead to dramatic effects and a major change in the characteristics of the water system. Some variables may be linked with feed-back mechanisms. Water management systems are not goal-seeking. Their persistence depends on how fluctuations or changes in the input from various factors do not lead to pronounced changes in the structure of the relationships which can lead to an alteration of the state of the system.

As an example of reading and working with the graphic model (Fig. 4). The utilization of water in a system, for example, is influence by the transport and distribution of water, which in turn depends on storage, water harvesting, climate, and local relief in the manner shown by the arrows. Utilization is also a function of technology, economy, and ideology, which are also interrelated. Attention to factors that directly influence utilization or transport of water, should not be coupled with an understand of more remote factors such as climate change, legislation, economic incentives from government, initiatives by NGOs, and the factors that motivate local users.

Climate is one of the most critical factors because it influences rainfall and evaporation which, in turn, influence vegetation and surface as well as groundwater availability and hence geomorphic processes. Climatic fluctuations especially in arid and semiarid regions are frequent and severe. Inter-annual variability in rainfall is very high and episodic changes are common on a multi-decadal scale, thus influencing the stability of water systems within the life-span of a few generations. Accordingly, water management systems in arid regions must cope with frequent annual and episodic variations if they are to remain viable. A transition from semiarid to arid climate with a reduction in rainfall may lead to a reduction in vegetation cover, increase in sand storms, and erosion. It may also lead to a lowering of the water table.

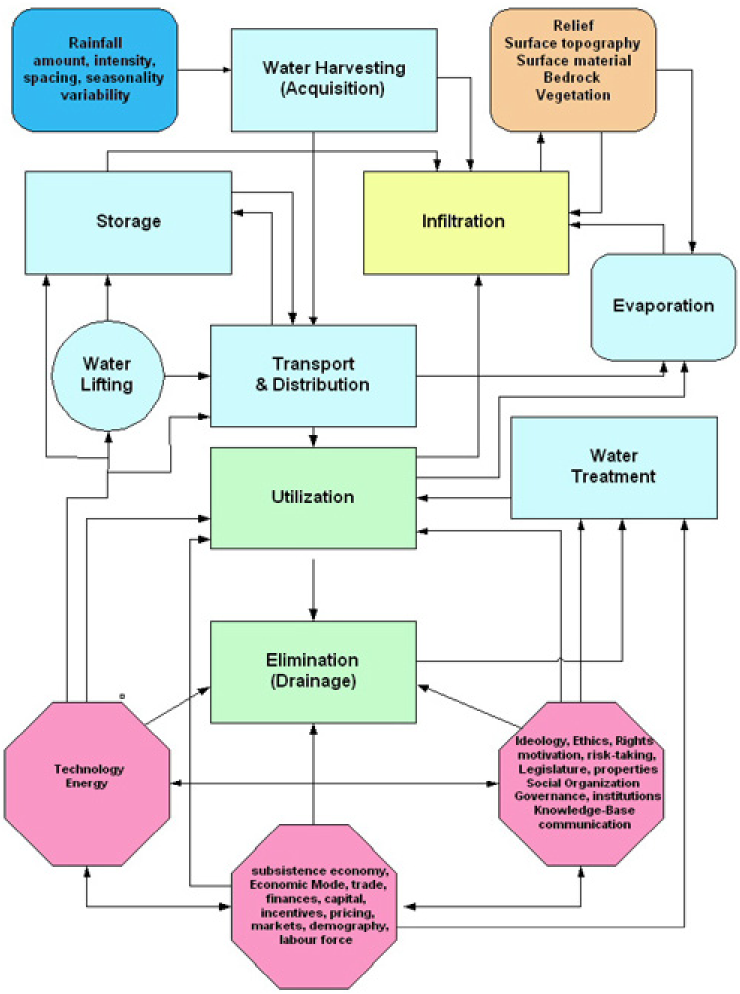

Figure 4 A graphic model showing the structure of water management systems and their interrelationships with ecological and cultural parameters.

Water systems in arid lands are extremely dynamic. For example, during the passage of storm pulse, the roots of olive and palm trees bind the narrow floodplain sediments, as water scours channels between such islands. On the levees of recently deposited flood loam, barley may be cultivated. The construction of cross wadi walls promotes sedimentation of fine grained deposits, which holds moisture, increases seed catch, and shrub growth on their upstream side. Downstream from walls, waterfalls may develop promoting the formation of deep erosional channels. The alluvial deposits vegetation on the wadi floor is frequently reworked by wind, rain, and flood storms. Grazing animals reduce the vegetation cover thus enhancing erosion and the reworking of surface sediments.

Human activities intervene to enhance the availability of water through storage, water transport, water lifting, and soil treatment. Water conservation and protection from wind, severe floods, and droughts are often practiced. However, the key factor in sustaining traditional water management systems in arid lands depends first of all on placing a premium on such traditional methods which have been shown to be successful in the fragile and harsh environment of the desert. However, such traditional systems may not be valued just for the economic value, but also for their historical and cultural significance. The deserts are places for reflection and contemplation. They provide a place that counteracts the noise of cities and the turmoil of modern living. Traditional systems are a testimony to human ingenuity, social cooperation, and frugality. They may require high inputs of labor but they do not pollute or poison the environment, and they are crucial for understanding the complex web of ecological relationships and how communities work with nature creating an ecodesign that capitalizes on a deep knowledge of the effects of human actions in a fickle landscape. It is the kind of engineering that lacks the arrogance that comes with heavy machinery and fossil fuels that have been the ruin of many landscapes. Sadly, the temptation of consumerism, the attraction of urban places, and the trap of modern living has invaded the desert. It is a threat that the desert has never known before; a threat that may change the desert from its splendid serenity into a degraded version of urban ghettos.

Conclusions

Sustainable development of traditional water systems requires a clear conceptual design of the dynamic interaction of ecological and cultural variables. Among crucial variables are the social components that govern the utilization and extraction of water resources. Understanding of the mechanism by which social agents operate within different cultural spheres with different agendas is essential for mobilizing resources and implementation of plans of action.

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Ancient Water Catchment Techniques for Proper Management of Mediterranean Ecosystems

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Abstract: Traditional knowledge are the ancient techniques and practices of a territory passed on through the generations and used for water harvesting, soil management, use and protection of natural areas, rural architecture, and for organising urban centres. They are the historical knowledge of humanity that allowed building architecture and landscapes with a universal value protected by UNESCO in the category of cultural landscapes. An appropriate use of natural resources, such as water, soil, and energy, is made possible by using traditional knowledge that establishes the harmony of architecture with the environment, the symbiosis of the techniques of organisation of space with the traditions, the social habits, the spiritual values and the fusion between practical aspects and beauty. Today, traditional knowledge is in danger and its disappearance would not only cause the loss of people's capability to keep and pass on the artistic and natural heritage, but also of an extraordinary source of knowledge and cultural diversity from which appropriate innovative solutions can be derived today and in the future. UNESCO launched a global programme for an inventory assigned to IPOGEA -Research Centre on Traditional and Local Knowledge. The project gathers and protects historical knowledge and promotes and certifies innovative practices based on the modern re-proposal of tradition as well. The main targets are the firms, the natural areas, and the historical centres which will be assigned quality trademarks and acknowledgements of international excellence in production or use of good practices and innovative solutions. Each technology, proposition and experience achieved will provide a spin-off on an international scale and each good practice will contribute to safeguarding the whole planet.

Keywords Cultural landscape; ecosystems management; traditional knowledge; water harvesting.

Water Harvesting Techniques in the Mediterranean Area

Three sides of the Mediterranean Basin are connected with areas where humankind had to cope with dry land areas; its isles are completely lacking in underground or ground water sources, where complex civilizations developed and even in its more northern areas it undergoes a changing and catastrophic environment. Therefore, most of traditional techniques relative to the water organization for water harvesting, conservation and diversion are widespread as well as the systems of slope protection and the creation of soil that have different characteristics according to the environment. In southern Italy and in Spain there are also systems like, for example, underground drainage tunnels that are common in oasis towns in North Africa and in the Eastern World that have been handed down by Islamic civilization or by more ancient civilizations.

The several water saving techniques used by the Nabatean agriculture, the condensation caves and pits, the stone arrangement for rainfall harvesting, the underground dams are not only widespread in the Negev desert (Evenari, 1982) but also in the whole Mediterranean area. In Petra (Jordan) they present their urban ecosystem synthesis (Zaydine, 1991) but they can be also found in Tunisia, in Libya and in southern Italy and in particular in the isles thanks to the influence of prehistoric or widespread traditions imported by current exchanges. The techniques of Andalusia agriculture in Spain are widely represented because of the influence of the Islamic civilization. In the isle of Ibiza there is a similar irrigation practice called feixes designed according to an ingenious hydraulic organization (Laurenao, 2005). The fields are divided into long and narrow rectangular plots by means of a network of canals having the twofold function of draining the water in excess, thus collecting and saving it and of irrigating the fields during drought seasons. In fact, if these works were not carried out it would be a swampy area in some seasons and arid or flooded by seawater in other seasons. In this way, it is possible to carry out a self-regulating process which allows the practice of intensive cultivations of both marshlands and arid lands. Open canals are about 1m deep and flow at a lower level than the plots of land thus keeping them dry. The land excavated for building the canals is used to raise the level of the cultivated land. During hot seasons when the land undergoes high evaporation, the plots absorb the necessary quantity of moisture directly from the subsoil and from the walls of the canals by osmosis and capillarity. The process is then fostered by further underground canalisations excavated in the plots. These underground canals are built with porous stones and pine-tree branches covered with a layer of Posidonia algae collected along the coast. This method ensures the good running water pipings and at the same time it allows to obtain a certain level of permeability in order to give the land the quantity of water necessary to keep it humid. Therefore, the irrigation is carried out from the subsoil directly to the plant roots. This technique enables to save water that would be lost because of evaporation by using open irrigation methods.

Traditional techniques can be found not only on southern Mediterranean shores and in southern areas of Europe but also in northern France and even in the Swiss mountains, where specific geomorphologic conditions cause aridity. This situation depends on the position of the mountain slopes compared with the direction of the dominant winds, which release all their moisture as they rise up the sides. Once they have reached the top, they lash against the slopes below with high pressure dry wind currents that dissolve the clouds. This is the phenomenon of the foothill deserts that in Switzerland creates dry, arid conditions in the valleys. In the region of Valais and the province of Sion on the contrary there are green pastures and plentiful vineyards. The landscape is not the result of natural conditions, but rather of a skilful use of a traditional local technique called bisse. This consists of a series of channels made of wood or carved out of the rock, which extend up into the mountains as far as the sources of the brooks and the perennial glaciers, running for many kilometres. They slope very gently down the steep edges, remaining at a high altitude to convey the water along above the natural course of the bed river and use the force of gravity alone to irrigate distant valleys. Otherwise, they would completely lack water. This system is supported by social cohesion, by water boards and companies similar to those that manage Andalusian agriculture or the Saharan drainage tunnels. Just as in northern Africa and in Spain, this system generates a particular landscape where the location of the settlements is determined by the layout and the outlets of the bisses.

The most widespread system that can be defined as one of the typical features of the Mediterranean area is the terracing which can be found from the Middle East to Greece and from Italy to Portugal. Terracing associated with olive and wine growing actually contributes to shaping the landscape. The slopes and hills in the northern Mediterranean have stood up to erosion over time and their present shape is the result of that long-lasting titanic action.

Along with the dry stone walls, the stone barrows (specchie) and the tholos constructions (trulli), terracing is typical of the Apulian region in the south of Italy. Here, the terraced slopes of Amalfi and in the north of Italy, the Cinque Terre in Liguria, create fascinating and traditional urban ecosystems. In Sardinia and in the isle of Ibiza there are systems of fields surrounded by dry stone walls called tanka, which is a term deriving from an ancient Mediterranean toponym.

The majority of the ancient Mediterranean sites follow the layout of the terracing and the water systems network. These sites adopt the techniques of rainfall harvesting, protected vegetable gardens, the use of organic waste for the creation of humus, the methods of passive architecture and of climate control for food storage and for energy saving as well as the practices of recycling productive and food residues. The aesthetic qualities, the beauty of natural materials, the comfort of architecture and spaces, and the organic relationship with the landscape that these ancient towns boast are especially due to the intrinsic qualities of traditional techniques and to the search for symbiosis and harmony intrinsic to local knowledge. The survival of the poor archaic societies of the whole Mediterranean areas depends on the accurate and economical management of natural resources. The close link between traditional farming techniques and settlements make the traditional historic centres a fundamental element for environmental safeguard. In the Mediterranean area, which is characterized by intensive historical settlements, each part of the environment is not only the result of natural process, but rather represents a cultural landscape where historical centres are the crystallization of knowledge appropriate to the correct environmental management and maintenance (Laurenao, 1998).

The Case Study of Matera, Southern Italy

The Sassi of Matera represents a typical example of traditional use of water resources in the Mediterranean. The local knowledge system adopted is found in a wide set of situations ranging from the troglodyte dwellings of the Loire valley, in France, to Petra, in Jordan, to the towns carved out of the calcareous rock in Cappadocia, in Turkey, to the underground settlements of Matmata in Tunisia, to the villages along the canyons in Algeria and in Morocco up to Andalusia and Nabatean water farming techniques. The towns are built along the borders of deep valleys, the Gravine, that have a small water carrying capacity or do not have any. The settlements are not placed on the bottom of the canyon like one could expect if it were to provide water, but on the upper part, along the plateau and its steep slopes. In fact, the resources of the maze-like troglodyte dwellings of the Sassi of Matera and of the other stone towns of the Gravine are the rain and the dew that are harvested in drains and in cave-dwellings (Laureano, 1997). The time stratification of traditional knowledge according to the classification adopted for social groupings, hunter-gatherers, farmer-breeders, agropastoralists shows the progressive determination of a complex system of knowledge and appropriate use of resources until the creation of stone oasis and of the urban ecosystem.

Hunter-gatherers

Human beings have settled the area from the Palaeolithic onwards, as evidenced by a number of stone findings in the Grotta dei Pipistrelli (The Cave of Bats) and by an intact skeleton of a hominoid found in a karst pit near Altamura which has been dated at about 250,000 years old. The Grotta dei Pipistrelli is a natural formation but its structure is made up of a passageway, the entrance of which gives out onto the slope and the other end of which emerges through a karst sink hole onto the plain and is a model for later artificial constructions.

Farmer-breeders

During the Neolithic age, a number of techniques were developed for digging in the calcareous highland and for harvesting water. Bell-shaped cisterns, huts and small canals were enclosed in deep ditches, forming circles and ellipses and were therefore called entrenched villages (Tiné, 1967; 1983). It is nonetheless likely that the ditches were not used for defensive purposes, but rather they were used in Neolithic practices of animal husbandry and farming. An analysis of aerial photographs showing where vegetation grew more thickly also show drainage systems used for water harvesting or humus collection, and the maze-like systems called corral that were necessary for agricultural and animal grazing. The recent excavation of the Neolithic complex of Casale del Dolce near Anagni underpins this hypothesis.

Agro-pastoralists

The Age of Metals provided new tools which made it easier to excavate caves and pits. As the environment deteriorated, these caves became ever more attractive as human dwellings. In fact, the progressive loss of the vegetation cover left the surface villages without shelter, left the land unprotected, thus causing a shortage of wood for building and heating purposes. The climate ranged from freezing winters to broiling summers. The absolute lack in water in the rivers or on the slope made it necessary to harvest meteoric water in underground cisterns. An increasing popular form of dwelling was the pit courtyard which had been developed during the Neolithic age subsequent to the development of excavation techniques where tunnels radiated out from a central shaft.

This dwelling model also arose in remote areas such as Matmata, in Tunisia and on the dry plains of China and was the origin of the courtyard dwelling used by the Sumerians, both in antiquity and during the Islamic era. An excavated house near the Neolithic site of Murgia Timone, across from the Sassi of Matera, proves just how effective this type of construction is. The house is rectangular in shape like the megaron of Crete and is divided into three spaces made up of two open rooms and a third underground room. The courtyard is used as a water reservoir, it is an open and sunny space, which is protected by its walls and which can be used for the preparation of the food. At the opposite end is a garden that is used for waste and as a compost heap, which has been carved out of the rock. The garden is absolutely necessary given the poor soil and the need to protect plants. The caves keep a constant temperature throughout the whole year and are ideal shelters for men and animals, for the storage of grains and water conservation.

It is interesting to remark that after the structure was discovered and freed of sediments, the underground part of the cistern soon filled up with water, even though there had been no rainfall. Therefore, the system started working again using capillary infiltration and condensation. Even the barrows of the Bronze Age took their shape from water harvesting practices, both functionally and ritually. The barrows consisted of a double circle through which ran a corridor with a room excavated down the centre. What is interesting to notice is that these structures were introduced along the excavation of the archaic Neolithic walls, which had been abandoned when the buildings were constructed but which can still be used as moisture diversion systems. What has been found in Matera is quite similar to prehistoric structures made up of barrows and underground rooms in the Sahara desert (Laurenao, 1989). Actually, these are solar tombs made up of concentric circles around the barrow. They could also be ancient methods for the collection of moisture and dew and could belong to cults devoted to the practice of water harvesting (Pirenne, 1977; 1990).

Similar interpretations could be made of the dry stone structures spread throughout the dry lands of Apulia where stone mounds harvest the night dew thus replenishing the soil with moisture (Nebbia, 1961). Indeed, the roots of centuries-old olive trees all point to the low walls that are a staple of the farmland. The walls, the barrows, the trulli and the mounds of calcareous rock called specchie are all structures of water condensation and conservation (Cantelli, 1994). These structures carry out their tasks during the day and at night. In the broiling sun, the wind carries traces of moisture which seep into the interstices of the stone mounds, whose internal temperature is lower than the outside temperature because it is not exposed to the sun and it has an underground chamber. The decrease in temperature causes the condensation of drops that fall into the cavity. The same water accumulates and provides further moisture and coolness by amplifying the efficiency of the condensation chamber. Overnight, the process is reversed and condensation occurs externally so that dew settles on the surface; the dew slides into the interstices and is harvested in the underground chamber.

Stone oases

By developing the original prehistoric techniques, an adapted habitat system that uses the combination of different water production techniques: catchment, distillation, and condensation are carried out in the Sassi of Matera. During the torrential rainfalls, the terracing and the water collection systems protect the slopes from erosion and gravity pulls the water down towards the cisterns in the caves. During dry spells, the dug out caves suck out the moisture in the air at night: the moisture condenses in the final underground cistern, which is always full even if it is not connected to outside canals or ducts. The result is a multitude of underground storeys topped by long tunnels leading downward underground. Their slope allows the sun's rays to penetrate down to the bottom when heat is most necessary. In winter, the sun's rays are more oblique and can penetrate the underground areas. During the warm season, when the sun is at its zenith, it shines only on the entrance to the underground caves, which thus remain fresh and humid.

We know up to ten storeys of caves one atop the other, with dozens of bell-shaped cisterns all connected to each other by means of canals and water filter systems. Like in the Sahara oasis the system of local knowledge enables, in a situation without water resources, to realize good living conditions thanks to the appropriate use of techniques and to their perfect interaction with the environment.

Urban ecosystem

The Medieval monasticism contributed to this archaic texture. The hermitages, the parish churches, the farmhouses that are located in checkpoints of hydraulic works represent the poles of the urban growth process. The two main drainage systems called “grabiglioni” that provide tillable land and humus by sewage collection are surrounded by two urban sections called Sasso Caveoso and Sasso Barisano. In the middle there is the Civita, the fortified acropolis that represents the ancient shelter in case of danger where the Cathedral was built. Along the boundaries of the highland where there are the large cisterns and the ditches, the cave silos for grain storage and the craftsmen's workshops.

The vertical structure of the town allows the use of gravity for water distribution and protects from wind blowing on the plateau. Matera boasts hundreds of rock-hewn churches painted with beautiful Byzantine frescoes or built on the plateau and bearing monumental facades carved out of the tufa according to the architectural style of the period of construction: medieval, classic or baroque. However, the maze of small streets, stairs and underground passageways continues to follow the ancient hydraulic structure. Therefore, it is still possible to understand the urban layout of the Sassi of Matera by starting from the original matrix of the underground spaces, the cisterns and the terraced gardens as well as from that system of traditional knowledge that allowed a concentrated use of resources without depleting them.

Collapse and rebirth

During the 1950's The Sassi of Matera were closed due to their neglected condition, and 20,000 inhabitants were moved to other neighbourhoods. The abandoned houses became property of the state and a wall was erected to prevent them from being occupied. The Sassi of Matera were transformed into a ghost town, the greatest troglodyte centre in the whole of Europe was completely abandoned. The dwellings were neither occupied nor ventilated leading to a rapid degradation. The churches carved from the rock and decorated with beautiful medieval frescoes soon crumbled away as a result of theft and pillage.

In 1986, largely thanks to the motivation of individuals involved in cultural activities, the Italian Government allocated 100 billion liras to restore the Sassi and undertake the work necessary to improve its sanitary conditions and urbanization, and to encourage private individuals to take up residence there. All the state properties were entrusted to the Mayor of Matera, responsible for financing the project. The turning point in the management of the Sassi came about with their inscription in 1993 as an UNESCO World Heritage Site. Matera became a destination for both national and international tourists and the individual requests to return and live in the Sassi multiplied. The Mayor of Matera equipped the Sassi with a network of water systems, drains, gas, electricity and telecommunications whose cables were buried in underground trenches so not to disturb their architectural qualities or landscape. Around 3,000 people now live in the typical cave-homes, half-built, half hallowed out.

The restoration of traditional systems of water collection

The Sassi of Matera illustrates the natural resource management capabilities (water, sun and energy) that were once perfectly employed but are so often neglected today. The international debate on urban development makes this problem current and relevant. It is necessary to maximize the potential of a town at a local level to assure its harmonious and sustainable development. It is for this reason that the Ministry of the Environment chose Matera as an urban rehabilitation model within the framework of the Rio Conference and the United States Convention to Combat Desertification (UNCCD), in its directives and action plans.

The very encouraging experiment in Matera could be adopted in other urban centers such as the inland region of Lucania and the dwelling systems of the Gravine (canyons). Indeed, these sites offer similar architectural and environmental characteristics but have not benefited from similar renovation. Above all, this experiment is an exceptional example for those countries situated on the southern Mediterranean sea. In these countries, the progress of modernization often destroys traditional methods of managing space and threatens the ecological equilibrium of the whole region. Only by demonstrating the success of rich industrialized countries, like Italy, to restore traditional systems can countries that are less industrialized, be persuaded to do the same.

Ancient Water Techniques for a Sustainable Future

Using traditional knowledge does not mean to reapply directly the techniques of the past, but rather to understand the logic of this model of knowledge. It allowed societies, in the past, to manage ecosystems in balance, to carry out outstanding technical, artistic and architectonic work which are universally admired and has always been able to renew and adapt itself. Traditional knowledge is a dynamic system able to incorporate innovation subjected to the test of the long term and thus achieves local and environmental sustainability.

The Traditional Knowledge World Bank promotes traditional knowledge as advanced innovative knowledge appropriate to elaborate a new technological paradigm based on the progressive values of tradition: the capability of enhancing a society's internal resources and managing them at a local level; the versatility and the interpenetration of technical, ethical and aesthetic values; the production not per se but for the long-term benefit of the community. Activities are based on the principle according to which each has to enable another one without leaving behind waste; energy use is based on cycles in constant renewal; the purpose, including economic interest, is to protect the ecosystems, the cultural complexity and diversity and all living beings. The project aims to prefigure a new model of development and a technological dimension connected with historical memory.

Traditional knowledge consists of practical (instrumental) and normative knowledge concerning the ecological, socio-economic and cultural environment. Traditional knowledge originates from people and is transmitted to people by recognizable and experienced actors. It is systemic (inter-sectorial and holistic), experimental (empirical and practical), handed down from generation to generation and culturally enhanced. Such a kind of knowledge supports diversity and enhances and reproduces local resources (UNCCD, 1999a; b; c).

Traditional knowledge is to be considered as part of an extensive system which hands down and accumulates shared knowledge whose proficiency and evolution is appreciable over long and very long periods. The functioning principle of the traditional systems is based on a strong cohesion between society, culture and the economy. Their efficacy depends on the interaction between several factors which should be carefully considered: aesthetic and ethical values complete the interaction between environmental, productive, technological and social aspects. Traditional techniques, therefore, cannot be reduced to a list of mere isolated technical solutions able to solve a specific problem. To catch the full meaning and importance of traditional techniques they must be always highly contextualised, not only into the local environmental situation, but to a precise historical moment and the complex social construction which originated them. The understanding of the logic of traditional techniques' use and of their success in terms of environmental sustainability and efficacy over long periods is fundamental not only to safeguard a vast cultural heritage but as a new paradigm on which the modern re-proposition of traditional techniques must be founded.

As a matter of fact, using traditional knowledge today means to re-interpret the logic as innovative advanced knowledge. Its values allowed societies, in the past, to manage ecosystems in balance, to carry out technical, artistic and architectonic works universally accepted. Traditional knowledge is a dynamic system able to incorporate innovation subjected to the test of the long term and the local and environmental sustainability.

Innovative use of ancient water techniques in agriculture

Prehistoric traditional techniques, which were used to build the Italian agricultural landscape, are today re-proposed in agriculture as the best practices to replenish soils, save water and combat hydrogeological instability and desertification. The technique of the drainage ditches spread in the Apulia district of Daunia 6,000 years ago when Neolithic communities built more than 3,000 villages surrounded by trenches in the shape of a crescent. The ditches met environmental needs by draining water and drying some areas to be tilled during the humid season and by working as drinking troughs for cattle, humus collection and water reserves during dry season. After this practice has been replaced by mechanized agriculture, today these places are suffering terrible inundations in winter and extreme drought in summer. On the Ethiopian highlands, on the slopes of the Rift Valley ridges, there are many villages where multipurpose ditches systems are still used to store and manage water resources, gather sewage and produce fertilizers.

The atmospheric water condensed inside caves or mounds of stones and the dry limestone walls are used by all the ancient societies in arid areas. Today, authentic aerial wells, atmospheric condensers producing water from vapour, are used in the desert. They produce water from atmospheric moisture according to the principles and resources of very ancient techniques. The practice of setting cistern-jars full of water or calcareous masses close to the plants to provide irrigation is today re-proposed with innovative techniques which enable to overcome constraints in ancient systems through modern drop irrigation. These traditional innovative techniques are used, for example, during the processes of reforestation of arid areas, thus allowing each single shrub to be supplied with the quantity of water it needs during the phases of growing as long as the plant will get independent vegetative power. Within the framework of this family of techniques a big company elaborated an enzymatically degradable product called dry water which, set into the soil close to the roots, progressively transforms into the necessary water supply.

The drainage tunnels are underground tunnels spread over arid areas since 3,000 years and which are still working today in the Sahara Desert, in China and in Iran to supply the oases with water resources. They allow absorbing the right quantity of water for the replenishment of the environment itself. This solution could be re-proposed, also in Italy, as an alternative to the excavation of wells which lower the groundwater and deeply perforate the soil, thus causing pollution and the salinisation on the surface. In the Sahara Desert, people are experimenting the use of techniques to relieve the hard excavation work by introducing small machines planned for the purpose. This innovative category includes the whole of mechanical adapted tools which range from mini-tractors for the excavation of lunettes for water harvesting to new machines for sustainable agriculture.

The re-proposition in this field of ancient techniques enables to get important successes to combat erosion and soil degradation. In southern Italy there is successful experimentation with practices such as the grassing and sowing on “hard soil”. The first consists in making the grass grow under the orchards and in the olive groves, thus it forms a protective cover to avoid ploughing which causes erosion. The second consists in sowing wheat over unploughed soils. This technique enables to protect soils, to reduce costs and to have better results than by ploughing. This practice is most advantageous during drought periods because ears of wheat grow less high and need a lesser quantity of water and chemical fertilizers.

Innovative use of ancient water techniques in settlement and architecture

Several innovative techniques coming from tradition are being experimented in urban fields. The building of most of the ancient centres followed the layout of the terracing and the water systems network. As a matter of fact, the rainwater harvesting techniques, the areas with the walled gardens, the use of organic remains for the production of humus, the passive architecture methods and climate control for food conservation and for energy saving and the practices of recycling production and food residues have been integrated and perpetuated in the very structure of the ancient centres. This category includes all innovative techniques in the photovoltaic, sun warming, water catchment, composting, and waste recycling fields. In some advanced contexts e.g. in Tokyo, a number of industries are now proposing by law the roofed-garden technique in new houses where the vegetable covering on the terraces of the modern buildings, which brings to mind the hanging-gardens in Babylonia. This keeps optimal climatic conditions inside the houses, harvests water and becomes an area for entertainment and contemplation. The micro-solutions for city quarters and houses represent a large innovative sector in the waste recycling field. Several mini-compost machines to be placed inside the gardens or in common areas of the quarters have been realized to directly absorb organic waste and supply the gardens with humus. A water compost machine is a device set beneath the toilet bowl, which directly transforms waste into compost. Biomass mini-reactors which transform waste into kitchen gases as well as greater plants for heating the whole house have been also realized. Also small and large-scale solutions for sewage water have been found. In Germany, modern houses have been equipped with a vertical marsh, a device which reproduces the processes of water decantation and filtration still existing naturally in marshlands. The process is reproduced along the wall of the building in glass interspaces where sewage waters seep into, infiltrate and constantly recycle themselves by gravity. In Calcutta, an innovative traditional technique used on a very large scale solved the serious problem of used waters. Sewage waters, traditionally re-used in rice-fields, are today turned into a resource for irrigating and fertilising rice fields by using proper innovative systems of sewage waters filtration and sterilization.

A very large series of products, materials and know-how necessary to high-quality architecture form a further innovative sector. The aesthetic components that we appreciate in ancient towns, the beauty of the natural materials, the comfort of the buildings and spaces, the organic relationship with the landscape are due to the intrinsic qualities of the traditional techniques and to the search for the symbiosis and the harmony embedded in the local practices. In this field, experiences of firms re-proposing market materials and processes derived from tradition, such as lime, natural clay and pozzolana, both for rehabilitation and new constructions are now largely spread.

The competitiveness of the past

Thus, we must speak about an on-going construction of tradition. To guarantee its future does not mean to reduce or inhibit capacities of innovation, though this idea has been undergone over time to critiques and biases and weakened by the lack of communication and exchange of successful experiences as well.

With emigration and the dramatic transfer from traditional habitats into new urban agglomerations, the rapid abandonment of the agricultural sector by large segments of the population and with the superficial suggestion of the absolute superiority of modern technology, the process of conservation and dissemination of knowledge is interrupted and lost. On the contrary, the good welfare conditions of people favour social cohesion, confidence within cultural identity and enable the safeguarding of traditional systems through the guarantee of a high remuneration of the work necessary to maintain them. It explains the apparent paradox of those rich countries which were able to maintain high levels of traditional techniques, and succeeded in paying for the necessary efforts with a great increase in product value. Thus, we can state that tradition is a feature of ‘successful modernity’, capable of getting benefits and values from it. To re-propose tradition by resuming its historical relationship with people's innovative and creative power is decisive to safeguard landscape and realize sustainable futures.

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Water Resources Management in Ancient and Modern Egypt: Can we Learn from the Pharaonic Past?

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Abstract: This paper aims to discuss two fundamental aspects of a country like Egypt, that is on the one hand the often discussed part of the State for the management of the water-resources during the centuries, and on the other hand the application of the principle of the "*future of tradition*", presented by the UNESCO consultant Pietro LAUREANO, that means the use of ancient and medieval methods for solving modern problems of today concerning the water-resources. The example of Egypt is very interesting in this context, as its economy has always been directly connected to the river Nile, the vital artery of the country during the centuries.

Introduction

Examining the story of the historical research concerning water and wastewater management in Ancient Egypt on can observe an interesting analogy between the development of the Modern World and specific studies about the Ancient World. During the first global crisis of energetic resources in the late 60tees and 70tees J. BONNEAU started to study fiscal problems concerning the Nile inundations, K. W. BUTZER described a model of Cultural Ecology concerning the "Early Hydraulic Civilization in Egypt" while E. ENDESFELDER and W. SCHENKEL were discussing the technological problems of water management[1]. The latter indicates in his fundamental work about the "revolution of irrigation" the reflection about the limits of mankind's future as a motivation for his studies[2]. Surely it's not a coincidence that the scientific research paid attention to the water management problem in antiquity exactly in the moment the Western World had to realize the limits of natural resources. It seems that the historical research tried to deal with modern fears, speaking about similar problems in the Ancient World. In 1977 at Nairobi took place the first United Nations Conference about desertification[3] and in the late Seventies ecologists spoke the first time about the problem of the Green- house Effect. At the same time in Europe the first Ecological parties were founded and Greenpeace organized spectacular protest actions against ecological crimes. Between the 1981 and the 1987 the "*Maison de l'Orient*" published four volumes concerning "*L´Homme et l'eau en Méditerranée et au Proche Orient*"[4]. In the Nineties studies like P.

1 Bonneau 1964; Butzer 1976; Endesfelder 1979; Schenkel 1978; Schenkel 1975.
2 Schenkel 1978, p. 14.
3 *United Nations Conference on Desertification* – UNCOD (Nairobi, August-September 1977).
4 The results of the research were published at Lyon in the series *Travaux de la Maison de l´Orient (TMO)*: Metral / Sanlaville 1981; Metral / Metral 1982; Louis 1986; Louis / Metral / Metral 1987. Above all the paper of Faggi 1987 in the IV volume is a very critical and modern contribution, a forerunner for the scientific attitude of the Nineties.

LAUREANO'S "*The Upside Down Pyramid*"[5] dealt with topics concerning ecological catastrophes and in the 1994 the United Nations ratified at Paris the *United Nations Convention of Combat against Desertification* (UNCCD)[6].

The year 2003 was proclaimed "Year of the Water": In September 2003 at Havana, Cuba was organized the Sixth International Conference of the UNCCD (COP 6)[7] and in October 2003 in Luxemburg the "Frontinus Society" held a Conference about the Ancient *qanat* and a possible reuse of this irrigation type in Maroc.

The Water Resources Management in Egypt through the Centuries

Since five millenniums the river Nile with a length of 973 km between Aswan and Cairo and a difference of altitude of only 79 m supplies a natural irrigation caused by the regular inundation cycles due to the rainfalls over the mountains of Abyssinia[8]. Consequently "*the convex floodplan of the Nile is inundated naturally, in response to the predictable rhythm of annual runoff. The floods fill the channel first and then spill out at breaks or low points in levees to fill the lower-lying basins with 0,5 to 2,5 metres of water. After the flood crest has moved on downstream, the water level in the basins begins to fall,* […] *moving back to the channel through openings in the levees*"[9]. The Nile inundations leave organic mineral substances on the agricultural fields causing a fertilizing effect and the flowing away of the water washes away the salt of the soils. The lack of a centralized administration of irrigation in Ancient Egypt caused the institution of a customary right and different kinds of local uses regarding the management of the water resources. After 5 millenniums this model was abandoned with the construction of the Aswan High Dam[10], the first centralized state measure which brought many consequences for the social and economic history of Egypt. Until the introduction of the High Dam the state administration was responsible only for bigger enterprises like the digging of canals and water basins while it was the task of the local rural communities to organize their maintenance and the irrigation by opening and closing of the floodgates at the right moment.

The method of natural irrigation due to the Nile inundation was enough for one harvest a year and the only possibility to increase the number of harvests was to apply a system of artificial "basin irrigation" with or without levering devices[11]. The inundation water flew over the banks of the Nile and created mud hills in which the farmers dug dikes, floodgates, ditches and canals to be able to distribute the water according to their needs. The first

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5 Laureano 1995; Laureano 2001.
6 www.unccd.int.
7 www.unccd.int/knowledge/importantDates.php, 2.
8 The Nile inundations are influenced also by the summer monsoon in Ethiopia and in the Southern Sudan as well as by the rain seasons in Uganda and Tanzania: Butzer 1978, p. 14. Metral / Metral 1982, p. 12, points out that the irrigation technologies in Egypt follow the natural rhythms. This phenomenon has been described also by ancient writers like Herodot. This natural rhythm and the seasonal rainfalls in Inner Africa as its causes goes ahead since at least 25.000 years with some small modifications. In any case we have to consider that the quantity of water resources in Egypt nearly has not changed during the last 5000 years while the number of inhabitants and water users has increased from 3 millions in the New Kingdom (5 millions in the Ptolemaic Age) to more or less 64 millions of the modern Egypt (The numbers were taken from Wells 2001, p. 357).
9 Butzer 2001, 184.
10 Schenkel (1978: 73), defines the Dam as "*Bewässerungsdenkmal des Sadd el-´âlî*", a *Monument of Irrigation*. Cfr. inoltre Metral / Metral 1987, p. 95.
11 Since the natural inundation sometimes was less to guarantee the nutrition of the increasing population it was necessary to develop a control system to establish an artificial irrigation system.

levering device with a quite small range, the so-called *shaduf* or sweep was introduced during the New Kingdom for the irrigation of gardens as illustrated by Amarna reliefs[12] and the more efficient *saqiya*, an animal-driven water wheel, which made possible an artificial irrigation the whole year, is first verified archaeologically in Ptolemaic times[13].

According to BUTZER the transition from natural irrigation to artificial irrigation can be dated at the end of the Predynastic Period[14] while ENDESFELDER assigns it to the beginning of the Old Kingdom as a consequence of the necessity to increase the agricultural production since the central administration wanted to use the *surplus* for the construction of public buildings and for the wages of the rapidly increasing number of civil servants[15]. According to SCHENKEL artificial irrigation was invented in the period between the end of the Old Kingdom and the end of the First Intermediate Period[16], indicating as a cause a heavy famine. EYRE illustrates the possibility of an origin of an all-year-irrigation during the Middle Kingdom and bases his hypothesis on the gardens of the *Fayum*, which were not reached by the natural Nile inundations[17]. Without any doubt the colonization and the reclamation of agricultural soil of the *Fayum* by Sesostris I and Amenemhat III introduced remarkable innovations for the irrigation systems[18]. During the New Kingdom the local authorities were responsible of the water resources management, because "*the realities of power were more «feudal» than bureaucratic. As in medieval Egypt, in Pharaonic and Ptolemaic Egypt power laid on control over the ruling class and in the solidarity of that class, not in the detailed administration of the individual peasantry by an impersonal and centralized civil service. The role of the impersonal «state» was typically that of delegation rather than direct control*" [19]. It's quite impossible to prove whether the local authorities were given precise directives regarding the water resources management or whether they managed the water resources exclusively according to their own decisions[20]. Anyway, the intensive cultivation of the Ptolemaic and the Roman period have surely caused an institutionalization of specific civil servants.

The feudal system of the water resources management lasted until the year 1833 which brought the "*conversion of the Nile floodplain and delta to perennial irrigation with the benefit of modern technology. An increasing number of river barriers impounded water in Egypt, raising the low-water level 3 metres or more to carry it over long distances in great canals; this permitted two or even three plantings per year. This effort culminated with the Aswan High Dam, completed in 1971, which holds back all the Nile waters for distribution over the country at any season*"[21]. In Nubia "recessional agriculture" with the traditional basin irrigation system continued well until the mid-twentieth century which makes clear that its productivity was quite satisfactory[22]. Today the Egyptian Minister of Water Resources and Irrigation[23] is responsible for the water resources management.

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12 Butzer 1984, coll. 520-521; Butzer 2001, 185.
13 Butzer 2001, 186.
14 Butzer 2001, p. 185. Wells 2001, p. 357, dates the first experiments towards an artificial irrigation in the Predynastic Period an defines them as local phenomenons which did not concern the whole country.
15 Endesfelder 1979, p. 42.
16 Schenkel 1978, p. 36.
17 Eyre 1994, p. 72.
18 Schenkel 1978, p. 66. Schenkel 1986, col. 1157, points out the increasing economic possibilities of the temples to which belonged wide agricultural territories.
19 Eyre 1994, p. 74.
20 Schenkel 1986, col. 1158.
21 Butzer 2001, 183.
22 Butzer 2001, 183; Butzer 2001, 184: "*In Nubia prior to completion of the Aswan High Dam, farmers sowed the channel banks of the river the moment the flood began to recede.* […] *In this case from the*

The Legislation regarding Water Resources in Egypt during the Centuries

SCHENKEL explains the nearly complete lack of information among the ancient sources about the technological and juridical development of irrigation as a result of a too slow and undramatic evolution to deserve to be mentioned by ancient writers[24].

Even if during the last five millenniums Egypt was ruled by many different rulers with many different legislation, there is in any case a constant guideline through the legislations of the various centuries concerning the distinction between public water resources (canals) and private water resources (wells). Without claiming to be exhaustive, the second part of this contribution wants to discuss the most important historical moments regarding the Egyptian laws about water research management.

Pharaonic Age - It is quite probably that from the Predynastic Period until the Saitic Period (XXVI Dynasty) the rules concerning the water resources use were never codified, being established by the local authorities. The identification of the flowing of the Nile as a metaphor of the cosmic order guaranteed by the Pharaoh as its supreme legislator[25] is a proof for a merely symbolic function of the latter regarding the water resources management and due to the natural rhythm of the Nile inundations there was no need for inventing respective laws. Great public works like the digging of canals and basins depended directly on the Pharaoh[26] while the irrigation subordinated the customary right approved by a royal decree[27]. The central administration of the Pharaonic state dealt mainly with the fiscal aspects of agriculture and with the drain of agricultural lands while the responsibility of the water resources distribution depended on the chiefs of the agricultural communities and villages[28].

Ptolemaic Period - On the one hand the Ptolemaic law system uses the symbolic titles of the pharaonic tradition and translates the nomenclature of administration in Greek, on the other hand it was adapted to the challenges of a more extensive agricultural system.

The *saqiya* permitted a very efficient artificial irrigation independently from the rhythm of the Nile inundations and maybe for the first time in Egyptian history there was a need to codify the artificial distribution of the water resources. A Ptolemaic Greek "water engineer" was responsible for the sharing of the water resources and for the establishing of an irrigation plan[29] and his staff constituted of native Egyptian collaborators[30]. This model of a direct involving of the local communities was repeated 2300 year later with a *World Bank* project that will be discussed at the end of this contribution. From the moment that the state authority made available the water resources, the farmers could use them for free and the

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ethnographic present, the wet basin lands are sown as soon as the summer floods recede, with essentially no effort expended to control the influx or egress of water".

23 The current Minister Mahmoud Abu-Zeid is also President of the International Water Resources Association.

24 Schenkel 1978, p. 74; cfr. inoltre Endesfelder 1979, p. 37.

25 Endesfelder 1979, p. 38, focuses on the importance of a high Nile level as a proof for divine support at least during the Pharao's goverment jubilee for his image.

26 Metral / Metral 1982, p. 64.

27 Metral / Metral 1982, pp. 65-66. This decree was applied in different ways in the different districts with a big difference between Southern Egypt and the Nile Delta.

28 Metral / Metral 1982, p. 66. Metral / Metral 1982, p. 80. Due to the juridic idea of the Pharaonic period we could define this dualism as a kind of "*principle of extension of the personal control of the Pharao*" which would explain the centralistic control of the construction of dikes and canals on the one hand and the customary right regarding the water distribution on the other hand.

29 Metral / SANLAVILLE 1981, p. 112.

30 Metral / SANLAVILLE 1981, p. 113. The Egyptians thought that the Greek knew nothing about water resources management.

maintenance of the canals and dikes had to be guaranteed by the Sovereign[31]. Various papyrus of the Ptolemaic period contain references for the existence of rules for the water distribution and they use the word *nomos* indicating the different districts and the word *ethos* as a proof for a customary right, but still maybe neither could reach the status of a law[32] under the Ptolemaic Pharaohs.

Roman legislation - The Roman right of the post-classical period and of Justinians period had to be adapted to new challenges deriving from the Easter parts of the Roman Empire where the economy depended on big rivers like the Nile, its inundations and the constructions of canals and dikes. Therefore modifications regarding the existing rules were introduced substantial[33]. Due to the importance of Egyptian grain for the Roman economy the legislation showed a particular interest for the water resources question, discussing for the first time the problem of distinction between public and private water resources and its importance for the different ways of water use[34]. This distinction was not necessary until the Roman conquest of Egypt because the Pharaoh until the Ptolemaic period was *de iure* the official owner of the Egyptian soil and consequently also of its water resources. According to the classical jurisdiction until the Age of the Severan Emperors all perennial rivers like the Nile and its branches and canals were considered public goods, a principle expressed also by the Justinian laws[35]. Therefore paradoxically the Roman Emperor in his nominal function as Egyptian Pharaoh due to the Egyptian tradition was *de iure* and symbolically owner of the Nile water, while the Roman right defined the latter *res communes omnium*[36].

Byzantine legislation - The rules concerning water resources management in the *Codex Iustinianus* can be defined as a codification of ancient customs and of common sense solutions[37]. The customary right has still a substantial importance for the irrigation in Egypt but at the same moment it was also codified as law, protecting specially the farmers and their water use. Above all the customary right to scoop water with the *saqiya*, which was typical for North Africa in general, was very important[38].

Islamic and Ottoman legislation - With the Islamic conquest of Egypt arrived an agricultural revolution like in Andalusia and in Sicily with innovative cultivation and irrigation techniques[39]. Since we know early medieval agronomy texts, it seems very probably that within the new system existed also specific irrigation laws for arid areas. Obviously the Islamic right is strictly connected to the Koranic tradition which introduced the so-called "*right to be thirsty*", that means that it could not be refused to anyone to drink water neither in the case of public water resources nor in the case of private ones[40]. Since 1524 the Ottoman legislation uses the Ancient Egyptian principles according to which the local governors were responsible for the maintaining of the irrigation systems. In 1667 a new juridical system called *iltizam* was introduced and administrated by the so-called *multazim* who controlled the agricultural areas and the digging of canals independently from the

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31 Metral / Metral 1982, p. 73.
32 Bonneau 1982, p. 75.
33 Astuti 1958, p. 349. Ulpianus, *Digesto*, 43, 12, I, 5: "*Nilum, qui incremento suo Aegyptum operit*."
34 Astuti 1958, p. 349: The modern Italian legislation defined public waters the one which are important for a use of general interest (Italian law nr. 1775, December 1933, articles I-II). Astuti 1958, p. 350, points out the problem of the instability of criteria and the changing of parameters to define the difference and the relationship between *publicum* and *privatum* throughout the different historical and juridical experiences of different historic periods.
35 Astuti 1958, p. 351.
36 Astuti 1958, p. 352.
37 Metral / Metral 1982, p. 115.
38 Bonneau 1982, p. 76.
39 Louis / Metral / Metral 1987, p. 61.
40 Métral 1982, p. 134.

Ottoman central administration. Consequently, the politics of the *multazim* and their way of handling the lease contracts[41] determined everything and one could call it a kind of "partial privatisation" of the water resources management. From 1667 the dike registers (*dafatir al-jusur*) of the Imperial Treasure Ministery at Cairo with a list of public dikes and the maintaining works carried out, were not compiled anymore. The central government tried to regain the control over the irrigation works, asking the local *sheikhs*, the heads of the rural communities to declare to the *qadis*, the province judges, that every year the maintaining of dikes and canals had been carried out in a regular and correct way[42].

According to the Koranic tradition water belongs to the *res communes omnium* called *mubah* in Arab and cannot be subject of economic transactions: water has no owner and everyone can use it freely and for free[43]. Maybe this principle could be a worldwide model for the modern water resources management.

Napoleonic and British legislation - During his short reign in Egypt Napoleon, who was very interested in irrigation in Egypt, introduced the law that all navigable rivers belong directly to the king[44]. Paradoxically for the three Napoleonic years again the ruler of Egypt was the owner of the Nile, as the Pharaohs have been it 4000 years before. The British Protectorate in Egypt (1882/1914-1922/1936) was characterized by a strong interest for the cultivation of cotton, the motor of the European industry around 1900 and for the use of technical innovations of the Industrial Revolution like steam pumps used for irrigation.

The water resources management in modern Egypt - Since the 1950's and the Nasser government (since 1956) the State was directly involved more and more in the water resources management. A special governmental intervention was the "*New Valley Project*" (*El-Wadi El-Gadid*) which has been developed for the oasis of the depression of the Western Desert *Siwa*, *el-Bahria*, *el-Farafra*, *el-Dahla* and *el-Kharga*[45]. The project, which the Italian scholar FAGGI defined a "*Nationalisation of water*"[46], was an element of Nasser's politics of National mobilisation regarding all the development of irrigation systems for the agricultural production. The goal of the project was a "*structural modification of the water resources management mechanisms*" assigned to the government areas of competence, which have belonged for a very long time to the rural communities[47]. This state intervention caused the enormous risk to compromise the traditional local administration of the water resources, which worked excellently for 5000 years and which had been damaged yet by another Nasser project, that is the construction of the Aswan High Dam with all its consequences like the interruption of the perfect natural rhythm of the Nile inundations and the Egyptian agriculture based upon it. The digging of 1000 wells to irrigate 19.000 hectares of soil was another measure of the *New Valley Project* to reinforce a direct governmental control of the agricultural resources. A special law defined the main goals of the project as the issuing of a governmental authorisation concerning the digging of wells and a state controlled distribution of agricultural soils for free[48]. The excessive "intervention politicy" of the

[41] LOUIS / Metral / Metral 1987, p. 85.
[42] LOUIS / Metral / Metral 1987, p. 85.
[43] Métral / Metral 1982, p. 128.
[44] Astuti 1958, p. 385. Calderini 1920, p. 37, points out Napoleon's interest for the water resource managements rules.
[45] Faggi 1987, p. 104, Fig. 1.
[46] Faggi 1987: the title of his analysis is "*Étatisation de l'eau*".
[47] Faggi 1987, p. 104.
[48] Faggi 1987, p. 106. These goals were defined with the laws 100/1964, 59/1979 e 143/1981. The most important governmental organ for the water resources administration was the *General Authority for Desert Development*, today *New Valley Development Authority*: the Desert areas under the control of this organ were not available anymore for the rural communities but depended directly of an official Bureau for Regional Development.

Egyptian government has gradually destroyed the relationship between the population and the natural resources, which constituted the basis for the self-sufficiency of the rural communities[49]. The consequence was a direct dependence of the governmental institutions. The digging of very deep wells, which supplied more water than the traditional ones, caused a lowering of the ground water level and therefore a lowering of the level of the traditional wells and in many cases even their drying up[50]. In case of lack of water the farmers can now simply make an application for a new dig to the *Development Authority,* which has substituted any personal initiative compromising at the same time the consciousness of the real costs for such governmental interventions[51]. The phenomenon of excessive irrigation causes an oversalting of the soils, which had to be resolved by governmental drain interventions, another former task of the local communities. The "*Nationalisation of water*" has created a new necessity of the State because "*only the State can solve the problem that he had created with his interventions*" [52]. Another consequence of the new situation of a destroyed agricultural self-sufficiency was an increasing unemployment of the poorest farmers, solved by the State by creating employment with new jobs inside the increasing public administration; this status can be defined as a provoked crisis to legitimate a stronger role of the State inside the regional administration[53].

When the error of a too heavily intervening State was recognized in the 1990's, the Egyptian government tried to give back the responsibility for decisions to the local communities. While FAGGI in 1987 was complaining about the loss of consciousness among the Bedouins regarding the water costs paid by the State and water waste due to excessive irrigation and negligence in maintaining the canals[54], 7 years later a *World Bank* project in the area of Matruh[55] was involving actively the local Bedouins and succeeded in creating a new consciousness for the water resources problem among the local communities[56]. With this new development Egypt started to turn back slowly and cautiously to the original way of local irrigation administration, developed for 5000 years, where the State had exclusively a

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[49] Faggi 1987, p. 107.
[50] Faggi 1987, p. 107, e Tav. 1.
[51] Faggi 1987, p. 109.
[52] Faggi 1987, p. 109.
[53] Faggi 1987, p. 110.
[54] Faggi 1987, p. 106: "*Encore, le coût élevé de l´eau imposait l´utilisation parcimonieuse de cette ressource vitale, évitant ainsi l´excès d´irrigation et donc la remontée de la nappe*". Faggi 1987, p. 109: "*Par ailleurs, la perte du coût réel de l´eau, qui est fournie gratuitement par l'État, en a fait perdre le sens de parcimonie: on irrigue en excès et l´entretien des canaux est négligé. L`évidente conséquence est la présence sur les zones cultivées du phénomène de l'hydrophormisme et de la salinisation, entraînant de fortes pertes nettes de la production*".
[55] The project is called *Matruh Resource Managment Project*: www.worldbank.org/wbi/sourcebook/sb0206.htm, p. 1: in the Matruh area are living about 250.000 persons and 85% of them are Bedouins. In spite of the Egyptian government's efforts to integrate them into the society, the Bedouins live in a quite isolated and closed way inside their tribes, whose authorities exercise still many administrative and juristic functions. In any case the Bedouins are among the poorest and most vulnerable groups of the Egyptian population. The *World Bank* project has been approved in May 1993 and has started in February 1994 and it "*provides 800 underground cisterns, earth and stone contour dikes on 6.200 feddans (1 feddan equals 1.037 acres), cemented stone or gabion dikes across wadis to intercept the water flow and create about 500 feddans of new fruit orchards and rangeland improvement and management of 14.000 feddans*". [*Ibidem*, p. 5].
[56] www.worldbank.org/wbi/sourcebook/sb0206.htm, pp. 2-3: "first *was established a local task force consisting of 10 people from the central government, 20 from local government and local institutions, and 10 from the Bedouins community. Local government authorities chose the Bedouin representatives on the basis of their judgment about whom the community trusted and respected*". The Bedouins explained to the responsibles of the project the local circumstances and the result was the creation of a mutual confidence. The responsibles focused also on Bedouin women, involving them in many tasks.

supervising role. We can only hope that the idea of the *Matruh Resource Managment Project* will be also applied in the future in other areas of Egypt.

The distinction between public and private water resources, in antiquity codified by the Roman right, was discussed recently by the Egyptian Minister of Water Resources and Irrigation Mahmoud Abu Zeid during a conference about the possibility of an partial privatisation of the water resources management. The question was whether "*Water should be treated as a purely private good, as a public good or as a basic human need?*" [57]. The suggested solution follows the Pharaonic tradition because "*one alternative for lowering the operation and maintenance costs is to* [re-]*transfer some of the responsibilities to the water users themselves*"[58]. "*Egypt is now in the process of doing this through the Irrigation Improvement Programmer (IIP), Irrigation Management Transfer (IMT) and Matching Irrigation Supply and Demand (MISD)*"[59]. The advantage of re-transferring responsibility to the farmers stems from their "*feeling of commitment to the efficient operation and maintenance of the system; participation in operation and maintenance provides them with a sense of ownership and greater direct responsibility for the effectiveness of the delivery system.* […] *A worthwhile consideration is to have the farmers participate in water management decision making that affects them, such as the valuation of services and the collection of fees*"[60]. The price of Water as a public and private good at the same time is situated between the mechanisms of the Free Market and the governmental interventions. "*Therefore, it is up to the governments, in co-operation with major stakeholders, to choose the proper mechanisms to provide the funds necessary for sustaining the system and meeting the needs of the poor*"[61]. The only two countries of the Mediterranean area where water for agricultural irrigation is free are Egypt and Albany, *which does not encourage to save water at all*"[62]. On the other hand, the water resources management is simplified because there is no need for administrative institutions regarding the water *tariff*. Any water price increases the consciousness of the importance of water, encouraging the users to avoid waste, but too high tariffs don't meet the needs of the poor.

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[57] Abu Zeid, *Ceremony*, p. 1. The same problem was discussed for a guideline of the European Community which declares that "*water is not a commercial good like other ones, but a patrimony that has to be protected and defended*" (guideline 2000/60/CE of the European Parliament and of the Council of October 23th 2003 for a common behaviour in Europe regarding the water resources; in *G.U.C.E.*, L 327, 22 dicembre 2000). The European Commission has also emphasized the importance of water-prices which have to be affordable also for the poorest parts of the modern society [The Italian edition is called *Libro Verde sui servizi di interesse generale*, published in may 2003 (Bruxelles, 21 may 2003, COM (2003) 270 final version)]. Mahmoud Abu Zeid has published various contributions about the government-established water-price and the possibility of a partial privatisation of water resources management.

[58] Abu Zeid, *Water Pricing*, p. 4: "*Water Pricing Influence on Irrigation Efficiencies*".

[59] Abu Zeid, *Water Pricing*, p. 4.

[60] Abu Zeid, *Water Pricing*, p. 5.

[61] Abu Zeid, *Water Pricing*, p. 11.

[62] Chohin-Kuper / Rieu, Montginoul 2003, p. 1, Cap. 2.1.; p. 2, table 1; p. 6, Cap. 3.3. The water price in Greece for agricultural irrigation is oscillating between 95 and 220 US$/ha while in the Lebanon it amounts to 285 US$/ha. Chohin-Kuper / Rieu / Montginoul 2003, p. 1, Cap. 2.1: "*The extreme case, where structure is of little importance, is where water is free (Egypt and Albania), which does not encourage to save water at all. At the opposite extreme, Israel has introduced a pricing structure giving high incentive to save water*…". In Egypt there are no incentives to save water like in France or in Israel. The water tariff for a Typical Houshold in Egypt is one of the lowest of all Near East and Northern African countries: in Cairo in 1993 it amounted to 0,05 US$/cum, compared to 0,90 US$/cum at Ramallah (1994) and to 0,32 US$/cum in Tunisi. The Water Tariff at Ramallah is nearly 20 times higher than the price at Cairo. In Europe and in the United States the municipal water tariffs are in the range of 1 US$/cum to 5 US$/cum [the statistical numbers were taken from www.lnweb18.worldbank.org/mna/mena.nsf "*Water Pricing in the Municipal Sector*", p. 1 (diagram).]

During a videoconference discussion in 2002 about "*Public-Private Partnership in Irrigation and Water Resources Management*" within the framework of a *Global Dialogue in Sustainable Development and Sustainable Water Use* collaborators of the World Bank's MNA Rural Development and Environment Group, of the Distance Learning Centers in Cairo and Amman, and of the World Bank Country Office in San'a, Yemen achieved a very interesting result regarding the Egyptian water resources management[63]: "*The branch canals, distributaries and tertiary, and the construction and maintenance of pump stations for irrigation is being transferred gradually to the Water Users Associations, where the private sector can play an active role as services provider. The private sector can enhance and improve the efficiency of the services offered to the farmers to achieve the ultimate goal of Egypt, which is to increase the agricultural production*"[64]. Activities that can be transferred to the commercial private sector are such as the construction, operation and maintenance of pumping stations, canals and groundwater wells, the water distribution among farmers and the supply of modern irrigation systems[65]. The rural communities of the Pharaonic Egypt carried out exactly these tasks. The consequence of the modern private sector involvement will be a positive impact on the efficiency and the lowing of costs since "*the water losses will be minimized, the availability of irrigation water will be adequate, more fairness and equity among all farmers will be achieved, the effectiveness in operation and maintenance will be promoted, and better irrigation services and new capital sources will be provided*" [66].

The Principle of the "Future of Tradition"

The Italian architect and UNESCO consultant Pietro LAUREANO has presented an alternative system to combat the desertification with traditional knowledge, calling it the "*Future of Tradition*"[67].

Laureano analyses the economic-social structures of big Empires, which based their economy upon big rivers like Egypt and he describes the problematic long term consequences of increasing expansion, demographic increase and rise of the agricultural production, such as hypertrophy of the population and of the territory, authoritarianism, governmental centralisation and above all an increasing destruction of environment towards an ecological catastrophe[68]. Laureano observes as well that in the shadow of the big empires could survived societies who had chosen arid and inhospitable areas transforming them into agricultural areas for an self-sufficiency existence. They are using traditional knowledge, accumulated during the millenniums to innovate and amplify the use of local resources due to irrigation on a small scale[69]. The importance of traditional agricultural knowledge has

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63 *Videoconference* 2002, p. 2.
64 *Videoconference* 2002, p. 2.
65 *Videoconference* 2002, p. 2.
66 *Videoconference* 2002, p. 6.
67 Although this system has been developed based on field-studies in Algeria, Jordan and Southern Italy it could be applied also in Egypt.
68 Laureano 2001, p. 271; Id. 1995, p. 287. Wittfogel 1957 was the first scholar who tried to prove a correlation between river inundation based agriculture and the birth of a despotic central administration like in Mesopotamia and Egypt.
69 Laureano 2001, p. 271: "*Ai margini dei grandi imperi sopravvivono società che hanno scelto zone impervie e difficilmente appetibili per trasformarle in situazioni di esistenza autosufficienti. Queste comunità autopoietiche utilizzano l'esperienza accumulata del sapere tradizionale e divengono centri di innovazione per l´amplificazione e l´uso appropriato delle risorse locali. L'economia agricola, con irrigazione su piccola scala* […] *dà luogo a nuclei di piccoli proprietari in possesso degli animali e degli strumenti di produzione*". Laureano 1995, pp. 288-289: "*Le tecniche utilizzate sono fondate sulla combinazione vantaggiosa di disponibilità minime e sull'utilizzo di principi sottili di umidità, fertilità e vivibilità*".

been recognized by an UNESCO - *International Council for Science* (ICSU) declaration, defining them cultural patrimony[70].

In Egypt the traditional knowledge regarding agriculture and irrigation can be applied above all in the area of the oasis where the small water resources have imposed on their inhabitants always a responsible use of the water resources and that's why they have developed a local and decentralized management of agricultural and irrigations resources which could be taken as a model. Maybe the Egyptian government could get an inspiration from the Pharaonic past and traditional agricultural knowledge for possible solutions of modern problems concerning the water resources management.

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[70] Laureano 2001, p. 253: "*Il sistema delle conoscenze tradizionali e locali come dinamica espressione di percezione e comprensione del mondo può fornire, e storicamente ha fornito, un valido contributo alla scienza e alla tecnologia, e per questo motivo c´è la necessità di preservare, proteggere, ricercare e promuovere questo patrimonio culturale e di conoscenza empirica*".

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Geology, Geomorphology, and History and Recent Status of Water Resources of the Pediada, Crete, Greece

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Abstract: The Pediada region in central Crete has been a study case (for many disciplines) for testing whether the development of a civilization depends on its environment. The region is best suited for such a study since it has been densely occupied for the past 5,000 years and has sustained major palatial societies during the Bronze Age, city-states in later periods and the capital of Crete in modern times. In this paper we examine how the geology and geomorphology of the region may have affected the civilizations that developed within it. Furthermore the hydrological and hydrogeological settings of the study area are reviewed. The water resources of the Pediada in the historical and modern periods are discussed and the explicit evidence for the correlation of ancient sites and springs is presented. Our results have shown that the physical environment has contributed enormously to the presence of civilizations in the Pediada region.

Keywords Ancient civilizations; Crete; geomorphology; Pediada; water resources.

Introduction

The Pediada region in central Crete extends south from the northern coast and west of the Lassithi mountains and is the inland of Heraklion Prefecture. It is the region that gave life and sustained the two major Bronze Age palatial sites of Knossos and Malia lying at its northwest and northeast corners respectively, as well as the newly identified palatial site of Galatas at its southwestern part (Fig. 1). It is not a flat plain as its name in Greek suggests, but, being an extension of the Lassithi mountains, it forms a plateau that rises immediately south of the strip of the north coast line and consists of small plains and undulating countryside; it is watered by the Karteros river and its tributaries as well as some tributaries of Anapodaris river to the south. It is a very fertile region forming a vital source for the present economy of the island.

The Pediada has been occupied continuously since the Neolithic period (*ca*. 3500 B.C.), but, as it was revealed through the Pediada Survey Project, it was during the Bronze Age (especially between 1900-1450 B.C.) that it reached its highest peak of development as part of the Minoan Civilization (Panagiotakis, 2003). It was densely occupied and must have contributed enormously to the development and sustenance of the Bronze Age Palatial economies as well as to the economies of its later (1st millennium) six major city-states (Lyktos, Lykastos, Chersonissos, Arkades, Eltynaia, Choumeri Kefala).

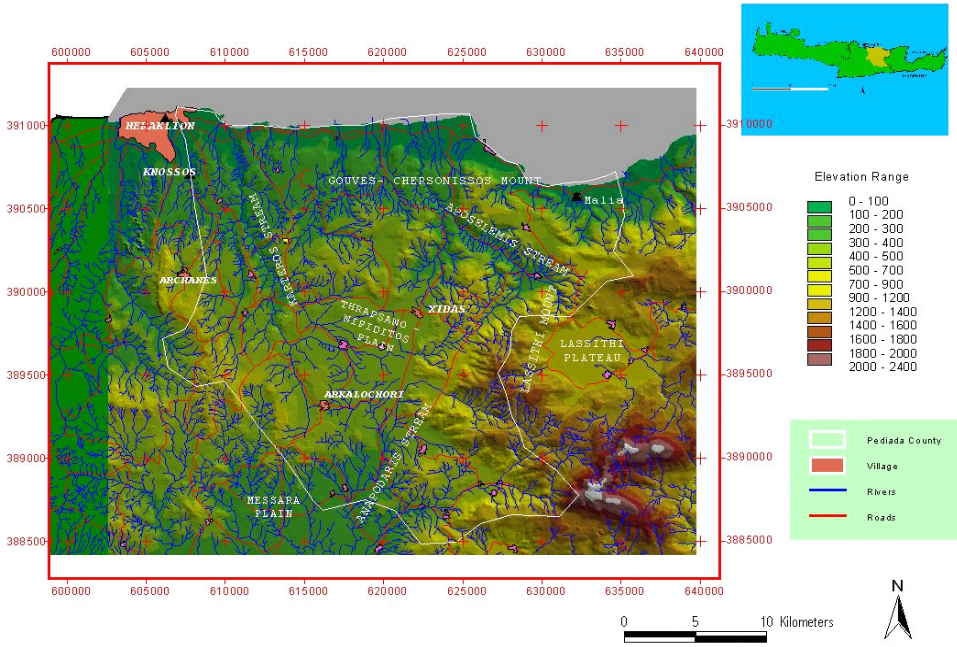

Figure 1 Physical map of Pediada area.

The continuous presence of man and civilization in this region is not independent of the physical characteristics of the area. The geomorphology and the geological background have contributed significantly: they have provided some of the main factors for the development of a civilization, i.e., protection and fertile land (Fassoulas and Panagiotakis, 2004). Another important factor, which is water, appears to be diachronically present in sufficient quantities, although precipitation is not high. The water resources of the island of Crete by definition are determined by the hydrological regime of the area but a predominant role is played by the hydrogeological regime as ground water, through natural spring flows or yield by wells. In arid or semi-arid climatic conditions this underground resource can much enhance the surface water supply.

In this study we examine how the geology and geomorphology of the region may have influenced the occurrence of water resources in the area, as well as the way these have affected the civilizations that developed within it.

Geology-Geomorphology

It is well known that Crete has a complex geological structure as a result of the Alpine and present-day orogenic processes (Fytrolakis, 1980). Mesozoic marine sequences occurring in nappe structures constitute the main body of the island over which Tertiary and Quaternary sediments have been deposited (Creutzburg *et al.*, 1977). Syn and post-depositional tectonism fragmented the island forming grabens and horsts (Fassoulas, 2001).

In the Pediada region almost all nappes of Crete are outcropped (Fig. 2; IGME, 1989; 1994). The lower Plattenkal platy marble and Phyllite-quartzite nappe, constituted mainly of phyllites, quartzites and metavolcanics, occurs at the eastern Lassithi mountains. The overlying Tripolitsa nappe, composed of Mesozoic limestone and dolomite and an overlying flysch, occurs all over the northern ridge up to the coast and the northern Lassithi mountains.

Over the Tripolitsa nappe, at the northeastern part of the Pediada region, occurs the Pindos nappe consisting of Mesozoic limestone and Tertiary flysch.

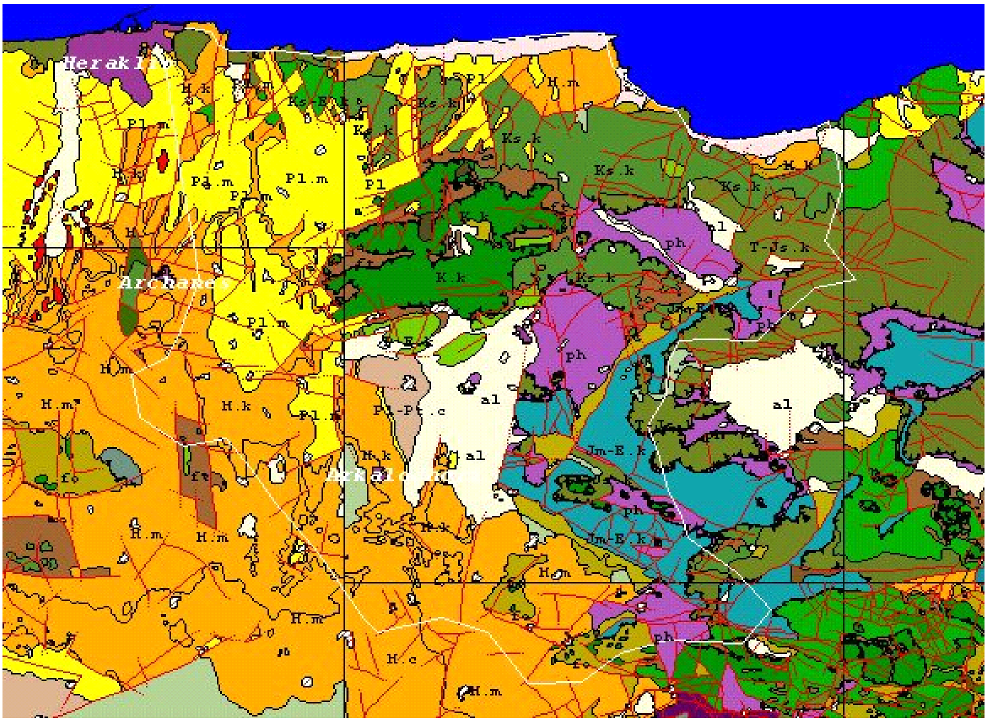

Figure 2 Geological map of study area (al, alluvial; Pl-Pt.c, Pleistocene; Pl, Pleiocene sediments; Pl.m, Pleiocene marls; M.k, Miocene limestone; M.m, Miocene marls and marly limestone; M.c, Miocene conglomerates; K.k, Pindos limestone; ft, Tripolitza flysch; Ks.k, T-Js.k, Tripolitza limestone; ph, Phyllites-quartzites; Jm-E.k, Plattenkalk limestone. Red lines indicate faults).

During Neogene times many faults developed that fragmented the island into small islands and marine basins. Several sedimentary formations were deposited then over the basement rocks and it is those present today in the Pediada region. Marls, conglomerates, sandstones and an overlying limestone have deposited in these basins. Pliocene, marly conglomerate and the gray marls rest over the limestone everywhere in the Pediada. In Upper Pliocene-Pleistocene terrestrial reddish conglomerates, sands and clay were deposited in the new valleys formed by the early streams. Holocene alluvial sediments and soils cover the present river valleys and the low plateaus. The most fertile areas in the Pediada are thus covered by the Neogene and Quaternary rocks, while the older Mesozoic rocks occur in the surrounding mountains and in some cases in deep river cuts.

The landscape at the broad Pediada region is characterized by a step like mode that declines gradually from the high Lassithi mountains (2000m.) to Karteros river valley to the west (Fig. 1). Normal faults trending in several directions (Fig. 2) are responsible for the creation of three main levels (steps): the high Lassithi mountains (L1), the intermediate zone (L2) and the western lowlands (L3) which consist of the Omphalion Pedion (Thrapsano-Nipiditos plain in Fig. 1) and the Karteros valleys; they are also responsible for the many abrupt, minor relief changes (Fassoulas and Panagiotakis, 2004). Most of these lie in general NE-SW, parallel to the main fault directions. A big active fault (Kastelli f.) occurring at the foothill of the Lassithi mountains caused a relief change of about 800 m and the formation of the L1 and L2 levels. Another N-S trending fault with a vertical offset of about 200 m borders the L2 and L3 levels. Minor other faults occurring at the lowlands of the Pediada area fragment the plateau forming the flat area of the Omphalion Pedion (Figs. 1, 2).

Deep erosion has been accelerated due to vertical movements. In carbonate rocks gorges were developed normal to the fault alignment as a result of karstic weathering and uplift of the footwall (Fassoulas, 2001). Selective erosion, and weathering contrast between carbonate and pelitic sediments resulted in rockslides, gliding and landslides. This was more intense along fault zones where tectonic terraces were finally formed exposing steep cliffs and slopes. River activity was also affected by the individual vertical movements resulting into stream bending (from the early westwards to the present northwards), deep weathering and finally the formation of small gorges, ravines and river valleys. The neogene limestone being more resistive to erosion than the rest of the sediments is outcropped on the top of the low hills, having a general inclination to the east.

Hydrological Setting

The hydrologic characteristics of the Pediada are largely determined by its geology and geography, with climate also playing a dominant part. The precipitation indicates both temporal and spatial distribution (Papagrigoriou *et al.*, 2002). About 60% of the annual precipitation occurs in the winter months, while negligible rain falls during the summer. The average precipitation for a wet, a normal, a dry and a very dry hydrological year is 1,108 mm, 816 mm, 525 mm, and 287 mm respectively. Rainfall decreases from north to south and increases toward higher altitudes with a precipitation-elevation ratio of 0.61 mm/m. Pertinent studies of statistical analysis of the recorded data have shown that no significant trend of precipitation can be observed. The mean annual temperature range lies between 17°C to 20°C. The prevailing wind direction is north and northwesterly. The driest months of the year are June and July (mean relative humidity 60%) and the most humid month is December (67%). The mean potential evapotranspiration varies from 1,370 mm/yr to 1,570 mm/yr.

Three main hydrogeological units can be distinguished: the Karstic aquifers, the neogene-quaternary aquifers, and the aquiclude and aquitards of impervious formations. The Karstic aquifers are formed in carbonate rocks (limestone, marble) occupying the Lassithi mountains chain and the Goubes - Chersonissos zone (Fig. 3). Hydrogeologically, the limestone is characterized as high to moderate permeable. It is estimated that 40% - 55 % of the mean annual precipitation infiltrates into these formations, creating a renewable annual groundwater (Perleros *et al.*, 2003). Of this a high portion is discharged into the sea, with the rest outflowing through three main karstic springs; Malia, Gramatikaki and Kastamonitsa (Fig. 3). The first two have mean annual discharge 2.7 millions and 0.5 million m³, respectively and their water is polluted by seawater intrusion. The Kastamonitsa spring has an intermittent flow. The hydrograph shows that during the summer the discharge continuously decreases (almost nullifies), while in the winter it is at high rates.

The neogene - quaternary aquifer comprises porous alluvial deposits and marly limestone and sandstones with permeability varying from high to low. They occupy the central – west part of the study area. It is estimated that 10% - 25% of the mean annual precipitation infiltrates into these formations, creating a renewable annual groundwater which is discharged by “low capacity” springs or yielded through shafts. Four main Neogene - Quaternary hydrogeological basins are formed. Three of them, the Thrapsano-Nipiditos, Embaros and Filisia-Astrakoi are located on the interior of the study area; a large portion of their groundwater is discharged through three main springs - the Migilisi, the Embaros and the Astrakoi cluster (Miliara, Kria Vryssi, Neraidospilio, Fontana) respectively (Paritsis, 2000; Fig. 3). The mean annual discharge is 1.1, 1.7 and 2.5 million m³, respectively (YEB, 2003). From the distribution curves it may be inferred that the Thrapsano-Nipiditos and Astrakoi aquifer are extensive and a relatively respectable, although diminished outflow is retained even in the dry years. On the contrary, the aquifer of Embaros is more restricted causing the outflow during the summer to be reduced to nothing, even in wet hydrological years. In addition there exist many small springs of little real hydrologic significance, although even such small springs may provide water enough for a small settlement or for a farm. In the Pediada 183 small springs and 104 wells have been mapped by Panagiotakis (2003). It should be noted, that, most of the springs are located on faults since faults facilitate the flow of water underground.

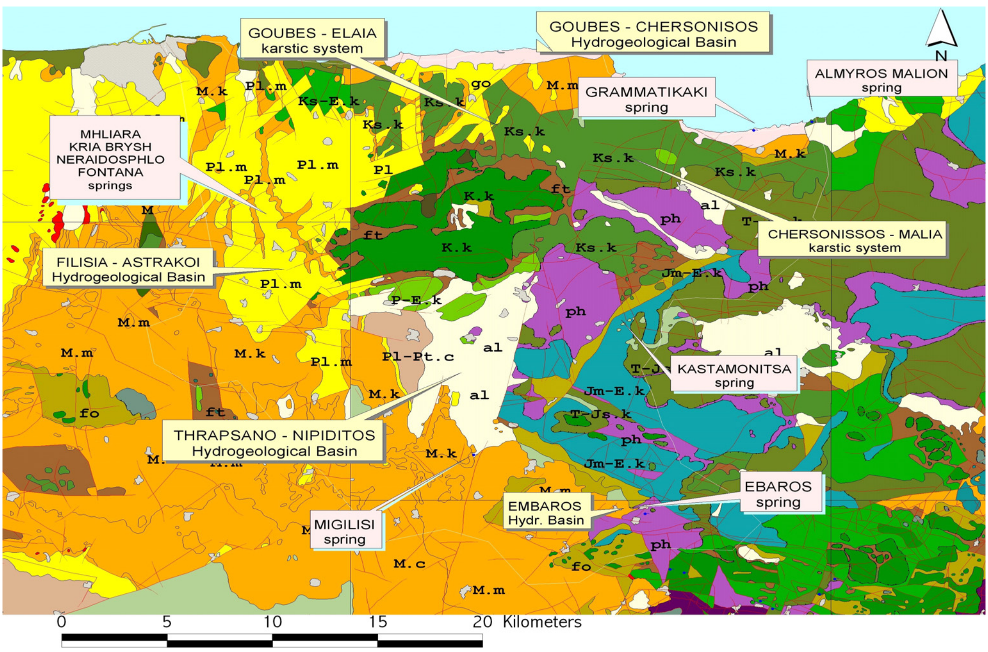

Figure 3 Hydrologeological units and main Springs (labels same as Fig.2).

In the Pediada four main water basins are formed: Karteros, Aposelemis, Goubes and Anapodaris. They are drained through the homonymous stream system (Fig. 1). The first three flow down to the north and the fourth to the south. None of them have a perennial flow, except at their debouchments into the sea and at some inland small portions, where they are fed by local springs. The estimated annual hydrological balance of the Pediada is depicted in mm for a normal, a wet, a dry and a very dry year (Table 1).

Table 1 Hydrological balance of Pediada area.

Hydrologic conditions	Precipitation	Actual evapotranspiration	Runoff	Infiltration
Normal year	780	490	75	215
Wet year	1,059	665	102	292
Dry year	502	315	48	139
Very dry year	274	172	26	76

Water Resources through Time

The general picture of the recent water resources of the Pediada discussed above could be characterized of limited surface water restricted in the winter season. The only available water resources from April to November are those originated from the groundwater either forming outflows of springs or pumping from wells which are constructed in the main aquifers. The water conveyance network system from all main aquifers of the Pediada (Malia, Thrapsano–Nipiditos, Filisia, Episkopi; Fig. 3) to supply the capital town of Heraklion, is a characteristic infrastructure for solving the deficiency of demand-supply water balance of a town.

The water resources of the recent past (20th century), as summarized above, could be argued that it soundly describes the hydrological conditions (both in the study area and the island as a whole) as they are based on long time series data. Furthermore, any projection of these recent climatic and hydrological conditions into the past historical times can only be achieved if one possesses qualitative information about any climate changes relative to modern conditions (i.e., more arid/more wet). Numerous inconsistencies, constraints and assumptions are seen in the relevant literature (through archaeology, paleoclimatology, geology, forestry, biology, etc.).

Therefore any such attempt is fraught with difficulties as open questions remain concerning (mainly) the climatic and hydrological conditions of the broader area and secondarily of the hydrogeological regime. Furthermore not many such studies exist that are concerned with Crete. Consequently, in the following section only some general factors and considerations are discussed about these presumed earlier climatological and hydrological conditions and thus about the water resources of the Pediada.

Climate changes occurring in historical times influence directly the water resources, as a result of changes to the distribution pattern and the amount both of precipitation and of evapo-transpiration. Studies do not imply significantly different climatic conditions in Crete from the Neolithic period to the present day. In Minoan times the climate was probably only slightly warmer and more arid than today (McCoy, 1980), though in Classical and Roman times it was a trifle colder and wetter. The precipitation indicates spatial and temporal distribution. About 60% of the annual precipitation occured in the winter months while negligible rainfall during the summer. In a drier year the annual precipitation was spread across fewer winter months. The existence of more extensive tree-cover than today (Asteriou, 1977), it is argued, would enhance the absorption of rain and thus replenishment of the groundwater, with consequent lesser surface runoff.

Because of the geology, the topography and the elongated shape of the island, many small hydrological basins are formed, whose surface water is discharged to the sea through a stream-network system with intermittent flow during the year. The Pediada can be characterized as having only limited surface water during the summer period, except for those areas that are portions of riverbeds, estuaries and springs, which are fed with groundwater.

The only available water resources during arid periods or even in drier years come from groundwater. In the Pediada two types of aquifers occur: the Karstic and the Neogene-Quaternary - both have relatively high potential. The Karstic aquifers are mainly drained by two coastal saline springs: Almyros-Malia and Gramatikaki. A number of submerged springs deliver water directly into the sea at the north coast; and finally the springs of Kastamonitsa have an intermittent flow. The position of today's partly submerged ancient settlements on the coast (Malia, Chersonissos) reveal a relative rise in the sea level. Thus the coastal springs might earlier have been less affected by the intrusion of sea water. The groundwater of the inland Neogene–Quaternary aquifers is discharged mainly through springs, e.g., the Astrakoi cluster, Migilissi and Embaros. These too have relatively high potential even in dry years, with the exception of the last which has no outflow during the summer, even in wet years.

The stratigraphy of the Neogene–Quaternary rock formations, where permeable inclined strata (marly-limestones and sandstone) overlie impermeable ones (clay, marls), is often found to occupy the tops of hills. This arrangement creates aquifers, which though of insignificant hydrological potential, have yet vital importance for small settlements and farms. Their water is discharged by many small springs, though during extended dry years the yield is dramatically decreased, and may even dry up. The springs, both main and small, are closely connected with ancient settlements located in higher elevations as shown through the Pediada Survey Project (Panagiotakis, 2003). During arid climatic conditions, a lowering of the water table occurs and springs dry up but the aquifers can be more extensively exploited by digging wells, especially in the Tertiary–Quaternary strata as these consist of soft material like clays, sands and gravels.

The number of Minoan and Roman settlements detected and mapped by Panagiotakis (2003) displays an inverse correlation to their water resources. Somewhat surprisingly in arid hydrological conditions more Minoan settlements existed than in the wet conditions of the Roman period. The existence in neighboring areas of contrasting levels of water resources (surplus vs deficit) has affected the development of remarkable water conveyance systems, from as far back in time as the Roman period (Spanakis, 1981: ancient Lyttos, Chersonissos).

In conclusion, it must be emphasized that though both the hydrological–hydrogeological regime and the water resources of modern Crete are well defined, yet to project these back in time introduces uncertainties since we do not have enough information yet for the paleoclimatic conditions.

Conclusions

A civilization can hardly develop in a hostile environment. In our study case, the Pediada region, where the Pediada Survey Project brought to light large numbers of archaeological sites covering all periods for the past 5000 years, it is evident that this diachronic development depends on the position of the Pediada and its regional environment. The Pediada offers the most propitious features for the development of a civilization - even today it is one of the most densely populated and most wealthy regions in Crete. The role played by its landscape, the geological and geomorphological structures as well as the water resources should be seen as catalytic for its wealth.

Most of the land is fertile as a result of the marly and sandy sediments; water supply is abundant all over the region due to the special structure of the neogene limestone that is fragmented in many parts and inclined due to faulting and simultaneously sandwiched between the impermeable marly sediments. The Karteros and Anapodaris rivers (with their tributaries) are developed mainly due to the high precipitation occurring at the mountains surrounding the Pediada and to the presence of the impermeable marly rocks. In the cases where streams run over either the Mesozoic or Neogene limestone, water sinks underground recharging the underground water tanks. On the other hand the neogene limestone being more resistive to erosion than the rest of the sediments is outcropped on the top of the low hills, having a general inclination to the east. Hydrology in these areas is thus governed by the structure and appearance not only of the limestone in between the impermeable sediments over- and underlying it, but also of the occurrence of the many faults. Faults act either as underground dams that force water to rise towards the surface or underground water routes that can transport water to large distances, even in areas where rock permeability or precipitation do not enable water to sink underground depending on their age, the physical characteristics of the fault environments and if they are active or not,.

Springs occur thus as over flooding or drainage springs along the contact of the limestone with the overlying or underlying sediments especially where erosion has exhumed it (as in gorges and river valleys). Furthermore, springs appear along fault zones in front of tectonic terraces as tectonic or over flooding springs. And it is remarkable that most archaeological sites are located near springs and water occurrences. In the Pediada region it is thus apparent that the individual geological and geomorphological conditions resulted in a well developed set of water appearances, that independent to climate, sea-level or geological changes, offered diachronically the necessary water resources capable to host civilizations for 5,000 years.

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Ancient Hydro-structures for Water Management in Chogha Zanbil, Shushtar and Dezful, Iran

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Abstract: Ancient Iranians were one of the most progressive people in knowledge especially in water engineering. Discovered ancient hydro structures with thousands of years old prove it. Khuzestan province with fertile lands and flowering rivers was a suit region for human to live, so different cities and civilizations were founded in this province from thousands of years ago. They built many buildings and left them. So this province is like a paradise for archeologists. The ruins of them such as hydro structures are being seen now. Iranian history until *ca.* 600 A.D., when Arabs invaded Iran is known as ancient Iran. Elamite, Medians, Achaemenians, Solokid, Parthians and Sasanian are known dynasties that rolled on ancient Iran respectively.

Keywords Chogha Zanbil; Dezful; Hydro structures; Khuzestan; Shushtar; water management.

Chogha Zanbil Hydro Structures

Water purification system

Elamites were different families whose known history dates back to *ca.* 2800 B.C. until *ca.* 650 B.C. Ashore Bani Pal, the Assyrian king attacked them, destroyed their cities and omitted them. They had two capitals, Susa in Khuzestan today province and Anshan in Fars province or ancient Persia. They believed in a multi god religion. They built their god's statue and put them in their temples. The most important and famous heritage of this dynasty is a ziggurat that was used as a temple (Fig. 1). It is recorded in the UNESCO's world list of cultural heritages. Because of its shape which is similar to an inverted basket, local people call it Chogha Zanbil which means basket hill. It was located at the center of a city which was called Dur Untash, means the city of Untash. Untash Napirasha, the powerful king of Elamite built this city in *ca.* 1250 B.C.

It was a pilgrimage city (Girshman, 1966). They built special temples for every god or goddess and put their statues or carvings there. The ziggurat was a temple for Inshushinak and Napirasha, two high ranked gods of Elamite. Three walls were built respectively to protect this city as fortifications. A hydro structure was discovered under the third or outer wall. It contains two reservoirs in two sides of the wall, a big reservoir outside the city and a small one inside. Bricks were used to build it. Its bricks were water resisted by gypsum and natural bitumen. Nine sloped canals connect them. Figures 2 and 3 show outer and inner reservoirs of this hydro structure. The volume of outer reservoir is about 350 m^3.

Figure 1 Chogha Zanbil temple.

There are two ideas about this structure. Some believe it was a system to send out the rain run off, (Mofidi Nasrabadi, 2004) other believes it was the oldest water purification system. The second group believes water entered to outer reservoir then became calm and its clays were settled down. As the water level rose in outer reservoir it went up from the sloped connectors and purified water entered the inner reservoir. During discovery they discovered some charcoal in outer reservoir. Some say the charcoal was used to purify water.

Figure 2 Outer reservoir.

Figure 3 Inner reservoir.

Rain water channels

This ziggurat is safer comparing with other ziggurats; brick cover and progressive rainwater channels are stability factors of this ziggurat. Four water channels were built in each side of the ziggurat to collect and send out the rainwater. Figure 4 shows one of the waterways of the ziggurat. The bricks of channels are water resisted with gypsum and bitumen. The vertical squired waterways channels were built in the center of brick cover of the ziggurat. It comes down vertically then changes to a horizontal channel with an arch ceiling on the top of lower floor surface. Then it changes to a vertical squared channel and continues to convey the water to ground surface. To protect it from water falling erosion, brick steps were built where the channel direction changes. A progressive system of earthen pipes would collect and sent out the raining water.

Figure 4 Rainwater channel.

Shushtar Water Structures

Achaemanians were a powerful dynasty who got the power in ancient Iran. Cyrus the grate founded this kingdom dynasty in *ca.* 550 B.C. Figure 5 shows his charter, which is known as the first charter of human rights. It's written with cuneiform letters on a backed clay cylinder and being kept in British Museum. Persepolis in Fars province or ancient Persia is their most famous heritage (Fig. 6). They had a powerful and wide country from India to Egypt. Governing this country depends on food production. Farmers have to irrigate their fields to produce food. So Acheamenian constructed many water structures especially in Kuzestan that their winter capital, Susa city was located in.

Figure 5 Cyrus's Freedom Charter, the first Charter of human rights.

Figure 6 Persepolis.

Daryon canal

Karoon nice and huge river flows in Khuzestan province. Its discharge differs from 63 to 6240 CMS in different seasons and years in Gotvand (Shushtar) discharge measurement station. It arrives to North West of Shushtar city and divides in to two branches then surrounds the city. We can see many ancient hydro structures in Shushtar. One of them is Daryon or Dara canal. Some believe its name shows that it was built by the order of Darius the great, the powerful king of Achaemanians. It was built to irrigate the eastern lands of the river. It is connected to the river by a 200 m tunnel under the Calasstell ancient castle. Daryon canal is still being used. New instruments were established at the tunnel entrance in recent years (Fig. 7). After digging Gargar canal the land that was irrigated by Daryon canal was surrounded by two branches of Karoon, Shotayt and Gargar, so it was called Miyan-Ab means among water.

Sasanians were another dynasty that rolled in Iran ancient and so in Khuzestan as a province of Iran. They built different hydro structures such as dams, bridges and canals. We can see some of them that are being used now, Such as Gargar Bridge and Dezful Bridge in Shushtar and Dezful cities (Afshar Sistani, 2001). High discharge flow of the Karoon River makes many problems to build structures on it. So it was divided to two branches in North West of Shushtar by a bridge diversion dam, which is called Beand-e Mizan, means adjusting dam (Fig. 8). Band-e Mizan was constructed in 250 A.D. It was destroyed by flood but was reconstructed again. It is an arched wall against water that divides Karoon water to two parts, 2/6 and 4/6 in two branches that are called Gargar and Shotayt respectively. Daryon canal connects to Shotayt. It seems local natural cliffs provided a part of this wall. There are ten waterways in this wall, nine on the east and a wider one on the west of the wall. It is about 70 m long and 5 m height. There is an ancient tower on the west side of the wall that is called Kolah Farangi Tower.

Figure 7 Daryon entrance.

Figure 8 Mizan diversion dam.

Gargar canal

They dug Gargar canal to reduce the discharge of Karoon River. Gargar Canal conveyances 2/6 parts of the Karoon River water and 4/6 parts of the water are being delivered by Shotayt channel. Two branches connect to each other's after passing 40 km in Band-e Ghir. It is said there were three reasons for digging Gargar: (a) To reduce the discharge of Karoon Rivers not only to control the flood but also to make different structures on it; (b) to make a water obstruction against enemies as a forth; and (c) to irrigate the southern land of the river, because the natural slope is from South to North (Farokh Ahmadi, 2005).

Gargar bridge and waterfalls

They faced with a strong and hard cliff during digging Gargar. This cliff is being called Gargar Bridge now (Fig. 9). So they built three main and some lateral tunnels to divert water through them. Water passes through these tunnels with high speed then falls to the canal as nice water falls (Fig. 8). High velocity water flowing through tunnels provided an adequate energy to move stones of water mills. Therefore water mills were built there. Gargar Bridge and waterfalls are in the queue to be recorded in the world list of cultural heritages. The first Iranian electricity generator (hydro power) was constructed here in 1944.

Figure 9 Gargar bridge and Shushtar waterfalls.

Shadorvan dam bridge

The water level in Shotayt, the branch of Karoon that feeds Daryon canal, felt down after digging Gargar. So water couldn't enter to the tunnel. They had to raise water level. Shadorvan Dam Bridge was constructed on Shotayt branch not only to be used as a bridge but also as a diversion dam to raise water level to enter to Daryon or Mian Ab tunnel. The ruin of this structure is still being seen (Fig. 10). It is about 200 m long, 5 m height and 8 metes wide. It was built in 250 A.D. Shapour the first, the Sasanian king ordered to build it. He defeated Valerian, the roman king who had attacked to Iran with his army. Then Shapour forced them to build this structure to recompense the destruction that they had done to Iranian boundary city. The scene of Shapour and Valerian was engraved on a stone carving in Naghsh-e Rostam, in 6 km north of Persepolis. Shapour is sitting on his horse in a very dignified cloth and is sitting on the ground in front of him (Fig. 11).

Figure 10 Shadorvan bridge.

Figure 11 Shapour I and Valorian.

Shadorvan Dam Bridge that is the hugest water structure in Shushtar contained 44 waterways, 24 of them are being seen now, 16 with roof and 8 without roof. Two cubic pillars are constructed in two sides of the waterway. They were built sharp against the water flow to reduce the resistance of structure in front of the water. Small waterways were built above some pillars to pass excess water during flood time (Fig. 12). Some water ways of the bridge were constructed in lower level may be to wash sediments from the dam bridge. Huge stones were used to build the base of the bridge (Fig. 13). Steel pines connected the stones to each other then water resisted by melted plumb. Shotayt river flows from north of the city and after passing 40 km connect to Gargar in Band-e Ghir. Dez River connects to them in the same place and the grate Karoon river forms.

Figure 12 Small upper water way.

Figure 13 Lower water ways and huge stones.

Lashkar bridge

The safest hydro structure in Shushtar is Lashkar Bridge that was constructed on Daryon canal (Fig. 14). It is 183 m with 12 waterways. It is 4 m wide. The bridge contains two curves. Big and small stones were used to construct it, Sarooj, which is a traditional plaster and bricks. The ceilings of waterways are in arched shape. The height of bridge is 5 and 10 m respectively from the base of the bridge and the floor of the river. Two water ways were constructed above each other were the canal is deeper.

Figure 14 Lashkar bridge.

Dezful bridge

Dezful is an ancient city in North West of Khuzestan. Gondi Shapour ancient university was found near this city, beside a village that is called Shah Abad. Astronomy, Medicine, mathematics and religious subjects were thought in this university. A bridge is being seen in Dezful city on Dez River. It contains two parts that are connected to each other, an ancient part that was built about 1750 years ago, in Sasanians era and a new part. Cars pass on it now. It shows ancient Iranians' advanced knowledge of civil and water engineering (Fig. 15).

Figure 15 Dezful bridge.

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Water Sustainability of Ancient Civilizations in Mesoamerica and the American Southwest

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Abstract: Many civilizations, which were great centers of power and culture, were built in locations that could not support the populations that developed. Throughout history, arid and semi-arid lands seem to have produced more people than they can sustain. I will attempt to make comparisons between civilizations of the past in Mesoamerica and the American southwest and the present world in the context of water resources sustainability. Water has always been a very important factor in the development and survival of societies. A central theme of this paper is very simply the ancients have warned us.

Keywords Ancient civilizations; sustainability; water resources.

Introduction

What is water resources sustainability?

Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life.

Frameworks for civilizations to collapse

Diamond (2005) proposed a five-point framework for the collapse of societies: (a) damage that people inadvertently inflict on their environment, (b) climate change, (c) hostile neighbors, (d) decreased support by friendly neighbors, and (e) society's responses to its problems. I will refer to this framework throughout the discussions even though some don't like the use of the term collapse when discussing civilizations. There is no doubt that the ancient societies in Mesoamerica and the Southwestern United States that I discuss did collapse partially from the depletion of natural resources and climate change, particularly as related to water. This depletion of natural resources and climate changes then led to other events relating to Diamond framework that caused the eventual complete collapse.

Mesoamerica

Many Mesoamerican civilizations developed and failed for various reasons. The period or era from about 150 A.D. to 900 A.D. (called the Classic) was the most remarkable in the development of Mesoamerica (Coe, 1994). Figure 1 shows Mexico during the classic period. During the Classic Period the people of Mexico and the Maya area built civilizations

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comparable with advanced civilizations in other parts of the world. In Mesoamerica the ancient urban civilizations developed in arid highlands where irrigation (hydraulic) agriculture allowed high population densities. In the tropical lowlands, however, there was a dependence on slash-and-burn (milpa) agriculture which kept the bulk of the population scattered in small hamlets. Sanders and Price (1968) suggest that the non-urban lowland civilization resulted from responses to pressures set up by the hydraulic, urban civilization. Teotihuacan (City of the Gods) in Mexico is the earliest example of highland urbanism.

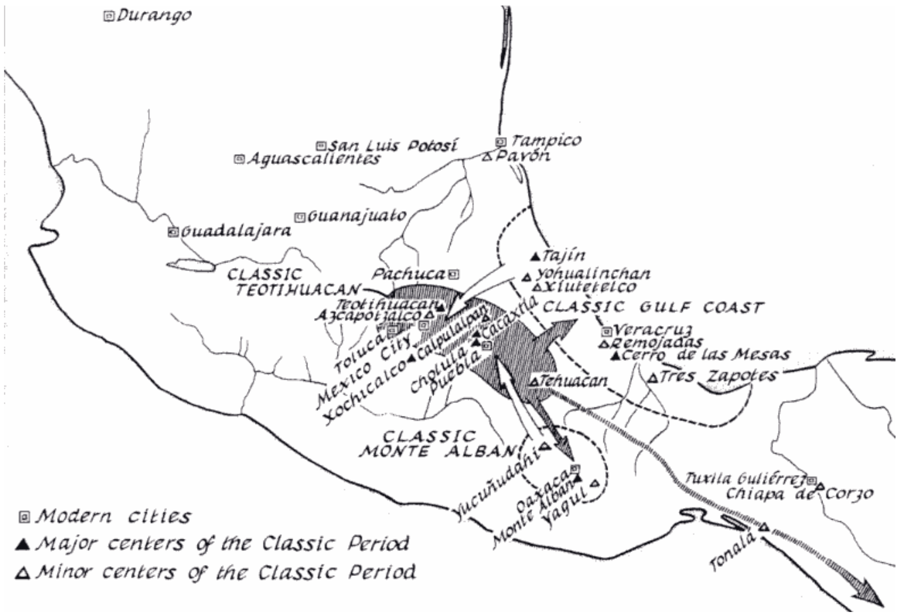

Figure 1 Classic period in Mexico showing the area (shaded) covered by the Teotihuacan civilization and its extensions in Mexico (Coe, 1994).

Teotihuacans

Teotihuacan was a very impressive civilization which evolved about twenty-five miles north of Mexico City around the same time as Rome. Prior to 300 B.C., Teotihuacan valley had a small population spread over the valley and was the dominant urban center in Mesoamerica throughout the classic period. By 100 A.D. Teotihuacan covered an area of 12 km² which has been linked to the development of so-called hydraulic agriculture (Haviland, 1970). The urban area expanded in size, there was an increased socio-economic diversity, and an expanding political influence. At its height, around 600 A.D., Teotihuacan was fully urban with a population of approximately 85,000 people and covering an area of 19 km² (Haviland, 1970). Millon (1993) has estimated that the maximum population was approximately 125,000 during the Xolalpan phase. Teotihuacan was the largest urban center of the time in Mesoamerica.

Around 300 B.C. the use of canals for irrigation rapidly spread throughout the central highland basin, the location of Teotihuacan (Doolittle, 1990). South of Teotihuacan near Amanalco, Texcoco east of the Basin of Mexico), irrigation would have consisted of diverting water from shallow spring-fed streams into simple irrigation canals and then onto fields only a few meters away. Flood water systems also were used. Northeast of

Teotihuacan, south of Otumba, a series of ancient irrigation canals (dating between 300 and 100 B.C.) were excavated. Other canals in the same area date to 900 A.D. to 1600 A.D. Evidence also exists of canals that were built between 200 A.D. and 800 A.D. near Teotihuacan. One of these was the first confirmed relocation of a natural stream. The reader can refer to Doolittle (1990) for further information on these canals

The city of Teotihuacan was abandoned mysteriously around 600 A.D. to 700 A.D. During this time the collapse of civilized life occurred in most of central Mexico. One possible cause was the erosion and desiccation of the region resulting from the destruction of the surrounding forests that were used for the burning of the lime that went into the building of Teotihuacan. The increasing aridity of the climate in Mexico may have been a related factor. The entire edifice of the Teotihuacan state may have perished from the loss of agriculture. Even though the city had no outer defensive walls, Millon (1993) believes that it was not an open city easy for hostile outsiders to attack. The collapse of Teotihuacan opened civilized Mexico to nomadic tribes from the north. Human malnourishment has been indicated from skeletal remains.

Xochicalco

After the disintegration of Teotihuacan's empire in the 7th century A.D., foreigners from the Gulf Coast lowlands and the Yucatan Peninsula appeared in central Mexico. Cacaxtla and Xochicalco, both of Mayan influence, are two regional centers that became important with the disappearance of Teotihuacan. Xochicalco (in the place of the house of flowers), was located on hill top approximately 38 km from Cuernavaca, Mexico, and became one of the great Mesoamerican cities in the late classic period (650 - 900 A.D.). Figures 2 (a) and (b) show scenes of the city, which was well thought out with terraces, streets, plazas, and buildings. Despite the very Mayan influences, the predominant style and architecture is that of Teotihuacan. There were no rivers or streams or wells to obtain water. Water was collected in the large plaza area and conveyed into cisterns such as the one shown in Figure 2 (c). From the cisterns water was conveyed to other areas of the city using pipe as shown in Figure 2(d). The collapse/abandonment of Xochicalco, most likely, resulted from drought, warfare, and internal political struggles.

Crisis overtook all the Classic civilizations of Mesoamerica (including the Mayans), forcing the abandonment of most of the cities. Some anthropologists believe the crisis may have been a lessening of the food supply caused by a drying out of the land and a loss of water sources to the area. Speculation is that this might have been caused by a combination of a climactic shift towards aridness that appears to have happened all over Mexico during the Classic period and the residents having cut all the timber in the valley. Originally there were cedar, cypress, pine, and oak forests; today there are cactus, yucca, agave, and California pepper trees. Such a change in vegetation indicates a significant climate shift.

The Maya

The ancient Maya lived in a vast area covering parts of present-day Guatemala, Mexico, Belize, and the western areas of Honduras and El Salvador as shown in Figure 3. Mayans settled in the last millennium B.C. and their civilization flourished until around 870 A.D. The environment that the Mayans lived in was less fragile than that of the semi-arid lands where the Anasazi and Hohokam lived. Tikal was one of the largest lowland Maya centers, located some 300 km north of present day Guatemala City. The city was located in a rain forest setting with a present day average annual rainfall of 135 cm.

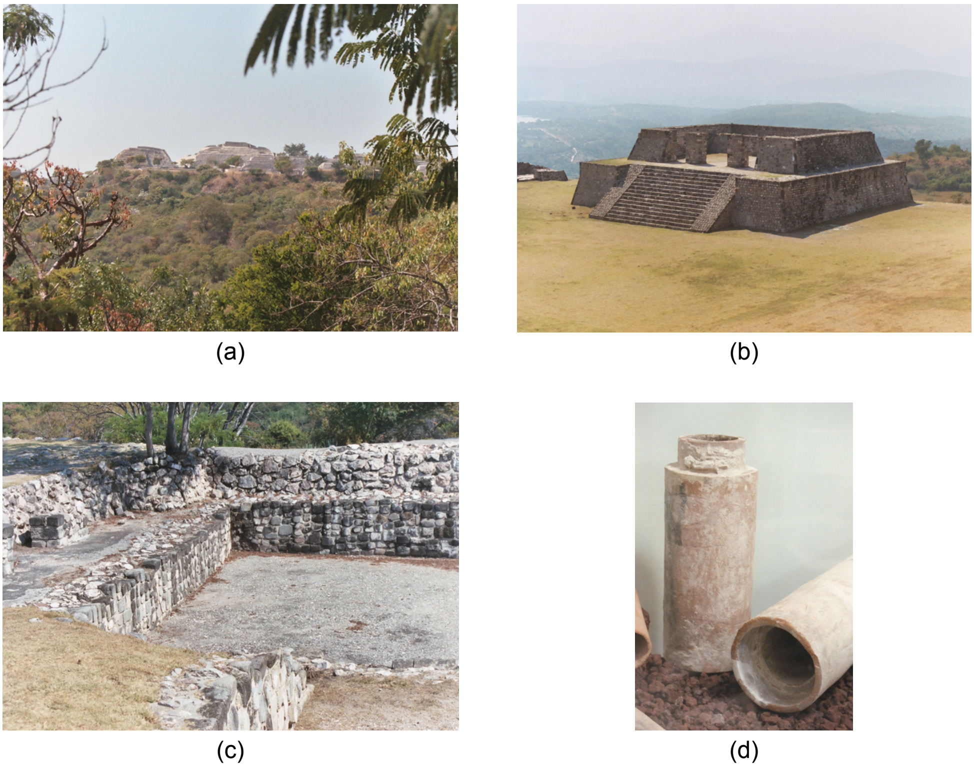

Figure 2 Photos of Xochicalco: (a) View showing Xochicalco on hilltop, (b) view from Xochicalco, (c) cistern, and (d) water pipes.

The urbanism of Tikal was not because of irrigated (hydraulic) agriculture. A number of artificial reservoirs were built in Tikal, which became more and more important as the population increased. With the continued growth, the pressure for land and food reached a position when the population growth stopped or a point of unsustainability. The Mayas settled in the lowlands of the Yucatan Peninsula and the neighboring coastal regions (Fig. 3). The large aquifer under this area is in an extensive, porous limestone layer (Karst terrain), which allows tropical rainfall to percolate down to the aquifer. Because of this and the fact that few rivers or streams exist in the area, surface water is scarce. One important water supply source for the Maya, particularly in the north, was the underground caves (Fig. 4) called cenotes (se-NO-tes), which also had religious significance (portals to the underworld where they journeyed after death to meet the gods and ancestors). In Yucatan there are over 2,200 identified and mapped cenotes. In the south the depths to the water table were too great for cenotes.

Natural surface depressions were lined to reduce seepage losses and were used as reservoirs. Another source was water that collected when soil was removed for house construction in depressions called aguados. The Maya also constructed cisterns called chultans in limestone rock under buildings and ceremonial plazas. Drainage systems were developed from buildings and courtyards to divert surface runoff into the chultans. In the lowlands the Maya typically used one or more of these methods for obtaining and storing water supplies (Matheny *et al.*, 1983). Rainfall varies significantly from the north (457 mm/yr) to the south (2,540 mm/yr) of the Yucatan Peninsula. The soils are also deeper in the southern part resulting in more productive agriculture and consequently supported more people. Rainfall was very unpredictable, resulting in droughts that destroyed crops. Ironically though, the water problems were more severe in the wetter southern part. Ground elevations increased from the north to the south causing the depths down to the water table to be greater in the south.

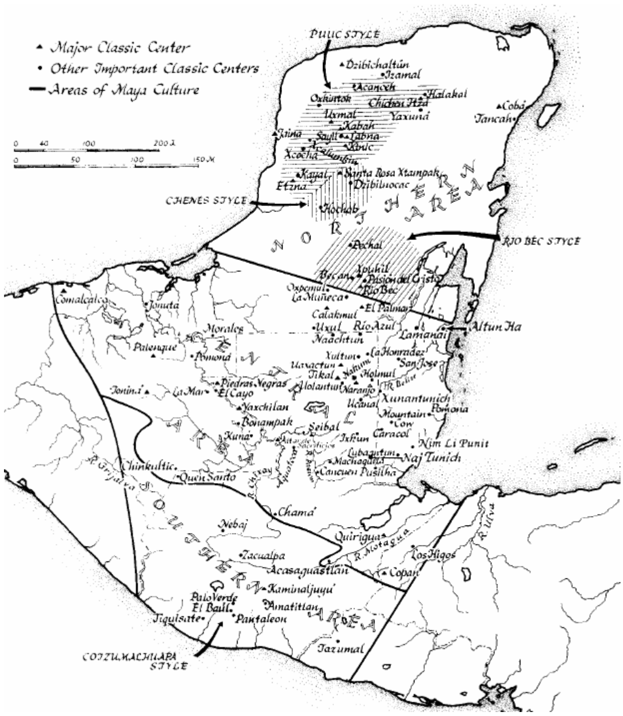

Figure 3 Maya sites during the Classic period (Coe, 1993).

Figure 4 Sacred cenote at Chichen Itza (which means mouth of the well of the Itzas). The word cenote is derived from *tz'onot*, the Maya term for the natural sinkholes. This cenote is, which measures about 50m form north to south and 60m from east to west, was used for sacrifices of young men and women, warriors and even children to keep alive the prophecy that all would live again. Shown at the left is the remains of a building once used as a steam bath, or temezcal, to purify those who were to be sacrificed. Those sacrificed were tossed from a platform that jutted out over the edge of the cenote.

Centuries before the Spanish arrived, the collapse of many other great Mayan cities occurred within a fairly short time period. Several reasons have emerged as to why these cities collapsed, including overpopulation and the consequential exhaustion of land resources possibly coupled with a prolonged drought. A drought from 125 A.D. until 250 A.D. caused the pre-classic collapse at El Mirador and other locations. A drought around 600 A.D. caused a decline at Tikal and other locations. Around 760 A.D. a drought started that resulted in the Mayan classic collapse in different locations from 760 A.D. to 910 A.D.

The soil of the rain forest is actually poor in nutrients so that crops could be grown for only two or three years, then to go fallow for up to 18 years. This required ever increasing destruction of the rain forest (and animal habitat) to feed a growing population. Other secondary reasons for the collapse include increased warfare; a bloated ruling class requiring more and more support from the worker classes; increased sacrifices extending to the lower classes; and possible epidemics. The Maya collapsed as a result of four of the five-factor framework of Diamond (2005). Trade or cessation of trade with friendly societies was not a factor for the Maya.

American Southwest

Three major cultures - the Anasazi, the Hohokam, and the Mogollon- existed in the American southwest during the late pre-contact period (Fig. 5). The concept of prehistoric regional systems has been used to describe these cultures (Crown and Judge, 1991). The Hohokam and Chaco regional systems have received particular attention as two of the most important. The extent of the Hohokam regional system has been defined by ball courts and material culture, and the Chaco regional system has been defined by roads and other architectural criteria. Each of these occupied a distinctive ecological niche within the southwestern environment, and as a consequence their infrastructures significantly differed. The American southwest is a difficult and fragile environment consisting of arid and semi-arid lands.

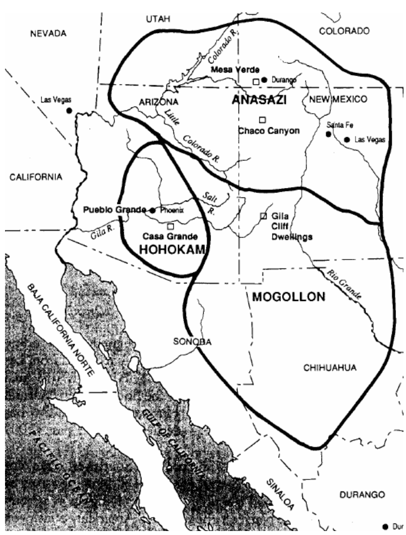

Figure 5 Three cultures in the American southwest (Thomas, 1994).

The Hohokam (300 B.C. to 1450 A.D.)

Hohokam, translated as "the people who vanished", is the name given to their prehistoric predecessors by the present-day Pima Indians. The Hohokam built a complex irrigation system in the desert lowlands of the Salt-Gila River Basin, Arizona. They built more than 300 miles of major canals and over 700 miles of distribution canals in the Salt River Valley, which have been identified, see Figure 6. The Hohokam civilization started in the Valley somewhere between 300 B.C. and 1 A.D. (Crown and Judge, 1991) and extended to A.D. 1450 (Lister and Lister, 1983). A schematic representation of the major components of a Hohokam irrigation system is shown in Figure 7. The Hohokam canal system was built with no technology other than stone tools, sharpened sticks, and carrying baskets.

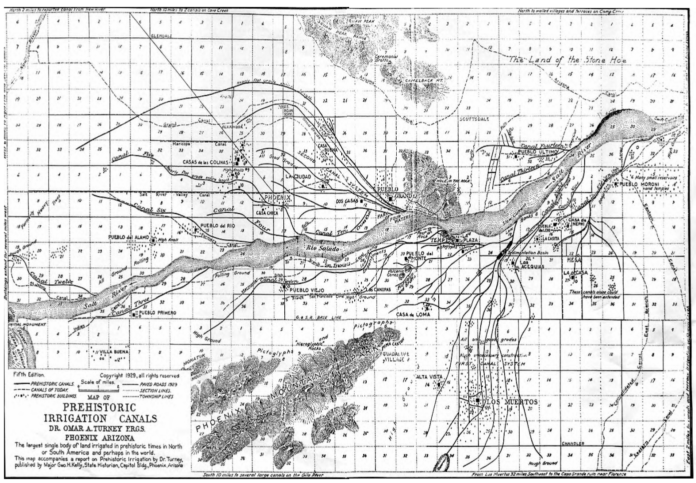

Figure 6 Hohokam canal system in Salt river valley (Turney, 1929).

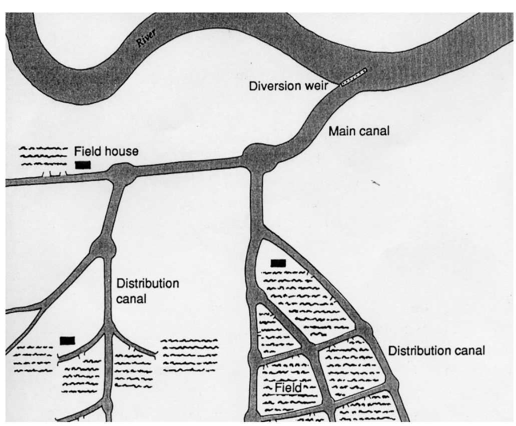

Figure 7 Components of Hohokam irrigation system (Masse, 1991).

In 899 A.D. a flood caused decentralization and widespread population movement of the Hohokams from the Salt-Gila River Basin to areas where they had to rely upon dry farming. The dry farming provided a more secure subsistence base. Eventual collapse of the Hohokam regional system resulted from a combination of several factors. These included flooding in the 1080's, hydrologic degradation in the early 1100's, and larger communities forcibly recruiting labor or levying tribute from surrounding populations (Crown and Judge, 1991). In 1358 a major flood ultimately destroyed the canal networks, resulting in the depopulation of the Hohokam area. Culturally drained the Hohokam faced obliteration about 1450. Parts of the irrigation system had been in service for almost fifteen hundred years, which may have fallen into disrepair, canals silted in need of extensive maintenance, and problems with salt. See Woodbury (1960), Haury (1978), and Masse (1981) for further information.

The Chaco Anasazi (600 A.D. to 1200 A.D.)

In the high deserts of the Colorado Plateau (Fig. 8), the Anasazi (a Dine' (Navajo) word meaning "enemy ancestors"), also called the "ancient ones", had their homeland. When the first people arrived in Chaco Canyon, there were abundant trees, a high groundwater table, and level floodplains without arroyos. This was most likely an ideal environment (conditions) for agriculture in this area. Chaco is beautiful with four distant mountain ranges: the San Juan Mountains to the north; the Jemez Mountains to the east; the Chuska Mountains to the west; and the Zuni Mountains to the south.

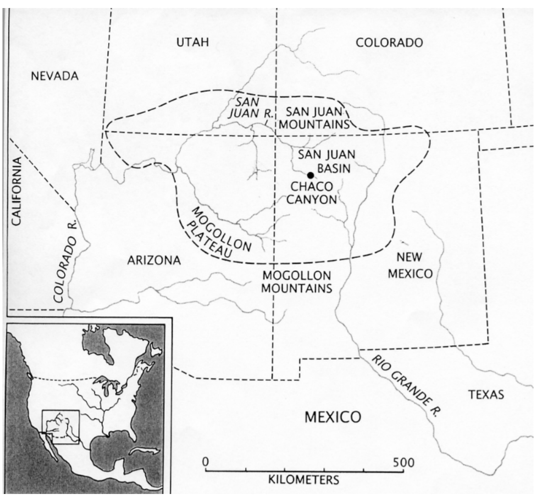

Figure 8 Anasazi Region Showing Chaco Canyon (Lekson *et al.*, 1988).

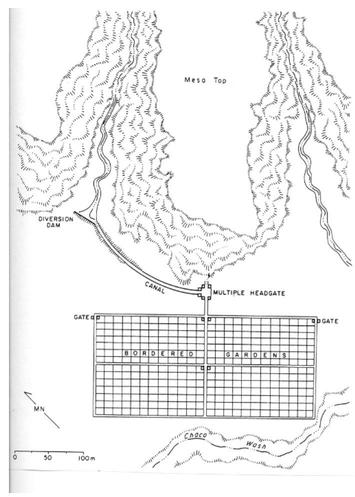

Figure 9 Water-control System in Chaco Canyon (Vivian, 1974).

The first Anasazi settlers, also called basket makers, arrived in Mesa Verdi around A.D. 600. They entered the early Pueblo phase (A.D. 700-900) which was the time they transitioned from pit houses to surface dwellings, evidenced by their dramatic adobe dwellings, or pueblos. Chaco Canyon was the center of Anasazi civilization, with many large pueblos probably serving as administrative and ceremonial centers for a widespread population of the Chaco regional system. Also of particular note is the extensive road system, built by a people who did not rely on either wheeled vehicles or draft animals. The longest and best-defined roads (constructed between 1075 A.D. and 1140 A.D.) extended over 50 miles in length. The rise and fall of the Chacoan civilization was from 600 A.D. to 1200 A.D., with the peak decade being 1110 A.D. to 1120 A.D..

Chaco Canyon is situated in the San Juan Basin in northwestern New Mexico as shown in Figure 8. The basin has limited surface water, most of which is discharged from ephemeral washes and arroyos. Figure 9 illustrates the method of collecting and diverting runoff throughout Chaco Canyon. The water, collected from the side canyon that drained from the top of the upper mesa was diverted into canals by either an earthen or a masonry dam near the mouth of the side canyon (Vivian, 1990). These canals averaged 4.5 m in width and 1.4 m in depth; some were lined with stone slabs and others were bordered by masonry walls. The canals ended at a masonry head gate, where water was then diverted to the fields in small ditches or to overflow ponds and small reservoirs.

The diversion of water into the canals combined with the clearing of vegetation resulted in the eroding (cutting) of deep arroyos to depths below the fields being irrigated. By 1000 A.D. the forests of pinyon and juniper trees had been completely deforested to build roofs, and even today pinyon and juniper trees do not grow there as shown in Figure 10. Between 1125 A.D.and 1180 A.D., very little rain fell in the region. After 1180, rainfall briefly returned to normal. Another drought occurred from 1270 A.D.to 1274 A.D., followed by a period of normal rainfall. In 1275 A.D., yet another drought began which lasted 14 years.

Figure 10 Chaco Canyon.

Of the five-factor framework for social collapse suggested by Diamond (2005), the only factor that did not play a role in the collapse of the Anasazi was hostile neighbors. Water sustainability was affected by the deforestation, the erosion (cutting) of the arroyos from the diversion of water resulting in lowering the groundwater levels and the supply source to the irrigated fields, and finally the repeated periods of drought caused the final collapse.

The Past and the Future

Relevance of the ancients

What relevance does the collapse of ancient civilizations have upon modern societies? When I look at the rapid development and population increases in the south western United States, with limited water resources, I continue to hope that our government will do something. So many areas are being developed without regard to the future availability of water. In many cases paper water (water created on paper that really doesn't exist) is being used to justify these projects. In recent decades we have not been exposed to the repeated severe droughts that historically have occurred. Neither have we been faced with the realties of what a global climate change might bring.

One might argue that if the ancient societies had our present day technologies, they would not have failed. In my opinion we have those technologies and there is a good chance we will fail. I don't think that even newer technologies are the answer for our present day problems. We have the technologies to have prevented the problems such as the Aral Sea. The technologies have existed to have prevented many of the problems associated with the water problems of Mexico City. The technologies have been available to have prevented much of the resulting flood damages of New Orleans from Hurricane Katrina. What we need is for society to have the will, possibly the political and institutional will, to decide to fund and apply the available technology/solutions. Remember the ancients have warned us.

The unsustainable American southwest

Quoting Falkenmach and Lindh (1993), "Water's fundamental importance in sustaining life and a culture makes any threat to an area's water supply a threat to its economic life as well." The American west and southwest is an excellent example of a region that has a non-sustainable water base for economic activity in the future. This is a region with arid and semiarid climates that has attracted a large and growing population. Unfortunately the people of this region have relied on expensive supply-side projects such as the Central Arizona Project to import water from the Colorado River. Another is the importation of water to southern California cities via aqueducts from northern California and the Colorado River. There are many others.

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Machu Picchu Water Supply

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Abstract: The water supply development and engineering achievements of the Inca at Machu Picchu demonstrate that the Inca were knowledgeable water engineers. The Inca engineers efficiently developed difficult water supplies at selected locations and designed fountain hydraulics for effective water use and function. The Inca mastered technology transfer and adopted techniques and methods from preceding times. The engineering works at Machu Picchu are described, including the Inca spring and canal, fountain design, and drainage. Finally, the paper includes a description of the discovery of a long-hidden Inca trail and adjacent fountains.

Keywords Canal; drainage; fountain; hydraulics; hydrology; Inca; Machu Picchu; trail; water supply.

Introduction

Machu Picchu was a royal estate built by the Inca before the arrival of the Spanish Conquistadors (Fig. 1). It was abandoned after the Inca Empire collapsed and endured under a thick rain forest until the 20th Century. Scientists, engineers, and laymen alike continue to marvel at the wonders of Machu Picchu and its magical ambiance and advanced hydrological layout. Machu Picchu is an unlikely place to construct a royal estate due to remoteness, geologic faults, landslide potential, and, particularly, water availability. The water engineering achievements of the Inca at Machu Picchu, when defined in technical terms common to modern engineers, demonstrate that the Inca were indeed good water engineers. They were able to learn from previous cultures and adopted selected technologies for their own use. Also, they had the uncanny ability to plan public works and infrastructure in a manner that fit this difficult site with full consideration of the needs of the architects and residents.

Figure 1 The “Lost city of the Inca” incorporates unique water management features.

The Ancient Royal Estate

In the 1913 issue of *National Geographic* magazine, Prof. H. Bingham first announced to the world that the "Inca were good engineers" (Bingham, 1913). He concluded this after his 1912 clearing and mapping of Machu Picchu. Started in A.D. 1450 as a royal estate of the emperor Pachacuti (Rowe, 1990), the Machu Picchu location was an unlikely place to build what would become, 500 years later, South America's most well known archaeological site. Machu Picchu is a breathtaking monument to the water supply engineering skills of the Inca people. Machu Picchu likely ceased normal operation by A.D. 1540 due to the Spanish conquest and collapse of the Inca Empire. While Machu Picchu is judged to have been mostly abandoned by A.D. 1540, final abandonment did not happen until A.D. 1572 (Rowe, 1990). Fortunately, the site sat alone and isolated, except for a few Quechua Indians, until Bingham made his heralded discovery in 1911 (Bingham, 1930).

Although the Inca did not have a written language, the well-preserved remains of Machu Picchu show that they had an advanced understanding of such principles as hydrology and hydraulics. By studying Inca engineering techniques, in conjunction with the natural environment, we are able to supplement existing archeological theory on Inca practices, religion and the significance of Machu Picchu. The technical planning of Machu Picchu is surely the key to the site's longevity and functionality. Their strong knowledge of hydrology helped make it a grand and operational retreat high in the most rugged of terrain. Built on a ridge between the mountains of Machu Picchu and Huayna Picchu to house a resident population of 300 with a peak population of 1,000, the Inca engineers worked with nature to create a community with a reliable water supply, good storm drainage, flat areas for agriculture, and building foundations that would meet the challenges of steep, unstable slopes and high rainfall. They constructed a remarkable Inca Trail system, which would connect Machu Picchu with the outside world, not only via Cusco, but downstream to the Vilcabamba region. Analysis of the Inca civil engineering achievements at Machu Picchu, ranging from their use of hydrologic and hydraulic principles to their erosion control and soil stewardship, makes it clear that they adopted technologies from other peoples and past empires. Then, as now, technology transfer was a key factor to engineering success.

Site selection and water supply

The Machu Picchu site is extraordinary; modern visitors say it is breathtaking. The Inca planners and engineers would have judged the site to be well suited for a royal estate. First, it is surrounded on three sides by the steep, roaring, and sacred Urubamba River. Second, the site is on a graben between two regional faults that created the two sharp peaks of Huayna Picchu and Machu Picchu Mountains. Across the river is the steep Putucusi peak that has a rounded profile like a half orange when viewed from Machu Picchu. Even today, all three peaks are considered to be holy mountains by the Quechua Indians. Further away is the triangular-shaped mountain called Yanantin and the glacier-capped flanks of Mt. Veronica. Some 20 km south is Mt. Salcantay (6,257 m elevation). Arrow stones on the Intiwatana and Huayna Picchu summits point toward Mt. Salcantay.

Without the perennial spring on the north slope of Machu Picchu Mountain, there would have been no Machu Picchu to admire. Before the Emperor's selection of the site for his royal estate, the civil engineers would have had to determine that a suitable water supply would be found. Pachacuti was a ruler to be reckoned with, and the engineers had to be sure of their water supply evaluations. The high mountain ridge between two prominent peaks would appear to be an unlikely location for ancient people to have found a pure, reliable groundwater source. However, the nearly 2,000 mm of annual rainfall, a modestly-sized tributary drainage basin, igneous bedrock, and extensive faulting at the site, collectively provided the engineers with a reliable domestic source of water. The spring found and developed on the steep north slope of Machu Picchu Mountain made it feasible for the Inca ruler to build his sanctuary at this stunning location.

Engineering was the basis of the architectural layout of Machu Picchu

By locating the spring and designing a canal to carry the water into the site, Inca hydrologists and hydraulic engineers were responsible for establishing the location of the focal point of Machu Picchu-the Temple of the Sun and the emperor's residence. It was important for the emperor to have the first uppermost fountain close at hand (Fig. 2).

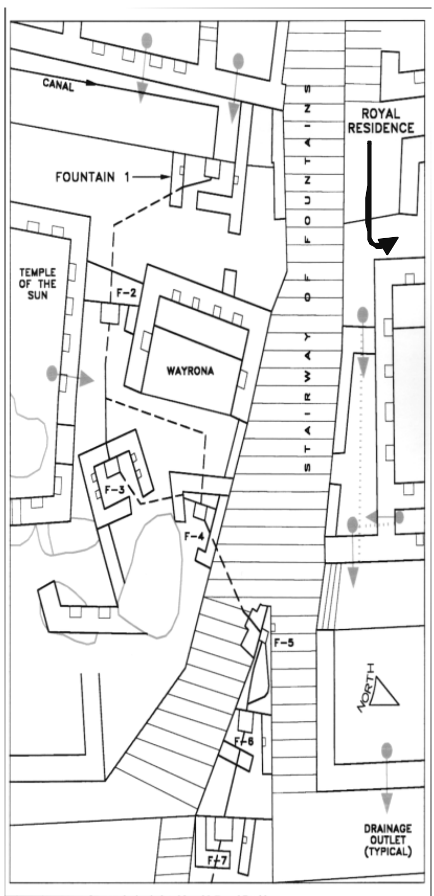

Figure 2 The 16 fountains of Machu Picchu provided a reliable domestic water supply.

The Inca must have planned Machu Picchu in stages. Their civil engineers would have first identified a suitable water supply, developed the water to "prove-up" its dependable yield, and then laid out a suitable canal right-of-way on a proper slope. The next step would have been to insure the location of a "first fountain" before being able to locate the Royal Residence next to the fountain. The engineers at Machu Picchu were remarkably successful with the water supply. Fountain No. 1 was identified, the Royal Residence location was set, and a series of fountains were constructed to carry a clean potable water supply down through the urban sector of Machu Picchu. The steep adjacent Stairway of the Fountains was constructed so that the fountains were accessible for the residents using their ceramic *aryballos* or water bottles.

Overview of Machu Picchu Hydraulic Works

The spring

The Machu Picchu geologic fault caused fracturing and crushing of the adjacent hard granite rock, which in turn resulted in a natural spring on the north slope of Machu Picchu Mountain (Wright *et al.*, 1997a). While the water supply for the fountains was derived from a natural spring, using a clever groundwater interception structure, an effective spring collection works enhanced the yield of this spring (Fig. 3). There is a direct correlation between precipitation and spring yield. Figure 4 shows that precipitation variations during the year resulted in seasonal variations of Inca spring flow.

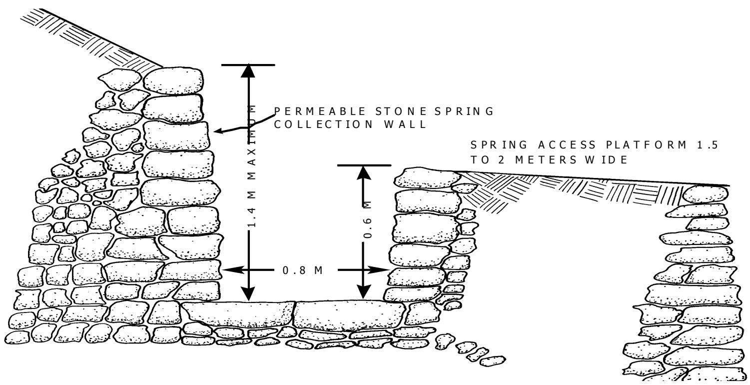

Figure 3 The Inca Spring headwork was carefully constructed into the steep hillside to capture the flow derived from the fractured granite bedrock.

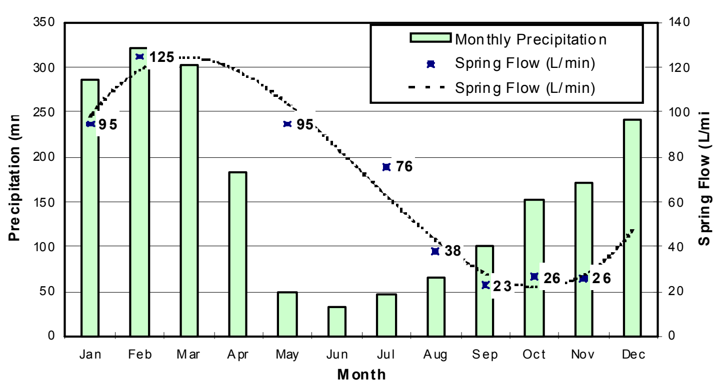

Figure 4 Yield from the Inca Spring was monitored during several seasons to define its relationship to the occurrence of rainfall.

Water supply canal

A small stone-lined canal carried domestic water by gravity flow from the Machu Picchu spring to the city center at Fountain No. 1. The locations of the water supply canal are prescribed by the constraints of gravity flow of water from the primary spring (Wright *et al.*, 1997b). The canal traversed the steep mountainside on a narrow terrace formed by a sturdy and well-founded wall, in some places 4 m high. The 749 m long canal was built at an engineered slope with a typical hydraulic cross-section of 13 x 12 cm, so as to be capable of handling up to 300 L/min, the measured spring yield being 23 to 125 L/min, as shown in Figure 4. Stones that are partially cut and laid out on a different terrace show that the Inca engineers were in the process of constructing a branch canal off of the main canal at the time of abandonment, utilizing the excess capacity of the main canal.

The fountains

The Inca canal delivered its water supply by gravity flow to Fountain No. 1 at an elevation of 2,437 m, which then defined the location of the entrance to the Royal Residence so the emperor would have first use of the pure spring water. Here, the Temple of the Sun, the Sacred Fountain, and the Wayrona would also be built. Also incorporated into the special complex would be Fountain Nos. 2 through 6 (Fig. 2). The Temple of the Sun was Machu Picchu's urban focal point: a solar observatory and religious center, with a series of 16 fountains. The aesthetic and functional layout and construction of the fountains make them a notable example of pre-Colombian civil engineering and planning. The fountains are in series except for the Sacred Fountain (No. 3), which now has an optional flow bypass to allow water delivery directly from Fountain No. 2 to Fountain No. 4. The bypass is likely a modern addition. Downhill, another 10 fountains were constructed in series for domestic water supply purposes with the last fountain being a private water supply accessible only from the Temple of the Condor. The remaining water was then carried in a buried conduit and then an open channel for discharge to waste into the Main Drain (a.k.a. Dry Moat). The hydraulic design of the fountains allowed for reasonable operation for a flow of between 10 and 100 L/min. At over 100 L/min, the control orifice in Fountain No. 4 would reject excess water for overflow down the granite stairway of the fountains (Wright *et al.*, 1997c).

Drainage

The focal point of the drainage was the Main Drain that separated the Agricultural Sector from the Urban Sector. It was designed for receiving gravity drainage from both the north and south. The Main Drain was built on the line of a minor geologic fault extending up from the Urubamba River near the base of Putucusi Mountain. With nearly 2,000 mm annual precipitation, it was imperative that extensive storm drainage engineering be incorporated throughout the ridge-top royal estate. For instance, there were a total of 129 formal drainage outlets incorporated into the urban sector wall construction. These are no ordinary wall holes, but carefully planned and adequately sized structural openings established at just the right elevation to drain interior floor surfaces. Runoff from thatched roofs and compacted urban surfaces was high, and for that reason, a relatively safe set of drainage criteria was used that accounted for the high rainfall amounts. By examining the size and pattern of drainage outlets at Machu Picchu, it was possible to define the empirical hydraulic criteria used by Inca engineers (Table 1) (Wright *et al.*, 1999).

New Discoveries: Fountains and Inca Trail Excavations

Fountains on the lower East Flank

The Machu Picchu Paleohydrological Survey Project team was aware of long-hidden fountains on the lower east flank of the Machu Picchu ridge (Valencia and Gibaja, 1992). In 1969, Dr. Valencia, now the local registered archaeologist for this project, had inspected the area after a forest fire there, but unfortunately his sketches were lost. In 1995, the team began exploring the east flank by cutting random trails using local Quechua *macheteros*.

Table 1 Urban surface runoff criteria for wall drainage outlets.

Primary	Magnitude
Tributary area per drainage outlet	200 m²
Drainage outlet size, typical	10 cm by 13 cm
Drainage outlet capacity, maximum	650 L/min
Design rainfall intensity	200 mm/h
Rational formula runoff "C"	0.8
Design flow per drainage outlet	500 L/min

A utilitarian bath-like structure was found in 1995, followed by a second similar fountain in 1996. The first was adjacent to the Outer Wall, while the second was situated around a sharp bluff. In August 1996, two ceremonial fountains were discovered closer to the cliff base of Huayna Picchu. Finally, in early 1997, while the Indian *macheteros* were recutting vegetation that had filled in between field visits, they missed their bearings and ended up at another fountain some 150 m beyond the ceremonial fountains. This fountain had been heavily damaged by a large rock fall; however, an adjacent walled-in cave was undamaged. We named these fountains, Fountain Nos. 1 to 5. Our access to these fountains was via the Outer Wall leading down from the agricultural sector.

In November 1997, an attempt was made to cut a trail through the rainforest from the stairway below Conjunto 13 of Machu Picchu, but to no avail due to the thick and tangled vegetation. In September 1998, the Instituto Nacional de Cultura issued an excavation permit for five east flank fountains. Excavations were commenced the same month. The technical results of the excavations were remarkable for five reasons: (a) Fountain Nos. 3 and 4 had been so well planned and executed by the Inca that upon excavation and cleaning out of the spring water supply, they immediately began to flow as they had 450 years ago. After a short while the water was clear enough to drink; (b) the physical setting of the two fountains was extraordinary in its commanding view; (c) the water supply for Fountain No. 5 was a well-constructed, stone-lined tunnel into the hillside to collect groundwater; (d) the jet-forming channels for the two ceremonial fountains were carefully formed using a Venturi-like shape which would speed up the flow of water, causing the jet of water to spring free of the stone wall during low flow conditions; and (e) adjacent to Fountain Nos. 3, 4, and 5, the primary Inca Trail from Machu Picchu down to the Urubamba River was uncovered. The trail, with 3 m wide granite staircases, was in excellent condition showing good erosion control methods and stability against earthslides on the steep slope.

Inca trail to the Urubamba river

Even though we made the two newly excavated ceremonial fountains flow again, it was the primary Inca Trail that was the highlight of the excavation work. We realized that the fountains and terraces, each extraordinary in their own right, were actually parts of the infrastructure of the long-lost trail. The configuration of fountains, terraces, and spectacular 10-step, 3 m wide granite staircases made it clear that this was the main Inca Trail down from Machu Picchu to the Vilcabamba region. Scholars have examined the several other pathways off the Machu Picchu ridge and each time found them to be too narrow or too skimpy. This trail, however, met the criteria to qualify as the main route.

The Inca planning and construction of the uncovered portion of the trail included a drainage infrastructure. At one location, an underground stone conduit discharged to a channel running parallel to a second long set of stairs, while adjacent to the conduit is a surface drain which discharged onto a terrace. A special feature of both Fountain Nos. 3 and 4 was a narrowing of the approach channel where the water jets outward causing the flowing water to speed up and spurt out further than without the narrowing. This is evidence that the Inca engineers understood the fundamental mechanics of water flow, and that they had the knowledge to enhance the hydraulic operation of the two fountains to account for periods of low flow. To ensure that the two ceremonial fountains would not overflow during periods of excessive water yield, a hydraulic bifurcation was built just upstream of Fountain No. 4 so excess water would be diverted into a stone-formed conduit to discharge to an adjacent drainage channel (Fig. 5).

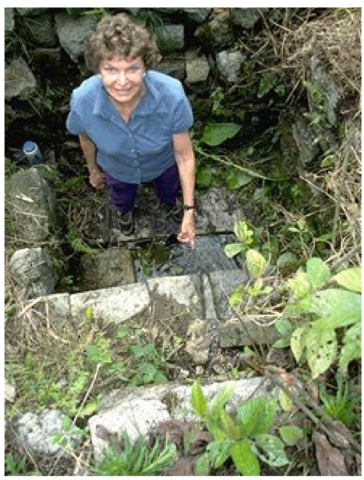

Figure 5 The adjacent drainage channel.

The two ceremonial fountains were built in series with a fine 14-step granite staircase connecting to the Inca Trail. The staircase ends on a viewing platform above the fountains. The result was a perfectly framed view of the spectacular triangular summit of Yanantin Peak. On the right is the near-vertical profile of Putucusi Mountain; while on the left is the profile of the steep Huayna Picchu Mountain. The bottom is the Urubamba River.

Fountain Nos. 1 and 2 along the Inca Trail are categorized as utilitarian fountains because neither include falling jets of water, and they do not represent the artistic achievement of the other Machu Picchu fountains. Nevertheless, as engineering achievements, Fountain Nos. 1 and 2 are notable in their function, reliability, and location. Adjacent to Fountain No. 1 are the remains of three buildings that likely were residences for agricultural field workers. The “long house” is between Fountain Nos. 1 and 2. It likely served to sleep workers and to store grain. Fountain No. 1 had been damaged by a rockfall; however, the rockfall left the adjacent, well-constructed wall with a fine lintel beam lying in the doorway opening. Fountain No. 5 was special in several respects even though an old rock had totally smashed the fountain area. Here, at Fountain No. 5 was a water tunnel 0.8 m wide and over 1 m high with a slab roof of cut granite. The tunnel extended into the hillside 2.8 m, but was destroyed where it exited the hillside. Above the tunnel is a walled-in cave that, when excavated, showed that it was filled with earth and stones to nearly roof level.

Conclusions

The engineering work at Machu Picchu, ranging from the Inca spring and canal to its drainage and fountain design, represents Inca knowledge of the fundamentals of physics, hydraulics and mathematics. It would appear that the Inca hydrologists were masters of technology transfer and adoption of building techniques and methods from preceding times.

The results of the excavations of five Machu Picchu lower east flank fountains demonstrated the ability of the Inca engineers to efficiently develop difficult water supplies at selected locations and to design fountain hydraulics for efficient water use and function. The hydraulics of the two ceremonial fountains was designed to optimize the velocity of the jet of water in low-flow periods and to limit the water flow in wet periods. The similarity of the two excavated ceremonial fountains to others in the Machu Picchu area was noted. When we finally closed down the excavations, there was one final obligation. It was a ceremony at Fountain Nos. 3 and 4 requested by the *macheteros*. Florencio Almiro Dueñas led the ceremony in Quechua (language of the Inca) with the following:

> *Today, having finished our excavations at Machu Picchu next to this water fountain, I call to the spirits of the Gods of Machu Picchu, Putucusi, Intipunka, and Mandor. Here is Pachamama – pacha earth, beautiful mother, do not let the fountains go dry; every year water must flow forth so that we can drink.*

Florencio then took a piece of bread, put it into the hole he had dug, and covered it as an offering to the gods.

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The Management of Water Resources in Chersonissos, Crete, Greece, During the Roman Period

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Abstract: During the Roman imperial period, increasingly complex systems for the tapping, transfer, storage and consumption of water were utilized across the Mediterranean. In Crete, a wealth of such remains (including aqueducts, reservoirs, cisterns, bathhouses etc.) have been documented over the past centuries through field exploration, survey and excavation. This poster presents and discusses the relevant evidence for water management dating to the Roman period from the town of Chersonissos and its hinterland. Starting with the discussion of water sources and the aqueduct, the paper traces the course of the supply network through the excavated remains of water conduits, cisterns and bathhouses.

Keywords Aqueduct; baths; Chersonissos; Roman; water supply.

Introduction

During the Roman period, Chersonissos, a town on the north-central coast of Crete, appears to have experienced a significant degree of civic growth and prosperity, as suggested by both textual and archaeological evidence (Chaniotis, 2006). Among the most visible indicators of this prosperity are the numerous remains of installations of the Roman period related to the supply and consumption of water that have been excavated in recent years by the 23rd Ephorate of Prehistoric and Classical Antiquities in the modern town of Limenas Chersonissou. The purpose of this paper is to assemble and present for the first time in an integrated manner this evidence for the water supply network and the management of water resources in the town during the Roman imperial and Late Roman/ Early Byzantine period (late 1st century B.C.-7th century A.D.).

Water Tapping and Transfer: The Aqueduct of Chersonissos

The existence of an aqueduct that supplied Chersonissos during the Roman period has been known since at least the 16th century A.D., when the Venetian traveller Onorio Belli first noted and described its impressive remains in the vicinity of the ancient town (Chatzi-Vallianou, 1985: 123). Recent archaeological discoveries and research suggest that during the Roman period the city was supplied from a separate aqueduct than the one that served Lyttos (Oikonomakis, 1984: 84-88; Mandalaki, 2001). The aqueduct tapped one of the numerous fresh water sources that are located in the wider area of Kalo Chorio in the Pediada region, and which continue to be used to the present.

The architectural remains of the aqueduct can be first encountered in the riverbed of the Aposelemis river near Kamares on the road to Kastelli Pediadas (Fig. 1). They comprise a series of massive 12 m high piers of the arcades that supported the conduit which were built in concrete at the core and faced with ashlar blocks, and the terraces of the aqueduct bridge, which lie on the left bank of the river, higher than the modern road. After straddling the riverbed and the nearby slope over the road, the aqueduct turns N towards Chersonissos, at which point two conduits can be discerned running parallel to each other, one flush to the right-hand side river bank, the other about 50 m higher. Although this bifurcation may be the result of two different construction phases, it is equally possible that the course was originally designed to split into two conduits, a usual feature of Roman aqueduct construction.

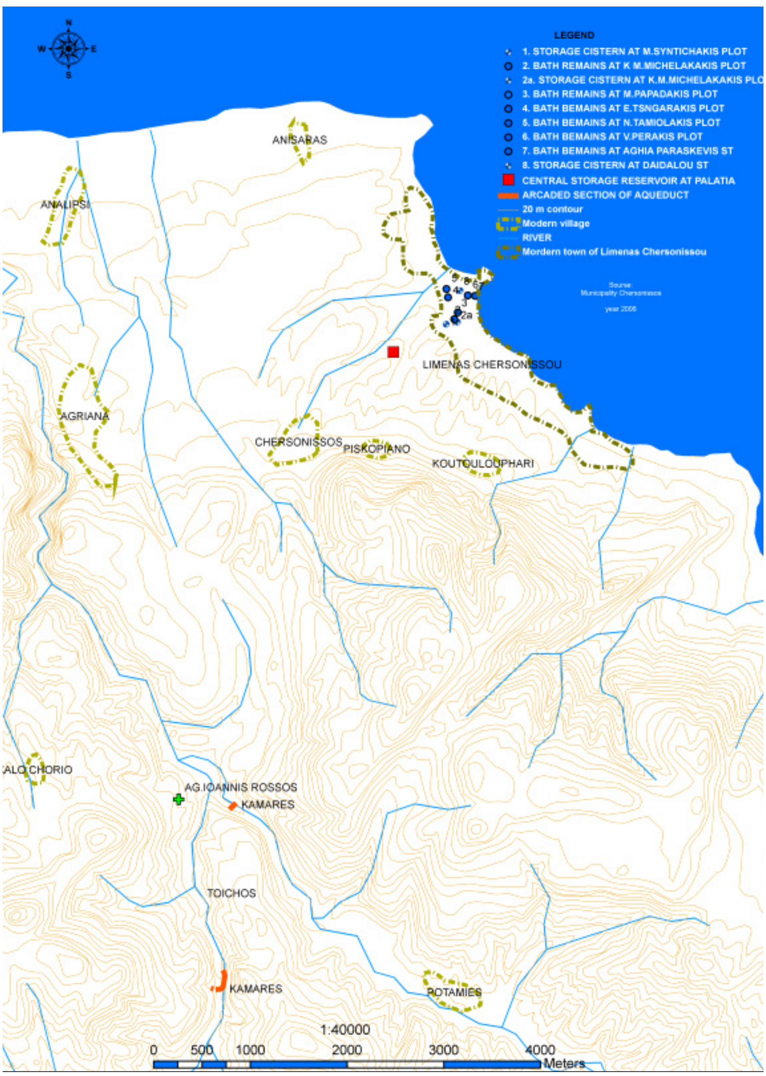

Figure 1 Remains of the water supply network of Chersonissos during the Roman period.

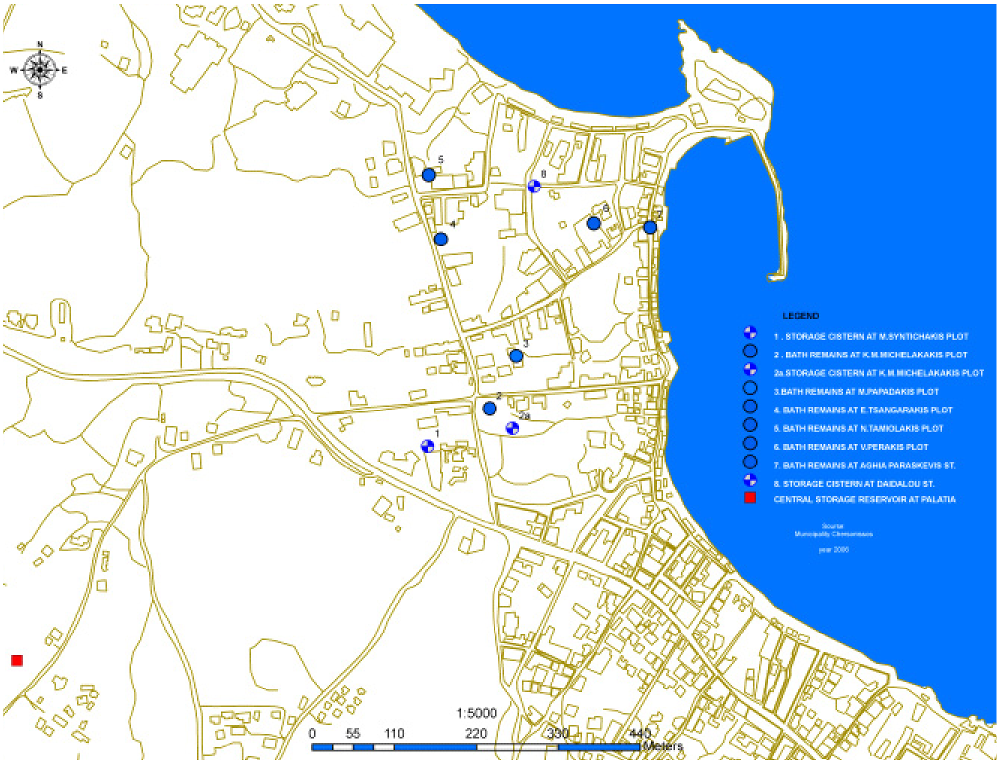

Figure 2 Distribution of excavated remains of Roman baths and cisterns in the modern town of Limenas Chersonissou.

The lowest conduit is very sparsely preserved but some segments discovered in the area of Aghios Ioannis Rossos suggest that, rather than carrying on to Chersonissos, the conduit turned W. The course of the higher conduit can be followed more precisely, since the level of its flow channel, the aperture of which measures 0.35 m, survives at Toichos. After an increase in its height, the conduit crosses again the riverbed of Aposelemis and continues on to the opposite bank. Since at this point the aqueduct was raised at a high altitude, it is likely that the conduit functioned with the help of a pressure siphon (Oikonomakis, 1984: 87), a method described in detail by Roman architect Vitruvius (VIII.VI.5) and used extensively in aqueducts of the Roman period.

Water Collection and Storage: The Central Reservoir

From the junction of the roads leading to Kastelli and Potamies up to Chersonissos, there are no visible traces of the aqueduct. The discharge end of the main conduit however survives at the SE corner of the huge terminal reservoir at Palatia, about 800 m to the S of the ancient town (Figs. 1 and 2). The reservoir has been only partly excavated and measures 55 x 18.50 x 5.50 m^3 (Mandalaki, 2001). It is largely subterranean, projecting on the surface by 1 m at the W wall, and it is divided in three oblong 5 m wide halls that run parallel to each other and which are connected to each other by arches. The walls are built in poured concrete and faced with brick, a characteristic feature of masonry style of the early 2nd century A.D. (Adam, 1994, 145-150), while the flat roof, which has largely collapsed, was constructed in poured concrete, small stones and rubble and was thickly plastered (Adam, 1994: 127-128).

From its size and extent, the cistern can be securely identified as the central reservoir and distribution tank (*castellum divisorium*) into which the aqueduct discharged and from which, through secondary conduits, water was re-directed for use in the urban area. Apart from this, the reservoir also functioned as a *piscina limaria*, a kind of huge settling tank aimed at separating heavy residues, dirt and floating particles from the water. This function is suggested by the placement of the arched apertures between the halls at non-corresponding intervals, which made the course of the water longer and thus facilitated a greater degree of filtering (Cagnat and Chapot, 1916: 87, Fig. 42).

The capacity of the Chersonissos reservoir can be calculated at 5,500 m^3. The enormous size of the construction indicates, on the one hand, the increased everyday demand on water and, on the other, the need for water storage, possibly due to discontinuous flow or low-scale supply. This is also suggested by the fairly narrow conduit discovered at Toichos (see above) and the even smaller width of its outlet (0.28 m) into the reservoir. Constructions for water collection of similarly large dimensions dated to the Roman imperial period are also known from regions with particularly acute problems of water shortage, such as North Africa and Syria (Cagnat and Chapot, 1916: 85-91; Adam, 1994: 248-251).

The Urban Distribution Network and its Maintenance

The exact course that water followed to reach its outlets in the town remains unclear, since no trace of the secondary conduit(s) that originally issued from the reservoir survived. It is likely however that at least one such channel issued into an oblong cistern at the entrance of the town, which possibly fed the baths near the theatre (Fig. 2, plot nos. 2 and 2a) and other similar facilities to the N. Although other such larger features have as yet not been identified, a number of cisterns of smaller capacity (about 50 m^3) which supplied private and public buildings have been excavated in other locations in the town (Fig. 2: plot nos. 1 and 8). In general, the distribution network appears to have been highly organized, aiming at the self-sufficiency of its constituent parts and the restriction of careless use of water, especially in times of stress or shortage.

As it was the case elsewhere in the Roman empire, the aqueduct and the urban distribution network necessitated regular maintenance and occasionally also repairs for its smooth function (Hodge, 1992: 311, 320; Oikonomakis, 1984: 81). During excavations in Chersonissos, relevant evidence, in the form of additional terracotta pipes, has come to light. These were placed in parallel to the built conduits, as at the discharge of the main conduit into the reservoir at Palatia, or in a different direction from these, as at the smaller cistern that supplied the baths near the theatre (Fig. 2: plot no. 2a). The terracotta pipes were probably installed only provisionally until the mains were repaired and normal supply could resume. Conversely, it is not unlikely that these features reflect an independent system of water supply, which was established after parts of the main urban network ceased to function.

Water Consumption in the Town: The Case of Baths

The urban distribution system must have catered for a diverse demand on water in the town but the greatest quantity of water was arguably used to supply the numerous bathing establishments (cf. Hodge 1992: 265; Yegül 1992: 391). Rescue excavations in recent years have produced evidence for six such buildings dating to the Roman imperial period. According to the present data, Roman bath-houses tend to cluster in the area known in previous times as ”Polis”, in close proximity to civic buildings. Due to the modern urban context and rescue nature of archaeological excavation at Chersonissos, discoveries are fragmentary and most times do not allow a full recovery of the building plan.

Apparently the most extensive bath building was excavated in 1981 and 2006 (Fig. 2: plot no. 2) close to the theatre. The 1981 excavations had already revealed the eastern part of a hypocaust room (possibly a *caldarium*) and two water cisterns, one in contact with the hypocaust room, the other about 50 m to the SE of it. Excavations during the 2006 season extended underneath Sanoudaki St. and included further architectural remains, fragments of mosaic pavements and part of another cistern. The best-preserved bath remains come from Tsangarakis plot (Fig. 2: plot no. 4) and include parts of the cold baths with two plunge bath tubs and two pools, a small part of the hot baths and other areas (undressing rooms, service corridors). The bath, originally built in the Roman imperial period experienced a number of modifications until Early Byzantine times.

To the N of the former plot, part of a private bath-house was discovered in the plot of M. Papadakis (Fig. 2: plot no. 3). The plot produced evidence for one important public building in the W and another of possibly domestic character with a dense network of terracotta and lead water pipes in the E. The bath was situated in the NE part, and its remains comprise part of a room with a hypocaust floor and small rectangular spaces with marble veneer on their walls that continue beyond the limit of the neighbouring plot to the N. Further architectural remains of baths have been excavated at Perakis and Tamiolakis plots at the core and in the N part of the “Polis” area respectively (Fig. 2: plot nos. 5, 6). In the former, two plunge basins, possibly of the *frigidarium*, were discovered. In the latter, the extant remains consist of a large hypocaust hall, flanked by two water cisterns that were plastered with a strong hydraulic mortar. A system of terracotta pipes and slab-covered built channels stretches to the E of these features. To the NE, excavation revealed a mosaic floor.

Further to the N, on the coastal road of the town and to the E of the Roman harbour, a bath building was discovered during works for the municipal sewage system in 2002-2003 (Fig. 2: plot no. 7). Preliminary study of the architecture and finds indicates that the building was constructed in the Roman imperial period and remained in use until Late Roman times. The largest room in the SE consisted of a central hypocaust area in the middle and a brick-built bath basin at the S corner. The hypocaust hall continued to the rooms in the NW, where, at the SW corner excavation brought to light another bath basin. In this part, a short bench and a small horse-shoe shaped hearth built around the 7th century A.D. suggest that by then the building had partly ceased to function as a bath-house. The nature of re-use remains unclear but the discovery of glass slag suggests some small-scale industrial activity, similar to the evidence noted in baths in other areas of the Late Antique Mediterranean (Stirling, 2001; Leone, 2003).

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Water Management in the Pediada Region in Central Crete, Greece, through Time

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Introduction

In the south Aegean, where it rains during the winter only, water has to be actively managed to take people through the dry seasons. In this paper, I shall discuss the history of water management in the Pediada as revealed in an archaeological survey carried out by the author (Panagiotakis, 2003). This paper will examine, in a broad manner, the development of the spring or fountain house from the Minoan period to the Ottoman. As no excavation has been conducted, the dating of the Pediada fountain houses has been based on the various architectural elements present. Often it is difficult to pinpoint a single date as there is a blending of architectural elements that betray renovations and refurbishing in different periods.

The Minoan Period

The earliest evidence for water management in Crete (and Europe on the whole) comes from the palace of Knossos, where a sophisticated system of drainage, and perhaps of fresh water supply, existed in the second millennium B.C. (Evans, 1921: 225-230; 1930: 236-253; Macdonald and Driessen, 1988; Angelakis and Koutsoyiannis, 2006; on earlier evidence for water management in the Indus valley and in Mesopotamia see Crouch, 1993: 21). Though the palace of Knossos is not my primary concern, my starting point will be the ‘Caravanserai’, which I see as a link between the Knossos palace and the Pediada, as it lies by the main road that connected the palace with the whole central Crete (the Pediada included). The ‘Caravanserai’ was in Evans’s words a ‘Hostel at terminus of Great South Road’ (Evans, 1928: 116-120; Schofield, 1996: 27-33). It had bath installations for ‘foot-washing’, ‘bath-tubs’ with some evidence for ‘hot-water supply’ and an underground ‘spring-chamber’.

The ‘spring-chamber’, which is situated immediately west of the ‘Caravanserai’ consists of a basin (similar to the ‘foot-washing’ one) that played the role of a reservoir (Evans, 1928: figs. 60-1; Fig. 1). Gypsum-lined walls rise round three of its sides; the back wall has a niche flanked by two ledges. It was entered from east through three steps (Evans, 1928: 123-136). It was an underground chamber and water sprang naturally from the bottom of the basin, which was lined with pebbles. An overflow duct joined the drain of the ‘foot-bath’ and they both continued ‘beneath the roadway’ (Evans, 1928: 126).

Similar spring houses of rectangular or circular form have been found at the palace at Zakros (Platon, 1974: 172-185) and a circular one at Archanes (Evans, 1928: 66, fig. 30).

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Evans conjectured, on the basis of building stones over the Archanes one that it had a vaulted roof. According to Evans the ‘Caravanserai’ spring house, on the basis of the finds (a clay hut with a goddess-like figure inside, vases with offerings and lamps), ‘had taken on the character of a shrine’ in the LM III period (Evans, 1928: 128). Similar evidence for the sacred nature of at least some springs comes from the palace at Zakros, where offerings were deposited in a well (Platon, 1974: 182-185). The ‘Caravanserai’, with evidence of three different expressions of water management, is to now a unique example outside the palaces, but it may not have been unique in Minoan Crete.

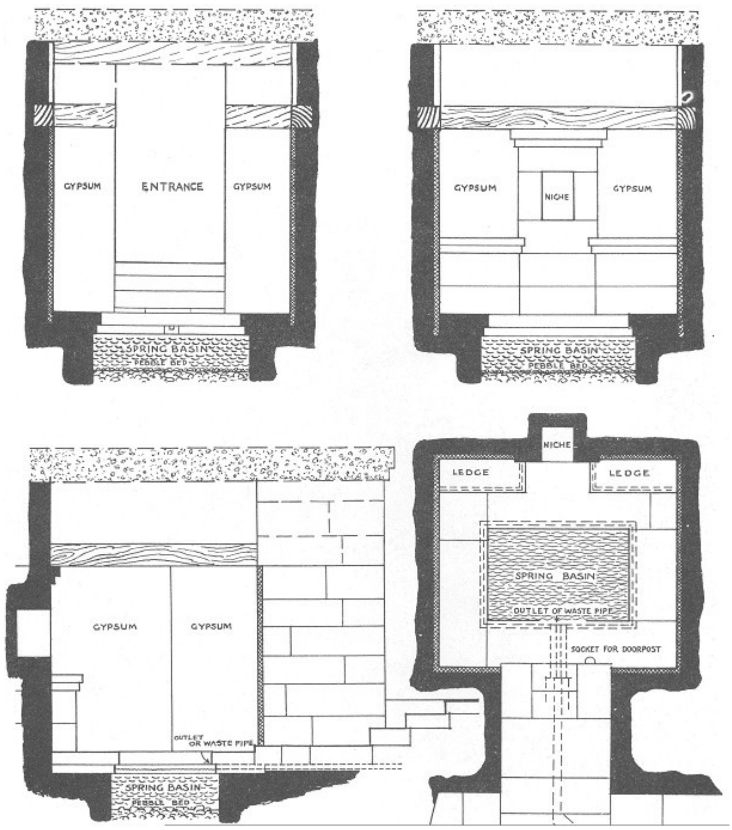

Figure 1 The ‘Caravanserai’ Spring chamber (after Evans, 1928: fig 61).

In the Pediada region most of the Minoan sites identified have been built by natural springs but it is impossible now to tell if these springs were used in their simplest form or they were adorned with fountain houses. There is, however, evidence for the use of built water cisterns used to collect and save the rain water. Their position in relation to the associated architectural remains suggests that they were underground circular cisterns at appropriate spots (usually at the corners of the buildings), where they could collect the rain water from the roof. Such cisterns and the occasional stone drain or clay fragments of pipes and drains confirm the existence of a water management system in the Pediada. From the elaborate and sophisticated water supply systems and bath installations in the Palaces, the ‘Caravanserai’ and the scattered evidence from the Pediada, we can deduce that the Minoan hydraulic engineers understood water and its capacities and knew how to exploit it in order to guarantee efficiency.

Graeco-Roman Period

No evidence survives between the Minoan period and the Graeco-Roman to suggest that the water systems developed in the Minoan period continued. One could argue that all the hydraulic engineers' knowledge was lost with the Minoans and was re-gained only much later in the Graeco-Roman period, but it may be far from the truth. During Classical Antiquity many Greek cities provide evidence of water management, which seems to have been closely related to the process of urbanization. As Crouch says, 'development of water supply, waste removal, and drainage made dense settlement possible' (Crouch, 1993: 19).

In the Pediada, where major cities existed, such water systems must have existed too. Nothing, however, has survived that can be safely dated to the Greek period (Archaic, Classical, Hellenistic) - perhaps the result of demolition in later periods? The water system during the Roman period, however, was of such magnitude that some forms of it have endured time. Evidence for Roman water management comes in the form of fountain houses, water cisterns, aqueducts and baths. Three fountain houses identified bear architectural characteristics typical of the Roman period. For as Dunkley wrote on Greek fountain houses 'their architectural details … and to some extent their material and size, vary according to the period of construction' (1935-1936: 144).

The earliest and most important *fountain house* identified is situated on the north (lower) spur of the Astritsi Kephala hill, an extensive site during the Minoan period and one of the city-states in later times. It is located on the east slope of the hill (Fig. 2), which had been cut back to accommodate it (Panagiotakis, 2006); it is surrounded by the remains (building stones, pottery sherds and wine and olive presses) of an extensive multi-period settlement with the toponym *Agios Nikolaos*. The structure comprises a single chamber, opening to the east: a large, rectangular basin that acted as a reservoir (on an east-west axis: 2.60 x 1.70 x 1.00 m) into which the spring discharges (the spring is still active); a vaulted ceiling springs from the side walls (3.33 m. height, measuring from the bottom of the basin). The roof, now covered over with stones and a layer of soil, is further completely hidden by thick ivy growth. It is impossible to tell whether it is flat or gable (on the shape of the roofs of fountain houses see Lavagne, 1988: figs 20-28). Both the ceiling and the walls are covered by a whitish waterproof plaster while the bottom of the basin today is made up from ten red tiles (rectangular and square) with incised crosses (Fig. 3) and a limestone slab (0.90 x 0.50 m).

Figure 2 The Agios Nikolaos fountain house at Astritsi.

Figure 3 The Agios Nikolaos fountain house (at Astritsi), detail of its floor.

The water emerges from the back wall of the fountain house through two openings: an arched shaped one and an ovoid. Two much larger openings (0.70 x 0.40 m) of rectangular form exist too: one in each side wall. They are in fact stone-lined tunnels, cut into the soft rock or soil to increase the flow of the spring. There is also a clay take-off pipe at the top of the east wall of the basin.

The fountain house was also enlivened by some decorative elements (Fig. 1): (a) at the top of the basin a decorative zone of plaster running along three sides; (b) the walls over the basin have been ornamented by setting in them two running bands of red tiles that stand proud of the wall plaster; the same tiles somewhat define the pointed top of the arched spring opening at the west wall and also the large tunnels in the north and south walls (their top and sides). The upper band is immediately below the vaulted ceiling giving the impression that the vault is supported by it. The same band in turn appears to be supported by the two pairs of vertical bands flanking the tunnels, so giving them the impression of being half columns. Further shallow niches are created by the tile bands: one each at the south-west and north-west corners, flanking thus the west wall with its two springs.

As it stands, the fountain house looks different from all the known Classical Greek fountain houses presented by Dunkley (1935-1936: 144) and Glaser (1983). Even so, some elements conform to the basic characteristics of Greek and later fountain houses: basins are common to all spring fountains that go back to the 7th or to the 6th century B.C. (e.g., the fountain houses Pirene and Glauke at Korinth and at Megara, Dunkley 1935-1936: 145-152). The stone-lined tunnels recall the fountain house at Ialyssos in Rhodes, of the Classical Greek period (Glazer, 1983: 90-92; Di Vita, 1996: 50, fig. 122). The red tiles on the floor recall similar ones (without the incised decoration) in the island of Kos, of Hellenistic or Roman date (Grigoriadou, 1997: 652-653). The earliest fountain house described as having an arched roof may be the one at Acrocorinth, of Hellenistic date (Dunkley, 1935-1936: 183). Vaulted ceilings and roofs are more common during the Roman as well as later periods; in fact the Roman fountains usually have a vaulted ceiling with a pediment (Lavagne, 1988: figs 20-24, 27).

The decorative tile-banding in the walls of the Astritsi fountain house recalls embellishments of large public fountain houses as well as private smaller ones of Roman date (Lavagne 1988). For decorative vertical bands of tiles forming false half-columns to ‘support’ the vaulted ceiling, a comparable example can be seen in Pompei (Brödner, 1983: fig. T 36b). The fountain house as it stands today may be the result of alterations and modifications of different periods. The original basin with the tunnels curved in the natural rock and the stone floor slab may be the earliest architectural elements to be created but whether they were constructed in the Archaic, Classical Greek, Hellenistic or Roman period has to remain open. Most embellishments, however, should belong to the Roman period. This accords well with the extensive Roman settlements that have been identified by the author by as well as near the fountain house and along the west branch of the Karteros river (that flows below the fountain house). Moreover, remains of bath installations exist only 500 m. north-east of the fountain house on the opposite side of the river.

A similar fountain house has been identified at Agia Anna by the village Demati, at the southern border of the Pediada (dry now, Fig. 4). It is of slightly smaller dimensions but consists of a rectangular underground basin; its walls finish in a vault similar to that at Astritsi. The walls have been plastered in the same way; even the border band of plaster at the top of the basin is repeated. The walls of the Demati fountain house, however, have been constructed or lined with red Roman tiles and the entrance is lined with dressed stone blocks. The back wall has also been so built with a decorative arch, created by placing tiles in a radial arrangement; this arch may have defined the actual spring outlet then (all the lower part of this wall has been demolished). These features point to the Roman date as the date of the construction of the Demati fountain house as it now stands. Its tile facing in fact recalls the smaller nymphaeum at Gortys (On nymphaea see Letzner, 1990; also Harrison, 1993: 165).

Figure 4 The Agia Anna fountain house at Demati.

Another smaller fountain house situated at Leukochori consists of a rectangular, underground basin (Fig. 5), an arched ceiling with a decorative plaster band at the top of the basin and anta similar to the Astritsi fountain house. The arch and anta are built of stones but there are remains (over the left anta) of red tiles placed in a radial way creating an arch that may have originally formed the face of the vaulted roof; tiles were occasionally used during the Ottoman period but they are of a different kind (see for instance the tiles used in the vaulted roof of the *Σέιχ Σου* fountain house at Thessaloniki, of the Ottoman period, Velenis, 2005: fig. 34-37). Unlike the Astritsi and the Demati fountain houses the Leukochori one is fed with water that springs up from its bottom, where there is a well-like depression. These last two fountain houses share one feature: the red tiles which are most probably of Roman date.

Figure 5 The fountain house at Leukochori.

If the three fountain houses discussed were built or took this final architectural form in the Roman period, this accords well with the known water management structures built in the Pediada region during the same period: the aqueducts (the longest in Crete), that transverse the Pediada landscape bringing water to the major Pediada Roman cities: Chersonissos, Lyktos (Oikonomakis, 1984; 1986; Harrison, 1993: 196-202), the Kephala at Ini. The same cities had baths that were governed by rules and regulations (Sanders, 1983: 15; Harrison, 1993; Van Effenterre, 1976: 205) and water cisterns, the size of which point to their importance and to the importance of water during the Roman period. Underground water cisterns were also constructed in private buildings to collect and save the rain water from the roofs.

The Venetian and the Ottoman Periods

During the Venetian period the Pediada was densely populated. Being rich in water there was an important water system, now expressed mainly in water cisterns and fountain houses. An important water cistern has been identified at the Venetian Akropolis of Galatas attached to the church of the virgin Mary. The cistern is rectangular, lined with water-proof plaster and small boats have been incised on its walls. Other water cisterns now in ruins have been recorded but one, by the church of Agios Dimitrios at Voni is of particular significance as it is associated with nymphs (νεράιδες).

An important fountain house is situated at Agios Nikolaos at Askoi by the Venetian village with the same name (Fig. 6). It consists of a rectangular, underground basin with a vaulted ceiling with one side left open. The opening is lined with dressed limestone blocks that form an arch. The water springs up from the floor. The walls have been covered with water-proof plaster and incised boats decorate them. The architecture of this fountain house is the same as of the three attributed to the Graeco-Roman period. However, it lacks the red Roman tiles; the presence of the incised boats may point to the Venetian period for that aspect at least. Whether the fountain house was built earlier and was refurbished in the Venetian period is impossible to tell.

Figure 6 The Agios Nikolaos fountain house (at Askoi).

Figure 7 The Plevri Kamara fountain house at Founarous- by Sambas.

Of the same type are three more fountain houses; it is only in the size and details on the dressed stone blocks that surround their entrances that they vary. They are: Plevri Kamara at Sambas (by the Venetian village Founarous and a Venetian bridge, Fig. 7); Porteles at Agies Paraskies (Fig. 8), Panagia at Sambas (Fig. 9). The water wells up from the floor in all cases. Another type of fountain house seems to have developed either during the Venetian or the Ottoman period. The fountain house Koutsounari at Miliarisi consists of a rectangular above ground basin (into which the spring runs) with a window-like opening at one side (Fig. 10). The ceiling and roof are flat. A facade wall (of dressed stone) supported by two pillars creates a niche in the middle with an arched top and a spout that discharges into a trough (that fits into the niche). Above the spout a rectangular space defined by a stone band may have marked the position of a sign or dedication.

Figure 8 The Porteles fountain house at Agies Paraskies.

Figure 9 The Panagia fountain house at Sambas.

Figure 10 The Koutsounari fountain house at Miliarisi.

Of exactly the same type is the fountain house at the village Mikri Episkopi (Fig. 11). It lacks, however, the defined space on the facade wall for a sign or a dedication. Of the same type again is another fountain house at Mousouta (Fig. 12) that had been photographed by Gerola (1902-1905: Vol. IV: 75). This is even more elaborate, as it has columns at the two corners of the facade wall; the wall itself does not have a niche but an elaborate spout that empties into a trough below. It somewhat recalls the fountain house Mbembo at Iraklio, of Venetian date (Spanakis, 1981: fig. 21-22). These three fountain houses may have been built during the Venetian period or even later.

Conclusions on the architectural development of the fountain house from the Minoan to the Venetian-Ottoman period.

The practical use of a fountain house was to collect spring water during the night in order to cover the needs of the day. A basin as reservoir is thus the most necessary element. From this brief review, it is clear that all fountain houses from the Minoan period to the Venetian-Ottoman had such a basin. In most cases it is set underground – only the fountain house with a facade wall has an above ground level basin (or but half underground): this type was created during the Venetian-Ottoman period.

Figure 11 The fountain house at Mikri Episkopi.

Figure 12 The fountain house at Mousouta.

It seems therefore that two forms exist in all periods: (a) rectangular underground basin (in the Minoan period circular as well) with a vaulted ceiling with one side open; the spout is on the back wall and the whole structure is incorporated in a hillside that has been cut back to accommodate it; (b) rectangular over ground basin with a flat ceiling and a facade wall (sometimes with a niche and in varying size) with one or more troughs; often part of it is incorporated into a hill or a building.

The Artistic/Aesthetic and Religious Aspects of Spring Water and fountain houses

The Minoans used water not only for utilitarian purposes but for artistic/aesthetic and religious purposes too. The artistic/aesthetic aspect is evidenced in the way the 'Caravanserai' 'spring-chamber' was built and decorated: polished gypsum slabs covered the walls, the back wall had a niche further enhanced. Further evidence comes from the House of Frescoes, immediately west of the palace at Knossos, where a fresco fragment depicts cascading water that Evans described as an artificial 'fountain or jet d'eau' (Evans, 1928: 460-462, fig. 272; 1930, pl. xxii). The artefacts associated with cult found in the 'spring-chamber' at 'Caravanserai' and the palace at Zakros provide ample evidence for the religious aspect of the water of these particular springs during the Minoan period.

For the Greeks too, water served the same threefold purpose. It is well attested that most Archaic and Classical Greek cities used to furnish their springs with basins and 'architectural adornments' (Hodge, 1992: 25). However, it was during the Hellenistic period that fountains became more ornate and thus more pleasing aesthetically and adorned not only the cities but also royal and private residences of the elite. This same desire was taken to new heights by the Romans in their beautiful estates and town residences. Every city had at least one public fountain that consisted of a shallow basin, but all cities of some eminence had fountain houses and nymphaea.

The decorative elements of the Pediada fountain houses especially the Astritsi and the Demati ones are evidenced of the artistic/aesthetic views of the person(s) who made or had them made. Whether though this person was a Hellenistic lord or a member of the Roman elite has to remain open. Not surprisingly, the same trend for elaborate fountain houses continued into the Venetian-Ottoman period.

The religious aspect of spring water evident in the 'Caravanserai' fountain house may have continued into the following periods in different expressions. To assess this, one should ask the question why some springs were furnished with cisterns and fountain houses and not others. For instance the Astritsi fountain house is surrounded by many other springs and a river flows just below it. It is, I think, possible that the spring of this particular fountain house had something more to offer than plain water. We know from the Classical Greek writers that the Greeks could appreciate good quality in water. Hippocrates (Ιπποκράτους, Περί Αέρων, Υδάτων, Τόπων, 30, 32, late 5th and early 4th centuries B.C.) wrote that 'the best water for drinking is that from high places and from earthly hills, because this water is sweet and clear – warm in the winter and cold in the summer because it comes from deep springs' (after Crouch, 1993: 50-51). He also discussed the orientation of springs and that of cities: an eastern exposure gives the city clear, sweet-smelling, soft, delightful water, 'because the rising sun purifies' the site and its water. He further stated that 'the best springs open to the east'.

It should be stressed that many of the springs in the Pediada region (the 'Caravanserai' included) conform to the rules stated by Hippocrates. Arguably the Astritsi fountain house, facing east and with a niche created by the decorative tile bands, appropriate for small cult figurines, may have been used during Classical antiquity as a nymphaeum. Other fountain houses in the Pediada may have also acted as nymphaea. Inscriptions on Venetian and Ottoman fountains in Heraklion (Spanakis, 1981: 93-97) and in Rhodes (Sigala, 2000) stress the charitable aspect of the person endowing them. And it may not be coincidental that most of the fountain houses recorded in the Pediada are next to Christian churches and the now ruined water cistern at Agios Dimitrios has been associated in the minds of the people living in the area with nymphs.

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The Ancient Spring of Vourina on the Island of Cos in the Dodecanese, Greece: A Historical and Morphological Approach

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Abstract: The present paper will endeavor the historical and morphological approach of the ancient spring of Vourina on the island of Cos in the Dodecanese. We hope that it will stimulate the archaeological world and other distinguished researchers to carry out an exhaustive archaeological study of this monument, disregarded and lacking the recognition it deserves in view of its archaeological, historical and architectural value. The spring of Vourina is particularly interesting as a work for the management of spring waters, to the extent that it is fully built in stone without the use of mortar, with an impressive result from aesthetic and construction viewpoint. Equally interesting is a comparison between the spring and similar hydraulic works in antiquity as well as its accurate dating with the use of modern techniques. It is worth stressing its uninterrupted functioning throughout the ages and the constant use of its water for the water supply of the city of Cos until our days.

Keywords Ancient Greece; ancient technology; Cos island; hydrology; springs.

Introduction

All over the island of Cos, over hillsides and gullies, there are innumerable springs with an abundant flow of fresh water[1]. According to written testimonies[2] these springs have existed since ancient times. Their presence is due to the rich aquifers created by the increased precipitations and the morphology of the lightly sloped terrain[3]. The exploitation of these water resources, in combination with the waters from wells and, at a later date, drillings have supported in the past the irrigation of the island's rich cultivations. Today, as the agricultural sector is shrinking and farming cultivations have been minimized to make way for the tourist mono-cultivation, the spring waters with the strongest flow are stored in reservoirs in order to supply water to the settlements of Cos.

In the texts of European travelers[4] one can find the names of the island's most important springs, listed in chronological order: Hippocratic Fountain (Ippokratiki Krini), Phandikos, Likastos or Apodomarvi, Lambi, Nikaste (Likastos) or Apodomia, Sphandio, Licasti or Apodomaria, Soffodino, Nicastro or Apodimia, Spring of Hippocrates, Vourina and Kokkinonero. Obviously the slightly altered names refer to the same water spring and the descriptions can help, but also mislead their identification with earlier or later names. This matter is particularly interesting and constitutes a challenging research field for researchers studying the place-names of Cos[5].

Out of the 136 recorded springs, mentioned by Mihalis Efts. Skandalidis in "*Place-names and names of the island of* Cos" in 2002, it is known that the springs of Vourina or Vorina, Kephalovryssi, Harmyli, Dromiko and Tsesimes supplied the island with water. The archaeologist Georgios Styl. Mastoropoulos[6] writes about the springs of Antimahia: ... *Usually springs have a built structure with troughs or small cisterns, usually elongated, serving the collection of flowing water and the watering of animals. Sometimes an artificial gallery has been created, reaching deep into the ground (Kymari, Portes, Poria). Some springs have dried out in our days because of the numerous drillings carried out at lower levels, by the plain...* He also mentions 42 springs, including wells, and describes in details the most interesting ones.

The present paper will endeavor the historical and morphological approach of the Vourina spring, with the hope that it will stimulate the archaeological world and other distinguished researchers[7] to carry out an exhaustive archaeological study of this monument, disregarded and lacking the recognition it deserves in view of its archaeological, historical and architectural value. The spring of Vourina is particularly interesting as a work for the management of spring waters, to the extent that it is fully built in stone without the use of mortar, with an impressive result from aesthetic and construction viewpoint. Equally interesting is a comparison between the spring and similar hydraulic works in antiquity[8] as well as its accurate dating with the use of modern techniques. It is worth stressing its uninterrupted functioning throughout the ages and the constant use of its water for the water supply of the city of Cos until our days.

Historical Approach

The first mention of the ancient spring of Vourina is made by the grammarian and elegiac poet Philetas of Cos (340 - 285 B.C.): *Νάσσατο δ'εν προχοήσι μελαμπέτροιο Βυρίνης* (Push with strength the opening of the dark rock of Vourina). He is followed by the bucolic poet Theocritus (310 to 305 - 285 B.C.), who in his VII Idyll «Thalyssia. The spring journey» (v. 6-7) notes: *Χάλκωνος, Βούριννον ος εκ ποδός άνυε κράναν, ευ γ' ενερεισάμενος πέτρα γόνυ·* (Halkonas, after striking the rock with his foot, pressing it hard with his knee, opened the spring of Vourina). According to Theocritus therefore, the builder of this spring is Halkonas, the mythical king of the dynasty of the Meropoi of Cos, whose appearance is dated long before the Trojan War[9], around 1400 B.C. The accurate dating of Vourina has not, to date, been possible, although it is considered to be an autochtonous construction. The construction itself, built in large stones, resembles a cyclopean structure, and some researchers compare it to the treasury of Atreus at Mycenae or with the tomb of Agamemnon[10].

The name of the spring is found written in the feminine nominative form: Vyrini, Vourina, Vourinna or Vourrina, Voureina, Vouriea, Vourreia, Vorrina or Vorina, Vorini and Vouris. Nikanoras of Cos (117 B.C.), annotator of Theocritus, calls the spring Vourin because the rock from which it gushes forth resembles the snout of an ox[11]. Modern authors have also dwelt on the origin of the spring's name. Mihalis D. Paxinos advocates that the name comes from the Pelasgian name *vorì* (pronounced vourì) or *vorì-ja* (articulated), which was possibly attributed to the cypress tree. It is possible, he writes, that the original name of the location was *Vourì,* Hellenized into *Vourina* - since it characterized only the neighboring spring - which the Mycenaeans, arriving in Cos at a later date, transcribed into Kyparisso[12], referring to the lexicographer Isychius. Mihalis Efst. Skandalidis considers the place-name *Vourina* (fem.) as being ancient Greek and meaning the large, inexhaustible spring[13].

Over approximately one century, some foreign travelers[14] called it the *Spring of Hippocrates,* possibly because they believed that Hippocrates used its waters at the

Asclepeion. However, it is clear from the text of some travelers and researchers, as well as from medieval documents, that the Spring of Hippocrates was at the outskirts of the medieval town of Cos, in the area where the so-called *Palaces of Hippocrates*[15] were also located. Evidently, some traveler either misunderstood or received a mistaken information and included in his writings the name of Spring of Hippocrates instead of Spring of Vourina; this misnomer was maintained in later texts until the Bavarian Professor of Archaeology at the University of Athens, Ludwig Ross, visited Cos and re-established the spring's real name *Vourinna*[16]. Short texts on the spring of Vourina were written by the following researchers: the Frenchman Charles F. M. Texier[17], Ludwig Ross[18], the Coan Stamatis Pandelides[19], the Coan Iakovos Zarraftis[20] and Thrassyvoulos Hatziarapis[21].

In ancient times, the wider area of Vourina was covered in dense woods. Theocritus (*VII Idyll, v. 8-9)* says: *ται δε παρ' αυτάν αίγειροι πτελέαι τε εϋσκιον άλσος έφαινον, χλωροίσιν πετάλοισι κατηρεφέες κομόωσαι* (fresh, leafy trees rustled there, poplars and elms that formed with their greenery dark shaded woods)[22]. Today, we encounter a cluster of plane-trees and poplars close to the spring[23]. The water of the spring, excellent in quality, had also «therapeutic virtues», as revealed by the following votive inscription located at its gutter and published by Stam. Pandelides[24]: *Σαραπίδισι Θεοίς*[25] *πάσι θεραπεύσεις Απολλωνίδας Αλεξανδρεύς χαριστεία* (Serve all the Sarapeian Gods - Votive offering of Apollonidas of Alexandria). However, this inscription disappeared, together with many others, in the first half of the 19th century, on the orders of Mustafa Bey, the Ottoman Governor of Cos, who believed that ancient Greek inscriptions cultivated the revolutionary flame in the souls of the island's inhabitants[26].

The remains of old aqueducts bear witness to the fact that the inexhaustible spring of Vourina supplied the city of Cos with water. During the Ottoman occupation the water flowed from the fountain built by the Turkish Admiral Ghazi Hassan Pasha in 1786 A.D. in the central square of the town, by Hippocrates' plane-tree[27]. During the first period of the Italian occupation (1912-1923), a double reservoir was built in the area of Ambavri, collecting the water of the spring and distributing it to all the neighborhoods. The inhabitants were able to collect water from one of the fountains located in various places across town and in a limited number of houses. Today, the spring of Vourina still supplies water, together with other springs and modern drillings, to the entire city of Cos. Pictorial representations of Vourina were made by the traveler John H. Allan[28] in 1843 (Fig. 1), who calls it *Spring of Hippocrates* and by Athina Tarsouli[29]. Detailed drawings of the source[30] were made by the Danish architect L. A. Winstrup[31] in 1850 (Fig. 2), who calls it *Sacred spring of Theocritus at Vourina* and by Stam. Pandelides[32] in 1861, who calls it *Hippocrates' spring in Cos* in spite of the fact that he himself says that «there is no reason» for the spring to be called Spring of Hippocrates. Sketches were made in 1993 by Ioulia K. Papaeftychiou[33] and in 1996 by Olga Lekou and Isabella Papamandellou[34]. The authors were unable to find any accurate rendering of the spring, whether older or modern.

Morphological Approach

The spring of Vourina is set in a beautiful location on the north-eastern slopes of Mount Dikaios (Oromedon) at an altitude of 320 m, overlooking the shores of Asia Minor. At a mere distance of approximately 5 km from the city, the site of the spring cannot be seen because of a small-sized geo-morphological ridge located on the very axis of the spring's entrance and the view towards the city. The presence of the spring in the area is discreet and goes almost unnoticed by visitors.

Figure 1 J.H. Allan - Fountain of Hippocrates Cos, 1843.

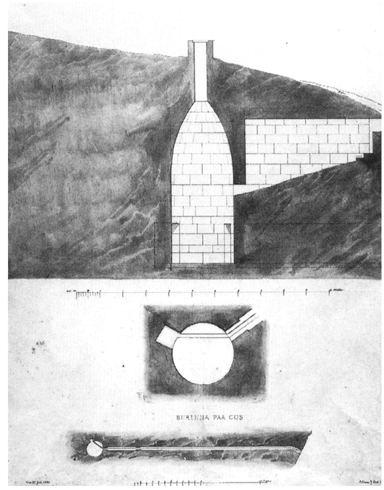

Figure 2 L.A. Winstrup - Burinna paa Cos, 1850.

Three small-sized openings on the side of the mountain over an area of approximately 100 m², each with a different orientation and different altitude, betray the presence of the spring. A cluster of high trees in a barren landscape, a few meters from the mountain road, betrays the presence of water. Going up the slope, on the small plateau where the trees are located, one sees an elongated watering trough for sheep and goats.

At a short distance one can see a small opening, closed by ironwork, next to which is located a fountain with a basin. This opening, difficult to see in the rocky landscape, is the entrance to the spring and is formed by three large carved rocks, placed according to the «beam over pillar» system. The spring is at the base of an invisible external underground circular construction, sheltered by a dome with a small opening at the top and accessible through a dark tunnel. At a higher place, to the east, there is the entrance of an auxiliary smaller chamber, evidently used for guarding and monitoring the functioning of the spring and at an even higher place, westwards, one can find the opening of the dome, resembling the mouth of a well.

The walls surrounding the circular construction and the dome are carefully built with carved rectangular stones, while the tunnel is built in large boulders sometimes ending in an arched crown (Fig. 3) and sometimes roofed with the monolithic slabs of the «beam over pillar» system(Fig. 4). Approximately halfway into the tunnel, one notices a slight shift of its axis to the right, marked by two square pillars, jutting out, with flattened articulations that support the roof (Fig. 4). The joint-filling and the perfect fitting of the boulders is quite impressive, without voids or defects, in spite of their large dimensions and weight. There is absolutely no trace of mortar between the stone structural elements of the construction. The vaulted construction where the spring is located has a diameter of approximately 3.20 m, a circumference of 10 m and a height of 7 m until the lighting and airing opening at the top of the dome. The tunnel leading to the chamber is approximately 30 m long, 2 m high and its width varies between 70 centimeters and one meter. The auxiliary smaller chamber communicates with the vaulted constructions by means of a small opening located approximately at half the 7 meter height (Fig. 5). The water springs from an opening in the rock and pours into a stone trough, continuing its course along the tunnel, in a carved duct in the past and nowadays in pipes.

Figure 3 Large boulders ending in an arched crown.

Figure 4 The two square pillars of the tunnel.

Figure 5 The opening of the auxiliary smaller chamber.

Particularly interesting are the descriptions and the questions raised by a number of architect researchers in relation to the dating of the spring; they themselves base their reflections on the corresponding concerns of older writers and researchers. Olga Lekou and Isabella Papamandellou write[35]:

... It would seem that the small chamber was destined to the guarding of the spring and the monitoring of its smooth functioning. There are however also different opinions. According to Curtius[36] the window of the smaller chamber served no other purpose than the creation of a draft in the vaulted space and in the event the lower passage was blacked, it would be a second place through which the water could flow out. According to Merckel[37] the smaller chamber was probably a Nymphaion. As to the narrow passage formed by pilasters in the tunnel, Texier[38] believes that it was the door that when closed turned the spring into a small reservoir. Then, quite possibly, the opening of the vaulted space played the role of a small well mouth wherefrom water was drawn with the help of buckets. It is also believed that in the event of a war the opening was covered with dirt in order to protect the precious water from the enemies.

The construction bears many similarities with the Mycenaean tomb of Agamemnon, built around 1330 B.C. As in Vourina, the tomb was formed by a bee-hive shaped chamber, accessible in this case by an open passageway. On the side of the entrance of the vaulted chamber, in Vourina there is the spring, in the tomb a small room. The construction of the chamber of Vourina, in its lower section, is similar to the one of the tomb of Atreus and only the last courses of masonry, closing the top of the dome, are formed by cuneiform stones contrary to the burial monument where the courses are corbelled. According to Texier, this remark could take away from this construction its archaic character. Another difference can be noticed in the covering of the openings. In the tomb of Atreus the top is closed with a monolithic stone with a supporting triangle above it; in Vourina openings are bridged with cuneiform voussoirs. The above mentioned correlations to the Mycenaean monument support the view that the spring dates approximately to the same period. Nothing however excludes the possibility that it was an autochtonous construction, as advocated by Lacroix[39]. Similarities with other monuments, such as the Tullian building in the prisons of Rome, have also been noted...

Civil Engineer P. Loprestis writes[40] in 1937:

After air, water is the most useful element for man and this since ancient times, where no water is visible, people dug wells or galleries in order to find the water they needed ... In Samos, Polycrates built a tunnel to tap the aquifer, also in Cos a very deep well was built and called the fountain of Hippocrates...

The insertion of two hydraulic works of the Greek antiquity, among the corresponding Egyptian and Roman antiquities, evidently underlies their equal importance in terms of functioning and construction perfection.

At this point, one should mention the interventions made on the spring of Vourina during the Italian occupation (1912-1943). As Iak. Zarraftis[41] says the «military builders» of the Italian occupation wanted to reconstruct the spring, applying grandiose architectural plans in order to improve it. Fortunately, during the dismantling of one third of the ancient construction, the guardian of the Asclepieion realized what their intentions were and the result was that the spring was re-established in its original form, with the same carved boulders and carefully covered[42].

Conclusions

The historical and morphological approach of the spring, with simultaneous juxtapposition of mythological, historical and construction elements, confirms its undeniable archeological value and more. Its importance for the water supply of the modern city of Cos, both in terms of the quantity and of the quality of its waters, is also ascertained. By extension, it is imperative to proceed to archeological and comparative studies so as to accurately date the spring and valorize it as an archeological monument, as well as protect its functioning as a timeless hydraulic work, of capital importance for Cos.

The difficulties in the dating of the spring are well-known, beyond the conjectures and the reflections of the researchers that were mentioned and who place it within a wide chronological range: from the time of the descent of the Pelasgians 35 centuries ago, through the Mycenaean and the Hellenistic eras. Assuming that the spring of Vourina is a Mycenaean hydraulic work, its dating could be carried out either individually or in combination, depending on the various methods[43]:

(a) Evaluation of archeological findings that allow a clear correlation with the period that saw the beginning of the construction of, e.g., aqueducts.
(b) Stratigraphic comparisons with the surrounding environment, e.g. remains of constructions in the wider neighboring area of the mineral spring of Kokkinonero.
(c) General comparisons with the safely dated nearby sites, e.g. the Asclepieion of Cos.
(d) Tradition and its analysis, e.g., the legend attributing its construction to the mythical king Halkonas.
(e) Advanced dating techniques, e.g., thermoluminescence.
(f) And particularly in the present case, establishment of technical affinities with dated works: hydraulic system and construction details of a particularly special kind.

In conclusion, we point out that the present paper is a simple presentation of data with a view to stimulating interested researchers to carry out a systematic research, full recording and accurate dating of the spring of Vourina, always in cooperation with the competent Archeological Services.

Footnotes - References

1 Skandalidis Mih. Efst., *Place-names and names of the island of Cos*, Cos 2002. In the chapter on *Springs-Fountains,* pp. 161-168, are listed 136 cases, including mineral springs, lakes, marshes and wetlands. Fountains are identified with springs, evidently because the relevant constructions have been built on the locations where water gushes forth. He also mentions 17 wells, op. cit. p. 168, evidently the better known ones. Cf. Nik. Ath. Zarakas, *Place-names of the island of Cos*, *Ta Koaka*, vol. II, Athens 1981, p. 68-160 where a total of 124 springs, fountains and wells are mentioned.

2 As mentioned in the works of writers and researchers Iak. Zarraftis, Nik. Ath. Zarakas, Vass. S. Hatzivasiliou, Mih. Efst. Skandalidis and Al. Markoglou.

3 Hadzivasiliou Vas. S., *History of the island of Cos*, Athens 1990, pp. 16-18 and 20-24. Cf. Desio A., *Le isole Italiane dell' Egeo (Studi geologici e geografico-Fisici)*, Roma 1931-IX, with the hydrography of the island of Cos and the summary reference to its springs, pp. 134-135 (by kind permission from the archives of collector Antonis Sev. Maillis, M.D.). Cf. Papaeftychiou Ioulia K., *Works for the management of water resources, Ta Koaka*, vol. IX (in printing), Athens 2006.

4 Hatzivasiliou, *History*, op. cit. *Vourina, p.* 22, *Hippocratic Fountain* p. 267, *Lambi* pp. 269,343,346 and 347, *Kokkinonero* p. 411. Also Markoglou Al. I., *Cos in the engravings of European travelers and cartographers (15th-19th century),* Athens 2004, pp. 56,68,76,106,174,178,186,188 and 196 where the most important springs are listed.

5 Extensive reference to bibliographic sources and their analysis, see Papaeftychiou Ioulia K., *Works for the management of water resources, Ta Koaka*, op. cit. (footnote 3).

6 Mastoropoulos Georgios Styl., *Coan Antimacheia, Modern timeless approach*, Athens 2002, pp. 30-33.

7 The authors have already sent all published data to the renowned researched Prof. Dr. Jost Knauss, so as to draw his attention for the inclusion, in cooperation with the Hellenic Archaeological Services, of the Vourina spring in his research programs. Jost Knauss, former Professor of Civil Engineer at the Polytechnic of Munich, has been since 1984 researching and studying the Mycenaean hydraulic works in Greece and his name is accompanied by titles and distinctions. For a summary of the outcomes of his research see Prof. Dr. Jost Knauss, *Late Helladic hydraulic works. Research on the infrastructure of hydraulic works for water management during the Mycenaean period*, publication of the *Association for the study and dissemination of Greek history*, ISBN: 3-936300-00-3, Weilheim Oberbayern, Germany, March 2002.

8 For a comparison with similar hydraulic works see Prof. Dr. Jost Knauss, *Prehistoric fountains (wells) in the region of the Aegean. Their construction,* 5th International Conference of the *Association for the study and dissemination of Greek history* with the title *Trade: movement and exchange of goods, ideas and technologies in the Aegean and the Eastern Mediterranean*, Ohlstadt/Bavaria, 19-21 May 2006.

9 The genealogy of Halkonas, according to the ancient authors (Homer, Apollodorus, Plutarch, Esychius), was the following: Meropas (ruler of Cos) was the father of Klytia who married Eurypylos (king of Cos) and gave birth to Halkonas and Halkiope, wife of Hercules, who gave birth to Thessalus, whose sons Antiphus and Pheidippus led the islands of Cos, Nissiros, Kassos and Kalymnos in the Trojan expedition at the head of 30 ships.

10 Pandelides Stam. K., *On the Vourini spring on the island of Cos,* periodic publication *Pandora*, vol. XI, issue number 272/15-7-1861, p.182. Cf. also Lekou Olga - Papamandellou Isabella, *Water supply and hydraulic works in Cos from Antiquity to the Italian occupation*, Lecture at the National Technical University, Athens 1996, were the following thematic units were presented: Springs-Aqueducts-Wells (unpublished).

11 Hatzivasiliou, *History*, op. cit. Vourinna place-names (Vorrina, Vourin, Vyrina) included in the surviving monuments of Cos, pp. 164-165.

12 Paxinos Mihalis D., *Place-name paradoxes in Cos*, Koaka vol. V, Athens 1995, pp.229-230.

13 Skandalidis *Place-names*, op. cit. 61-65, with full documentation supporting his views.

14 Such as Friedrich Hasselquist in 1751 and Joseph Michaud in 1830. See Hatzivasiliou, *History,* op. cit. pp. 347 and 409.

15 For the first presentation of this subject, in the form of a pre-publication, see Hatzivasiliou Vassilis S., *The* «*Houses of Hippocrates*» *and their remains*, newspaper *To Vima tis Ko*, issue number 1600/18-4-2006, p.17 and newspaper *Stathmos* , issue number 285/26-5-2006.

16 Hatzivasiliou, *History*, op. cit. p. 411.

17 In his work *Description de l' Asie Mineure*, Paris (1839 - 1849), vol. 2 pp. 309-315 and second edition of the same *Asie Mineure*. *Description géographique historique et archéologique des provinces et villes,* Paris 1862, pp. 649-651.

18 In his work *Das Brunnenhaus der Burinna und das Heroon des Charmylos (Grab der Charmyleen) auf Cos* in *Arch.Zeitung, 8(Oktober 1850),* No 22, pp. 241-246 and in A.A.,2 (1861), pp. 389-393.

[19] Pandelides, *On the Vourini spring on the island of Cos,* op. cit. pp. 181-184.

[20] In his work *Thalyssia of Cos, or a paraphrase of the VII Idyll of Theocritus and study thereof,* Samos 1906, pp. 29-35.

[21] In his work *The Vourina of Theocritus. An interpretative, historical and archaeological essay on a village of Theocritus and on the famous spring of king Halkonas in Cos*, Athens 1911 (by kind permission from the archives of collector Antonis Sev. Maillis, M.D.).

[22] cf. Tarsouli Athina, *Dodecanese*, vol. III, Athens 1950, pp. 35-36.

[23] cf. Giorgallis Thanassis I., *Cos's past records*, Cos 2000, pp.46-47.

[24] Pandelides, *On the Vourini spring on the island of Cos,* op. cit. p. 182.

[25] The God Serapis or Sarapis, whose cult was brought to Cos from Egypt in the times of the Ptolemies (Hatzivasiliou, *History,* op. cit. pp. 111 and 153) resembles Pluto and Asclepius. He was the god of the afterworld and medicine and it would seem that the inscription in question existed also in Hellenistic times, first at the Asclepieion and then (unknown when) transferred and placed at the gutter of the spring, whose water was probably used by the Asclepius' doctors.

[26] Cf. Hatzivasiliou, *History,* op. cit. p. 412.

[27] Hatzivasiliou, *History,* op. cit. pp. 166-169 and 418.

[28] Allan John H., *A pictorial tour in the* Mediterranean, London 1843, p. 37 (by kind permission from the archives of collector Antonis Sev. Mavillis, M.D.). Cf. Markoglou, *Engravings*, op. cit. p. 175.

[29] Tarsouli Athina, *Dodecanese*, op. cit. p. 36.

[30] Georgia Kokkorou-Alevra, *Ludwig Ross and the antiquities of Cos*, Minutes of the International Conference *Ludwig Ross and Greece* Athens, 2-3 Окт. 2002), Berlin 2005, pp. 190-193, pict. 2-6 out of which numbers 2 and 3 are drawing representations of Vourina.

[31] Bendtsen Margit, *Sketches and measurings - Danish Architects in Greece, 1818-1862,* Copenhagen 1993 (by kind permission from the archives of collector Antonis Sev. Maillis, M.D.). Cf. Papaeftychiou Ioulia K., *Dry-stone buildings in Cos*, Koaka vol. VIII, Cos 2003, p.435.

[32] Pandelides Stam. K., *On the Vourini spring on the island of Cos,* op. cit. p. 183.

[33] Papaeftychiou Ioulia K., *Planning of networks for the enhancing of the cultural goods in the Municipality of Cos*, Koaka vol. VII, Cos 2002, p. 420.

[34] Lekou Olga and Papamandellou Isabella, *Water supply and hydraulic works in Cos from Antiquity to the Italian occupation*, Lecture at the National Technical University, Athens 1996, where the following thematic units were presented: Springs-Aqueducts-Wells (unpublished).

[35] An exhaustive mention to the construction of Vourina is to be found in the Lecture by Lekou and Papamandellou, op. cit., which is kept in the archives of student works at the National Technical University of Athens. It should be pointed out that published descriptions of the spring of Vourina, particularly those pertaining to construction, present small differences and divergences from one another, something quite normal in view of the fact that no accurate recording of the monument has been made. The present description is to be found in the above mentioned lecture.

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[39] Lacroix Louis, L' Univers Pittoresque. Europe Tome 38. *Les îles de la Grèce*. *Histoire et Description. Paris 1853*, p. 201.

[40] Loprestis P., *Hydrological. Guidelines for the discovery of springs, tapping of waters and enrichment thereof*, Athens 1937, p. 9 (by kind permission from the archives of collector Antonis Sev. Mavillis, M.D.).

[41] Zarraftis Iak. E.. E, *Coan*, vol. I, chapter 2, *Ancient location of Cos*, 1922 and re-published by the Hippocrateian Municipal Library of Cos, Cos 2005, pp. 102-103.

[42] No Italian drawings or documents in relation to the spring of Vourina have been found among the material of the Special Historical and Folk Archives of Cos, with the exception of the quantitative and qualitative analysis of its waters. It is possible that relevant documents can be found at the Italian Archaeological School of Athens, or in other archives, allowing for the identification of the section of the spring that was destroyed and reconstructed by the Italians. There might even be data in relation to the ι«ancient supply pipes» (according to Iak. Zarraftis) which the Italians discovered during the deep excavations on the eastern side of the spring.

[43] As mentioned by Prof. Jost Knauss, *Late Helladic hydraulic works,* op. cit p. 145.

Study of Social and Economical Sustainability of Native Water-harvesting (Abanbar) in Larestan District in Fars Province of Iran

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Abstract: Deficit and unsuitable time distribution of rainfall in most parts of Iran cause both drought and flood as two serious problems in the country. Residents of those areas have used native rainfall catchments systems in a wide range to adapt with nature and overcome the water shortage. The residents of Larestan region in south west of Iran have overcame water shortage and soil salinity by using these systems. The main objective of this study is an economical and social evaluation of *Abanbar* as a water harvesting system. The results show that the mentioned rainfall catchments system is sustainable from the social and economical point of view. The results also show that traditional water-harvesting systems are in accordance with socio-economic aspects in the region.

Keywords Abanbar; Fars; Iran; native rainfall catchments; socio-economic; sustainability.

Introduction

Applying new technologies to use natural resources could have terrible results on the environment. In addition the tendency to transfer and apply modern science and technology to get more and more from natural resources can cause deterioration of the human kind and its surrounding environment. Looking for sustainable approaches in developed and developing countries indicates that human kind realized its mistakes and tries to accept a new and special philosophy to face environmental issues through the so called “past modernism”. The essence of this new vision is to return to past social values, cultures, views and methods and to review and adapt them for modern life criteria. In other words, this new vision is to scope on local knowledge, which means a kind of sustainable development that is in accordance with cultural and social system and other characteristics that have roots in historical heritage of the society because of accepting and applying sustainable development in a region, where the historical, cultural, social and economical records of the region must be considered. It means that the approaches to achieve the sustainable development may be different in each region or country from other places around the world. As an example, we can refer to the adaptation of the people living in desert. The key for their survival is their hard work to undertake great attempts for survival. The most important achievement of this adaptation is providing water requirements as the critical factor to survive in the desert. It has been done by digging a chain of wells connected to each other by underground tunnels called Qanat. It ends with water catchments for harvesting available water.

Generally speaking, the world wide variations of rainfall catchments is the main reason for investigators and water resource specialists to search ways, such as those in Iran, to renew the traditional methods of direct use of rainfall. The overall objective of these researches is to increase the water security which is cutting down day by day. The main goal of this paper is to evaluate social and economical aspects of rainfall catchments called Abanbar in south west of Iran, named Larestan region. It also presents suggestions for supporting and improving their negative features.

Water Catchments Systems: Their Sustainability and Importance

Generally, sustainable water resource systems are those which are designed and managed to provide society's needs in the present and the future while keeping the stability and equilibrium of environmental and hydrological parameters (Gnadlinger, 2000). To achieve high level of sustainability in renewed water resource systems their capacity of those systems to supply enough water with desirable quality should be improved. Undoubtedly it is the precondition for such systems to provide future generation needs (Anonymous, 2002). Based on ideas and definitions of sustainable development four main aspects of sustainable water resources can be presented as: social, economical, technical and environmental sustainability. Therefore to reach sustainable development in water resources a special programming, design, operation and maintaining must be followed. According to Lax (1994) sustainable water resources must have also four criteria: Technically: effective design and management to make balance between demands and supply; environmentally: Negligible or no long term negative effects on environment. Economically: Total costs of construction and management can be returned. And socially: Society's support and tendency to pay for provided services. There are more opinions about water resources sustainability, presented by specialists, which may be summarized as keeping, improving and providing better life conditions for every one in society; better environmental conditions; and better economical conditions under which equality, self-dependence and enough productivity are provided to satisfy society's needs. Native water catchments systems have the following characteristics that well matched the criteria for sustainable water resource development: They are in accordance with regional environment and have long life period; they can be applied in both small and large scales; they can be constructed by local materials and simple traditional methods; finally, they have been managed by local culture.

The history of water catchments systems in arid and semi-arid areas backs to many years ago. Yu-si-fok (2000) from China reported that using rainfall is an essential way to supply irrigation and drinking water in arid and semi-arid regions of China. He noted that construction and maintaining the traditional water-collector systems helped the improvement of rural sanitary and increases the agriculture products in those areas. He concluded that the main reason of succession of these systems is the public participation in all phases of projects which is a key element to contrast such systems around the world. Rainfall catchments systems can also be found in Tahar desert of India, where water is stored in reservoirs called "Kand" (Mousavi, 2000). These systems have been constructed by participation of all users by using local material and technology. In some cases the rich people have constructed them for rural people. These systems could provide fresh water drink and saved people's time and energy, otherwise they have to walk for hours to get water. Ferrokh, and Sweden (1998) have also studied the water supply systems in India and found that the most common ways of water supply in this country are traditional systems which their sustainability of these systems is due to local residents' culture, construction methods and social systems adaptation.

Andrew (2000) has mentioned that using rainfall is essential for achieve sustainable water resource development. He has notified that water rainfall catchments are small scales and economical ways to supply water demands in arid and semi-arid areas and hence help to protect the environment. Talebbeydokhti (2000) has reported that the water catchments systems play an important role in sustainable economic development in Fars province because the stored water has been used in agriculture and increasing productions. He has also mentioned that this water is usually cheaper than water prepared by other resources such as ground water or dams. Water catchments systems in this region decrease people immigration and affect social and personal behavior of the people. The relation between people gathered around water reservoir get better, therefore the social relations have been improved. Finally, he concluded that by using new technology and improving the performance of local water catchments systems they could be suitable for sustainable development. Ghodosi (1997) in his paper has reported that establishment of large water supply systems is impossible in some places or they may have negative impacts on environment. He has also concluded that using regional rainfall catchments is a good solution to reach sustainable development.

Methods and Materials

The main objective of present research was social and economical evaluation of water catchments systems, Abanbar, in Larestan region in Fars province. Two specified goals were considered: (a) Social and economical evaluation of Abanbar in the region and (b) Introducing suggestions to improve their performance and maintenance. Larestan region is faced by water shortage due to intensive evaporation imposed by climatologic conditions, water salinity imposed by geological and Hydrological conditions and population increase. The region consists of four areas: Lar, Evaz, Khonj, and Grash. A survey method, which is one of subset of descriptive research method, was used. In this method the aim of investigation is to find the reasons to explain the phenomena (Abanbar).

Economical sustainability factors used to evaluate Abanbar systems are: The beneficiary use of the stored water for agriculture, livestock and drink; and the construction, maintenance, and repairing costs. The effects and proportionality of these systems by families and social economic conditions and their capability to supply water demands in drought periods. Social sustainability factors used to evaluate Abanbar are: Participation on decision and management of water catchments systems; improvement of social relations due to systems; immigration of rural people due to water shortage and people satisfaction of the systems. The scores of questions related to social and economical sustainability were computed separately in such a way that the sum of average scores for each category indicates the total sustainability of that category. To investigate the simultaneous affect of social and economical aspects the multi variable regression for each category and sum of two categories was used.

The investigated community was the users of Abanbar in the regions. Twenty five persons from each area (100 in the whole area) were selected randomly and they were asked to fill out a questionnaire or answer oral questions asked by interviewer. Each question in the questionnaire has a score ranging between 1 for very low to 5 for very high. Content validity of the questionnaire was established by a panel of experts in the field of agriculture, economists, socialist and water management. To evaluate the questionnaire reliability a pilot study was conducted. The questionnaire was filled out by 20 interviewees and tested by Cronbach's alpha (a reliability coefficient) method. The reliability coefficient for the questions within questionnaire to measure social and economical variables of sustainability in this research was as follows: Social variables: 0.5; economical variables, 0.77; validity coefficient for whole questionnaire, 0.63, which is acceptable for a non-experimental study. A uniform technique of interviewing was adopted, in order to reduce data collection errors. Since data gathering was done in person the response biases of those participant conducted earlier and later. Comparing the responses of those contacted earlier with the later responses on the dependent variables showed no statistically significant differences. Data collected from the participants were analyzed using SPSS (standard version 9.0 for windows).

Results and Discussion

Based of multi variables analysis, all social and economical factors have significant effects on sustainability and importance of Abanbars. In other words, these native water harvesting systems could improve social aspects in the region in terms of people participation in system construction and decision making how to manage the system. It also improves social and public relations. These native water harvesting systems could be beneficial in terms of economical aspects such as water supply for human, livestock and agriculture, especially during drought. The role of each social and economical factor can be jugged based on R^2 values in Table 1. The comparison of social and economical factor among four areas in the studied region shows the same result except for Evez area that social importance of Abanbars is significantly more than economical aspect. Generally speaking, the improvement of social relations increases the social sustainability of Abanbars that is in agreement with previous results in Iran (Talebbeydokhti, 2000) and Brazil (Lax, 1994). Economical sustainability factors show that more withdrawal of stored water can provide water for human, agriculture and livestock uses which show economical sustainability of Abanbars which are in agreement with previous results of Andrew (2000), and Pandey (2001).

Table 1 Multi variables regression to find out simultaneous effective economical and social factors.

Variables	Adjusted R^2	Regressions coefficient		
		B	ß	Significant
Livestock water supply	0.084	0.563	.0241	0.000
People participation on system construction	0.163	.0503	.0223	0.009
People participation on decision making	0.212	0.520	0.230	0.007
Livestock water supply during drought	0.265	0.450	0.260	0.006
Using non-local material in construction	0.298	0.691	0.286	0.002
Agriculture water supply during drought	0.348	0.834	0.204	0.001
Improvement of public relations	0.372	0.545	0.218	0.019
Improvement of social relationship	0.403	.0399	0.225	0.01
Constant=0.46 F=12.58 Sig. F=0.000				

Conclusions and suggestions:

The final conclusions and suggestions from this study are as bellow: (a) Traditional water supply systems have kept their capacity to overcome water shortage in rural areas till now and they must be maintained in order to provide more water safely; (b) In the new visions the public participation in development is a key factor and must be taken into account to all development programs, specially native water harvesting systems such as Abanbars; (c) To increase the water quality in rainfall catchments systems it is suggested that the pollutant sources around them must be controlled; (d) There are several regions with similar traditional water supply systems around the country such as Yazd and Khorasan provinces which must be evaluated in order to make a national decision to improve these systems efficiency; and and (e) As most of communities in arid zones are the low-income people the government investment is essential to construct and maintain native rainfall catchments systems as an effective way to supply water.

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Water Management Practices in Islam: The Example of the Historic City of Ghadames, Libya

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Abstract: The adobe constructed historic oasis city of Ghadames, Libya, one of Islam's oldest cities, was registered by UNESCO as a world heritage site in recognition of its highly organized social fabric, unique architecture and environment engineering practices. The objective of this paper is to describe the Islamic civilization's water management practices as applied in Ghadames. This objective is realized through a physical context summary of the city, the identification of the major Islamic water percepts and corresponding Ghadamsi applications. The city's remote but strategic location at the periphery of the Sahara desert has made it the gate to Africa while Islamic water management practices ensured its sustainability. These laws emanated from the universal right "percept" to quench thirst and to water crops have been implemented by dedicated administrative organs through a sophisticated management system revolving around Ghadamsi water year, time/volume measurement, and numerals for water sales, accounting and auditing. A well-engineered water distribution system was developed which was operated and maintained effectively to ensure a continuous supply to all users equally and adequately. Ghadamsi practices are simple, transparent and fair; they are fully considerate of both basic human needs and the value of water, a scarce resource in the desert. These practices can be readily extended to present day water challenges with promising results.

Keywords Ghadames; Islam; management; percepts; water.

Introduction

The adobe constructed historic oasis city of Ghadames (HCG), Libya, is one of Islam's oldest cities and the Sahara's most important cultural and trade center for many centuries. It was registered as a world heritage site by UNESCO in 1986 "as an outstanding example of a sustainable human settlement" in recognition of its impressive living heritage that has been preserved in the form of a highly organized social fabric, uniquely distinct architectural style, building and environmental engineering practices (Abufayed, 2003).

The city's significance and sustainability have been realized mostly through the highly efficient management practices of the city's eternal, life sustaining water source Ain AlFaras (AAF) which were founded on the percepts of Islam. The objective of this paper is to describe these percepts and practices as applied in Ghadames. This objective is achieved through an introductory background of the city's geohistoric background, the identification of the major Islamic water percepts and corresponding Ghadamsi applications. Based on an analysis of these percepts and applications, conclusions and recommendations are made with potential applications to more complex present day situations.

Physical Context

The HCG is remotely located at the northern periphery of the Sahara desert, about 600 km southwest of Tripoli, Libya, and only a few km from Tunisian and Algeria (Fig. 1). Because of its desert location and relatively low altitude (350 m above mean sea level), the city's prevalent climate is eremitic; extreme temperatures range from 55.2 ^{o} C to – 6.5 ^{o} C, precipitation averages only 36 mm/year, average evapotranspiration rates exceed 2700 mm/year and relative humidity averages only 33 %. Strong sand-laden southerly winds blow about 21 days per year making Ghadames Libya's windiest city.

The HCG was built on an area of about 7 ha around AAF (Fig. 2). Access to water and harsh environmental conditions necessitated locating the city inside the 200 ha almost circular oasis while limitations of arable land dictated a vertical expansion resulting in an extremely high population density (> 1000 persons/ha.). To ensure security, the oasis was fenced and access to the city was limited through 7 entrances/gates.

Figure 1 Location of Ghadames, Libya.

Water Supply and Distribution System

Ghadames is the gift of Ain AlFaras (AAF) "Arabic for spring of the mare", the eternal artesian spring, whose warm water flowed naturally through 5 canals passing underneath or around the city (Fig. 2).

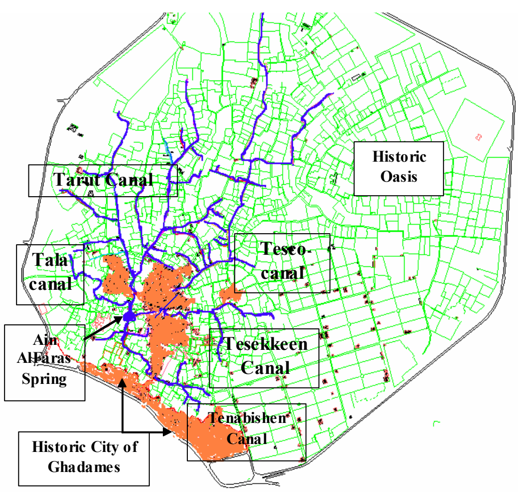

Figure 2 Historic city of Ghadames, oasis, Ain AlFaras and water conveyance system.

Water supply: the eternal AAF

The historic AAF is strategically located at the Midwestern part of the city. It flows at the bottom of an inverted cone-shaped (17 x 21 x 25 x 32 m^3) natural earthen reservoir with an average water depth of 6 m and an estimated volume of 700 m^3 (Fig. 3). It is surrounded by an adobe wall with two Ghadamsi arched diagonally opposing entrances and is surrounded by the AAF square. Its natural attraction and location make it a pilgrimage place for both residents and visitors.

Figure 3 Ain AlFaras Spring.

Spring water is estimated to be 16560-18430 years old (UNDP/UNOPS, 2003) with flowrates declining with time. Recent estimates report rates of 126-570 m^3/hr (Hongrois, 1987, UNDP/UNOPS, 2000). Flowing from a depth of about 400 m, spring water is relatively hot (Temperature = 28 ^oC) and brackish with a total dissolved solids concentration of about 1.5 g/L (UNDP/UNOPS, 2000).

Water distribution system

The spring's artesian water flows naturally upwards towards 5 canals passing through and around the city into the oasis orchards (Fig. 2). These canals branch into a complex network of smaller canals properly sized and sloped for gravity flow. Canals' portions passing underneath the city, totaling about 250 m, were all covered except for portions passing within the major city mosques and public washing sites. Special openings "manholes" were placed along the major canal to facilitate access for monitoring and maintenance purposes.

Under-city canals and major sections of open canals around the city were excavated and constructed from locally available flat-sided limestone laid on a 15-cm thick layer of white clayey soil to prevent root propagation into the canals. The joints between stones were sealed with a locally prepared material known as Shahba, a slurry made from of over-burnt gypsum powder with palm tree ash for water proofing. Other parts of the open canals were simply excavated into natural soil. Canal dimensions vary slightly; widths were 30-60 cm while depths were 30-100 cm. Outside the old city limits, canals were relatively narrow (20-30 cm) and shallow (30-70 cm).

Water supply and distribution system maintenance

Suspended matter carried over by spring water as well as sand, organic matter and debris settle within the spring and in the canals reducing flowrates and necessitating continuous maintenance.

AAF. Spring cleaning is conducted infrequently due to the difficulty of reaching the spring bottom and the slow rate of accumulation of fine material discharged with spring water or falling dust from wind storms. Moreover, grass growing along reservoir sides is removed manually seasonally. Cleaning is performed on pre-announced dates as a communal semi-ceremonial activity.

Canals. Open canals “outside the city” were cleaned manually as needed. Covered canals “underneath the city” used to be cleaned by a very slim person who enters the canal at specific access points and, laying on his back, pushes accumulated “mud” downstream by his feet towards the nearest “manhole” where it is removed.

Silt is removed at manholes strategically located within the covered canals. In the case of the largest canal, a downstream broad crested weir located within a mosque near the end of the city is used to signal the need for silt removal as the canal loses its pleasant turbulent water sound when it is fully silted. Maintenance is conducted by the operators except for major activities such as the clean up of AAF and the reconstruction of heavily damaged canal sections when communal efforts are volunteered.

Water Uses and Priorities

Water was the life line of the HCG. It was used for drinking, bathing, ablution, irrigation and ecological purposes. As Ghadamsi structures were constructed of sun dried adobe with very little resistance to water, water contact with such structures was avoided. Water for drinking and culinary purposes was brought by women from the nearest canal. Otherwise, water was used “in-situ” in the canals. Water uses were prioritized spatially and temporally according to user “quantitative and qualitative” requirements.

Drinking

Because it is the most critical qualitatively, drinking water was made available at specified locations along each of the three major canals and at two time periods of the day, namely, between dawn prayer and sunrise and between sunset prayer and last daily prayer. During these two periods, city residents are either engaged in prayers or sleeping so potential for pollution or interaction between “female” water fetchers and the male population are minimized.

Ablution and body cleaning “Bathing”

To facilitate ablution and bathing, canals are directed through major mosques within the city with special locations assigned for these purposes with due consideration to sex and age. As the water temperature is high, water heating during the cold season is not needed. Ablution places are also found along canals around the city and within the oasis.

Washing of clothes

Similarly, spaces are designated along the major canals for the purpose of cleaning of clothes, linen, etc.

Animal drinking

Local animals (sheep and goats) are raised within special spaces near the houses “funduq” or in the orchard. They are usually brought to specially assigned locations for drinking, but may obtain water anywhere on the open canal sections. Caravans are assigned water from the smallest canal.

Irrigation

The major part of AAF water wais used “or reused” for irrigating the 100 hectare oasis surrounding the city (Fig. 2). Oasis natural soil, largely not fertile, was piled in large dunes and replaced by fertile soil imported from areas nearby. Land was excavated and leveled in many parts of the oasis to ensure gravity flow.

Other uses

Water is sprayed along the major “busy” streets to increase the humidity levels during the dry season and to settle the fine dust raised by the city’s residents. Moreover, it is used to clean the mosque surroundings, ablution, bathing and other use points. Water is also used indirectly to supply building materials, namely palm trunks and fronds used as beams and mats supporting roof mortars.

Water Management: Islamic Percepts and Ghadamsi Practices

Water has a unique status in Islam; it is a gift from Allah that is life giving, life sustaining, and purifying. In Allah’s words, “*We made from water every living thing*” (*21:30) and “And you see the land dried up, but when We send down water upon it, it trembles, and swells, and grows…(22:5).”*. This status is reflected by the fact that water was mentioned 63 times in the Qur’aan; far more than any other substance. The significance of water is confirmed by the many sayings “hadiths” and practices of the prophet Muhammad throughout his life.

Fundamental Islamic water percepts

Because of its explicitly stated significance, water in Islam is a fundamental human right. This right is stated explicitly in the Quraan Islam’s holy book: “Tell them that water is to be shared by all of them” 54:28 and in the prophet’s documented sayings and actions “hadiths”: “Water (along with grazing pasture and fire) is to be shared by all”. The rights of water in Islam are, thus, guided by two fundamental percepts: Shafa and Shurb. Shafa (or the right to thirst), establishes the universal right for humans to quench their thirst and that of their livestock (animals); shirb, the right of irrigation, gives all users the right to water their crops. A subsequent strong and specific priority is that of satisfying ecological needs, i.e., all species are entitled to an amount and a quality of water that is adequate to their needs.

Because of its special value, water should be used with great care and not wasted or polluted; punishment is set for those who do harm to water. Water conservation is explicitly encouraged while its reuse is accepted and certainly “not forbidden”. Refusing “to give” surplus water is a sin against Allah and against man (De Chatel, 2002); clearly the worst of all sins. Islamic water management percepts are deduced from the many Qur’aanic verses, the prophet’s hadiths and practices/deeds related directly or indirectly to water. These percepts, translated into detailed Islamic water laws, the Shariaah, are aimed at ensuring a fair and equitable distribution of water within the community.

Water management: Ghadamsi practices

Guided by these percepts, the Ghadamsis built a sophisticated water conveyance infrastructure and developed a water management system that valued water as a vital and scarce resource and perfected means for: (a) water measurement, (b) water trade, and (c) water allocation, monitoring, and auditing. The managing authority also ensured optimum system operation and maintenance.

Water measurement system

The water measurement system was based on time units which were translated into volumetric units. The basic time measurement is the “qaadous” or the time needed to empty a standardized specially made container with a central opening at its bottom (Fig. 4). One qaadous equals 3 min; accordingly, a day has 480 qaadouses. Volumetric water measurements are expressed in terms of a larger unit, dhermeesah which equals 10 qadouses. Smaller units ranging from the “habbah” (18.75 seconds) to the “qiraat” (0.75 sec) (Abufayed, 2006) give an indication of the value of water to the Ghadamsis. The time clock is housed in a special building where it is operated on a 24-hour cycle by the qaddaas “time keeper”, a man known for his honesty and fairness.

Figure 4 Qaadous, room and operator.

The time of the day could, thus, be determined based o the number of qadouses emptied from sunrise on or after sunset. Based on this knowledge, the start/end times for a given water share are defined by the water administrators and made known to the concerned farmers and operators. The duration signifies the allocated time or the total volume share. To stress the significance of water transactions, the Ghadamsis invented the water year - May 1st to April 30th and reverted to the Ghadamsi numerals - developed originally for trade a profession they mastered for centuries - which proved equally valuable for water computations, and time/volume measurement systems. These numerals, expressed in terms of water units “dhermesas”, have the advantage of expressing very large or small numbers as one single numeral.

Water trade and book-keeping

All water volumes flowing from the eternal spring are owned “shared” by Ghadames residents and religious institutions “waqf”. They are divided into water units based on the qadous or water “clock”. The total number of shares is constant. Water was auctioned (bought, sold, and rented) on the last day of the water year (April, 30th). These transactions take place in the city’s major “market” square and are open to the public so they are transparent and fair. They are documented on the same day in a special register “zmaam” by the “katib” a specially designated registrar. Special water shares were reserved for community services and public purposes including fighting birds, orchard fence maintenance, poor persons welfare and children ceremonies and for paying taxes to occupiers.

Water allocation

“The people of the city allocate ‘water’ into known portions; no one can take more than his right. On ‘water’ they farm” (Theni, 1996). Spring water is distributed among the different users based on the relative demands exerted on each canal. These demands are mostly agricultural and are, thus, determined by the total sizes of orchards served by each canal assuming a constant demand per unit area per unit time. Based on the actual demands, flow is proportioned between the five canals at ratios of 1: 3: 9: 27: 81, i.e. 3^0 to 3^4).

To obtain the desired ratios, spring flow is regulated through broad crested weirs (4 upstream and 1 downstream). Upstream controls are in the form of ovally shaped openings carved into natural rectangular stones (Fig. 5). As stone surfaces of these controls erode, they are adjusted using a layer of lead. This adjustment is made based on measurement of actual flowrates in each canal; the flow from each canal is intercepted into a container of known volume placed in a specially excavated ditch so that the container is filled by gravity. The fill time is measured and flow rate determined.

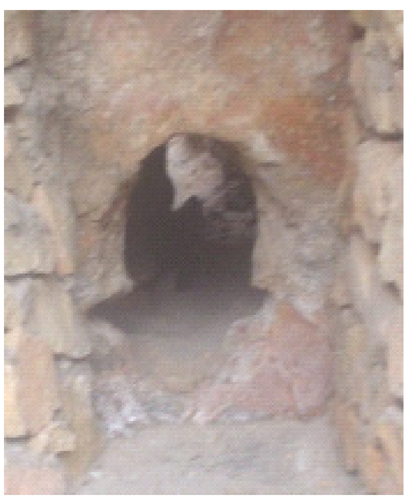

Figure 5 Oval control weir.

As domestic uses (drinking, ablution, cleansing, etc.) take precedence over all other uses, major canals are directed through optimized routes passing underneath or directly around the city within all major mosques. As such, city layout is affected markedly by water uses. Once water trade transactions are completed and documented, the time schedule is practically drawn with each user knowing his irrigation times throughout the year. These schedules are put in place by the management staff. Water is allocated among users temporally and spatially; each user is supplied with water starting and ending as scheduled (i.e., for the duration of his share) with the next user being the closest orchard downstream in order to minimize water losses and facilitate monitoring and follow-up. A water cycle “dhami” is completed when all orchards have been irrigated. Water cycles vary from one canal to another and seasonally (Abufayed, 2006).

Water administration

Water activities are conducted based on the water year. All water transactions as well as selection of the water management staff take place on April 30th and take effect on May 1; no transactions are allowed during the year to ensure stability of the water supply and value for the users and prices for the consumers. Staff changes are allowed under justifiable circumstances only. Administrative activities include supervising and documenting the water auctioning transactions, regulating, organization, monitoring and follow up of water supply schedule and operation and maintenance of the water supply system (AAF and network). Addressing problems arising during water use operations is another task of the water administration.

Water administration staff is selected by the city seniors during the final day of the water year; new or existing members are selected based on minimum value offers. They are paid in kind, i.e. in water shares. The total number including the covered canal cleaner and the spring guard is 18. They include ”ameen”, the register’s” keeper, 5 kaatib “registrars”, 5 “naa’ib” assistants, 3 canal operators/supervisors, and 2 clock operators “qaddaas”. The book keeper keeps records of water transactions and names of users and the number of their shares and updates them annually in a special gazelle hide register “zmaam” with a fixed number of pages. A copy of these records is passed to the assistants for day-to-day operations. The assistant provides the operator with the daily list of users and shares. He, in turn, informs the users of these schedules. The operator conducts the hourly operations informing the users of when their shares begin and end and ensures that water is used by the next user in case of absences and subsequent compensations. The numbers of keepers and assistants for the 3 largest canals are 2/2, 2/2 and 1/1, respectively.

As water was invaluable for sustenance, it was sold in very small quantities and only under severe conditions giving little room for monopoly and sharp price rises. System flexibility and stability were ensured also by the fact that trade was practically within a seemingly homogeneous and socially bound community. Stability was also enhanced by freezing transactions “prices” throughout the water year. As the number of inhabitants and the irrigated area are nearly constant, the demand-supply situation is stable. Maximum profitability is approached. The management system ensured that water was not lost, stolen or misused.

Sustainable agriculture

The effectiveness of the Ghadamsi water management practices was demonstrated over many centuries. Despite the orchards very small areas (< 1000 m²), organic agriculture flourished ensuring food sufficiency and providing building materials as well as a protective and attractive green built earned the city its historic name “Pearl of the Desert”.

Conclusions

Water management practices of the historic oasis city of Ghadames, Libya, are a direct application of Islamic water percepts. The effectiveness of these practices has been demonstrated over many centuries. This effectiveness may be attributed to the following: (a) Valuing water as a vital substance that needs to be used accordingly; (b) prioritizing water uses; (c) establishment of a management system that ensures water value and use priority through (i) sound measurement, regulation and allocation system, (ii) sound water system data base and documentation system, (iii) sound conveyance and distribution infrastructure, (iv) sound mechanism for selection of water administrative body, (v) sound monitoring, operation and maintenance system, and (vi) transparency of all water management elements/operations; (d) The success of these practices can be attributed also to the direct involvement of stakeholders in all management process steps/elements, and (e) the Ghadamsi experience can be expanded/modified to suit present day applications.

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Water Strategy and Space-management in Three Medieval Cities of the Maghreb: Qayrawan, Fez, Qalat Bani Hammad

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Abstract: The history of the ancient cities reminds some interesting informations about the water policy followed by the past. More especially those one situated in the Maghrib zone, where the physical and climatic items designate a quite different rainfall levels from North to South and from West to East. It means that in such a geographical context any urbanisation had necessary to be accompagnied by very performing water installations. This is the case of Qayrawan in Tunisia (7th century), Fez in Morocco (8th century) and Qalat Bani Hammad in Algeria (11th century), here described. The present paper aims to show how, at such distant past, the water resources have strongly influenced not only the choice of the future urban sites but also their very first space management. As a water strategy has been adopted upstream the town planning process integrating the socioeconomic needs and the environmental stakes, we can carefully suggest that Qayrawan, Fez and Qalat Bani Hammad were a quite sustainable cities before time. A beautiful lesson of humility.

Keywords Fez (8th century); Qalat Bani Hammad (10th century); Qayrawan (7th century); urban space management; water strategy.

Introduction

The history of the ancient cities reminds many interesting information about what is today designated as the urban hydraulic science. It seems that some of them have early established a collecting and supplying systems adapted to the local water potentialities in one hand, and to the urban population's needs in the other. That is the case of some cities dated of the third millenary as Mohenjo Daro (Pakistan), Mari (between Syria and Iraq), Habuba Kabira (Syria). The archaeological excavations in their respective sites have indeed emphasized the existence of primary water town mains[1].

Besides, according to a geographical consideration, the city has been often established at a watering place: river or lake, superficial or underground resource. In the Maghreb zone, the continental cities as well as the coastal ones did not escape to this paradigm. Several examples of urban settlements sustain the hypothesis supposing that water was not only implicated in the choice of the site, but has also strongly influenced the town space-management. As it is, it was necessary for the ancient settlers to undertake some hydraulic

[1] See: Viollet P-L, (2000). *L'hydraulique dans les civilisations anciennes. 5,000 ans d'histoire*. Ed Presses de l'Ecole des Ponts et Chaussées, Paris, 374p.

infrastructures which the architecture and technology have displayed their efficacy, solidity and elegance, still recognized nowadays.

Thus, a dialectal relationship between the water resources and the urban growth process became quite established. Such relation can now easily be deduced from the superposition of the hydrographical map and the historical urban sites' one, within the framework of the Maghrebian territory. It shows that the water has been transferred either to the new or to the previous occupied towns, the hilcok and the valley sites. Some aqueducts many kilometres long (like Cherchel in Algeria, Carthagene in Tunisia), number of canals and reservoirs (Tlemcen in Algeria) and supplying town mains (Algiers, Fez) witness about this human genius. Really, a water strategy is thus fundamentally necessary and conditional to all urbanisation, especially within the Maghrebian countries.

More, the water genius has often determined the emplacement, the spatial organisation and the longevity of the city. It has also influenced the urban architecture and economy as some more or less complex proceedings were used to collect, dispatch, distribute and stock the superficial or the underground water resources founded near or farther the urban agglomeration. In order to present the interesting deductions raised from our different analytic readings, we have firstly to analyse some specific studies and maps to remind the geographical and climate items of the Maghreb zone, especially the rainfall rates and the local water potentialities. Then, the evaluation of the water strategy followed by the Muslim sovereigns after the 7th century could be compared with the urban strategy adopted to establish the new cities of Qayrawan, Fez and Qalat Bani Hammad.

Within the framework of this paper, the question is whether to know how did the hydraulic strategy rather than the hydraulic technology precede, favour and accompany the space management process? How did the founder sovereigns prepare the future urban site in term of water supplying? How the water resources did influenced the very first space management? And finally, which role have the water resources played in the global development process and then in the longevity of those new cities?

Urban Settlements Anterior to the 7th Century

The urban history and the archaeological researches reveal the successive steps of the urban growth in North Africa. Concerning its spatial and temporal progress, it seems that the occupation of the territory has been pursued since the prehistoric times even when the economic activity and the urban increasing were comparatively more or less important at the different periods. The urbanisation processes of the territory where the climate, the rainfall rate and the hydrography are specific necessitate the domestication of the water resources. In fact, all the civilisations developed and successively superposed on its land have undertaken a real water policy at the risk of their vanishing.

After the Phoenicians having accosted on the Mediterranean coasts to establish the famous Punic scales to deal with the autochthones, it seems that the Greeks have installed some peopling settlements[2]. Later, the Phoenician counters, coastal in their majority, became real harbours and sometimes permanent cities[3]. At the same time, some towns have born within the interior zone of the Tell. Under the impulse of the Romans, some new towns have been raised and some others remodelled[4]. The most ancient important archaeological remains, still perceptible up to now, date from this epoch. Within the African occupied file,

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2 Wood R, Sir Mortimer W, (1966). *L'Afrique romaine*, Ed Arthaud, 160 p, pp 12-14.
3 Despois J (1964). *L'Afrique Blanche*, T.1, *L'Afrique du Nord*, op.cit, p 119.
4 Wood R, Sir Mortimer W, (1966). *L'Afrique romaine*, op.cit, p 24.

Rome has strongly marked its impact by a territorial urban framework, a strategic road system and a remarkable growth of the agricultural hydraulic[5].

All of the occupying forces have finally got the interest in developing the culture of the clearing lands of the plains and the steppic highlands. The great hydraulic vestiges sustain the importance of the works undertaken by the Romans in North Africa and those quite probably raised before either by the Carthaginians or the autochthones[6]. In such natural environment, fairly irrigated or quite arid, one has obviously and firstly to make the settlements along the watercourses, which had to be carefully managed[7]. Nevertheless, when the local resources became insufficient, it was necessary to collect the water from the long distances to supply the growing urban centres. The dams and aqueducts of Cartage, Cherchel and Algiers have been used to this end[8]. By another way, the rainfall waters were stocked in some underground public cisterns surrounding the cities [9] from where they were conducted to the different districts across the fountains[10].

Urbanisation's Circumstances of the Maghreb in the 7th Century

The history reported by several authors, generally anterior to the 7th century, often describes an “unknown Maghreb”[11] conquered by the Muslims coming propagate the Islam in the North of Africa. Some reconnoitring missions had then to be accomplished across the territory, very probably with the assistance of the autochthones themselves. Indeed, in his relation of the *Islamic Feth* of North Africa, *Ibn Abd al-Hakam*[12] says that, during his moving, after every city reached, *Uqba* asked his guide “is there anything after you?”

According to several other historical witnesses, it seems that the Muslims coming from Orient founded some precious auxiliaries amongst the Romans and the sedentary autochthones[13]. They knew the country quite well, more especially the watering places, and have hardly probable contributed to the choice of the roads itinerary and the sites implantation of the resting-places, the *ribats* and the new cities founded *ex nihilo*. Contrary to the Phoenicians and the Romans, the Muslims have penetrated the North of Africa overland. They likely have adopted such strategy to avoid the North defensive lines and fortified towns[14], being certainly counselled by their auxiliaries and in any case precisely informed according to the fast land-raids tactic towards the North[15]. They have discovered

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5 Despois J (1964). *L'Afrique Blanche*, T.1, *L'Afrique du Nord*, op.cit, p 120.

6 Julien Ch-A, (1956). *Histoire de l'Afrique du Nord*, T.1, Ed Payot, 333p, p 153.

7 *Idem*, p 153.

8 It seems that the Romans appealed to some engineers in special charge with the water supplying works. Two kinds of aqueducts were then built: (a) composed by one file of high arcades and (b) composed by three level of crossing archs.
Ricard P, (1924). *Pour comprendre l'art musulman dans l'Afrique du Nord et en Espagne*, Ed Hachette, 352p, p 40.

9 Julien Ch-A, (1956). *Histoire de l'Afrique du Nord*, T.1, op.cit, p 154.

10 Ricard P, (1924). *Pour comprendre l'art musulman dans l'Afrique du Nord et en Espagne*, op.cit, p 41.

11 Cambuzat P-L, (1986). *L'évolution des cités du Tell en Ifrikya du VIIè au XIè siècle*, T.1, Ed OPU, Alger, 227p, p 29.

12 See: Ibn Abd al-Hakam(803-871). *Conquête de l'Afrique u Nord et de l'Espagne*, 2nd édition revue et corrigée par Gateau A (1942). Ed Carbonel, Alger. According to Marçais G, the Egyptian traduction of Ibn Abd al-Hakam is the only one directly and entirely transmitted.

13 Cambuzat P-L, (1986). *L'évolution des cités du Tell en Ifrikya du VIIè au XIè siècle*, T.1, op.cit, p 36.

14 See: Cambuzat P-L, (1986). *L'évolution des cités du Tell en Ifrikya du VIIè au XIè siècle*, T.1, op.cit, pp 34-38.

15 *Idem*, p 35.

here a rich and fertile country that was already an oil exporter[16], and by the interior lands, some presaharian steppic plains thinly populated[17].

Since then, some ancient cities situated above the principal connecting roads, would have a new economic, social, cultural and urban development. It was the case of Cirta becoming Qasantina in Algeria, Tangis becoming Tanger in Morocco, Hadrumetum becoming Susse and Taparura becoming Sfax in Tunisia[18]. Meanwhile, other cities as Qayrawan in Tunisia, Fez in Morocco and Qalat Bani Hammad in Algeria were newly built and populated on some entirely virgin soils. The history of their foundation can lead to discover the urban water policy then adopted by the local sovereigns.

Hydraulic Strategy and Space-Management in the Maghrebian Cities founded *Ex Nihilo* since the 7th Century

Among the urban factors strongly dependant on the water resources, the choice of the future urban site is the first and may be the most important. Nevertheless, some other urban items are no less interesting to be analysed and compared with the physical ones as the urban density, the spatial organisation of the neighbourhoods, the repartition of the socioeconomic activities and, at last, the longevity of the city.

Qayrawan in Tunisia-7th century

Physical items: Qayrawan is situated by the South of Tunis, the Tunisian Capital, within a wide plain only 60 m high and about 100 km long on 40 km large. The rainfall rate is here quite unequally and the temperatures vary a lot between the dry summer and the humid winter[19]. The comparatively important *wads* irrigating its plain sometimes overflow[20] creating a permanent wide swampy zone by the eastern side of the city[21]. As it is, the land seems to be no more protected against the floods than the scarcity events. That is why the population had continually to change the roads' tracing running along the out rivers and to stock all kinds of the local available water resources[22]. But, even in such a semi-arid climate zone, the city is still sufficiently watered as it receives about 300 to 400 mm/yr[23]. Thus, the local underground sheets are supplied with both the rainfalls' and the rivers' waters[24].

Hydraulic strategy: One of the first related episodes about the water inquiring during the *Islamic Feth* of the Maghreb stages *Uqba*[25] and his companions tired and thirsty praying and invoking God. Suddenly, excavating the soil, his horse uncovered a water source[26] and then all could drink and empty their bottles. Later, *Uqba* and his companions gone towards the future site of Qayrawan where they get cleaned and divided the territory into parcels to raise

16 See: Planhol (de) X, (1968). *Les fondements géographiques de l'histoire de l'Islam*, Ed Flammarion, 442p.
17 Cambuzat P-L, (1986). *L'évolution des cités du Tell en Ifrikya du VIIè au XIè siècle*, T.1, op.cit, p 36.
18 See: Cambuzat P-L, (1986). *L'évolution des cités du Tell en Ifrikya du VIIè au XIè siècle*, T.2, op.cit
19 See the website: www.Kairouan.org
20 *Idem.*
21 *Idem.*
22 Hamza M, (1988). *Les bassins aghlabides à Kairouan, une leçon d'ingénierie*, in *L'eau dans le Maghreb. Un aperçu sur le présent, l'héritage et l'avenir*, Ed PUND, pp 145-148, p 6.
23 Despois J (1964). *L'Afrique Blanche*, T.1, *L'Afrique du Nord*, op.cit, p 514.
24 See the website: www.Kairouan.org
25 Ukba *Ibn Nafi*, one of the famous muslim conquerrors of the Maghrib, founder of Qayrawan in 670 that is inscribed on the list of the Organisation des Villes du Patrimoine Monsial (OVPM) since 1988. See the website of the OPVM.
26 The place is named *Ma Faras* (the water of the horse).

the new city[27]. The most interesting information concerning the hydraulic system of Qayrawan is posterior to its foundation epoch and dated from the Aghlabides[28]. Qayrawan, becoming an important political and religious capital, henceforth calling for a real water policy so that it had been necessary to systematize the collecting and the distributing of both the superficial and the underground water resources.

Qayrawan owes to the Aghlabides some important drifting and stocking water works, also the reservoirs and drawing cisterns. Since then, the city had also a main town system to evacuate the wastewaters[29]. Having the same care, after them the Fatimides have pursued the realisation of many canals conducting water from the surrounding mountains to empty the public reservoirs[30]. It seems that both of them have adopted an ancient technique dated from the 2nd millenary to build their aqueducts[31]. It consisted in recovering the interior basin's faces with a watertight mortar made from tile crushed[32]. The water distribution across the urban districts is no more detailed by the documents we have consulted. Nevertheless, the hydraulic equipments of Qayrawan witness about a real local knowledge of a specific hydraulic technology[33]. For example, the juxtaposition of two basins, one great and another little behind where the water can clear out of its carried alluvions, confirms as well a previous regard for a water epuration proceeding[34]. Likewise, the just opposite arrangement was quite efficay to reduce the water's debit at the entrance of the city and then to prevent any flood event[35]. The rainfall waters' collecting in some buried or opened air cisterns has also known a large development during the 9th century[36]. In fact, either the superficial and the underground water resources were drawed and deviated towards the city and its gardens, more precisely to derift dams and aqueducts conducting the water to the great public cisterns[37].

Urban strategy: According to the historical statements, *Uqba* planned to raise a real Islamic city that also could be used as a supporting military camp, such a city having a great *masjid*, some little others and many dwellings near *Dar al-imara*[38]. At last, a wide city[39], able to receive a large population for whom it would be necessary to resolve the water's question[40]. The comparatively frequent flood events in the region of Qayrawan probably

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[27] See: Ibn Abd al-Hakam (803-871). *Conquête de l'Afrique d u Nord et de l'Espagne*, op.cit.

[28] In fact, before the Aghlabides, under the Abbasides, Qayrawan has yet developped the agricultural and horse-farming economy and many other handycraft activities that necessitated the construction of some underground canals and circular open air reservoirs. In the beginning of the 9th century, the Aghlabides will use the same site to built their famous Great Basin. Hamza M, (1988). *Les bassins aghlabides à Kairouan, une leçon d'ingénierie*, in *L'eau dans le Maghreb. Un aperçu sur le présent, l'héritage et l'avenir*, Ed PUND, pp 145-148, p 6.

[29] Marçais G, (1954). L'architecture *musulmane d'Occident*, Ed Arts et métiers graphiques, p. 541, p. 37.

[30] *Idem*, p 147.

[31] See: Bonnin J, (1984). *L'eau dans l'antiquité. L'hydraulique avant notre ère*, Ed Eyrolles.

[32] See the website of Muslim Heritage. *Water management and hydraulic technology*. Foundation for science technology and civilisation.

It seems that the most important works have yet been realised between the 8th and the 9th century. Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p. 37.

[34] Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p37.

[35] The famous Great Basin near the northern gate of the city was precedeed by a little one receiving the river's water running cross an aqueduct, discharging when the level went over almost 2 meters and then reducing its debit. Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p38.

[36] According to al-Bakri cited by Marçais, Qayrawan have then about 15 ones. *Idem*, p 37.

[37] Three kinds of installation have been raised: To stock the waters, only one great open air cistern was built. To favour the decantation process, two basins different by their diameters were necessary. To supply the population, a supplementary drawing cistern was associated to the two previous basins. Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p37.

[38] The Government Palace. Al-Nuweyri cited by Cambuzat P-L, op.cit, pp 43-45.

[39] 3600 arms ± 6500 m. Ibn Al-Athir cited by Cambuzat P-L, op.cit, p 45.

[40] *Encyclopédie de l'Islam* (1978). T. IV, op.cit

leaded the predecessor of *Uqba*[41] to choose another site, *al-Qarn*, on such a heightened land within the same region, well protected from the Byzantine attacks[42]. Meanwhile, *Uqba* finally opted for this site because it seems to him that it was the only one that had both military and natural advantages[43]. In fact, concerning *the* choice of the site, contradictory legends have been reported. Some authors maintain that *Uqba* made the bad one as the steppe is quite unfavourable to any economic development of a great capital[44] and, what is more, covered by trees and infested with wild beasts, savage animals and reptiles[45]. Really, the foundation of Qayrawan has been held within an alluvial plain near the sea and the mountain at once[46]. At the very time the existence of such the flora and faun rather properly designate the important natural potentialities of the site and then, of course, the obvious availability of a subsequent water resources[47]. Indeed, *Uqba*, a quite trained chief, coming himself from an arid country, could not neglect the strategic and vital importance of the water. He also quite probably well knew the nomad's tactic observing the birds' flight to locate the watering places within such a hostile land. Thus, at least in term of natural potentialities, the hypothesis of a bad site's choice cannot be sustained any more. It seems that *Uqba* himself has traced the *masjid*'s and the government house's emplacements within a urban perimeter 7.5 km long[48] supposing a surface of about 3.5 km². The first population has been estimated to 50,000 inhabitants[49] with a high urban density at this time, beyond 14,000 inhabitants/km² (about 140 inh/ha).Later, during the 9th century, at its very apogee, the city integrated the two near fortified royal residences of al-Abassiya (built by 800) and Raqada (built by 870)[50]. Its surface reached then about 16 km² wide and its population some thousands inhabitants more[51].

The resulted increasing water needs necessitated then some additional water works to supply the numerous *masjids*, *hammams* and houses[52]. In fact, the successive royal dynasties have undertaken many works to conduct the river's water to the great public basins just near the town's gates. There were some underground canals, reservoirs and cisterns from where the water has been firstly distributed to the public equipments and then very probably to the different urban districts[53]. Besides, since the 7th century, some activities closely dependants on water have been developed and quite organised by the city's limits along its numerous

[41] Muawiya Ibn Hudaij.
[42] Mahfoudi F, Baccouch S, Yazidi B, (2004). *L'histoire de l'eau et des installations hydrauliques dans le bassin kairouan*, op.cit, p 3.
[43] *Idem*, p 4.
[44] *Encyclopédie de l'Islam* (1978). T. IV, Nouvelle édition, Ed G-P Maisonneuve & Larose S.A, pp 857-864.
[45] See: Ibn Abd al-Hakam(803-871). *Conquête de l'Afrique u Nord et de l'Espagne*, op.cit.
[46] Cambuzat P-L, (1986). *L'évolution des cités du Tell en Ifrikya du VIIè au XIè siècle*, T.1, p 43.
[47] Indeed, it seems that at the vey beginng of its foundation, Uqba insisted on being close near by the valley and the wad. See: Mahfoudi F, Baccouch S, Yazidi B, (2004). *L'histoire de l'eau et des installations hydrauliques dans le bassin kairouan*, Tunis, 82p, pp 10-11.
[48] *Encyclopédie de l'Islam* (1978). T. IV, op.cit, p 861.
[49] *Idem*.
[50] *Idem*.
[51] Later, under the Fatimides, the city's perimeter will reach about 22 Km. *Encyclopédie de l'Islam* (1978). T. IV, op.cit, p 863. Nowadays the *madina* is about 54 hectares wide. See the web site of the Organisation des Villes du Patrimoine Mondial.
[52] The city has then about 48 hammams. *Idem*. It is interesting to note here that, because of the local climate and the hydrographical items, the city had high and strong ramparts and also a strait ruelles at the time when the houses have all augmented their food products stocking areas. See the website: www. Kairouan.org
[53] The city was divided into quarters according to the social appurtenances *Encyclopédie de l'Islam* (1978). T. IV, op.cit, p 861.

rivers[54]. There were for example the *wad of al-Qassarin*, the western river of the wool washers and the *koudiat al-Fakharin,* the ceramists' hillock and the vegetables' merchants by the eastern side near another *wad*[55]. By the West, at about 3500 m of Qayrawan, there was a singular construction named *Qasr al-Ma'* namely the Water's Palace. *Qasr al-Ma'* seems to be a very ancient water work built on an antique site regularly occupied till the 10th century by the Zirides[56]. Some archaeological vestiges have been founded on the site: a great basin, a previous hole, a water-tower and many other holes drawing the fresh water from the local underground sheet[57]. It is a fact that all the future urban growth programs have been undertaken on the Westside of the city, towards *Qasr al-Ma'*[58] obviously because of the water resources availability there.

From this distant past up to now, Qayrawan, as a urban settlement, has always based its economy on the agricultural and handicraft activities. Despite the violent natural disasters, the city has never been completely deserted[59]. Only the political conflicts and the consequent wars have leaded to its temporary depopulating by the beginning of the 11th century[60]. Even if it has later definitely loosen its status of a capital, it has preserved its spiritual aura not only at the Maghreb scale but also at the wide Islamic world one.

Fez in Morocco (8th century)

Physical items: Fez is situated at the confluence of the *Wadi Fez*'s affluents, by the North of the western side of a wide and very fertile plain within the Sebu hydrographical basin, one of the richest regions of Morocco[61]. At about 300 m up, the climate is continental but still influenced by the oceanic conditions[62] as the rainfall rate reaches about 750 mm/yr even unequally distributed cross the seasons and the geographic zones[63]. The water sources arrive from different directions and are more numerous by the left bank of the *Wadi Fez*[64]. The origin of the *Wadi,*[65] that is some kilometres long, is about ten kilometres farther by the West. It catches the *Sebu* River by the East after a course of six kilometres[66]. As its flow is regular, it does not product a flooding but very rarely. Indeed, the history relates only two flood events at Fez[67].

Hydraulic strategy: The first important water supplying known work seems to have be initiated by the Almoravides[68]. A first derivation has been then operated above the *Wadi Fas*[69]. Meanwhile, the construction of this aqueducts supplying the Andalusians' quarter is

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[54] Mahfoudi F, Baccouch S, Yazidi B, (2004). *L'histoire de l'eau et des installations hydrauliques dans le bassin kairouan*, Tunis, 82p, p 6.
[55] *Idem*.
[56] *Idem*, p 10.
[57] *Idem*, p 9.
[58] *Idem*.
[59] For example, at the beginning of the 10th century, Qayrawan sufferd an earthquake (911-12), a devastator flooding (920-21), a famine and epidemic events (929). *Encyclopédie de l'Islam* (1978). T. IV, op.cit, p 863.
[60] *Idem*.
[61] *Encyclopédie de l'Islam* (1965). T. II, pp 837-843, p837.
[62] Despois J & Raynal R, (1975). *Géographie de l'Afrique du Nord-Ouest*, Ed Payot, 570p, p 308.
[63] *Encyclopédie de l'Islam* (1978). T. II, pp 837-843, p 837.
[64] *Idem*.
[65] The origin of the *Wadi Fez* is named *Ras al-Ma* (the water's head). See the website of FES-CITY.
[66] See the website of FES-CITY.
[67] *Idem*.
[68] Between the 11th and the 12th century.
[69] El Hajjami A, (1988). *Fès, labyrinthes des voies d'eau* in *L'eau dans le Maghreb. Un aperçu sur le présent, l'héritage et l'avenir*, Ed PUND, pp 115-121, p 115.

owed to the Almohades about one century before[70]. Later, the Marinides will realise a great hydraulic works collecting the water of another source as like in 1276 when the Almoravide founder of the new city[71], *Yaqub al-Mansur*, got the *Ayn Omayer* exploited[72]. His son *Yusuf* entrusted an engineer coming from al-Andalus with some other supplying works. The expert then conceived and realised a water-wheel, such a wooden mechanical installation that numerous drums plunge into the river's current and bring the water till the aqueduct's canal[73]. This was the famous sevillan *noria* that was going to be newly introduced to the city[74].

By the beginning of the 16th century, Léon l'Africain has noted the presence of some of those very great mechanical *norias* still bringing the water from the river and pouring it out in the canals arranged above the ramparts walls to be conducted towards the palaces, gardens and *masjids*[75]. The water supplying of the different districts of Fez was naturally ensured as the ravines lay on the abundant waters from the surrounding sources[76]. As it is, the *Wadi Fez* offered the city such a complex separative system to conduct and evacuate water according to its quality and using. A tardy description (dated of the beginning of the 18th century) of the water supplying system notes the existence of two town mains' levels: one high level conducting the clean waters and another, lower, evacuating the wastewaters[77]. It was quite probably the matter of an ancient system established at a previous date. The main town system was then composed by three kinds of canals[78]: (a) Principal canals: about 2 m in diameter, running along the river's branches, more often covered by some bricked curves to preserve the water's cleanness and quality; (b) secondary canals: about 5 to 45 centimetres in diameter, draining the water to the different quarters across some baked clay canalisations; and (c) tertiary canals: same diameter, distributing water to the houses and the public equipments. It seems that the water resources were principally capted from the left bank of the *Wadi Fez* and then drained towards the city. The debit has been quite controlled at the entrance of the city to preserve it from any flood events[79].

Urban strategy: History traces back the foundation of Fez to the end of the 8th century by *Idris Ibn Abdallah*[80] who came from Western to take refuge in the Maghreb[81]. Becoming *Imam* of the *Awraba* tribe, it seems that he firstly settled in a site of an ancient roman city named *Volubilis*[82]. Later, he decided to found a new city, *Madinat Fas* on the right bank of *Wadi Fas*[83]. After him, his son preferred developing the left bank even a little less provided than the right one to raise *Fas al-Aliya* [84]. In fact, the historical city of Fez[85] is constituted of

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70 Likely by 1207. Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p 226.
71 The joiner of the two cities is quite considred as the very founder of Fez. He also provided it with many *funduqs*, *hammams* and watermills that's all suppose important water needs. See the website of FES-CITY.
72 It is the matter of Fez-Djedid (New Fez), the Marinide city situated on a higher plateau si that it cannot be supplied by the same river. *Idem*, p 325.
73 *Idem*.
74 *Idem*.
75 Benjelloun M-E, (2006). See the website of *Fès*, in LABYRINTHES Magazine.
76 Despois J & Raynal R, (1975). *Géographie de l'Afrique du Nord-Ouest*, op.cit, p 311.
77 El Hajami A, (1988). *Fès, labyrinthes des voies d'eau,* op.cit, p 116.
78 *Idem*.
79 *Idem*.
80 *Idris Ibn Abdallah* or *Idris I* has raised *Madinat Fez* by 789. After him, his son initiated *Fez al-Aliya* by 908-9.See the website of *Fès*, in LABYRINTHES Magazine
81 *Encyclopédie de l'Islam* (1965). T. II, op.cit, p 838.
82 Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p 3.
83 *Encyclopédie de l'Islam* (1965). T. II, op.cit, p 837.
84 The water resources were impouned from the left bank at *Lâyun* quarter (the sources' quarter). El Hajjam A, (1988). *Fès, labyrinthes des voies d'eau* in *L'eau dans le Maghreb. Un aperçu sur le présent, l'héritage et l'avenir*, op.cit, p 116.

those two populated twin towns joined and then spreaded about three centuries later by the Almoravides[86]. Here the vital water's question was naturally resolved. The site's choice has been without any doubt based on the local waters' abundance, either superficial or underground ones. Although, when the Marinides raised *Fez el-Jadid* by the mid of the 13th century, they had to invest the western plateau to supplied more easily the new quarters with another source situated upstream[87]. It has then occupied an flat land overhanging the river while *Fez al-Bali* entirely integrated its two banks[88].

Likewise, the urbanisation and the important economic activities were strongly dependant of this factor. Fez has been then a quite commercial, industrial, scientific, cultural and artistic capital. It is supposed that by the end of the 12th century, the city had about 120,000 houses[89] supposing almost 90 to 100,000 inhabitants and about 3,500 handicraft manufactures[90]. Meanwhile, it is interesting to note that the historical quarters of Fez were organised along the river's banks, around this system that widely determined the spatial distribution of the activities, especially those depending on the water resources like water-mills, tanneries, dyeing, abattoirs, etc[91]. After then, the urban growth followed a western direction towards the river's source upstream the site[92]. Really, very later, at the beginning of the 16th century, the city has enlarged *extra-muros* in the North-West side[93].

Since the Idrissides (the first founders of the city) and till the 17th century, the city has been well supplied with the river's water that runs across the different districts and bellow its little interior bridges[94]. The fresh water's canals[95] reached and gone through the *masjids*, palaces, houses and gardens that were likely numerous within the ramparts[96]. Likewise, the wastewaters were evacuated across the main sewer running along the *wads* arranged under the supplying canals[97]. From the 8th century and its foundation, Fez has been a so flourishing city that it has somehow conserved its Capital status despite the numerous political disorder episodes within the Maghreb. The epidemics, pestilences and wars have no more succeeded in depopulating the city than the current water's problems of nowadays could do. Indeed, the hydrography that has quite determined the activities' repartition is now paying such a heavy debt of nature. Fez suffers today with a serious pollution's and scarcity's problems[98].

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85 Named *Fez al-Bali*.

86 During the 11th century. The joined city is named *Fas al-Bali* as opposed to *Fas al-Djadid* the new quarters raised by the Marinides above the plain towards a western direction during the 13th century. *Encyclopédie de l'Islam*, op.cit, p 838.

87 *Ayn Omayer* up cited.

88 See the website of *Fès*, in LABYRINTHES Magazine

89 Benjelloun M-E, (2006). See the website of *Fès*, in LABYRINTHES Magazine

90 *Idem.*

91 El Hajjam A, (1988). *Fès, labyrinthes des voies d'eau* in *L'eau dans le Maghreb. Un aperçu sur le présent, l'héritage et l'avenir*, op.cit, p 120.

92 Such spatial spreading has likely accompanied the singular population increasing resulted from the arrival of hundreds refugee families from al-Andalus by the beginning of the 9th century (817-18) and later some others from Qayrawan by the beginning of the 10th century (908-9). That is probably why the water installations of Fez presented similiraties either with the Andalusian and the Qayrawni ones. See the website of *Fès*, in LABYRINTHES Magazine

93 Léon l'Africain cited in the *Encyclopédie de l'Islam* (1965). T. II, op.cit, p 838.

94 Benjelloun M-E, (2006). See the website of *Fès*, in LABYRINTHES Magazine

95 There were three water's qualitative levels. First, the fresh water capted from the sources or drawed from the holes for drinikng and ablutions. Second, the clean water capted from the river's affluents for all other usings except drinking. Third, the wastewaters. El Hajjam A, (1988). *Fès, labyrinthes des voies d'eau* in *L'eau dans le Maghreb. Un aperçu sur le présent, l'héritage et l'avenir*, op.cit, p 120.

96 Within the ramparts the city still has many free spaces, gardens and orchards. *Encyclopédie de l'Islam* (1965). T. II, op.cit, p 838.

97 El Hajjam A, (1988). *Fès, labyrinthes des voies d'eau* in *L'eau dans le Maghreb. Un aperçu sur le présent, l'héritage et l'avenir*, op.cit, p 120.

98 See the website of *Fès*, in LABYRINTHES Magazine, op.cit.

Qalat Bani Hammad in Algeria (10th century)

Physical items: Qalat Bani Hammad is situated within the high plain of the Hodna[99] that has two faces, one orientated towards the North, surrounded by the *Maadid* mountains, and one other orientated towards the South, open on the steppic zone. As it is, the Qalat is just raised at the Sahara's gate. Its continental climate is then semi-arid with only 200 to 350 mm/yr[100]. Nevertheless, the rainfall rate is better at the North side of the mountains [101] so that the Hodna, which is situated downstream the hydrographical basin, is really rich in underground water resources[102]. Even if the *wads* are here temporary, they sometimes overflow causing short but remarkable floods[103].

Hydraulic strategy: The city's hudro geographical situation has favoured the water providing for its growing population integrating a number of students and traders coming by the middle of the 11th century[104]. *Wadi Fraj*, orientated North-South, running along the Eastern limit of the city, has been used as a natural reservoir supplying the city's sources, decanted within some basins and then dispatched across the public canals[105]. The qayrawani population coming to refuge in the Qalat by the 11th century, has introduced both its urban life customs and water technology inherited – and likely improved- from the Aghlabides ancestors, from whom the great works realised at Qayrawan two centuries before provide. The upstream rivers well supplied the city's sources and the urban canals discharing within the several reservoirs installed all over the city. The same purifying system has been practiced using both decanation and drawing basins[106].

Urban strategy: Previously conceived as the Capital of the young independent Hammadide State[107], within the adversity tumult, Qalat Bani Hammad could not choice a best emplacement than the *Djabal Maadid* almost 1,500 m height[108]. Here, the strategic assets seem to have prevailed[109] as the city has been fastly fortified and populated[110]. In fact, since the 10th century, the cities newly raised looked like a military camps strongly influenced by the contemporary political events and power rivalries in the Maghreb[111]. It has also taken good advantage of the Qayrawan's political disorders as the qayrawani came to take refuge within its ramparts[112].

Within such an ephemeral city, has been raised *Dar al-Bhar* (the Sea Palace). The Palace was raised following an East-West axis when its principal supplying canals arrived from the North. According to the releif, it was obviously the best arrangement's formula. It had a great

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99 The plain of Hodna is about 400 meters up. Despois J (1964). *L'Afrique Blanche*, T.1, *L'Afrique du Nord*, op.cit, p 235.
100 *Idem*, p 189.
101 It reaches from 400 to 600 mm/yr. Despois J & Raynal R, (1975). *Géographie de l'Afrique du Nord-Ouest*, op.cit, p 189.
102 *Idem*, p 189.
103 *Idem*.
104 Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p 68.
105 *Idem,* p93. Many canals conveyed the water from the motains to the reservoirs. There were two kinds of reservoirs: ones for the decantation process and others for drawing.
106 Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p 93.
107 Hammad *Ibn Bologhine Ibn Ziri*, founded the city by the end of the 10th century. See: *Encyclopédie de l'Islam* (1978). T. IV, pp 499-502.
108 *Encyclopédie de l'Islam* (1978). T. IV, pp 499-502, p 499.
109 Meanwhile, the site was no less provided in water and the relief quite favourable to the supplying process. Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p 81.
110 According to Ibn Khaldun, the city has been populated by the transfert of the inhabitants of the near cities (M'sila, Suq Hamza), then arrived other populations from elsewhere. See the website of Muslim Heritage.
111 «The city's fortifications exceeded 7 km ». *Idem*.
112 Encyclopédie *de l'Islam* (1978). T. IV, pp 499-502, p 501.

artificial lake, 64 m long on 45 m large[113], where it goes that aquatic sports was quite usual[114]. It counted a group of constructions as *Qasr al-Manar* (Royal Palace) and depending magazines, cisterns and gardens[115]. It seems that the necessary water for the lake has been conveyed far away from the city and likely be from the northern Guraya Mountain[116]. Really, the North-Western side of the city, situated downstream the mountains, ity seems to be privileged in term of water potentialities. The urban growing procces could quite probably follow this direction.

Disappeared less than two centuries after its foundation (from the end of the 10th century to the end of the 12th one), it is quite probable that Qalat Bani Hammad, who knew a variable prosperity through the time, had not suffered from any serious water supplying problems as attest the numerous water works vestiges founded *in situ*[117]. In fact, the development of the Qalat has begun to be reduced and then to be stopped at the very time when the world commercial's roads became the maritime ones. Thus, by the 12th century, tired of dreaming the sea, the last Hammadide sovereign looked forward raising a new coastal Capital by the North named Mansouria (later becoming Bejaya)[118].

Synthesis and Conclusion

Following Table proposes a summary synthesis of the informations collected on the hydraulic strategy connected with the urban space management one and emphasizes some comparing items. Concluding the present description, we can observe that the water works undertaken in our three examples studied are quite variable according to the nature and the using of the local water resources. The superficial waters were derivate towards the urban agglomerations (or gardens) across some canals, aqueducts and *norias*. The underground ones were drawed by many holes. The rainfall waters were collected and stocked in some underground or open air cisterns and the exploitation process was based on the special system of the water decanting within great basins, from where the waters were conducted and distributed to the public equipments and fountains. That is for the hydraulic distributing policy, so far from nowadays and so efficient.

Concerning the space management strategy, some pertinent remarks can be noted and may be proposed in answering our first questions. (a) the three new cities founded between the 7th and the 10th centuries, have been a real watering places even they had later to exploit the surrounding water resources. It means that the hydraulic consideration has quite prevailed on the military defensive one; (b) these cities are situated at the very limit of the two great geographical regions of North Africa[119]. Fez, Qayrawan and Qalat Bani Hammad are almost at the same distance from the Mediterranean coast, and then their urban and hydraulic strategies could be objectively compared. Their water needs are localy ensured, principally from the surrounding rivers then the rainfall and the underground waters. Really, within such climate context, all kinds of water resources have to be exploited; (c) all have been Capitals of their respective kingdoms. They also have been a secure refuge for some populations

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113 Marçais G, (1954). *L'architecture musulmane d'Occident*, op.cit, p 81.
114 *Idem*, p 83.
115 *Idem.*
116 *Idem,* p 94.
117 *Idem,* p 83.
118 *Encyclopédie de l'Islam* (1978). T. IV, pp 499-502, p 501.
119 Let's remind that the geography of the Maghreb divides the North African territory ito two great natural regions: The mediterranean region, limited by the mountainous tellian and saharian Atlas massifs that distinguish the rainy North from the dry South and the steppe region and then the wide Sahara.
See: Despois J (1964). *L'Afrique Blanche*, T.1, *L'Afrique du Nord*, op.cit.

escaping wars and epidemics but quite probably not scarcity. That waht is supposing that they have to face such increasing water's demand either social (domestic needs) or economic one (manufactures, agriculture); (d) Fez and Qayrawan have later grown towards a western direction catching the water's source. Their socioeconomic activities have been developed along the rivers' banks; and (e) Fez and Qayrawan have pursued their growing up through the centuries, whereas Qalat Bani Hammad has rapidly disappeared even well supplied in water and well protected from floods and scarcity. If the historical events had to be favourable, it also could quite probably be developped by the rich in water North-Western direction.

Table 1 Synthesis and comparing items (Synthesized by the author from different writes).

Comparing items	Qayrawan (Tunisia – 7^{th} century)	Fez (Moroco- 8th century)	Qalat Bani Hammad (Algeria -10th century)
Political status	First Islamic city raised in the Maghreb. Regional Capital of the Umeyyade Califat, then sucessively first Capital of the Aghlabides and the Fatimides.	Capital of the Idrissides.	Capital of the Hammadides.
Pysical items	Wide plain surrounded by mountains. Semi-arid climate. 300 to 400 mm/yr.	Wide plain surrounded by mountains. Continental climate. 750 mm/yr.	High plain surrounded by mountains. Semi-arid climate. 200 to 350 mm/yr.
Local water resources	Superficial (many Wad) and underground water resources + rainfall waters.	Important superficial water resources (Wad Fez).	Superficial water (Wad Fraj) resources and important underground ones (Plain of Hodna).
Water supplying works	Aqueducts, canals, reservoirs, cisterns and holes. Purifying process of fresh water. Evacuation of the wastewaters cross a water town mains.	Aqueducts, canals, norias, fountains and reservoirs. Purifying process of fresh water. Evacuation of the wastewaters cross a water town mains.	Aqueduct, canals, sources, and reservoirs. Purifying process of fresh water. (no more information related to the evacuation of the wastewaters)
Water risks	Floods and scarcity.	-	Floods and scarcity.
Water risk management	Water stocking practice. Using of primary reservoirs reducing the arrival water's debit.	Water stocking practice. Using of primary reservoirs reducing the arrival water's debit.	Water stocking practice. (no more information related to the evacuation of the wastewaters)
Urban growing process	By a western direction towards an important underground water sheets.	By a western direction towards the main water springs.	It may be by the North-Western direction by the rich in water mountains.
Spatial repartition of the economic activities.	Organised along the rivers' banks.	Organised along the river' banks.	(no more information related to the evacuation of the wastewaters)

It is a fact that, during the centuries following their foundation, all those cities have never suffered with scarcity and have declined just because of the contemporary political conflicts and rivalries. Then we can carefully suggest the hypothesis supposing that if water is available at the departure's case and well managed following a judicious strategy, the city can grow without any heavy water's problems. Meanwhile, the urban growth process can only be continued as long as the population, the urban area and the economic activities do not reach a critical limit that seems to be closely connected with the natural potentialities and ecological capacities of the site. Over this limit, the water's problems appear provoking a serious and, may be, an irremediable disorder within the urban ecosystem. This is the lesson we have modestly to meditate today.

Water Measurement Tools and Water Division Structures in the Ancient Civilization of Iran

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Abstract: Indigenous knowledge of water division and using water measurement structures in ancient Iran (Persia) had been of significant importance in the past. These structures and tools have been used in many parts of the country. Since Iran is located in a dry region (arid and semi- arid area) water shortage had been of great concern for long periods. Digging many Qanats for extracting and conveying the water to long distance had been quite an achievement. Such system of Qanats had sometimes hundreds of kilometers of horizontal tunnels and vertical shafts. In this paper, some simple structures that were used for water measurements and for water division for allocating specific volume of water for different purposes in ancient civilization of Iran are introduced. The idea behind each structure and the fundamental mechanisms of their work are also discussed separately.

Keywords Ancient civilization; ancient Iran; indigenous knowledge; water division structures; water measurement tools.

Introduction

Water distribution among water users is a socio-economic problem in arid and semi-arid countries. Farmers have always been struggling to get more than their water rights. This has caused conflicts and loss of many lives. This phenomenon still exists in such countries. Therefore, genius approaches has been implemented to overcome this problem. Scientists and engineers have devised instruments for distributing water to the users based on equality, timely and justice. Some intelligent engineers proposed water distribution systems that still are used in Zayandehrud irrigation network, Isfahan, central Iran. Zayanderud (river) is shown in Figure 1. The idea of constructing water division and water structure tools to divide a specific flow for irrigation and domestic use is rooted in some ancient countries (Javan, 1996).

History reveals that waterworks began thousands of years ago in ancient China, Iran, Egypt and India. Many dams were constructed and underground water tunnels and Qanats were excavated by Persians during ancient times. These people had recognized the importance of irrigation for the survival of their civilizations. The traces of some of these projects, which are among the greatest in the history, still exist and are in use. In Iran, near Sialac Kashan, traces of irrigation channels have been found. These are about 6,000 years old (Jansen, 1983). The aim of this paper is to introduce some structures used for time measurement, water rights allocation and water division among different users.

Figure 1 Zayandehrud in central part of Iran with many ancient water structures.

Time Measurer (Time Pot) or Ajaneh

In ancient times in Iran water was divided among the users based on the three units: time based unit, volume based unit and land based unit. Time unit was measured as explained below. Volume unit was measured based on the time duration) and discharge rate (as called Sang). Land based unit was based on the area of land which was to be irrigated (Hassanli, 2001). In ancient times, about 1,100 years ago the time measurer was made to allocate a specific volume of river flows, canals streams and Qanats for a specific purpose. Allocation of water was based on a constant discharge rate and a specific time. In fact, allocation of water was based on the duration of time with constant discharge of volume. As shown in Figure 2, this simple structure was made out of a pan with known dimensions and a thin pot made out of copper with a small hole at its bottom. The pan was filled with water and the empty pot was placed on the water surface in the pan. Water seeped into the empty pot. As water seeped into the pot, it caused submergence and settling down in the pan. The time it took to submerge fully into the pan was a unit of time for allocating a river flow, canal, stream or Qanat according to the water right. For allocation the water flowing in rivers or canals for a specific purpose these tools were used. If it was needed to allocate more water based on water right, this process was repeated again for as many times as required. It is reported that in the past alternatively the pot was placed on water surface in the rivers or canals directly. After being settled down it was pulled out of stream again and placed on the water surface for submergence, the full submergence time took about 2 to 3 hours. However, the submergence depended on the size of the hole in the bottom of the pot. It has been reported that this type of time pot, also named as water clock, still preserved at the Human museum of Leningrad (Reza *et al.*, 1972). This type of time pot has been used in Kashan and Yazd until recent times. In these regions water right and water trading (buying and selling) was based on the frequency of the pot submergence.

Floating Ball (Water clock)

In ancient times Floating Ball was used for allocating a specific amount of water to the users. Figure 3 shows a Floating Ball used as a water clock in the past in Iran. It was made out of a ball (B) connected to a rod (C). This rod could move vertically both up and down by water level fluctuations. Water surface that caused fluctuations was discharged from a water tap connected to a small reservoir. Part (C) was installed against a graduated rod (E).

Another modification of this type of water clock is shown in Figure 4. In the modified water clock, instead of using vertical graduated rod a graduated quadrant (G) was used for the time measurement. The principle of its work was as explained above. However, the rod was connected to another rod which moved against a plate (G) divided into equal segments in ancient times. Part (A) had a specific shape and dimension. A constant discharge of water was dripping from the tap (D) into the pot. Filling the pot took a certain amount of time which was shown against the graduated rod (E).

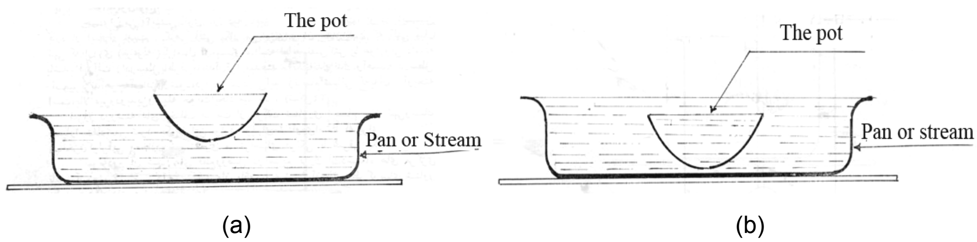
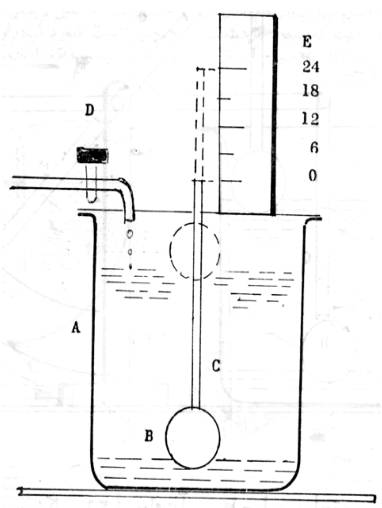


Figure 2 Time measurer or Ajaneh: (a) Placing the pot on the water surface=starting the time measurement, and (b) submergence of the pot=end of time measurement (Reza *et al.*, 1972).



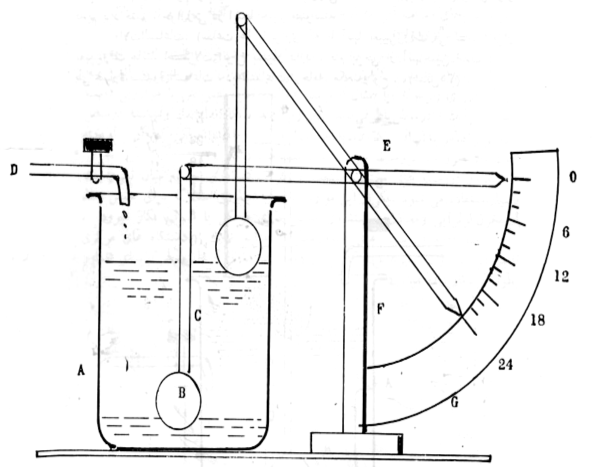


Figure 3 A floating Ball or water clock structure used for water right allocation (Reza *et al.*, 1977).

Figure 4 A modificated water clock structure (Reza *et al.*, 1977).

Water Division Structures

Since there were much water demands and limited amount of water, special devices were used to distribute and divide their share among them. Two types of such structures are shown in Figure 5. The structure shown in Figure 5 was a broad crested weir in which the width was divided in proportion to the discharge. The key point in this structure was to keep the head a constant value and a width as the variable based on the water right of users as the following equation shows:

$$Q = CL\,H^{\frac{3}{2}} \tag{1}$$

where,

Q = Discharge (m³/s),

C = Discharge coefficient,

L = Width of the weir (m), and

H = A constant head of water (m).

In this structure, the stop logs were used to maintain a constant head on the weir and stabilize water fluctuations. Another type of water division structure is shown in Figure 5b. This system did not need the upstream headwork. However, it consisted of small settling basins for suspended sediments and debris before entering the main stream.

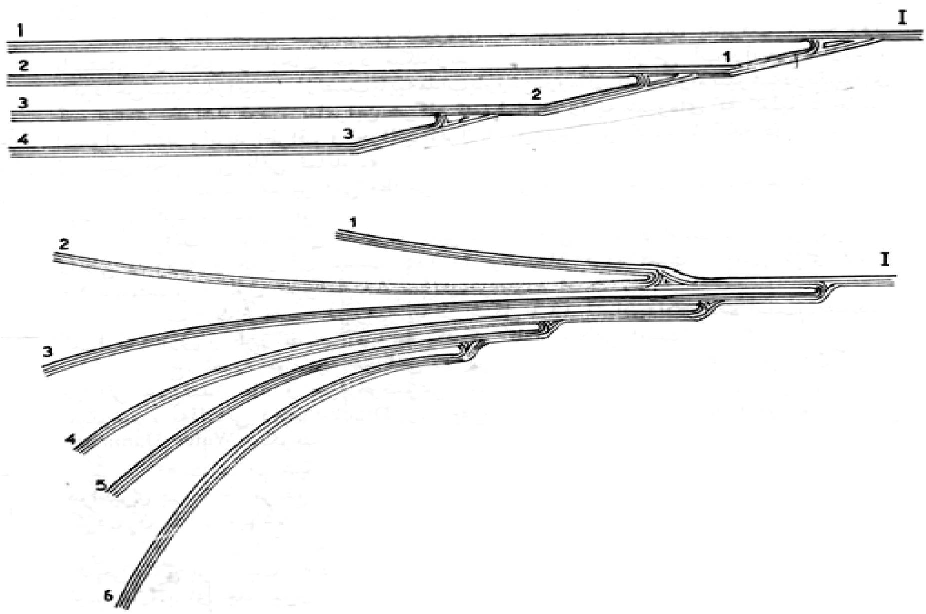


Figure 5 Two schematic layouts showing how a canal divided into the many branches each with a specific amount of water right.

The canals had different widths according to the water rights. The side canals had larger widths (lower water velocities) compared to the main canal with higher water velocities. A feature of this type of structure dividing water along the stream not at a certain point is shown in Figure 5b. Each settling basin could serve two of the downstream canals. Figure 7 shows the cross sections of division boxes. Another method that used until recent time in Iran was based on a constant time rotation. In this method a specific discharge of a canal or Qanat was allocated to anyone based on a week or every other week or 10 days rotation (Hassanli, 2001).

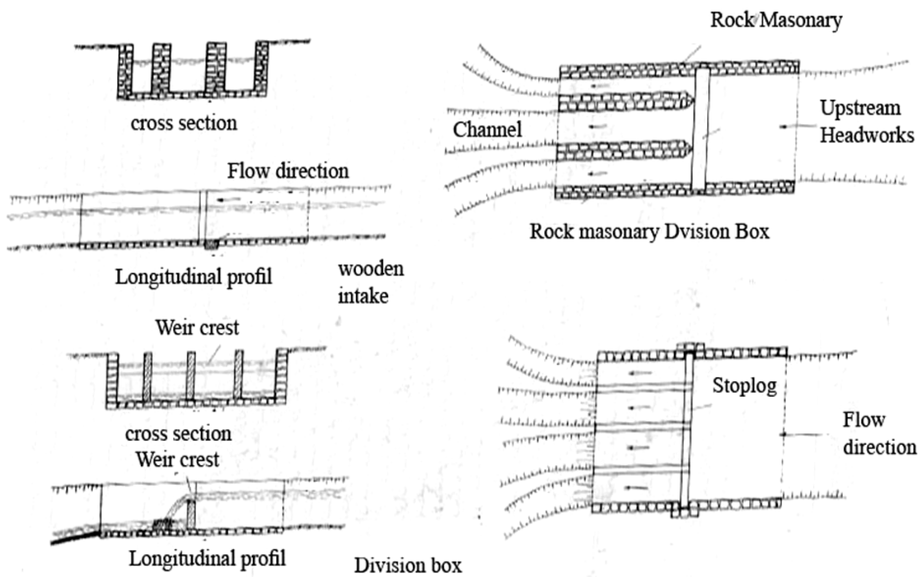


Figure 7 Cross sections of water division structures (Reza *et al.*, 1977).

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Stormwater and Sanitary Technologies

Potable Water and Sanitation in Tenochtitlan: Aztec Culture

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Abstract: A source of clean drinking water is essential, and the Aztecs were quite advanced in providing it. While London still drew its drinking water from the polluted Thames River as late as 1854, the Aztecs brought potable water to Tenochtitlán from springs on the mainland by means of the aqueduct built by Nezahualcoyotl between 1466 and 1478. A second aqueduct was constructed in 1499-1500 by the ruler Ahuizotl when the first aqueduct became inadequate. Although the Aztecs had no citywide drainage system, and much of the wastewater ended up in the lake surrounding the city, they had a system to handle human waste by means of privies in all public places and many private dwellings from which excrement was collected in canoes. The excrement was applied as fertilizer on chinampas or sold in the market to be used for tanning animal hides. Urine was collected in pottery vessels to be used later as a mordant for dyeing cloth. The Tenochtitlán environment was obviously healthy for its time, especially in comparison to European cities. Public and personal hygiene contributed to minimize the incidence and severity of illnesses.

Keywords Aztecs; Mexico City; sanitation; water; wastewater.

Introduction

The knowledge of works executed by the Aztecs is based on data that provide the old codices, the traditions gathered by the first historians of century XVI, the relations by them written and the ruins, which in reduced number exist of constructed works. The water and its intelligent handling went what indeed it allowed Tenochtitlán to be one of the political centers, religious and economic of greater importance in Mesoamerica. By means of a great talent to take advantage of the liquid appraised one, they managed to intensify the production of its foods, obtaining excessive to increase its population, the commerce and to maintain privileged a class dedicated to the development of sciences and the arts.

The intensification of agriculture, the creation of new cultivable grounds and the facilities of transport, favored the urban HD of population and concentrations. Reached the economic and demographic power in the valley of Mexico, combined with a military political organization closely related to the hydraulic organization, allowed to the domination of the populations and the resources of neighboring valleys. The water was a strategic element in the war and factor of domination through the control of the technology that the Aztecs generated to supply of the liquid appraised one to the region and to maintain occupied in their construction the towns that were under their government. The hydraulic systems in the lacustrine zone correspond to a same technology with similar hydraulic works: wear-dock and “albarradones”(docks); works of control of floods and drainage; construction of grounds

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to artificial for agriculture and for to live ; fresh water conduction by means of channels, drains and aqueducts: formation of lagoons and wetlands (marshes) artificial.

Climatic and Hydrologic Conditions

The Valley of Mexico is a closed river basin. Like result, it at heart appeared of the valley an extensive system of lakes of little depth, of lagoons and marshes, formed by pluvial precipitations, the originating permanent rivers, mainly of the Sierra Nevada, and many springs. The waters did not get to completely fill the low part of the river basin. A combination of infiltrations, with the intense evaporation characteristic of the region, limited the growth of the lacustrine zone (Fig. 1).

Figure 1 The lacustrine river basin of the Valley of Mexico.

The lakes, lagoons and marshes covered, towards the beginnings of century XVI, about 1000 km². The pluvial precipitation within the valley is concentrated in a single rainy season, that is very irregular in terms as much of its geographic distribution as seasonal.

Brief History of the Aztecs. Tenochtitlán

Tenochtitlan is one of the last cities of the pre-Hispanic Mexico that lasted solely 200 years due to the conquest of the Spaniards. The Aztecs in their passage to the plateau assimilated the technological antecedents of all the towns by which they passed including that already they were vacated (Teotihuacan and Tula). This entire heap was used to found the Mexica seat. Of the name of Mexitl, that is the name of the God Huitzilopochtli; Mexico was called. At the time of which Tenochtitlán was taken by the Spaniards the city was a square of 3 km of length with a suburban area of 1.000 ha. This surface was a geometric network of trapeé them, religious centers, units and set basically around two places: The Greater temple and the great seat of Tenochtitlán (Fig. 2). By the number of small islands to roads and bridges were constructed to unite the diverse districts. When growing the city was not sufficient reason why they were constructed chinampas (floating parcels, Fig. 3), first to cultivate and immediately to construct to houses of "adobe" (earth and lime).

Figure 2 The city of Tenochtitlán.

The used ways to unite the earth sections served simultaneously as docks that sometimes counted on floodgates to control the water levels. The roads were the main axes, one went from north to the south binding Tepeyac, Tlatelolco, Tenochtitlán and Coyoacán and the other of the orient to the west marked by Tlacopan and the center of the own Tenochtitlan. The city by the east was limited by a lake reason why it was necessary to use canoes to arrive at the Texcoco. To the south the Iztaplapa road is constructed that was where the lake was deeper.

Figure 3 Actual view of the Chinamanpas in Mexico City.

The greater challenge for the agriculture and the cultures of the valley was in the lacustrine system. Reason why they arose chinampas that extended by the fresh water lagoons of Chalco and Xochimilco, covering most with its surface. The lacustrine system, on the other hand, provided in the valley of Mexico the solution to a critical problem of the

Mesoamericans cultures: the one of the transport. Devoid on animals load, and without making use of the wheel, the civilization of Mesoamerica depended on the human transport, except where the lakes, the rivers and the sea facilitated aquatic ways. The lacustrine system of the valley was crossed by a true network of channels and deep drains, in most of the constructed cases artificially, around which an enormous number of canoes circulated.

The original lakes with the construction of roads and avenues were transformed into several lakes between which there were engineering installations for the control of floods and the lacustrine transport. In addition, the hydraulic system function of form that the salinization of chinampas was avoided. On the other hand, the geographic location of Tenochtitlán gave rise frequent to flood is that they prevailed until the contemporary Mexico (1940-1950).

Aztec Deities of the Water

For the Aztecs, Tláloc, wizard and God of the water were adored since he represented the God of the water, rain and storms. Tláloc was a benevolent God, but also feared for its multiple expressions to way of floods, drought, hail and ray, reasons for which there were to maintain it through sacrifices and orations contented. One imagined to him with hairdo accept in the head, with a species of double fan of paper of crust, and the face covered by a mask formed by ring (serpents) around the eyes and eyeteeth of viper leaving to him the mouth. The serpents simultaneously represented the lightning and the water. The Priest "or" Prince Wizard "was called to him". He was the one who summoned to clouds shaking his “sonaja” and forcing them to that they met around summits. Tláloc was also the God of agriculture (Fig. 3).

In the great Tenochtitlán, in the pyramid of the Teocalli two sanctuaries of equal importance were elevated in their peak: the red temple of Huitzilopochtli and the white and blue temple of Tláloc. The feminine deity of the water was the sister or wife of Tláloc, Chalchiutlicue (Fig. 4). She and Ra the goddess of the seas, of the lakes, springs, torrents and their representation is a tail or blue water obstacle that to drag in its clothes “itacate” (lunch) of a merchant, a soldier and a young woman, symbolizing who the water drags to be able, wealth and beauty. To her he adored himself to him in the springs, rivers and works of water supply, where the products of the water like flowers, jewels were offered to him and also human sacrifices and animals. This God lived along with in the Tlalocan Tláloc, in high mountains. The God of the water had assistants of small size and hair nets for the human eye, Tlaloques calls, that with a regadera in the hand obeyed the orders of Tláloc and with woods and objects they produced the thunderclap.

On the other hand, the paradise of the God of rain, the Tlalocan, it opened to his gardens to those who died drowned, thundered against by the ray or any accident or disease attributed to the water. Those that they died of this form were considered like distinguished by their God and envoys to the always green and humid paradise.

Potable Water Supply

With respect to the daily domestic consumption, initially it was carried in ample “cantaros” (mud containers) and stored in bathtubs, until the construction of the aqueducts like result of an engineering outpost. Precarious but safe it was the first time in the development of Tenochtitlán. It did not lack the precious necessary liquid for the life, assured by then pure waters of the lagoon and by some springs that appeared in small barren islands.

Figure 4 Representation of Tláloc (right) and Chalchiutlicue (left).

It was the sacred spring that was in the ceremonial center, Tozpálatl and that according to the tradition was in the place of the foundation of the city, the one that solved in the beginning the necessities of the population.The first attempt to bring water of the springs of Chapultepec towards Tenochtitlán was done constructing a sewer with stakes, reeds and mud, but by the low resistance of the materials it was little effective. The historian Gomara says to us: “although it is on built water, do not take advantage of her to drink, but that brings a source from Chapultepec, they bring it by two as fat sewers as an ox each one”. When he is the one dirty one, they throw it by the other until it is soiled. Of this source the city is supplied and the pools and sources are provided that there are in many houses, and in canoes they are selling of that water, with which pay certain rights (Palerm, 1990). The constructions were fed by means of aqueducts or using for it an underground distribution basically to provide pools and gardens. It was counted on botanical garden and the city enjoyed a great number of adorned green areas with flowers.

The springs were property of the town and administered by the Government, who determined the use, advantage and handling of the water. The entire town had the obligation to cooperate in the form that indicated the authorities for the accomplishment of hydraulic works. Gradually one went away forming in the city which would be a complex and magnificent system or network of aqueducts by where the potable water arrived. Often of joint way to these systems of pick up and it empties of the water, were constructed roads that connected to the most important cities of lake. Two aqueducts constructed with stuccoed mud tubes brought potable water to the center of Tenochtitlán: one came from Chapultepec and the other of Churubusco. The distribution of waters in the city became by sources and pools, but only the palaces and houses of the noble had their own takings. The town in general obtained them through canoes that filled in the bridges of the aqueduct, in where also were men who by payment filled the canoes. The potable water necessities, in fact, were few, since they were only used to drink and to bathe, because for the irrigation of chinampas and gardens water of the drains was used.

Aqueducts

Chimalpopoca emperor realized that the growth of the city, on the one hand, had almost exhausted the springs and, on the other hand, the Aztec activities were contaminating the lagoon; for that reason, he decided to bring waters of Chapultepec. As result had the first aqueduct of Chapultepec, it builds of great knowledge and talent that arrived until the Greater Temple (12 km in length and 7 ms of wide), but that was worn away little by little by its own waters, since the used sewer era of mud.

Almost thirty years later, the aqueduct of Chapultepec was destroyed because of the great flood of 1449, thus Nezahualcóyotl, constructed one second work on the same outline of the previous one. In this occasion it was used resistant materials much more, like lime, song and rubblework; in such a way that with some small repairs it continued giving service until years after the arrival of the Spanish conquerors. Ahuizotl governor in 1499 decided to bring more water of five springs pertaining to Coyoacán. The water of the springs was caught by means of a prey whose construction followed the line of the road of Xochimilco. A mud sewer was constructed and it completed with a network of distribution to sources and jets with underground connections under the lake for temples and palaces. In addition, spillways or garbage dumps settled down to throw to the channels the excess of water that came by the conduit, but conserving such amount of her that when arriving at the last jet, in Pahuatlán, where finished the city, it had sufficient height and volume to produce a great roar with his fall. In 1500 a catastrophic flood, product of a rain of more than forty days than culminated with a whirlwind, destroyed the work. The aqueduct was described in 1520 by Hernán Cortés (conqueror of Tenochtitlán):

> *Along one of the causeways to this great city run two aqueducts made of mortar. Each one is tow paces wide and some six feet deep, and along one of them a stream of very good fresh water, as wide as a man's body, flows into the heart of the city and from this they all drink. The other, which is empty, is used when they wish to clean the first channel. Where the aqueducts cross the bridges, the water passes along some channels which are as wide as an ox; and so they serve the whole city.Canoes paddle through all the streets selling the water; they take it from the aqueduct by placing the canoes beneath the bridges where those channels are, and on top there are men who fill the canoes and are paid for their work.*

Sanitation

The city was kept very clean streets in very quarter were swept and watered daily by a thousand public employees. Personal cleanliness and hygiene were prized highly by the Aztecs, as suggested by many references in early sources to soaps, deodorants, dentifrices, and breathe sweeteners. Due to the ground deficiency for to deposit the sweeping was incinerated. In fact, with the sweepings the public service occurred of you illuminate or, serving like partial fuel. The biodegradable sweepings was buried in the patios of the houses, used by the animals and if it were much shipment to mainland for his disposition.

The sweeping was collected in hulls ready in soft, where the population placed it. The sweeping was sold as installment in Tlateloco, it included apparently excretes it. Also it excretes it was used as installment in chinampas or earth bordering to the lake. All the houses collected tinkle it in recipients of to be used as soon mordent mud in the fabric dye. The city emphasized by its sanitary and environmental aspects. The house of Moctezuma to Ihuilcamina, or Teocalli, it counted with three patios; in one there was a source destined to distribute the water to all the building. In addition each room counted on a bath (Fig. 4). In the main seats of Tenochtitlán and the market, there were public ponds that were cleaned by underground water-drainages and they filled by pipes that brought water of Chapultepec, probably for the cleaning of the clothes. In this forest there was a great pond near the springs and a great well arrives of the hill. The pond was used for the water warehouse, leaving same the system of distribution. In addition, the Aztecs had temascales called steam baths, which were very low small houses, closed, in whose interior they fitted up to ten laid down people or seating for steam baths, in that was spent very little water. In them there was a furnace in which stones to red the alive one were warmed up and later water lay down to them to produce steam.

Figure 4 Ruins of the baths of Moctezuma.

Also they bathed with ten or twelve recipients of water. The Spanish conquerors were amazed at how often the Aztecs bathed, in contrast to European practice. Moctecuhzoma bathed twice a day, and everyone bathed often. Respect to the drainage, this consisted of several drains that they crossed the city of the west to east, emptying in the lake of the Texcoco. All counted on floodgates that allowed to evacuate by the mornings and to prevent the access of waters from the lagoon to the city during afternoon. It also included pipes in which the black waters of the city unloaded, but without solid wastes, since by hygiene and beauty it had special depots in which the solid remainders were spilled later to pay the culture systems.

The sanitary problem seems that it was controlled, since in the drains the detritus were not spilled, but that were stored in special places later to use them as installment; the historians are not few that admired the cleaning of the city, probably when comparing it with the conditions of health, not very adapted, which they existed in the European medieval cities. Due to its location, lower than the rest of the lakes, Tenochtitlán was exposed to great floods, reason why the Aztecs occurred to the task of giving causes to the swellings of the lakes and to turn aside the rivers and currents, initiating therefore the system of water-drainage that took in perfecting five centuries. The native population was basically healthy, due to good nutrition, relative freedom from epidemic pathogens, and sound public sanitation. However, dampness and pollution of the lakes did promote dysentery, rheumatism, and respiratory infections.

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Drainage System of Ancient Capitals in Japan

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Abstract: Ditches are constructed at both sides of a street in ancient capitals in Japan. Streets are not paved and ditches are made of earth. As the streets are laid out in a grid pattern, the ancient capitals have drainage system by ditches. In this paper, dimensions of ditches and evaluation of drainage system are discussed. The dimensions of ditches are made clear using historical literature and the archaeological excavation data. Considering the topography, the flow of drainage is examined. The drainage system between Nagaokakyo and Heiankyo is different from each other, but the drainage system is inferior to the present.

Keywords Ancient Capitals; drainage system; Heiankyo; Japan; Nagaokakyo.

Ancient Capitals of Japan

Ancient capitals of Japan began Fujiwarakyo (694-709) and followed to Heijyokyo (Nara, 710-739, 745-783), Nagaokakyo (784-793), and finished Heiankyo (Kyoto,794-1869). Position and characteristics of capitals are shown in Figure 1 and Table 1. In these capitals, the streets are laid out in a grid pattern influenced by Chinese system. From Fujiwarakyo to Nagaokakyo, there are natural rivers in these capitals, however, in Heiankyo we can find only 2 canals in N-S direction. Drinking water is taken from shallow well. Ditches are constructed at both sides of a street.

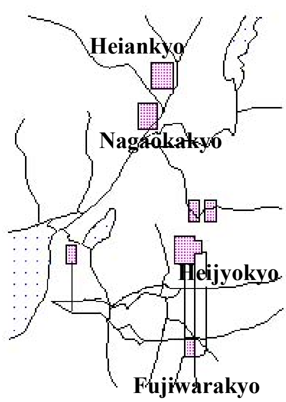

Figure 1 Ancient Capitals in Japan.

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Table 1 Characteristics of ancient Capitals in Japan.

Name	Period	Scale (km) E-W	Scale (km) N-S	Population
Fujiwarakyo	694-709	2.1	3.2	50.000
Heijyokyo	710-739, 745-783	4.3	4.8	max 200,000
Nagaokakyo	784-793	4.3	5	50.000
Heiankyo	794-1868	4.5	5.2	max 200,000

Width of Ditches

Archaeological excavation data gives us the dimensions of streets and ditches. Streets in Japanese capitals are not paved and ditches are made of earth. “Engisiki”, a historical literature of Heiankyo shows the width of streets, ditches, etc. (Figs. 2 and 3) The width of ditches are divided into 4 class, that is, 3, 4, 5, and 8 shaku. (1 shaku = 0.299m) The widest street is Suzaku-oji (A in Fig.2, central N-S street), and the width of Suzaku-oji is 280 shaku and the width of it’s ditch is 5 shaku at both sides of the street. Except for B, C and D in Figure 3, streets are symmetric on both sides. But, width by archaeological excavation is wider than those by Engisiki and the symmetry is not guaranteed. No historical literature on dimensions of ditches in other capitals is found. Table 2 shows a comparison of width and symmetry of ditches at ancient capitals in Japan. Figure 4 shows an example of un-symmetric ditches at a street in Heiankyo.

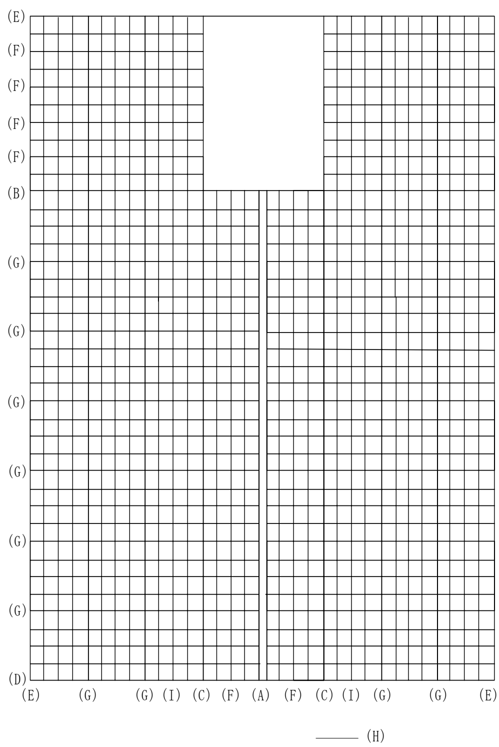

Figure 2 Streets at Heiankyo (Kyoto).

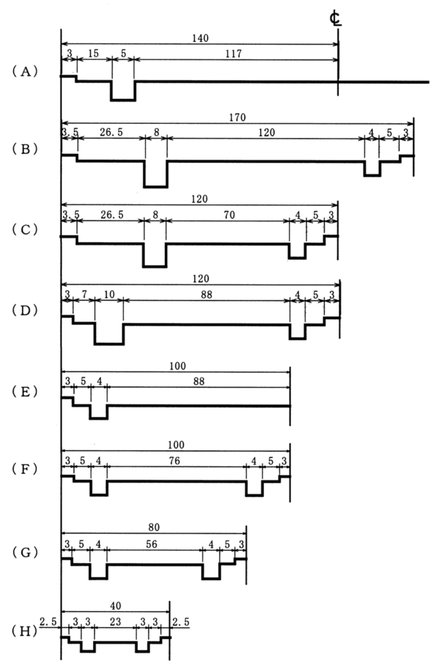

Figure 3 Widthes of streets at Heiankyo by Engisiki (depth is unknown).

Table 2 Comparison of width and Symmetry of ditch at ancient capitals in Japan.

		Width of ditch (m)			Symmetry of ditches (both sides)
		Suzaku-oji	Oji	Koji	
Fujiwarakyo		7.1	1.8,3.5	1.8	yes
Heijyokyo		-----	1-2	-----	no
Heiankyo	Engisiki	1.5	1.2; 2.4; 3.0	0.9	yes
	Excavation	3-10	1-7	0.7-3	no

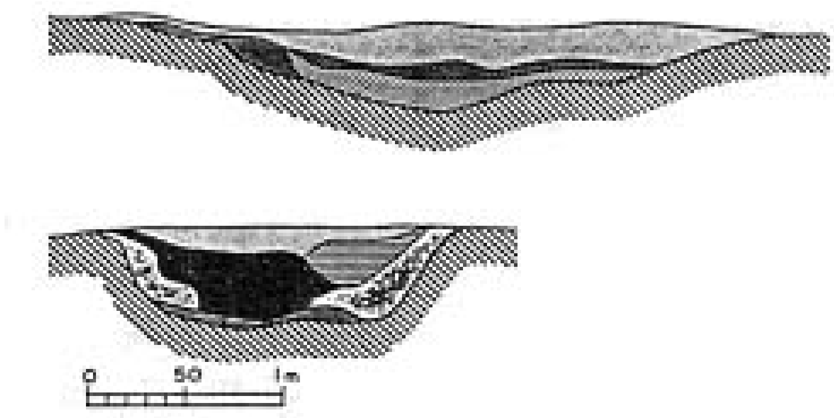

Figure 4 Example of un-symmetric ditches at Heiankyo.

Figure 5 shows existence of different width of ditches along a same street. Although archaeological excavation data is few, the width written in “Engisiki” is considered a plan. The dimension of ditches by archaeological excavation is reflected the constructed ditch.

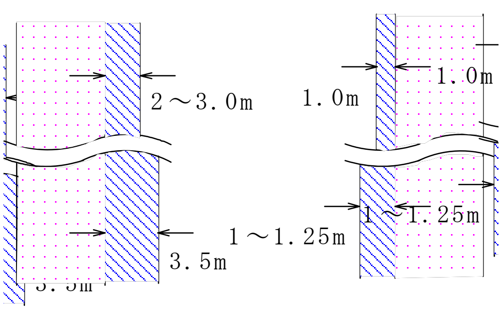

Figure 5 Different width of ditches along a same street in Heiankyo.

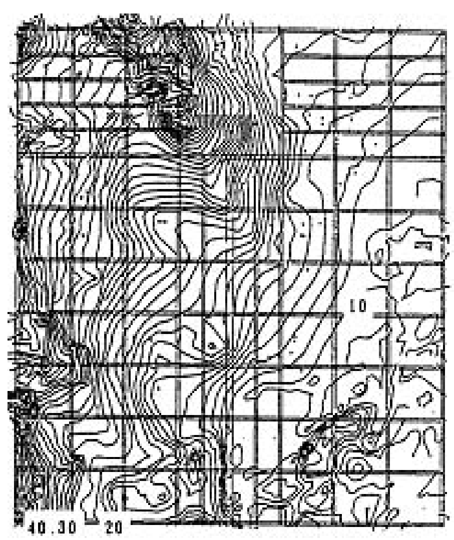

Figure 6 Contour line of Nagaokakyo.

Geographical Feature of Nagaokakyo and Heiankyo

Except Fujiwarakyo, Northern area of ancient capitals in Japan is higher than the southern area. According to archaeological excavation data, Figures 3 and 4 show the contour of Nagaokakyo and Heiankyo. In Nagaokakyo there are 4 natural rivers (Fig. 8). Storm water outside Nagaokakyo is considered to flow into these rivers. In Heiankyo, there is no natural river. Storm water from north may flows into Heiankyo. But, as a waterway with 22 m width is found by archaeological excavation, no storm water outside Heiankyo may flow into the inside.

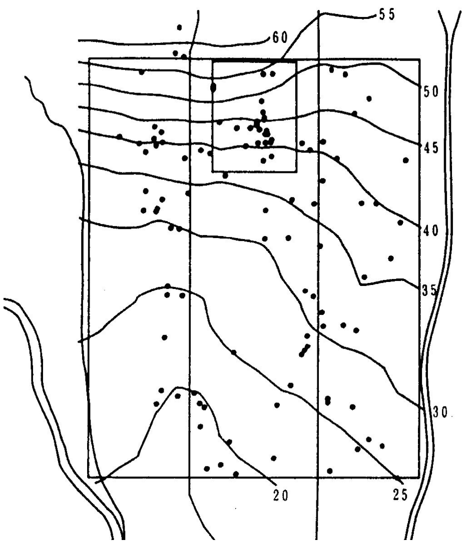

Figure 7 Contour line of Heiankyo.

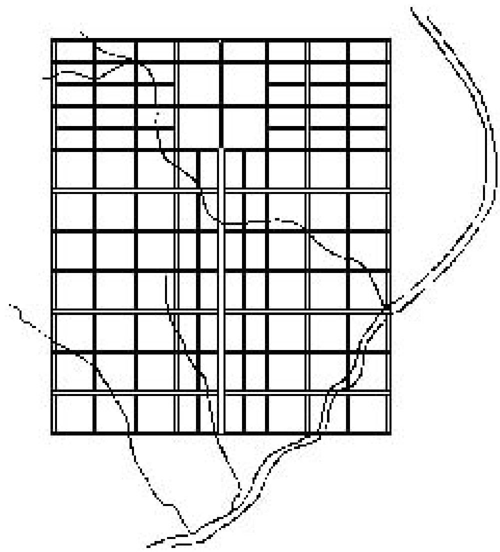

Figure 8 Rivers in Nagaokakyo.

Evaluation of Ditches as Drainage System at Nagaokakyo and Heiankyo

Considering the topography and natural rivers, Nagaokakyo is divided into 5 drainage basins (Fig.9) and Heiankyo is divided into 4 drainage basins (Fig. 10). Figure 11 shows a result of the evaluation of drainage system by use of rational model in Nagaokakyo in case of rainfall intensity 30 mm/hr. In many reaches of ditch, overflow is estimated.

Figure 12 shows a result of the evaluation of drainage system by SWMM at Heiankyo using width of historical literature in case of rainfall intensity 10-30 mm/hr. Figure 13 shows a result using width of excavation in same condition. Compared to the result Figure 12, Figure 13 is improved, but each of them is inferior to the present drainage system.

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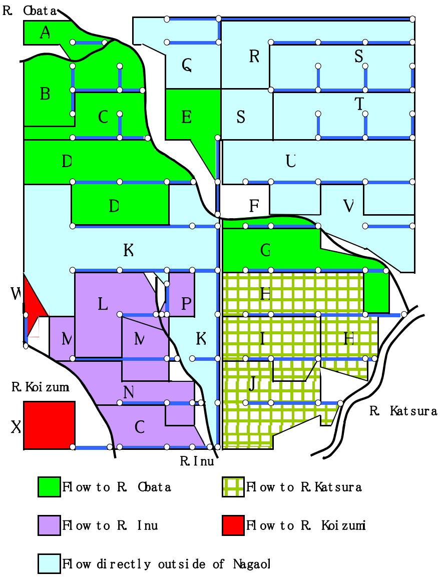

Figure 9 Drainage basins of Nagaokakyo.

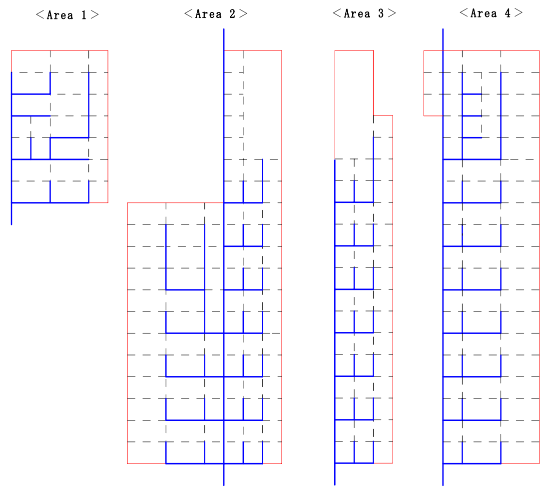

Figure 10 Drainage basins of Heiankyo.

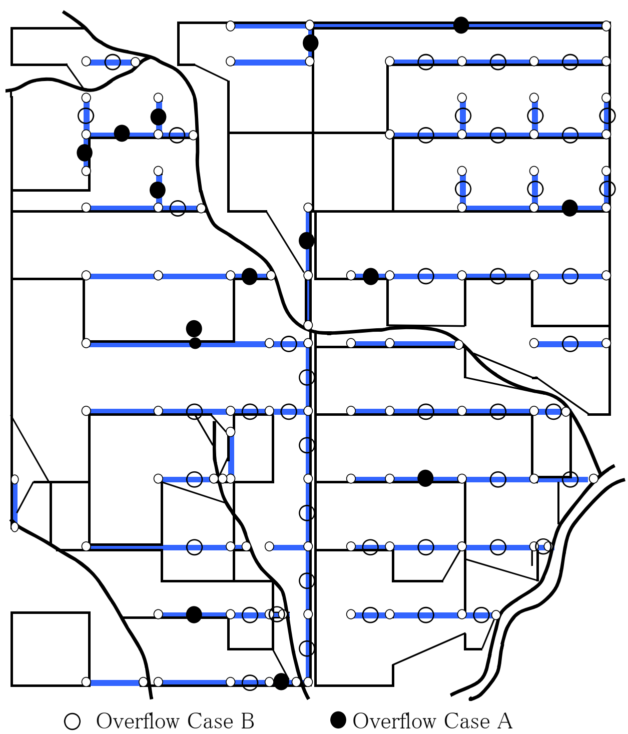

Figure 11 A result of the evaluation of drainage system at Nagaokakyo.

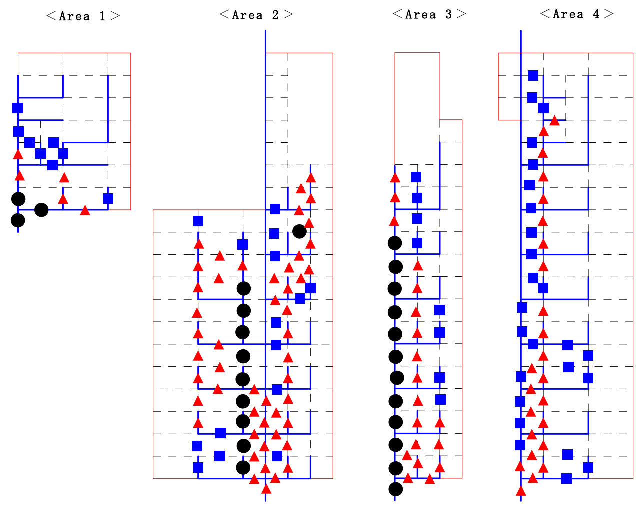

Figure 12 Overflow reaches at Heiankyo using width of historical literature in case of rainfall intensity 10-30 mm/hr.●: 10 mm/hr ▲: 20 mm/hr ■: 30 mm/hr.

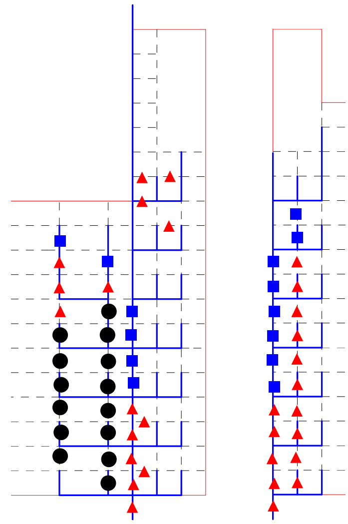

Figure 13 Overflow reaches at Heiankyo using width of excavation data in case of rainfall intensity 10-30 mm/hr. ●: 10 mm/hr ▲: 20 mm/hr ■: 30 mm/hr.

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Surface and Sub-surface Drainage Systems in Persepolis Complex, Iran

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Abstract: A study was made on the performance of surface and sub-surface drainage systems of Persepolis Palace Complex in southern Iran. The area was divided into different zones. For each zone rainfall intensity and runoff discharge was estimated. Based on the results obtained, the flood channels have the capacity of conveying the generated runoff. It was also concluded that some of the sub-surface drains and outlets need cleaning for their proper operation.

Keywords Persepolis; rainfall intensity; runoff; sub-surface drain.

Introduction

Persepolis complex is located at 55 km north of Shiraz, southern Iran. The construction of this complex began 520 B.C. under Darius the great. There are remains of several Palaces from Achamenid dynasty in this complex (Fig. 1). In 2003 fields study was made to investigate how the storm water was disposed at this site (Javaheri and Javaheri, 2001).

Runoff Disposal outside the Complex

To dispose the runoff from the northern mountain, a 60 m deep well with square cross section 4.2 x 4.2 m² was dug. This well acted as a reservoir for storing the runoff water (Fig. 2). To dispose the runoff from the eastern slopes a 180 m log gully with the dimensions of 7 x 2.6 m² was also dug. The spilled water from this gully would flow to the downstream Plain.

Figure 1 Persepolis complex.

Figure 2 Well with the collecting channels.

Runoff Disposal inside the Complex

The disposal of runoff water inside the complex consisted secondary of underground galleries connected to a main gallery. Special flumes to these galleries would direct runoff generated by rainfall.

Surface Drainage of the Upper Part (Northern Side)

As shown in Figure 3, the northern half of the complex with an area of 72,880 m² consisted of Gateway of nations (Xerxes Gateway), Apadana Palace, Palace of one hundred columns, the unfinished gateway, street of Martials, northern fortifications. In this part a flood channel (FC) 60 x 60 cm² with its laterals collects the runoff water generated by rainfall and convey it to QC3 underground gallery (Fig. 4). These two channels are connected to HC outlet through DC1. This channel (DC1) could also collect the runoff from 100-column palace. In Figure 5 a typical vertical shaft that conveys water to the sub-surface drain is shown (Tamavan, 2003).

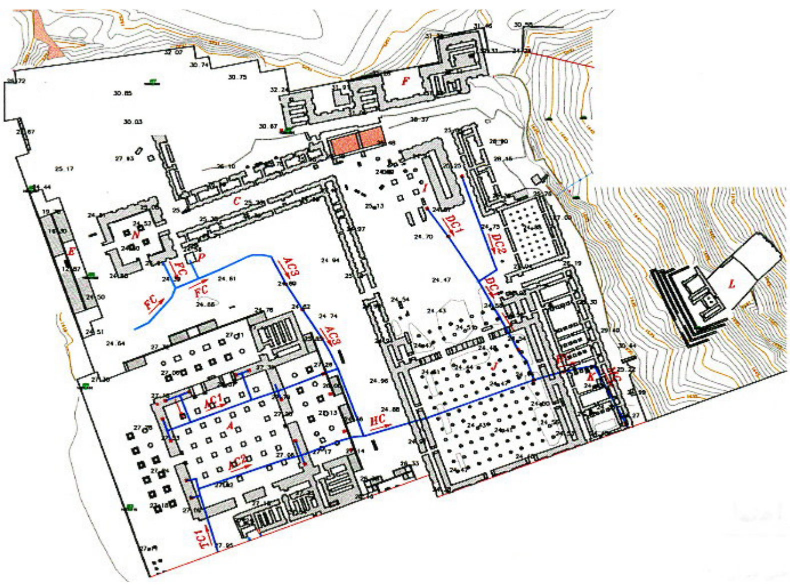

Figure 3 Drainage network in the northern part.

Figure 4 Flood channel FC in the northern side.

Figure 5 Vertical shaft conveying water to the subsurface drains.

Surface Drainage of the Lower Part (Southern Side)

According to Figure 6 this section with an area of 52,215 m² consists of the Darius Palace (Tachara Palace), Xerxes Palace (Hadish Palace), Council Hall, Harem of Xerxes, Treasury, and Eastern fortifications.

Figure 6 Drainage network in the southern part.

In this section the underground gallery sc begin from the westside and terminates at the main channel MC at the eastside. Another channel (AGC) shown in Figure 7 also collects runoff from the roof of Aapadana Palace and finally reaches the outlet at SC. The flood channel TC2 would also collect runoff from the southern side of Darius Palace and connects to AGC. Figure 8 shows how the runoff was conveyed through the foundation of Xerxes Palace. In the southeastern part of the complex the treasury was built. The bottom of the surface drains KC and KOC passing through this building was lined with bricks and bituminous (Fig. 14). Figures 15-18 show the entrance, outlet and the open sections of these drains. The covered channel KNC could drain the northern section of the condition of the treasury by the end of Achamenid era (Tamavan, 2003).

Figure 7 Subsurface drains of TC1(left) and AGC (right).

Engineering Analysis of the Drainage System

The analysis consisted of estimation of the maximum precipitation for different return periods, drainage area, runoff estimate, permeability of the land and soil resistance against erosion. Table 1 shows average monthly, seasonal and annual precipitation at Persepolis weather station. The analysis was made by using maximum 24 hour intensity and Gamble distribution which had the lowest standard deviation. Table 2 shows the results of rainfall intensity with 24 hour duration (Chow *et al.*, 1988).

Figure 8 Sub-surface drains in the foundation and yard of Xerxes palace.

Table 1 Average monthly, seasonal and annual rainfall at Persepolis weather station.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Annual
Av.(mm)	70.4	59.9	60.7	30.1	6.1	0.2	0.09	0.3	0.0	5.9	19.5	68.9	323.9
%	21.7	18.5	8.7	9.3	1.9	0.1	0.6	0.1	0.0	1.8	6.0	21.3	100
Season		Winter			Spring			Summer			Fall		
Av.(mm)	141.0			36.4			2.2			94.2			323.9
%	59.0			11.2			0.7			29.1			100

Table 2 Return periods and 24 h rainfall intensity in mm.

Return period (yr)	2	5	10	20	25	50	75	100	200	1000	2000
Precip.(mm)	38.6	56.9	69.0	80.7	84.4	95.8	102.5	107.0	118.3	144.3	155.6

Drainage Area

As mentioned before runoff was generated from two areas: the northern slopes (Rahmat Mountain) and the open areas of the complex. With respect to the location of walls of the palaces and their differences in elevation the complex was divided into 5 zones with the total area of 125,095 m².

Runoff Estimate

Estimation of maximum runoff was made using the Rational, Kook and Curve Number methods. Table 3 shows the runoff generated from a 2 hr intensity rainfall with 50 years return period for different zones (Linsley and Franzini, 1987).

Table 3 Maximum runoff generated from a 2 hr rainfall in m³/sec.

Zone		Area (m²)	Rainfall intensity (mm/h)	Runoff coeff.(C)	Max. discharge (m³/s)
Northern slope		138775	15	0.7	0.41
	I	42765	15	0.5	0.09
	II	30115	15	0.5	0.06
Persepolis yard	III	17394	15	0.5	0.04
	IV	15053	15	0.5	0.03
	V	19768	15	0.5	0.04

Evaluation of the Existing Drainage System

During 2001 an attempt was made to clean and remove the sediments collected in the sub-surface drains. However, due to technical problems cleaning could not be completed especially for the outlet system. Two channels DC1 and DC2 in the northern part are believed to be the supply line of permanent fresh water for the complex could not be cleaned too. Figure 9 shows the main channel in treasury section during and after cleaning operation.

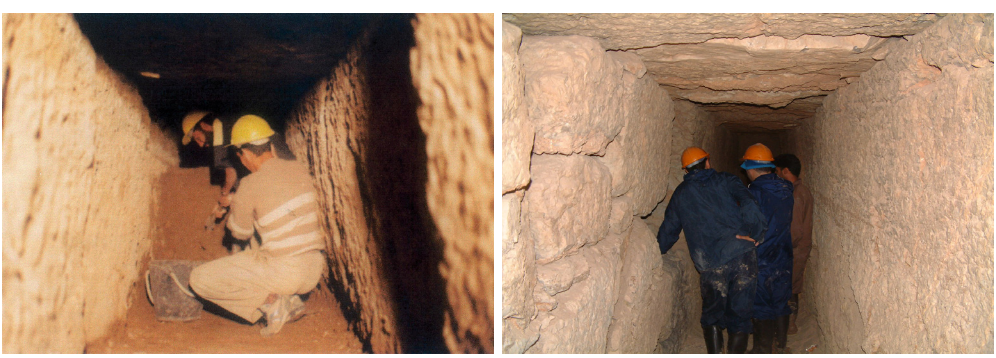

Figure 9 Main sub-surface canal during and after cleaning.

Conclusions and Recommendations

From this study the following conclusions and recommendations can be drawn:

(a) Field investigations revealed that clogging of the main drain outlet has caused some problems for the complex.

(b) The capacity of the existing drains is more than the estimated discharge from a runoff with 50 year return period.

(c) All the laterals drain into the main channel and their bed elevations are higher than the elevation of the main channel (MC). This facilitates the removal of the surface runoff.

(d) As shown in Figure 9, by cleaning the main channel, removal of the surface runoff could be facilitated and the main drain could be a tourist attraction too.

Acknowledgement

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A Roman Bath from Chersonisos, Crete, Greece: Preliminary Results of the Excavation at Tsangarakis Plot

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Abstract: During the Roman imperial period (31 B.C.-3rd century A.D.), the town of Chersonisos on the north-central coast of Crete experienced an intense urban re-development which is partly reflected in the prolific building of bath-houses. This paper presents the preliminary results of the excavation by the 23rd Ephorate of Prehistoric and Classical Antiquities of the most extensively preserved bath-house discovered so far in the town. The paper addresses the design, water supply and wastewater features, the architectural history of the building and its setting in the town, and compares the evidence with other known excavated examples in Crete and the Roman world.

Keywords Architecture; Chersonisos; Crete; Tsangarakis bath.

Introduction

The study of bath-houses, conspicuous and easily recognisable type-buildings of Roman towns and settlements, has in recent years experienced something of a renaissance (DeLaine, 1988). Despite this increase in general and specialist studies however, there are still regions across the Roman world, such as Crete, in which bath-houses have in few cases only become the focus of detailed study or systematic excavation (e.g., Andreadaki-Vlazaki, 1996; Themelis, 2004). Most of the reported discoveries are rarely published in detail but information from them is nevertheless extremely important in enriching existing knowledge about their architectural design, technology and function, and for assessing the spread of bathing habits during the Roman period across the island (cf. Farrington, 1999: 57 ff.).

Although water had served a number of basic needs of inhabitants of Crete since at least the Bronze Age (Angelakis and Spyridakis, 1996), the spread of purpose-built baths, both for public and private use, across Crete during the Roman imperial period has already been noted as a distinctive cultural phenomenon by previous scholars (Harrison, 1993). Chersonisos, a small town and holiday resort on the north-central coast of Crete (Sanders, 1982: 144-146) presents an interesting case-study of this process. During the Roman imperial period (31 B.C.-3rd century A.D.), in particular, Chersonisos, which by that time had gained independent city status from its neighbouring city of Lyttos (Chaniotis, 2006), experienced an intense urban re-development which is partly reflected in the building of many bathing establishments. No less than six such buildings have been discovered in the town, a fact

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which, given the random coverage of the site by excavation, is noteworthy (Galanaki *et al.*, 2006).

History of the Excavation, Topographical Setting, and Phasing

One of the most extensively preserved baths in Chersonisos has come to light during rescue work at Tsangarakis plot. The architectural remains extend over three neighbouring properties in the area known as Poli, to the E of Demokratias St, where in the past further remains of Roman bath houses have come to light (Fig. 1). The plot, is situated at a distance of approximately 295 m to the N of the theatre of the Roman city and about 230 m from the present coastline to the E.

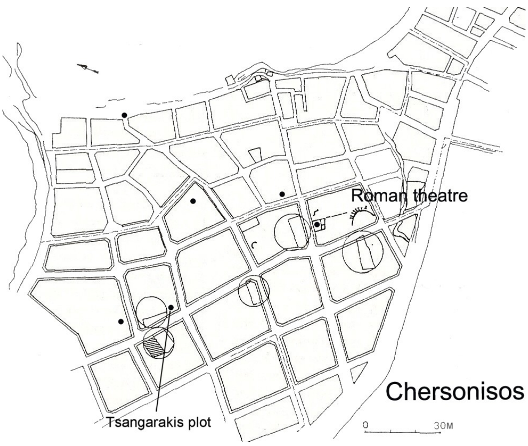

Figure 1 Distribution of Roman baths in Chersonisos.

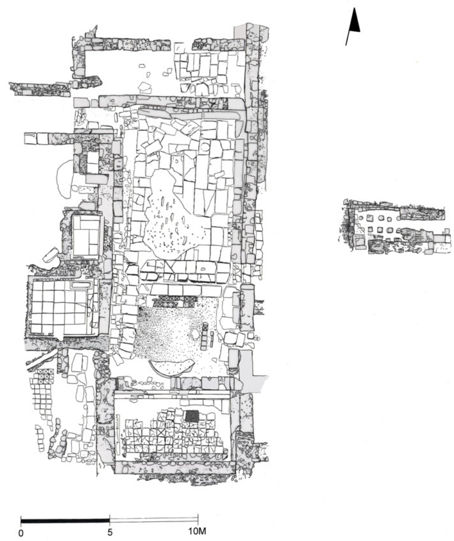

Figure 2 Tsangarakis bath. Current state plan (drawing by P. Stefanaki).

Excavation of the bath-house started in the mid-1980s when the N plot was excavated by the 13th Ephorate of Byzantine Antiquities, while at the end of 2001, the same Ephoreia opened three trial trenches in the E plot. During the same period, the 23rd Ephorate of Prehistoric and Classical Antiquities began excavation of the neighbouring central plot owned by Mr E. Tsangarakis. The architectural remains discovered in these three plots are presented here comprehensively, and in what follows we refer to the remains of the bath building in general as "Tsangarakis bath".

Due to restrictions imposed by the property limits, the W end of the building, which lies below the modern street, could not be ascertained during excavation. The regularity in the plan of the N side makes likely however that the western end coincides roughly with the western limit of the excavated plot. The bath is N-S orientated, and some preliminary observations on the relationship between its plan and the extant remains of ancient streets suggests that the building's orientation correlates with the excavated traces of the street grid of Chersonisos during the Roman period.

The current state of the excavated architectural remains reflect a complex web of constructions, modifications and spatial reorganization that took place during the centuries that the building was in use (Fig. 2). A first phase encompasses the initial construction of the building which probably took place in the later 1st/ early 2nd century A.D. During a second phase, later in the Roman imperial period (later 2nd or 3rd century A.D.), the building underwent some important changes, as a result of which its plan expanded significantly. In Late Roman/ Early Christian times, the building appears to have undergone further architectural interventions and changes, which suggest that it lost part of its original function as a bath. The final abandonment and structural collapse of the building took place possibly later in the Early Christian/Early Byzantine period. Whereas reference will be made to the entire history of the building as gained from the results of the excavation, the following parts of the paper concentrate primarily on the first two phases, when the Tsangarakis building functioned regularly as a bath.

The Bath Building during Phase 1

The building was built in a plot which did not produce any traces of previous occupation. Its foundations were set in the hard limestone bedrock and its walls were built using local limestone in large ashlar blocks for the lower part of the walls. In the upper part, the walls were built with bricks bonded in mortar (*opus testaceum*), a common masonry technique in Crete from the later 1st and especially in the 2nd century A.D. (Sanders, 1982). During the initial phase, the building comprised at least three rooms and features which can be securely identified as parts of the hot and cold baths and service areas of the bath house (Fig. 3).

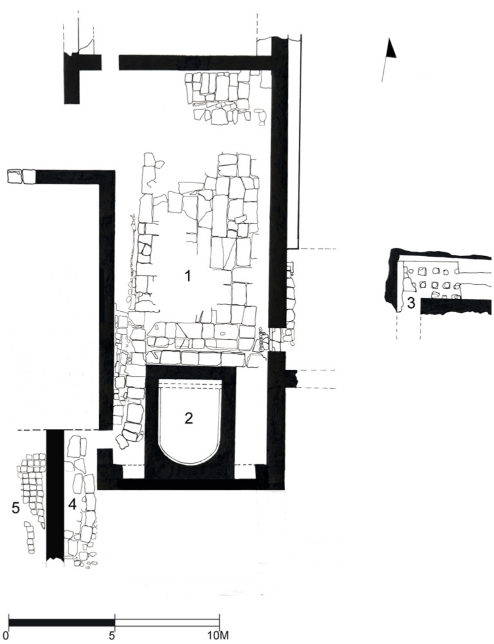

Figure 3 Phase 1 (based on plan in Fig. 2).

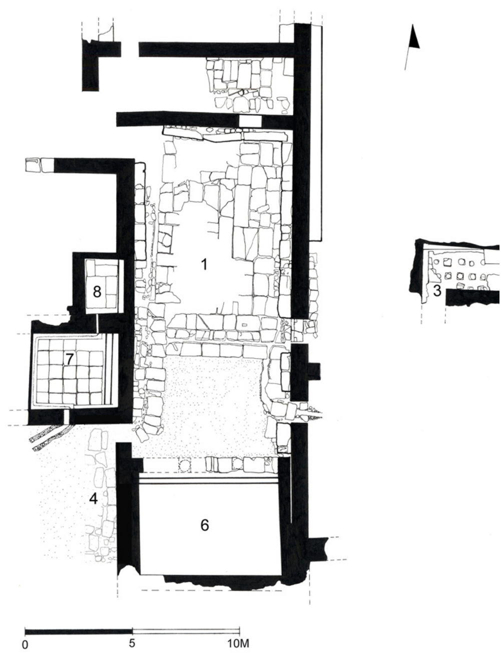

Figure 5 Phase 2 (based on plan in Fig. 2).

Room 1, an extensive angular-shaped area defined by thick walls on the N, E, and W sides, occupied a central position in the plan of the building. This room is aligned N-S, measures 13.15 x 7.31 m², and it was accessed through a wide space in the NW. The latter was connected with what seems to be the main entrance to the building, where a threshold slab and part of a mosaic pavement with geometric patterns were discovered. The size and apparent architectural disposition of the room at the centre of the building suggests that it had a multi-purpose function, reminiscent of the form of rooms identified as *apodyteria* (dressing rooms) in bath-houses across the Roman world (Nielsen, 1990: 156).

To the S of Room 1, lay another room (Room 2) where an apsidal pool was discovered. The feature, measuring 4.00 x 3.00 m², is aligned on the same axis as the room and its interior was plastered with thick layers of hydraulic mortar. Access to the pool was possible through a flight of steps probably from the N, which has not been completely excavated. Despite the partial excavation of this area, the presence of marble veneer and apparent lack of any heating system for the walls and floor suggest that the pool was part of the cold section of the baths, and at the same time indicates the function of Room 2 as part of the cold room (*frigidarium*).

Room 1 was paved with large rectangular flagstones of limestone and was connected with a series of other rooms to the E through an entrance, which still preserves the threshold block. This entrance included a double-door, as indicated by the tangential semi-circular grooves on the upper surface of the threshold slab, and led to a tile-paved room to the E, a very limited part of which could be excavated. During excavation to the E of this, a small part of the hot bathing suite of the building (*caldarium*) was discovered. This comprises part of the substructure of the hypocaust floor and part of one of a hot-water pool which the former supported.

The excavated part of the hypocaust section measures 2.59 x 1.85 m² and includes three rows of brick-built columns, placed parallel to each other and aligned from E to W (Fig. 5). Each row consisted of five columns built in round bricks 0.20 to 0.23 m in diameter, except for one column, which was built using square bricks 0.27 m long. The columns were capped successively by a layer of flat floor tiles and a thick sheet of mortar. On the layer of mortar lay the floor surface of the pool, constructed, similar to the substructure, with flat floor tiles, only a very small part of which have survived. Although excavation did not extend further to the S, based on preliminary observations in the field it was possible to ascertain the existence of another hypocaust-heated room at a distance of about 1.57 m to the one already discovered.

Figure 5 View of Room 1 (caldarium and stoke hole) from E.

Apart from the hypocaust floor, heating for the baths in this section of the building was provided by hot air circulation through the walls. Two vertical inlets, measuring 0.26 x 0.18 m² and 0.30 x 0.14 m², respectively, can still be seen placed at a distance of 0,80 m from each other along the interior face of the western wall. They were used either in undressed form or they were originally destined to receive hollow terracotta pipes (*tubuli*) of similar shape, as was usually the case in other Roman baths elsewhere (Yegül, 1992; Nielsen, 1990). The built hollows rise up from the bottom of the hypocaust so that their lowermost part was connected freely with the rest of the space.

The entire system was heated through a 2.86 x 0.49 m² large, oblong corridor that functioned as the stoke hole of the bath furnace (*praefurnium*), which lay beyond the limit of the excavated area to the E. The thick layers of burnt material, ash and charcoal recovered to the N of the hypocaust arguably stem from the clean-up of these service areas and provide some idea of the intensity of use and the demanding maintenance of the heating system that was necessary for the proper function of the bath-house[1]. At the SW corner of Room 1 a narrow opening lead to an oblong space (Room 4), 1.45 m wide and at least 6.46 m long. This room was only partly excavated, a fact which creates difficulties for its identification. The fact that from there one could access the main shaft of the subterranean drain indicates that the room may have functioned as a service corridor related to the cleaning and maintenance of the main sewer system of the building (see below). More problems of identification are posed by the partially excavated Room 5. This room, excavated to an extent of 5.72 x 1.58 m², was paved in square tiles and had probably an entrance from the S. Traces of the original destroyed N wall of the room were discovered underneath a later water channel, suggesting that the room continued further to the W.

The Bath Building during Phase 2: Additions and Expansion

During the later imperial period, the bath-house experienced some important changes in its plan, size and function of the individual rooms (Fig. 4). Room 1 was divided into two large sections, one in the south which was possibly used as another *apodyterium* and one in the N, possibly used as a service area. In the former, a row of stone-built benches, probably used by the bathers to rest and as storage compartments for their clothing and shoes, was built along the N, W and E walls. Further changes are attested in the W part of the building, where Room 4 appears to have become a space for dumping rubbish and was disused.

The most dramatic modifications took place in the cold section, whereby the arrangement and number of bathing elements in the cold section were re-organized. The apsidal pool in Room 2 was filled up and covered by a floor consisting of a water-resistant mortar of crushed tile that was bordered by a frieze of thin marble slabs at the edge. At the same time, a new entrance to this was opened on the E wall. To the S of Room 2, and set apart from it by a low balustrade wall, a large rectangular pool (Room 6) that was most probably used for cold baths (*natatio*, cf. Nielsen, 1990: 155) was constructed. This pool, which measures 6.23 x 4.17 m², was accessible from the N side via a series of two steps. The pool's floor was paved with irregularly sized marble slabs, while its walls, balustrade, and steps were also faced with marble veneer. The discovery of a limestone block with a smooth chiseled surface, situated off-centre in front of the balustrade, indicates the existence of a pair of columns fronting the descent to the pool and alluding to some form of enhanced architectural embellishment.

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[1] A large number of clay studs, used for fixing hollow tiles (tegulae mammatae) on walls, were discovered during excavation but since they were not recovered in situ, they may not be securely brought into association with the use of this system for the heating of the walls in the building. On the *tegulae mammatae*, see Adam 1999, 269; on their deployment in baths, see Yegül 1992, 363-365.

It was also during this phase that two smaller bath basins, one rectangular (Room 7), measuring 2.24 x 1.45 m², and one almost square (Room 8), measuring 3.10 x 3.02 m² were added to the W of the central Room 1. Both were accessed from the E through one and two steps respectively. Room 8 is paved with irregularly large slabs of marble and its walls are faced with marble veneer, similar to Room 7, which however is paved with square tile plaques. As a result of these changes, the area of the apodyterium and cold section, which now encompassed three different spaces in which bathing could be performed, expanded significantly. During this phase, the building appears to have carried a vaulted roof in the central hall, as suggested by the collapsed part which is still preserved in the middle of this space.

The Bath Building during Phase 3: Modifications and Disuse

During the Late Roman period, a number of modifications which resulted in the restriction of the bath-house's function took place. The transition from the second to the third phase is still poorly understood and awaits further study, and as a result only few aspects can be discussed here. A visible modification attested to the building's fabric that can be ascribed to this phase however is the disuse of the large pool, which now was paved with tile slabs. Furthermore, the walls of this room are now supported in the interior by limestone blocks and short walls, suggesting perhaps that the building had suffered some serious structural damage. This intervention to the standing fabric can be seen on the W wall of the old *apodyterium* and the newly built wall which runs on the three sides of the rectangular basin. In addition, the S section of the central hall becomes physically from the N, as the access between the two has now been blocked. Circulation around the building is now possible only through a corridor in the NW area of the central hall. The building became totally disused after the collapse of the roof, which, surprisingly must have stood in fairly good shape until the final abandonment of the building.

Aspects of the Water Supply and Wastewater Technology

The management of the water resource, from its supply outlet to its place of primary use, drainage and re-use must have been an important prerequisite for the smooth function of the Tsangarakis bath-house, as for other similar establishments elsewhere in the Roman world (Yegül, 1992: 389-395; Hodge, 1992). The fragmentary nature of the discovery presents difficulties for reconstructing the exact course followed by water from its supply outlet to the point that it entered the individual bath suites in any of its main phases of use, and as a result only some general remarks may be made. The downward slope in the E part of the building and the similar tilt of the drains discovered throughout its extent suggest that the main system of water supply of the bath was located in an area to the W, in the part nowadays lying below the modern road.

Since bath-houses normally required huge quantities and constant flow of water to function properly (Hodge, 1992: 265), it seems unlikely that the water supply of the bath-house depended on the pumping of water from lower-lying wells, which could create problems in times of drought and shortage. In the initial phase of construction, water most probably was made available either by means of pipes connected with the mains of the Chersonisos aqueduct, or was obtained from purpose-built water-collecting tanks and cisterns, in a manner similar to other examples known from Chersonisos (Galanaki *et al.*, 2006). During the second construction phase, when three pools were constructed in the cold section of the bath-house, this pattern appears to have been partly modified. Excavation in

Room 5 uncovered part of an open channel raised on a short wall which cut across the existing tile floor (Fig. 6) and which indicates the direction from which water flowed into the basin in Room 8. A tile-built open flow channel, starting from the middle part of the S wall of this room and running along the perimeter of its W wall directed the water into the neighbouring basin in Room 7 through a round pipe built in the N wall. This suggests that the basins could be filled at a controlled rate, either one at a time or using the excess water, when the southernmost basin (Room 8) had already filled with water.

Figure 6 Water channel in Room 5 from SW.

Figure 7 Main drainage (right) and surface drain (foreground).

The existence of various pools and baths in the building, especially in the later imperial period, necessitated not only the supply of these features with large quantities of water but also their unobstructed drainage. The solution applied to this problem at the Tsangarakis bath-house was simple and was aimed to serve this rudimentary functional purpose. A slab-paved main drainage channel begins from underneath Room 4 and, after taking a smooth turn, can be seen running along the W wall underneath the perimeter of the enlarged Room 1 (Fig. 7). In Room 1, the drain turns E and probably carried on to the area of the hot baths, thus re-directing the wastewater from the cold and hot cold bathing suites to the outside in the NE. This drain was constructed in the initial phase of the building in the early imperial period and continued to be used in the second phase. The wastewater from the pools of the *frigidarium* was piped out from small outlets, either carved into or placed between the courses of the stone masonry and tilted downwards to the main drain and situated at the corner in closest proximity to the latter. In phase 1, in addition, a narrow surface drain, best visible to the N of the large rectangular pool, running along the middle of Room 1, has been carved out on the floor slabs, leading the water spilling over from the apsidal pool into the subsurface drain (Fig. 7). A similar surface channel assisted in the drainage of the two small bath basins in phase 2.

Architectural Design, Interior Decoration and Mode of Circulation

In its initial architectural phase, the Tsangarakis bath appears to have been a typical small-to-medium size bathing establishment of the type generally characterized as *balneum*, as opposed to the larger and more opulent imperial *thermae* (Nielsen, 1990). The plan appears to display a certain degree of symmetry, in the first phase along the N-S axis, while in the second phase on the S-E, with the hot and cold bathing suites placed at opposing ends from each other across the central hall. The exact location of the warm bath section still poses a problem, as this was not discovered during excavation. Considering the location of the hot baths however, this is likely to have been placed to the E of the large rectangular pool and most probably in the unexcavated area which has direct access from the *frigidarium*.

If the above reconstruction is correct, the plan of the bath-house in both the first two architectural phases, following Krencker's typology (Krencker *et al.*, 1929), can be conjectured as that of a simple row type, in which bathers followed the same route in and out of the successive bathing suites (Nielsen, 1990). Bathers would enter the building from the northeast or from the corridor in the southwest and proceed to the *apodyterium*. After disrobing and placing their garments and shoes in the purpose-built niches and/ or wooden benches that were normally to be found in this area they would take turns in proceeding to the east in the area of the *tepidarium* to get accustomed to the warm environment of the building. Bathers would then enter the hot section and take turns in having individual baths in the pools (*alvei*) in this area. Following the same route they would return to the warm room(s) and finish their bathing routine with a plunge in one of the cold pools opening off the *frigidarium*.

Although the excavation produced little evidence for the interior appearance of the bath house in its original form, some finds recovered in contexts of later re-use may provide some general idea about furnishings and decoration. A headless male statue reused as a support for the water channel in Room 5 may have been originally placed in a niche of the central hall. The occurrence of statuary in various rooms in bath-houses is widely attested throughout the Roman world and varied according to the size, sophistication and the nature of patronage of a particular bath house (Yegül, 1992: passim; Fagan, 1999: 104 ff.). Other fixed elements such as a limestone tub which was discovered reused in the S plunge bath may have been originally used in an area of the bath-house before being transferred to this room in Late Antiquity.

Conclusion: The Bath-House in its Wider Context

On the basis of the present data, the Tsangarakis bath developed from a rather modest building, with a simple set of bathing suites in the early Roman imperial period into a more extensive and architecturally more pretentious establishment later in the same period. Given the partially discovered plan of the building, it is arguably a difficult task to place the Tsangarakis bath in the context of the vast number of known bath-houses from across the Roman world. This task is further hampered by the fact that, as already noted, relevant comparable material from Crete is still very sketchily known, but some general observations however relating to certain aspects of the building's plan and comparison with the existing material may prove useful for future more detailed research.

It is evident from the plan of these two initial phases that of particular importance for the design of the building was the large hall that probably functioned as an *apodyterium*, and from which a number of rooms with bathing facilities were accessed. In Crete, buildings with a similar oblong and/ or wide hall may be recognized in the small and, in particular, the large baths excavated at Eleutherna. In the large baths, built in the Late Hellenistic - Early Roman period, the oblong hall, paved with large limestone slabs, provides access to the bathing suite at the S part of the building, a series of what are interpreted as service areas and water cisterns in the N flank, as well as to the street on the outside of the building through a stairway (Themelis, 2004: 56-58, Fig. 57). In the small baths, constructed in the 2nd century

A.D., the oblong hall functions as a space that regulates circulation to and from the warm and hot bathing suites that lie to the W and S (Themelis, 2004: 49 ff. Fig. 43).

Such spaces are frequently to be found in Roman-period bath-houses in the Eastern Mediterranean and particularly North Africa, where they represent a typical feature in the bath architecture of the region (Farrington, 1999: 63-65). In the North African context, these spaces have been known as “corridors”, “wide rectangular halls” or “grand salles” (Yegül, 1992: 400). The main characteristic of this unit is their off-centre placement, their large size and their axial arrangement with respect to the rest of the plan which makes them easily accessible from both the outside and the other rooms in the bath building (Fagan, 1997: 7). As in the case of the Tsangarakis bath during its second phase, these spaces frequently provided access to pool(s) on one or more sides, in a way similar to the long corridor at the Trajanic/ Hadrianic baths at Cyrene in Libya (Yegül, 1992: 401, Fig. 491c). These large spaces are generally interpreted as dressing rooms and areas for socializing (Yegül, 1992: 400), which seems to correspond with the interpretation of Room 1 proposed above.

Despite these similarities however, the Tsangarakis bath displays some individual traits which set it apart from these African examples. While in African baths (and partly also the examples from Eleutherna cited above) hot and cold baths are placed in a random or half-axial relationship to the central hall, at Chersonisos these two bathing suites in the second phase are placed symmetrically opposite to each other, with the location of the cold pools mirroring those of the hot ones. This apparent symmetry may be the result of the size of the plot available for construction or certain decisions taken at the design level. Conversely, given the known administrative, cultural and economic ties between Crete and parts of North Africa during the Roman imperial period (Harrison, 1993), it may indicate a local rendition of an architectural form which was widely used in the region for the construction of bathing establishments.

Acknowledgements

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Lavatories in Ancient Greece

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Abstract: Lavatories can evidently be classified as a characteristic factor of living standard and economic prosperity. Many remains of ancient lavatories have been found in the greater region of the ancient Greek world. Some of them are dated even in the Minoan era (i.e., Knossos' Palace). Many references about them have been recorded in numerous ancient greek scripts. Despite the fact that many related archaeological finds are dated in a wide chronological range, the typical mature ancient Greek lavatory was probably formed in the Hellenistic period. That was the period of a great evolution of the ancient Greek water technology as well. Chambers for that function are found not only in private houses but also in many public buildings and sanctuaries (Gymnasia, Asclepieia, etc.). The features of the typical ancient lavatory are the bench type seats with the keyhole shaped defecation openings and the ditch underneath them, which is associated with both water supply or flushing conduit and sewer. The lavatory was usually situated in the area of the building most convenient for water supply and –or sewerage. The mature lavatory's layout was spread out all around the Roman Empire, acquiring more or less monumental appearance.

Keywords Ancient Greece; Ancient technology; Aristophanes; Hellenistic period; latrine; lavatory; sewerage; toilet.

Introduction

The subject of this article is not a result of some specialized study. It derives mostly after the experience through various projects that have been worked out by my architectural office, supported by limited bibliographic research. The hygienic installations can be classified as a characteristic factor of living standard and economic prosperity. Because of these reasons lavatories have become, and often still are, showing off elements. Besides it is indicative that many businessmen of tourism evaluate accommodation facilities and other installations for tourists, inspecting also their toilets.

Terms – Etymology

These areas are reported by ancient Greeks with various words. Usually were called *άφοδος -aphodos* or απόπατος-*apopatos* but also *αποχώρησις-apochoresis* (withdrawal). The term *θώκος -thokos* (seat, throne, chair) is also recorded. The last one is characteristic for lavatories' shape -as will be presented analytically below- and for the equivalent portable or fixed utensils. These artefacts were used for defecation before the formation and predominance of the typical ancient lavatory.

Its reference as *σωτηρία-sotiria* (salvation) for a public lavatory in ancient Smirni, is also rare. Indubitably it was in deed salvation for the ancient city the existence of such installations. The term *κοπρών-kopron* probably describes a construction relevant to the current small cesspits. According archaeological data, it was without any sewerage pipes which usually characterize the typical ancient lavatory-apopatos. Because of that lack of sewerage *koprodochoi* and *koprothikes* were essential as well as *koprologoi*, those who gathered the sewage. Finally it is evident that a specialized researcher identifies easily the ancient roots of most words that are used in Modern Greek referring to defecation. It is also remarkable that the basic terms include the concepts of isolation and privacy that undeniably puts the prefix -απο-.

Written Sources

Aristofanes

In Aristophanes' comedies one can be find the most significant ancient written reports on the lavatories and the related with them subjects. Apart from the term apopatos that is mentioned in "Plutus" (line 1185), in "Ecclesiazousae" (326, 351, 354) and in "Acharnians" (the Ambassador in Djkaiopolis in raw 81), its synonym aphodos is also written (Ecclesiazousae 1059) as well as the relevant kopron in "Thesmophoriazusae" (l.485) Moreover, the sanitary paper of that era, "spongia" (from sponge) is reported in "Frogs" (line 487). There Dionysus talks about it to Xanthia in a way equivalent with what today characterizes someone coward or timorous. Finally, in "Peace" (l. 9), the koprologoi are characterized in depreciatory manner, as vituperation (Hall and Geldart, 1967).

Other sources

Kopron is also reported in Demosthenes (25, 49) as well as in various inscriptions (i.e. IG2 1058II), while in an inscription from Pergamon (OGI 483.220 in Athen. Mitt. 27, 1902) the term *αφεδρών*-afedron is also reported. Aphodos is reported also by Hippocrates (Peri agmon, 16), who in addition uses for that place the word thokos (Epidemiae, 7,.47,.84). In Life of Lykourgos, Plutarch refers to lavatory as *apochorisis* and reports the problem of stench because of sewage at the streets of ancient Athens. Polydeukes refers to an immovable lavatory to distinguish it from the vessels (Bethe, 1900-37: 10 and 44).

Emergence of the Type and its Time Frame

There is documentation for similar installations in the Minoan and the Mycenaean period. Latrines are mentioned at scripts of the classical period, but none has been found, either public or private. Researchers that dealt systematically with that subject, agree on this point. However, some have argued for the existence of *kopron*-cesspit in houses of this period in Athens, specifically north of Areios Pagos.

Moreover, containers of clay for defecation -*koprodochoi*- are known (amjdes or skoramides from Athens) as well as anatomically shaped earthen seats (from Olynthus), looking like the current toilet seats. At these seats the absence of bottom combined with the form off the lower edge, justifies their use either over cesspits or along with some other mechanism for collection and drainage of excrements. Probably they are similar to a pre-existing type of lavatories. The existence of such utensils in Olynthus, that was destroyed by Philipp II in 348 B.C., could easily date them in the 5th century B.C.

An on floor earthen utensil with a sewerage pipe made also of clay was found in Olynthus. Its shape, according the excavator, suggests that it was used along with something else that was not preserved, a wooden seat or a small relevant board. Finally recent discoveries in Epidaurus, specifically at the foundations of Avaton, most probably represent one of the first equivalent stone samples of toilet seat, indeed a premature one. Research about the time of appearance of lavatories with this mature layout, suggests that this has probably happened in early 4^{th} ca. B.C. Basic issues for this hypothesis are, first the absence of lavatories in 5^{th} ca. B.C finds - however they are reported in the ancient scripts- and second the appearance of them approximately at the end of that century, according the existing documentation, in Thera, Amorgos and Delos.

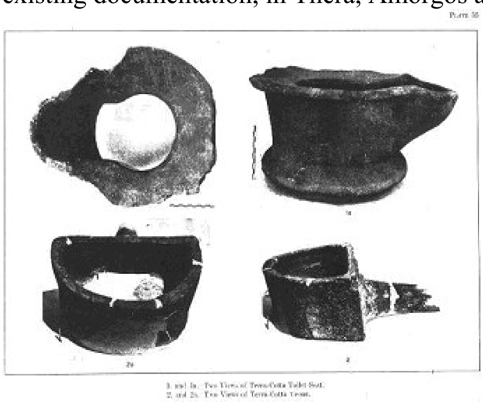

Figure 1 Earthen toilet seat and defecation vessel, Olynthos (Robinson, 1934).

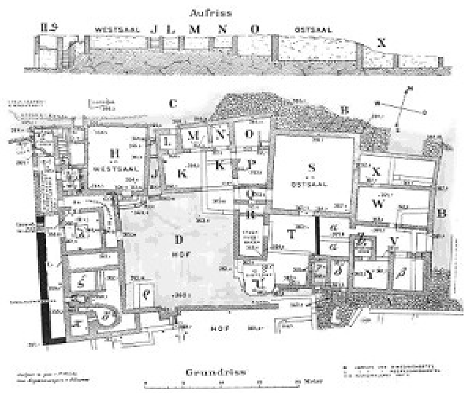

Figure 2 Small public lavatory in ancient Thera (von Gaertingen, Hiller, Thera).

A similar installation at Knossos' Palace (Angelakis *et al.*, 2005: 212), is a very early example to be considered as one of the first links of their evolution's chain. The number of lavatories that was found in residences and public buildings in Delos determines the island's importance regarding to the formation and study of ancient lavatories. Moreover the economic and social evolution of Delos during the post Peloponnesian war period as commercial and naval centre of the Helladic space justifies that importance. That society of seamen and tradesmen which had many engaging representations was logical to confront substantially a problem that deplored all the ancient cities.

The typical layout of the lavatory was formed during the next centuries in the greater Hellenic region with numerous examples not only in the islands but also at the continental territories. Many latrines dated in the 2^{nd} century B.C. have been preserved in residences (Delos, Thera, Amorgos, Dystos, Kassope, Erythrae, etc.) and in public buildings (Gymnasia, Palestrae, etc.). The mature formation of the lavatory's features in the late Hellenistic era was followed by its spread in the entire Roman Empire. Along with that spreading, lavatories were in a way "Romanized" if that term can be used. Therefore at the 1^{st} and 2^{nd} century B.C. lavatories are built in monumental forms and sizes, equivalent to other constructions of the Romans.

Description of the Typical Lavatory

Public and private lavatories

From the existing documentation it appears that the essential differences between private and public lavatories were mainly their size, represented by the number of defecation holes, and the existence or not of continuous water flow. There is evidence of privacy removal with the presence in the same small room from three individuals –in the private lavatories – up to tens of persons - in the public lavatories. It is also noteworthy that while in Thera there is a large number of public lavatories, in Delos abound the private ones.

Pipe network – Sewerage

The lavatory's layout is substantially determined by the ditch under the benches of defecation. The public lavatories were usually supplied with water of natural flow. On the other hand in many cases this was combined with flow from the kitchen or the bath tab. In both cases the sewers define the lavatory's layout and position in the building. Moreover, the requirements of sewerage put that room in the perimeter of a building at a side adjacent to a street. The sewage was drained through ditches along the streets or even in the open spaces in cases of small houses (i.e., in Dystos). The most typical position is at the corners of the buildings, while for the residences the placement in small spaces near the entrance is widespread, particularly in the Delos. Possibly it is after the cesspit's (kopron) placement by the entry of Athenian houses.

Lavatory's typical features

Peripheral ditch. The peripheral ditch usually lies along the three sides of the chamber, in a U shape, mostly uncovered. In smaller private lavatories is mainly deployed along the two sides in L shape. On the other hand in the later large public lavatories it lies along the four sides (Athens, Philippoi, Asklepieion on Kos, Pergamon, Epidaurus). There, the part in front of the door is completely covered. The input of water – by flow or carried with container - comes in a way that facilitates the sewerage. The ditch is adjusted to the level of natural flow of water, either acquiring much height (Roman Agora-Athens) or after adjustment of the lavatory's floor lever (Philippoi).

Lavatory seats. The bench shaped seat is always made out of stone slabs, 10-20 cm thick. It is usually 45-50 cm wide and with roughly that much distance from the floor. On the contrary the length varies depending on the size of lavatory and the number of defecation apertures on each slab and on the distance between them. Indicatively it ranges from 1.2 m in Minoa-Amorgos up to 2.3 m in the Philippoi. Under every lavatory's seats, even in the simplest ones, there exists a vertical slab that covers the void between the floor and the seat. The almost standard height of 45 cm as mentioned above is as high as that of a somehow typical chair. The seats' supporting presents interesting differentiation and typology. Four types can be distinguished. All of them are cantilevered, mostly covered except the type in Philippoi and Efessos. More specifically there are:

(a) The cantilevered stone slab protruding out of the wall. It occupies the 2 of 3 sides of the lavatory of the Gymnasium in Minoa-Amorgos. The other 1/3 is supported by a stone bracket. That type's implementation on small lavatories is obvious.

(b) The freely supported slab over stone beams, cantilevered or not. These beams are invisible, covered by the vertical plate which fills the void in front of the seat. It is the most typical form and the joists are roughly as high as is the seat from the floor. Their material is mostly out of cheaper stone than the rest visible structure. In original Roman lavatories is made of small brick pieces of wall, penetrated at their lower part by the peripheral ditch.

(c) Similar to the previous type where the stone joists protrude out the vertical plates and have been formed as neck mouldings of benches and exedras (Philippoi - Efessos).

(d) Finally the type where the freely supported seat slab is also supported by stone cantilever beams which are shorter and less wide than the seat. Characteristic examples are at the Asclepieia of Pergamon and Epidaurus.

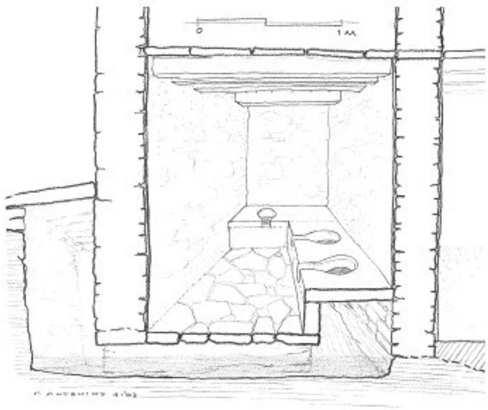

Figure 3 Restored view of Ithidiki's lavatory in Amorgos.

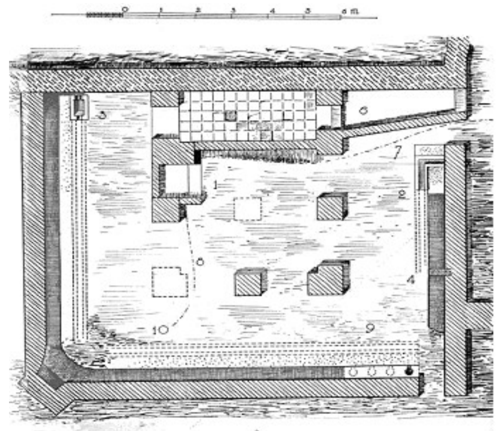

Figure 4 Public lavatory in Asclepieion of Kos (Hertzoc-Scatzmann, 1932).

Defecation's openings. As s mentioned before, the openings are on the seat and the distance between them varies. In Gymnasium of Minoa on Amorgos it is 85 cm while in the Roman Agora of Athens is just 51 cm. Obviously, at the big public lavatories which facilitated more people they were placed more densely. In most Roman latrines there is also dense openings' arrangement (i.e., in Ostia). Moreover it is very remarkable not only the shape but the ergonomy of the openings as well.

Their comparison with the known earthen defecation seats of Olynthus is still more interesting. The resemblance is not only to the keyhole shaped outline of the opening but also in their slanting verges. The width of that slanting in the stone openings varies from 4 cm in Minoa to only 1 cm in roman Agora of Athens. There is a hypothesis that this slanting was for an earthen cover but it can be reconsidered, since one of the two known covers of clay – that of Philippoi - does not have an equivalent edge. Probably, according its dimensions it could be a typical short earthen drum of hot bath floor supports. Another interpretation is that this slanting was curved in order to make the seat more comfortable than it would be with a sharp edge. There is much variety in the openings' shape. The rough but more ergonomic elliptical shape found in Amorgos becomes an object of formalization in the Roman period. The prolongation of the opening up to the front edge of the seat contributes to these variations. It must be noted that the form of openings remained substantially the same during the life time of that particular type of building.

Auxiliary elements. After the expansion of a lavatory other adjoining constructions were also created. Remarkable are the small holes for drainage of urine on the floor of Roman Agora's lavatory in Athens but also the explicit clue on something equivalent in Minoa Amorgos, 3 to 4 centuries earlier. Moreover the small peripheral ditch of continuous water flow, with semicircular cross-section, was widely applied. According to researchers, it was used for the cleaning of spongia, the sanitary paper of that time as mentioned before. In the middle of the chamber of many lavatories there was a small swallow reservoir. In Athens and Efessos it was surrounded by colonnade like a greek katakleiston or a roman impluvium. Probably it did not have only this use. It had a slope of roughly 1.5% as measured in the construction in Epidaurus. Possibly there it was used for the washing of spongia. A similar small central reservoir exists also in one public lavatory of Thira and perhaps had an equivalent function.

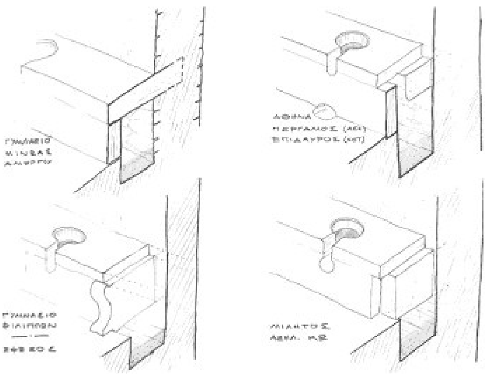

Figure 5 Formation and types of lavatory's seats supporting.

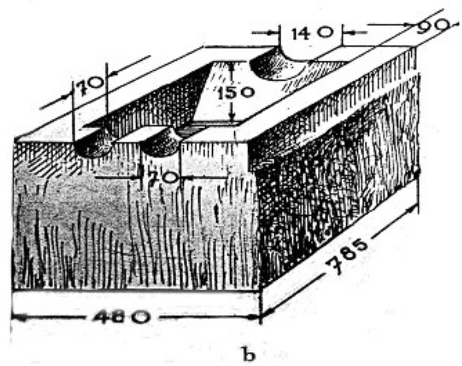

Figure 6 Conduit's end stone from Askleipieion of Kos, No 3 in Figure 4 (Hertzoc-Scatzmann, 1932).

The layout of the ground plan. Most ground plans have oblong shape in both public and private lavatories. At the known lavatories of Athens, Philippoi, Efessos and Epidaurus there is also a rectangular lobby with the entrance at the narrow side and the door to the main chamber at long one. Finally it should be noted the evolution of lavatory's ground plan at the Imperial era to more complex shapes and imposing layouts.

Examples

Public lavatories

One of the earliest well shaped lavatories is that of Minoa's Gymnasium on Amorgos. It is small in size built contemporarily with the Gymnasium at its south west corner, and dated in mid 4^{th} century B.C. Apart its surviving roof and the benches on three sides it is also characterized by the large conduit that supplied it with natural flow water. The sewerage used the well shaped conduit, parallel to the south wall of Gymnasium. It is dated in the end of 4^{th} ca. B.C. (Μαραγκού, 1986; 1987; 2002) and is preserved in a very good condition, but only the half of the monolithic floor exists. On the other hand the door remained almost intact and only two pieces of the door jamb have fallen down.

The Public lavatories of Thera are small in size but abound all over the excavated part of the ancient city. Despite their public use, they have small size. Even though they are structurally embodied to residences, their access was only from the communal space of streets. The ditches and sewers have been preserved but not any seats or defecation openings. Possibly they were not made of stone. The sewerage was facilitating through ditches in to the streets. Public lavatories have been found in the Palestras and the Gymnasium in Delos. In the Palestra of the Lake (Fig. 8), there are three spaces, formed after the rearrangement of the original classical building, that are attributed to that use. The neighbouring smaller and newer Palestra has a lavatory as well. In both buildings lavatories have been placed in the perimeter, and particularly near the path of some drainage. The north-eastern lavatory of the Lake's Palestra was probably supplied by the water from the bath or even the colonnaded atrium. In the south-western there was probably a small rectangular reservoir in the middle.

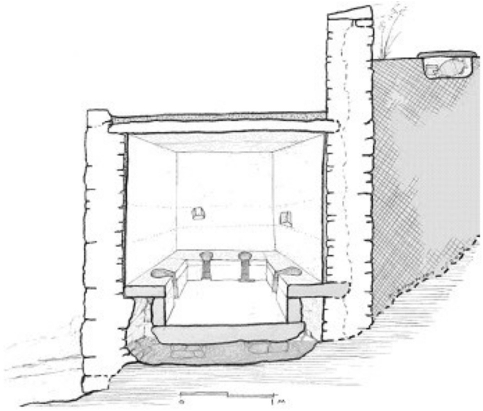

Figure 7 Restored view of the Gymnasium's lavatory on Amorgos.

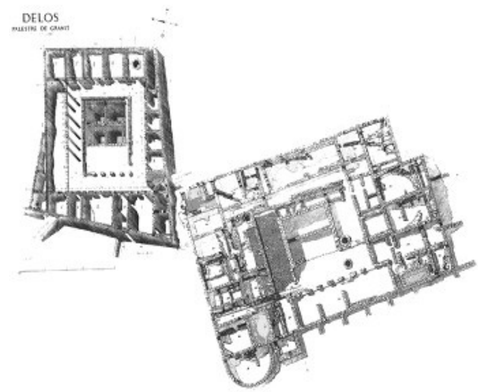

Figure 8 Recomposed ground plans of Palestras on Delos (Chamonard, 1924).

The lavatory of Asclepieion of Pergamon is characterized by its ground plan layout, which is more complicated than the usual rectangle form. In the Asclepieion of Kos the lavatory is part of a later extension of the lower portico in the perimeter towards west. Here it is very remarkable the monolithic reservoir which also drains the water from the small peripheral half pipe for the wash of spongja to the main conduit (Fig. 4, No 3 and Fig. 6 and Herzog-Schatzmann, 1932). At the Ventio's Thermae in Efessos the traditional Greek typology is maintained inside a typical Roman building. They are characterized by the oblong impluvium which is quite monumental for the size of the chamber. In the Gymnasiun of Philippoi the typical Greek layout is predominant, despite the roman modification of the building. Also the placement is much resembling that in lavatory of Kotyo's Portico in Epidaurus.

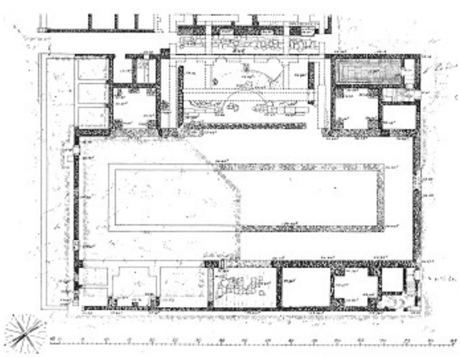

Figure 9 Gymnasiun of Philippoi, ground plan (Delorme, 1960).

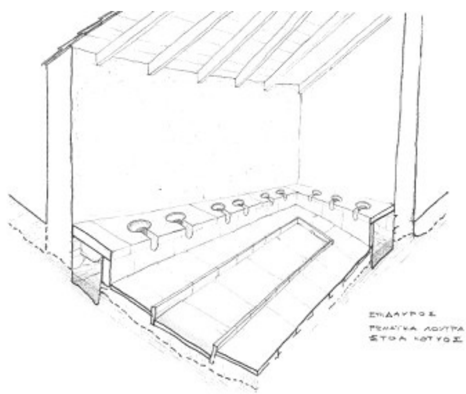

Figure 10 Restored view of the lavatory in Kotyo's Stoa,. Epidaurus.

In Athens two public lavatories dated in the Roman period have been preserved. In the south-eastern corner of the Attalos' Stoa and east of the Roman Agora. Both ground plans have almost square shape. The Roman market's lavatory is a mature construction of that period, since it was built after that Agora. In addition to the oblong entrance lobby, it is characterized by the deep conduit underneath the benches and the impluvium at the centre of the room. According the surviving parts it had 62 defecation openings which had corresponding urinal holes on the floor (Orlandos, 1940: 251-260).

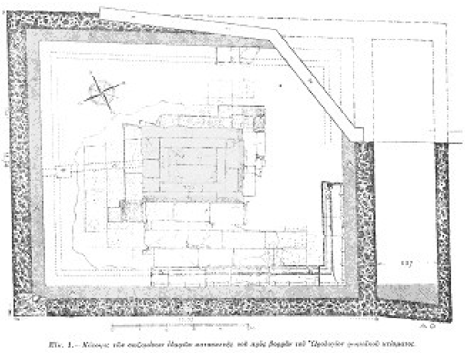

Figure 11 The lavatory outside Roman Agora, Athens (Orlandos, 1940).

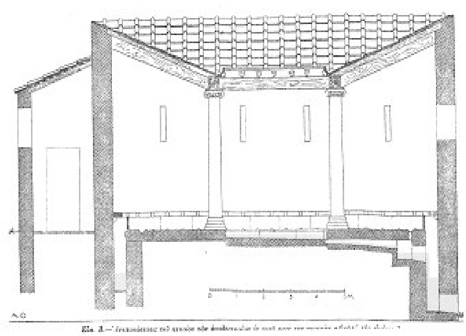

Figure 12 Restored longitudinal section.

Finally in Epidaurus the lavatory at the east end of Kotyos' portico could be possibly dated as one of the later buildings of this type in Greece. It has oblong ground plan and is supplied with water of natural flow coming most probably from the north-eastern baths. Most probably it was built when the portico was partly standing and the poor construction embodies stones of other collapsed buildings of the sanctuary. The elongated swallow tank in the middle, made of tiles, has a small sewerage pipe ending at the main peripheral conduit. Indicatively, three Roman examples are also reported. The lavatory of Pompei's Palestra, of the complex of Triklinon's in Ostia (Fig.13) and the Largo Argentina lavatory in Rome. The type of building was spread out not only around the Mediterranean but also up to the utmost of the Roman Empire.

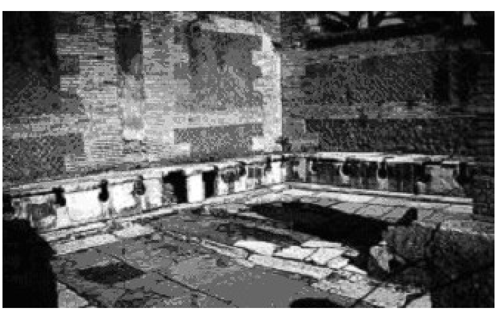

Figure 13 Lavatory of Triklinon's area in Ostia(Neudecker, 1994).

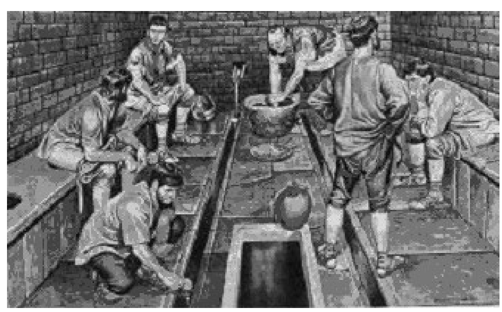

Figure 14 Restored view of a Roman public lavatory (Connoly, 2000).

Private lavatories

The case of the remains of earthen fixed utensil of sewerage in Olynthos could be reported as the older known residential lavatory. Common feature is its placement in the perimeter of building next to the street, where obviously was the sewerage. Most probably it was supplied by the water remaining from other household uses since the space that was found there any water supplying conduit. In Delos numerous domestic lavatories have been preserved. Their size is medium or small and their main ditch has an L plan shape. The small ones have the bench with the openings along only one side, while the large along the three sides. Most likely the seats with the keyhole shaped openings were wooden. The sewerage was applied via the conduits in the streets. Because the lack of water in the island the remaining water from other uses or from local cisterns was used.

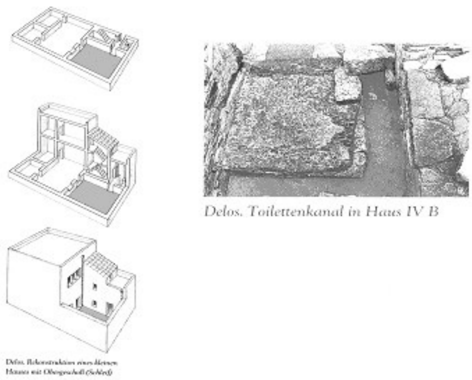

Figure 15 Lavatory of a house in Delos (Hoepfner, 1999).

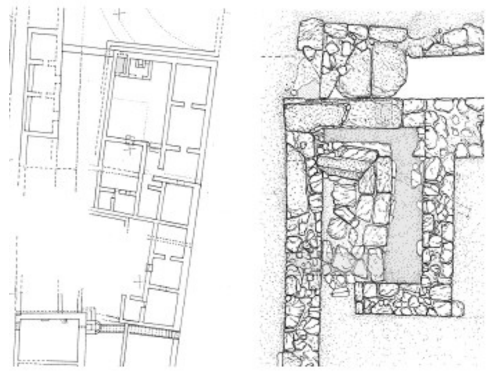

Figure 16 Ithidiki's residence in Minoa-Amorgos. General and detail ground plans.

The resemblance of Ithidiki's residence's lavatory, in Minoa Amorgos, with the equivalent ones in Delos is remarkable. On the other hand the main difference is that it was supplied by water of natural flow from the conduit attached to the outer wall and operates as both adducing and abducing. Most probably it carries water from drainage of buildings higher up. The inner conduit has an L plan and the room became part of a workshop in the roman period (possibly glass shop). The case of the lavatory in a house of Dystos describes the effect of the terrain on the constructions. The inclination led to shapes and layout with similarities to the lavatory in Minoa's Gymnasium. However the main difference is that in Dystos there is not natural water flow and also the sewage flows freely in the space just outside of the house, without any conduit! (Fig. 17 and 18).

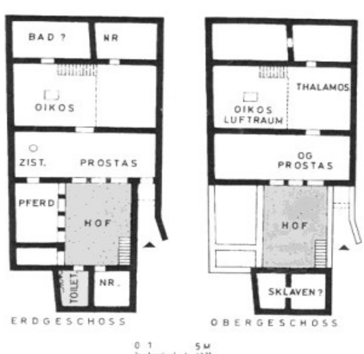

Figure 17 Dystos, restored plans of a typical house.

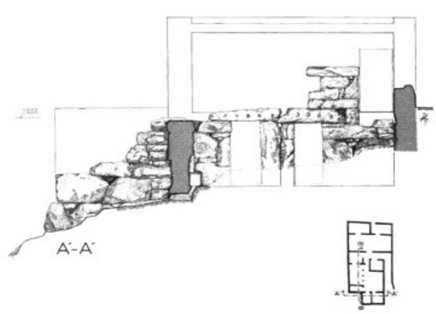

Figure 18 Section of the house's ruins (Hoepfner, 1999).

In Erythrae the lavatory was placed in the corner of the atrium and was put along the narrow side of room, just opposite from the door. The sewage was just led outside of the building. Finally it is mentioned that lavatories have been also found in other ancient towns as in Kassope behind Katagogeion. Private lavatories were widespread in the Roman Empire as are also the public ones. In Ostia a lavatory is a common feature in almost every house.

Conclusion

In conclusion, it is obvious that the shape, the layout and the structural techniques of lavatories in the antiquity depended on functional needs, anatomic requirements, constructional restrictions because of the materials applied, and the presence of water. Similarities appear in most of their elements not only among examples that abstain chronologically from each other, but also between private and public ones, rich and poor lavatories. A big difference with modern lavatories from those of the antiquity is the use of the latter by more than one individual at the same time. This remained during the life time of this type of toilet, and somehow that has survived up to nowadays in the public male urinals. Ancient lavatories' differences through years are focused in the change of their characteristics resulted by the implementation of the Roman building style, not only according to the size of constructions of but also to the materials. The essential differentiation between private and public ones, which is the number of users, has already been mentioned.

The appearance and evolution of such constructions are directly depended not only on the prosperity and the economic growth but also on the technological improvement. A similar evolution of the sanitary areas of houses and buildings has happened also in the last 50-100 years to the western type societies and is under deployment in the third world countries. After these remarks, the existence of numerous lavatories in the thriving Hellenistic societies around the Aegean and the wider region of Eastern Mediterranean is absolutely well expected. In the case of Delos, the large number of private lavatories is justified by the presence of affluent residents, tradesmen and seamen, on the island. Very important is also the case of Thera, with the numerous public lavatories which, according their placement, shape and size, could easily be private ones. The influences from the thriving Ptolemaic Egypt should not be ignored. Many lavatories are reported in descriptions in papyruses of that era, related to real estate matters.

Accordingly, spreading out of the henceforth mature lavatory's form by the world ruling Romans was normally expected. The morphological and institutional mutation of lavatory that period is justified by historical facts since during Vespasian's years of ruling, lavatories became important source of income for the imperial funds due to the entrance fee. That construction that was shaped initially and maturely formed during 4th and 3rd centuries B.C. was spread out round the Mediterranean by Roman engineers and generals - substantially without any particular changes.

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Olive Mill Wastewater Management in Antiquity

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Abstract: The present study examines the results of archaeological research and all the related information retrieved from the writings of ancient Greek and Roman authors on the use and the environmental effects of olive mill wastewater (OMW) since antiquity. The ancients were aware of the negative effects that the uncontrolled disposal of *amurca*, a predecessor of OMW, had on the environment while the controlled release was considered to be beneficial for the soil. *Amurca*, the watery bitter-tasting liquid residue obtained when the oil is drained from compressed olives, has been described by several ancient authors (Hippocrates, Theophrastus, Philon of Byzantium, Cato, Varro, Columella, Pliny the Elder, Virgil, Vitruvius, Dioscorides, Palladius, and in "Geoponika) and had many uses, especially in agriculture. The role of *amurca* is, however, difficult to assess, though it does seem to have been a universal remedy against insects, weeds, and plant diseases. Several of the uses of *amurca* are, in the light of recent research, questionable or not exactly applicable for modern day. However, the herbicidal and pesticidal properties of OMW have been confirmed by a large number of research studies. Moreover, OMW can be used, under controlled disposal conditions, as natural, low-cost fertilizer. The OMW contains a high organic load, substantial amounts of plant nutrients, mainly K, but also N, P and Mg, and is a low cost source of water, all of which favor its use as a soil fertilizer or organic amendment to the poor soils that abound so much in the countries where it originates. It is hoped that the results of the present study could revive the interest in procedures practiced in antiquity -with the most of them found to involve recycling rather than detoxification- in view of the serious polluting effects of OMW and of the destructive side-effects of certain synthetic pesticides and fertilizers on the environment.

Keywords Amurca; antiquity; oil; olive; olive mill wastewater.

Introduction

Large amounts of liquid and solid by-products arise during olive oil extraction and production of table olives. The disposal without any treatment of the wastewaters, arising mainly from the olive mill (OM) and to a lesser degree from the table olive industries, is known to cause serious environmental problems, especially in the countries around the Mediterranean basin. The uncontrolled disposal of olive mill wastewater (OMW) in the surrounding has the drawback of dispersing in the environment substances that are foul smelling and possibly pathogenic. In fact, higher application rates result in anomalous fermentations of the dispersed organic substances, which lead to changing the environmental conditions for microorganisms, the soil-air and the air-water balance and, therefore, to reduction of the soil fertility.

The OMW is composed of vegetation water, soft tissues of the olive fruit and water used at the different stages of oil production. The vegetation water in the olive fruit represents 45-50% of the weight of the fruit and a volume of up to 7 million m^3 is produced each year, in addition to the water added during the olive oil extraction process[1]. The problems created in managing these wastes have been extensively investigated during the last 50 years without finding a technically feasible, economically viable, and socially acceptable solution. In more recent years, the olive processing industries have come under increasing pressure from the controlling authorities to find a disposal/recycling system that meets present-day anti-pollution standards. A wide range of technological processes are available nowadays for reducing the pollutant effects of OMW and for its transformation into valuable products, the most suitable procedures being found to involve recycling rather than detoxification of this waste. Moreover, antipollution legislation has been forcing the utilization of OMW as an alternative to disposal. Thus, in view of the current need for upgrading by-products at all stages of the olive oil industry, increasing attention has been paid to discovering a use for OMW.

A predecessor of OMW is *amurca*. *Amurca*, the watery bitter-tasting liquid residue obtained when the oil is drained from compressed olives, has been described by several ancient authors (Hippocrates, Theophrastus, Philon of Byzantium, Cato, Varro, Columella, Pliny the Elder, Virgil, Vitruvius, Dioscorides, Palladius, and in "Geoponika). The Latin word *amurca* possibly originates from the Greek word *amorge* and seems to display traces of Etruscan mediation[2] (Staden von, 1996; Bonfante and Bonfante, 2003). The Greek term is mentioned, however, scarcely in the ancient Greek literature. It is cited once by Hippocrates[3] in a comparison: "When abscess of the liver is treated by the cautery or incision, if the pus which is discharged be pure and white, the patients recover, (for in this case it is situated in the coats of the liver) but if it resembles the *amorge* as it flows, they die (Hippocrates, "Aphorisms", VII, 45). Theophrastus[4] refers also to it[5] (Theophrastus, *De Causis Plantarum*, 4, A, 19(3)) as well as Philon of Byzantium[6,7] (Philon of Byzantium, "A treatise on Mechanics", B).

The definitions given by the ancient authors to *amurca* or *amorge* are varied. Varro[8] describes *amurca* as the watery residue obtained when the oil is drained from olive fruits (Varro, *Rerum rusticarum*, I, 64). Pliny the Elder[9] distinguishes two types of OMW, *amurca* and *sanies*[10], although most of the translators would make the same thing (Pliny the Elder, *Naturalis Historia*, XV, 3). The *sanies* of Pliny is the black water that the olives deposit when they are piled up and especially when they are subjected to the action of a machine consisting partly of bruising and partly of a squeezing apparatus (*trapetum*, *mola molearia*, *canallis et solea*, *torcular*, *prelum*, *tudicula*). According to Dioscorides[11], *amorge* is the

[1] The average world production of olive oil for the harvesting years 1999/2000-2002/2003 was 2,564,800 tn.

[2] Since the Etruscans only had the voiceless stops k, t, and p, they changed the letters g, d and b wherever they appeared in foreign words -Greek, Latin or Umbrian - to k, t and p (Bonfante and Bonfante, 2003). The u in *amurca* seems to betray also Etruscan mediation (Staden von, 1996). Thus, from the Greek word *amorge* came the Latin word *amurca* by way of Etruscans.

[3] Hippocrates (*ca.* 460 B.C.-377 B.C.), Greek physician born on the island of Cos, Greece.

[4] Theophrastus (*ca.* 372-*ca.* 287 B.C.), Greek philosopher born on the island of Lesvos; Aristotle's successor as head of the Peripatetics.

[5] "μέχρι τούτου γαρ το έλαιον εγγίνεσθαι δοκεί, από δε τούτου της σαρκός η αύξησις και έαν γε δη πλείω ύδατα και χείρον γίνεσθαι το έλαιον αμόργην λαμβάνον, πλείω πολλάκις δε και σηπομένου του καρπού" (Theophrastus, *ca.* 372-*ca.* 287 B.C. De Causis Plantarum, 4, A, 19, 3).

[6] Philon of Byzantium, *ca.* 280-*ca.* 220 B.C. Greek writer

[7] "και αράκους μάλιστα μεν πεφωτισμένους, ει δε μη, ως έχει, άλλους <δ'> έν *αμόργω* πεφυραμένους· ούτω γαρ άσηπτον γίνεται" (Philon of Byzantium, *ca.* 280-*ca.* 220 B.C.; A treatise on Mechanics).

[8] Varro Marcus Terentius (*ca.* 116-27 B.C.), Roman scholar and author.

[9] Pliny the Elder (Gaius Plinius Secundus, A.D. 23-79), Roman naturalist, encyclopedist and writer born in Verona.

[10] Oliva constat nucleo, oleo, carne, amurca. sanies haec est eius amara; fit ex aquis, ideo siccitatibus minima, riguis copiosa (Pliny the Elder, A.D. 23-79. Naturalis Historia, XV, 3).

[11] Dioscorides, (also known as Pedanius Dioscourides) Greek writer, probably lived A.D. *ca.* 40-*ca.* 90 in the time of the Roman Emperors Nero and Vespasiano.

sediment of oil which has been pressed out a boiled in a jar made of Cyprian brass until is the consistency of honey (Dioscorides, *De materia medica*, 1-134 *Amorge*).

The environmental effects of OMW on soil are known since antiquity. Varro already in the 1st century B.C. wrote: *Ex olea fructus duplex: oleum, quod omnibus notum, et amurca, cuius utilitatem quod ignorant plerique, licet videre e torculis oleariis fluere in agros ac non solum denigrare terram, sed multitudine facere sterilem*, i.e. "The olive yields two products: oil, well known to all, and *amurca*. As most people are ignorant of the value of the latter, you may see it flowing out from the olive presses on the fields, and not only blackening the ground but rendering it barren when there is a large quantity of it" (Varro, I, 55, 7).

The aims of the present study are: (a) to present the results of archaeological research and retrieve all the related information from the writings of ancient Greek and Roman authors on the use and the environmental effects of OMW since antiquity and (b) to evaluate the various applications of *amurca*, which may revive the interest in procedures practiced in antiquity in view of the polluting effects of OMW, and contribute to the development of integrated OMW management systems.

Water and Wastewater Management

Much water was needed for the operation of an OM, but without constant flow, as it was the case in water mills. Most of the OMs were built along the Mediterranean coast or close to rivers. Water might have been used coming out of wells or irrigation water or water from nearby streams or brooks, which are in abundance during the winter period the OMs operate. In prehistoric societies olive presses no doubt used the water supply system of the settlement, if available. Otherwise, they should have provided their own water, as did isolated olive presses in the countryside (Hadjisavvas, 1992). The late Bronze Age OMs used water from any important buildings with which they were associated. Usually, they were incorporated within public buildings. In other cases they formed part of the urban architecture and therefore used the water resources of the town or village within which they operated. In most cases wells were found in those sites. In later sites large cisterns were found near the excavated remains of olive presses (Hadjisavvas, 1992; Brun, 2004). During the classical and Hellenistic period olive oil production was directly associated with sanctuaries as shown by Hadjisavvas (1992). During the Roman period the production was no longer monopolized by the religious institutions but by a larger number of farmsteads equipped with an olive press.

In antiquity, as today, the production of olive oil involved three essential stages: (a) crushing, (b) pressing, and (c) separation of oil from water. Water was necessary in all the stages during the complex procedure of turning olives into oil. The main stages of olive oil extraction in a traditional olive press are depicted in Figure 1. Initially, olives were washed and crushed. The pulp was placed in woven bags or baskets (*fiscis*) and pressed. Hot water was poured on the pile of woven bags after the initial pressing, thus washing any remaining oil from them and the press bed. The hot water facilitates the flow and avoids the extracted liquid from becoming dense because of cold weather. According to Cato[12] "You may sprinkle such olives with salt, if you wish; and keep a high temperature in the pressing room and the storeroom" (Cato, *De agri cultura*, LXV). Hot water was also used before and after each pressing operation to wash old rancid oil, which could spoil the taste of fresh oil. The dregs and other impurities left on the surface of the press were washed away by water and disposed of in the area surrounding the press. The pressed liquid was carried from the press

[12] Cato the Elder or Cato the Censor (Marcus Porcius Cato) (234-149 B.C.), Roman statesman and writer.

bed (*areae*) to the vats through the circular channels and the outlets. There is archaeological indication that olive effluents have been damaging delicate shoreline environments for thousands of years around the Mediterranean. At the site of an olive press excavated in Cyprus were found many olive pits within a layer of blackened soil just below the central outlet of the press indicative of possible soil pollution (Hadjisavvas, 1992). This suggestion is supported by the discovery of many olive pits within a layer of blackened soil just (Hadjisavvas, 1992).

Figure 1 An OM, Nova Reperta (Johannes Stradanus, 1523-1605).

The liquid from the press was lead off into a reservoir where the oil was skimmed off the top, leaving behind a low-grade water extracted from the olives. The separated oil was stored ii settling vats for further purification. Cato, LXVI) writes. “As soon as the workmen press down the levers, at once the ladler must take off the oil with a shell very carefully, and without stopping, being careful not to take off the *amurca*. Pour the oil into the first vessel, then into the second, each time removing the dregs and the *amurca*. When you take the oil from the cauldron, skim off the *amurca*”.

There is not enough evidence relating to oil separation which represents the third stage in oil processing. A variety of methods, all based on the principle of gravitation were applied to separate oil from water. The simplest way was by skimming the floating oil by hand or with the help of a ladle. The second method was to draw off the water through a stoppered hole at the base of the receptacle tank (Fig. 2). In the third method, the floating oil was conveyed into a lateral tank through an outlet at the rim of the receptacle tank. All the above methods involve a second stage of settlement that was accomplished in settling vats. The fresh oil was “muddy” and time was needed for the impurities to settle to the bottom of the vat. The settling vats were provided usually with a central concave depression for the collection of the remaining impurities (Hadjisavvas, 1992). In cold weather when the oil remained in union with the *amurca* not withstanding these transferences, the separation was effected by mixing a little parched salt with the combined fluids; but when the cold was very intense, *nitrum*[13] was found to answer better. After the pressing operation the press beds and channels had to be cleaned. According to Cato “He (the watchman) must throw out the lees every day and keep cleaning the *amurca* until the oil reaches the last vat in the room. He

[13] A native double salt, consisting of a combination of neutral and acid sodium carbonate, $Na_2CO_3.2HNaCO_3.2H_2O$, occurring as a white crystalline fibrous deposit from certain soda brine springs and lakes.

must wipe off the baskets with a sponge, and change the vessel daily until the oil reaches the jar" (Cato, LXVII).

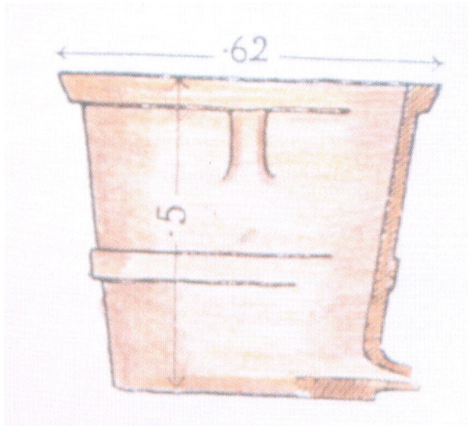

Figure 2 The receptacle tank (Faklaris and Stamatopoulou, 2003).

Amurca had to be discarded outside the installation or stored along with the dregs in an earthenware vessel. We learn from Varro "Some farmers use the following method of preserving it: After fifteen days the dregs which, being lighter, have risen to the top are blown off, and the fluid is turned into other vessels; this operation is repeated at the same intervals twelve times during the next six months, the last cleansing being done preferably when the moon is waning. Then they boil in copper vessels over a slow fire until is reduced to two-thirds its volume. It is then fit to be drawn off for use (Varro, I, 64) and "Experienced farmers store their *amurca* in jars, just as they do oil and wine" and for preserving *amurca* "There are also other methods, such as that in which must is added" (Varro, I, 61).

To this day wastewater is spilled into runnels in the nearby countryside of the villages during the olive harvest and extraction season. The offensive pungent smell of this wastewater pervades the air but we do not know if it was considered a nuisance by the inhabitants in antiquity. It is, however, improbable that this water was dumped onto the city streets through which people and pack animals had to be passed. The system of underground drainage and sewage channels, such as those in the Hellenistic city of Maresha[14] were used to carry off the effluents of the olive oil industry along with the unwanted liquids (Kloner, 2001).

Composition

The composition of *amurca* is difficult to deduce. However, on the basis of the information left by ancient writers and the similarity of the traditional olive presses with the basic types of machinery used in the antiquity the following assumptions can be made:

(a) *Amurca* was a bitter, watery liquid (Pliny the Elder, XV, 4) and this bitterness is now known to be chiefly due to the easily hydrolysable glycoside oleuropine whose structure has been elucidated.
(b) The *amurca* would also have contained traces of phytocidal, insecticidal, and fungicidal glyceride oils as well as oleic acid.
(c) Salt was sometimes added to the olives prior to pressing which may have resulted in additional phytotoxic properties.

[14] Present-day Tel Maresha, or Tell Sandahannah, WSW of Bethlehem.

(d) A further and complicating factor was that during the preparation of *amurca* as described by Varro (I, 64) the liquid was boiled to about two-thirds of its original volume in a copper vessel. In this way not only would the *amurca* become contaminated with traces of copper, but a number of extra products could be formed by hydrolytic processes. As copper salts are now known to be extremely effective against certain fungal diseases it is possible that the *amurca* prepared in this manner contained fungicidally active amounts of the metal.

(e) The composition of *amurca* would depend also on the olive oil extraction process. A method highly appraised in antiquity related to the production of olive oil without crushing the stones. The crushing devices used for that purpose were the *trapetum* and the *mola olearia*. Thus, the *Amurca* obtained would have reduced polluting load due to the removal of the not crushed stones; OMW produced according this method has, with respect to the wastewater produced by the conventional processes, the following features: lesser acidity, reduction of BOD_5 up to 8 times, smaller amount of organic compounds refractory to biological digestion and smaller amount of suspended solids (Niaounakis and Halvadakis, 2006); said wastewater is substantially free of compounds that are found primarily in olive stones, such as tyrosol and its derivatives which are substantially resistant to air/oxygen, bacterial and enzymatic degradation and are of a highly polluting nature. On the other hand the traditional press system produces the "strongest" OMW, with concentrations of the order of 100-200 g COD/L -see Table 1.

(f) The quantity of OMW produced in a traditional press is approximately 0.55 L/kg of olives.

Table 1 Average results of the characteristic parameters carried out on fresh OMW samples obtained from olive mills processing olives by pressure and 3-phase centrifugation systems (Di Giovacchino *et al.*, 1988).

Parameter	Unit	System	
		Pressure	3-phase centrifugation
pH		5.27	5.23
Dry matter	g/L	129.7	61.1
Specific weight		1.049	1.020
Oil	g/L	2.26	5.78
Reducing sugars	g/L	35.8	15.9
Total phenols	g/L	6.2	2.7
o-Diphenols	g/L	4.8	2.0
Hydroxytyrosol	mg/L	353	127
Precipitate with alcohol	g/L	30.4	24.6
Ash	g/L	20	6.4
COD	g/L	146	85.7
Organic nitrogen	mg/L	544	404
Total phosphorous	mg/L	485	185
Sodium	mg/L	110	36
Potassium	mg/L	2470	950
Calcium	mg/L	162	69
Magnesium	mg/L	194	90
Iron	mg/L	32.9	14
Copper	mg/L	3.12	1.59
Zinc	mg/L	3.57	2.06
Manganese	mg/L	5.32	1.55
Nickel	mg/L	0.78	0.57
Cobalt	mg/L	0.43	0.18
Lead	mg/L	1.05	0.42

The most recent techniques have radically changed the oil extraction concepts and methods. The continuous three-phase centrifugal process, introduced in the 1970s, increases notably processing capacity and extraction yield and reduces labor but increase the water demand. In the early nineties the two-phase centrifugal process was introduced, where no process water is used. This two-phase technology is considered to be very promising but in fact it simply transfers the problem of disposing of the waste from the OM to the oil refineries, where the spent olive residues, prior to oil solvent extraction, must be dried with considerably higher energy requirements than the case for traditional or continuous oil production processes.

Uses

Fertilizer/soil conditioner

The *amurca* of the ancients was recommended as a fertilizer for olive and fig trees (Cato, XXXVI, XCIII, XCIV), vines and fruit trees (Columella[15], XI, 2; "Geoponika"[16], II, 10), although these latter sources suggested that *amurca* used for this purpose must be free from salt. Cato recommends “Fertilizers for crops: ..Spread or pour *amurca* around trees, an *amphora*[17] to the larger, an *urn(a)*[18] to the smaller diluted with half its volume of water, after running a shallow trench around them” (Cato, XXXVI) . “If an olive tree is sterile, trench it and wrap it with straw. Make a mixture of equal parts of *amurca* and water and pour it around the tree; an *urn(a)* is sufficient for a large tree, and a proportionate quantity for the smaller trees. If you do the same thing for bearing trees they will be even more productive; do not wrap these with straw” (Cato, XCIII). Furthermore, “To make fig trees retain their fruit, do everything as for the olive, and in addition bank them deep in early spring. If you do this the fruit will not drop prematurely, the trees will not be scaly, and the will be much more productive” (Cato, XCIV).

“Some farmers sprinkle the wheat, too, with *amurca*, using a *quadrantal*[19] to about a thousand *modii*[20]” (Varro, I, 57, 2). Pliny the Elder quotes Virgil[21] -who says: " I have seen many sowers artificially prepare their seeds, and steep them first in *nitrum* and the black *amurca*), as recommending moisturizing beans with *nitrum* and *amurca* before sowing, to make them grow larger″ (Virgil, *Georgics*, I, 95; Pliny the Elder, XVII, 45). However, the use of OMW as a fertilizer is controversial. Many authors have observed phytotoxic effects in plants when this waste is used directly as an organic fertilizer and have, therefore, warned against its direct application (Niaounakis and Halvadakis, 2006). Such negative effects are associated with its high mineral salt content, low pH, and the presence of phytotoxic

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15 Columella Lucius Junius Moderatus (1st centuty A.D.), Roman writer on agriculture, born. in Gades (now Cádiz), Spain.

16 This book is a compilation of agricultural writings collected and published in the 6th or 7th century A.D. by Cassianus Bassus. For the most part little is known about the individual authors of the various sections except that many lived during the period 200 B.C. to 200 A.D. As with much of the writing of this time, the "Geoponika" is an undiscriminating collection of earlier works, many of which have been lost and can no longer be examined.

17 Amphora, Roman unit of volume equal with 2 urnae. This is equivalent to about 25.5 L. Also known in more modern times as the quadrantal.

18 Urna or urn, Roman unit of volume equal to 4 congii, 24 sextarii, or 1/2 amphora. This is equivalent to about 12.75 L.

19 see 16.

20 Modius (modii), Roman unit of volume equal with 8.7 L.

21 Virgil or Vergil (Publius Vergilius Maro, 70 B.C.-19 B.C.), greatest of Roman poets; born in Andes dist., near Mantua, in Cisalpine Gaul.

compounds, especially phenols. For this reason it would be necessary to carry out a previous treatment in order to utilize it.

The ancients were aware of the negative effects that the uncontrolled disposal of *amurca* had on the environment, while the controlled release was considered to be beneficial for the soil. Varro writes that "in moderate quantities, this fluid is not only extremely valuable for many purposes, but is especially valuable in agriculture, as it is usually poured around the roots of trees, chiefly olive trees, and wherever noxious weeds grow in the fields" (Varro, I, 55, 7). Therefore, the controlled release of this waste could be proved beneficial, as soil amendment, to the physical, chemical, and biological properties of the soil. The OMW contains a high organic load, substantial amounts of plant nutrients, mainly K, but also N, P and Mg -see Table 1, and is a low cost source of water, all of which favor its use as a soil fertilizer or organic amendment to the poor soils that abound so much in the countries where it originates (Di Giovacchino *et al.*, 2001; 2002).

Herbicide/pesticide

Since antiquity the OMW was known to have herbicide and pesticide properties and *amurca* is considered a precursor to modern pesticides in the classical period (Smith and Secox, 1975; Levinson and Levinson, 1998). Varro observed that vegetation was killed in the vicinity of olive presses (I, 55, 7) and he began recommending *amurca* application for all noxious weeds (I, 51, 1). He went on to state that amurca was poured around olive tree roots and "wherever noxious weeds grow in the fields". This latter use must be one of the earliest references to a specific weed killing preparation. Theophrastus (IV, 16) had earlier noticed that pouring olive oil over their roots could kill trees, young trees being more susceptible to this treatment than mature ones.

Amurca was also used for insect control. Thus, it is mentioned (Columella, II, 9) that unsalted amurca when applied to the furrows at the outbreak of an infestation would drive away the "destructive creatures", while applications of *amurca* and red earth, possibly sandarach (the red arsenic of Greeks), would keep vines free from beetles and ants (Columella, IV, 26). When mixed with soot, gnats could be driven away, and locusts were dispelled by using *amurca* containing extracts of cucumber or lupines, while caterpillars on cabbages were killed by an application of *amurca* and ox urine (Palladius[22], *De re rustica*, I, 122, 125, 135, 136). In addition to the above methods fumigation procedures were carried out. The mixture of *amurca*, sulfur and bitumen was heated in a copper vessel and the resulting viscous substance applied around the trunks and under the branches of vines for control of caterpillars (Cato, XCV; XVII, 47). Both Pliny the Elder (XVII, 47) and Palladius (I, 127) remark that the smoke from the boiling mixture of *amurca*, bitumen and sulfur (Cato, XCV) was successful in preventing caterpillars from attacking vines. A remedy for blight (Pliny the Elder, XVIII, 45) was to sprinkle the infected plant (vines) with *amurca*.

The treatment of seeds with *amurca* was considered to be useful against insects and other animal pests. Virgil (I, 90) recommends that all seeds be soaked in a mixture of *nitrum* and *amurca* before planting so that greater yields would be forthcoming. Columella (II, 10) held that this latter treatment was successful also in reducing attack by weevils in the mature seed. Protection of store grain by *amurca* has often been recommended by Greek and Roman writers from the 3rd century B.C. until the 4th century A.D., indicating the usefulness of this treatment. In the 3rd B.C. Philon of Byzantium described the use of *amorge* for the protection

[22] Palladius Rutilus Taurus Emilianus, Roman author who lived and wrote around the 4th century A.D.

of granaries and warehouses[23]. *Amurca* made into a paste with straw and applied to granary walls, appeared to be instrumental in keeping the grain free from weevils (Cato, XCII, CXXVIII). Cato stated that granary insects and mice can be prevented from damaging stored grain by applying *amurca* as follows: "mix amurca with a small amount of ground straw and clay; knead the mixture until it turns into a viscous paste. Cover the interior walls, floor and ceiling of the granary with this paste and then add a coat of amurca over the whole. When the latter are dried up, deposit cool grain in the treated store. Granary pests will be incapable of damaging grain kept in such stores". Moreover, Varro, Pliny the Elder and Palladius improved the above description by supplementing *amurca* with ground chalk and an insectistatic crushed foliage of coriander (*Coriandrum sativum*), fleabane (*Inula conyza*) or wormwood (*Arthemisia absinthium*) and recommended distributing those mixtures in the stored grain (Beavis, 1988; Levinson and Levinson, 1998). It is likely the above blends of *amurca* to have acted by clogging the wall crevices and cracks, which could have otherwise served as hiding and oviposition niches for pest species, as well as by suppressing substances which are capable of repelling and suppressing pest populations (Levinson and Levinson, 1998).

Amurca, when incorporated into threshing-floors, was also helpful in keeping ants away and preventing the growth of weeds. Both Cato (XCI, CXXIX) and Varro (I, 51, 1) recommend threshing-floors to be made from a mixture of soil and *amurca*. Columella, Palladius and the "Geoponika" also made mention of this practice. In this instance, the *amurca* and soil mixture seems to have dried to a hard plaster-like finish which was thus impervious to weeds, ants and moles. The foregoing represent some of the methods known to be available to the Greek and Roman agriculturalists for crop protection, though it is impossible to decide how extensively such practices were used. Nothing is known regarding the success of these remedies; there appears to be no mention made if comparisons were made between treated and control crops. However, a revived interest in pest-averting procedures practiced in antiquity may be worthwhile in view of the destructive side-effects of certain pesticides on the environment as well as the alarming increase and spread of pesticide resistance in storage insect species (Levinson and Levinson, 1998).

The herbicidal and pesticidal properties of OMW have been confirmed by a large number of research studies. On the basis of these studies the OMW may be considered as an alternative to chemical weed control in some important summer crops (maize and sunflower) and for most of the weeds in winter wheat and for insect control. In the light of the obtained results, it is, however, recommended that the use of crude OMW should be avoided, since it can cause leaf and fruit abscission (Bartolini *et al.*, 1994). Among the main antibacterial polyphenols occurring in OMW, catechol and 4-methylcatechol are phytotoxic, while hydroxytyrosol is the only promising OMW polyphenol, which can be used in agriculture as a pesticide for the protection of olive plants against *Bactrocera oleae* (Insecta: Diptera: Tephritidae) and the knot disease caused by *Pseudomonas syringae pv. Savastanoi*, since it is not phytotoxic (Fiume and Vita, 1977; Bartolini *et al.*, 1994; Capasso *et al.*, 1994). OMW can also be used for the control of nematoid phytoparasites as an alternative to strategies that employ synthetic nematoid suppressants (EU project LIFE00 ENV/IT000223 "TIRSAV").

Building material

Amurca was also used as a building material. As said earlier it was mixed with chopped straw and earth to make plaster and it was applied on the interior surfaces of a granary or

[23] Τίθεται δε και άλλον τρόπον εν υπερώοις διαληλειμμένοις εν αμόργω τους τοίχους και το έδαφος, και τα θυρίδας έχουσι και διεκπνοάς πλείους εστραμμένας προς βορράν και πεφραγμένας δικτύοις ίνα μηθ΄υπό των ορνίθων κατεσθίηται μήτε θηρία εγγίγνηται· ο πυρός <δ' ου> σήπτεται τεθέντος ωσαύτως όξους.

pounded onto earthen surfaces, like threshing floors, to harden them, retard mud and prevent insect infestation. Vitruvius recommends: "In order that the mortar in the joints may not suffer from frosts, drench it with a*murca* every year before winter begins. Thus treated, it will not let the hoarfrost enter it" (Vitruvius, "On Architecture"). The adhesive and stabilizing properties of OMW have been currently investigated and used in Tunisia for stabilizing clay bricks and in the construction of roads and agricultural tracks (Friaâ *et al.*, 1986a; 1986b; Mensi and Kallel, 1990).

Lubricant, polishing agent and protective finish

Boiled *amurca* was used to grease axles, belts, shoes and hides (Cato, XCVII). It was also used to protect wooden furniture from decay, and silver or bronze vessels or statuary and iron implements from oxidation. Cato recommends "Boil *amurca* down to one-half its initial volume and rub it over the whole surface of wooden furniture; it will prevent decay, and the article when rubbed will have a higher polish"; and further "You may also smear *amurca* on all types of bronze objects, but first scour them well. After you have anointed something, polish it when you want to use it. It will be shinier, and corrosion will not be a problem" (Cato, XCVIII). Pliny the Elder recalls Cato saying "We learn from him (Cato), also, that thongs, all articles made of leather, sandals, and axletrees used to be anointed with boiled *amurca*; which was employed also to preserve copper vessels against verdigrease (Pliny the Elder, XV, 8). However, with bronze objects, this treatment could spoil a stable, natural patina and foster corrosion (Humphrey *et al.*, 1998).

Furthermore, it has been suggested that the άλειφαρ (lubricant) of the Greeks could be based on olive oil or its derivatives. Several of its uses are similar to those of *amurca* (Amouretti, 1986). *Amurca* could also had been used in metallurgical works. Paparazzo (2003), by means of X-ray photoelectron spectroscopy (XPS) and scanning Auger microscopy (SAM), found high concentrations of carbon at the joint of a Roman lead pipe (*fistula*) and at the surface of a Roman bronze statue, indicating that an organic material such as olive oil was used during soldering to minimize oxidation. These experiments confirmed Pliny's assertion that "lead is not able to be joined to itself without tin, nor is the former to the latter without oil" (Pliny the Elder, XXXIII, 94). It can be considered that the oil minimizes lead oxidation merely by shielding the bronze or lead surface against ambient O_2 exposure and by its reduced chemical behavior -compared to other hydrocarbon-based substances such as pitch and bitumen.

Use in animal feeding

Amurca was used to treat malnutrition in livestock. According to Cato "To keep cattle well and strong, and to increase the appetite of those which are off their feed, sprinkle the feed which you give with *amurca*. Feed in small quantities at first to let them grow accustomed to it, and then increase. Give them less often a draught of equal parts of *amurca* and water. Do this every fourth or fifth day. This treatment will keep them in better condition, disease will stay away from them" (Cato, CIII; see also Columella, VI, 4, 4).

OMW contains about 4-5% sugars and minerals that are ideal substrate for yeasts or other suitable fungi. This situation can be used for the production of a protein mass that contains carbohydrates, lipids, minerals and vitamins, i.e., animal feed. The treatment results also in the production of the BOD_5 by 80%. As to the nutritional acceptability of OMW, negative opinions exist which are due to the presence of anti-digestive principles. It has been reported that the use of concentrated OMW by ruminants induces diarrhea because of high concentration of potassium and phenolic compounds (Salvemini, 1985). The excessive amounts of these compounds may prevent the recovery as animal feeding of by-products from the purification of this wastewater. Therefore, and in spite of all the provided evidence, the studies in the nutritive value of OMW and possibilities for their use in animal rations are not conclusive to be able to draw accurate conclusions.

Medicinal uses

Pliny the Elder gives 21 remedies of *amurca*. "It is extremely serviceable as a strengthener of the gums and for the cure of ulcers of the mouth; it has the effect, also, of strengthening loose teeth in the sockets, and an application of it is good for erysipelas and spreading ulcers. For chilblains, the *amurca* of the black olive is the best, as also as a fomentation for infants; that of the white olive is used, with wool, as a pessary for affections of the uterus. Of both kinds, however, the *amurca* is much more serviceable when boiled; this being done in a vessel of Cyprian copper, to the consistency of honey. Thus prepared, it is used, according to the necessities of the case, with either vinegar, old wine, or honied wine, for the treatment of maladies of the mouth, teeth, and ears, and for running ulcers, diseases of the generative organs, and chaps on various parts of the body. It is employed topically, for the cure of wounds, in a linen pledget, and for sprains, in wool: as a medicament, it is of great utility, more particularly when old, as in such case it effects the cure of fistula. It is used as an injection for ulcerations of the fundament, the generative organs, and the uterus, and is employed topically for incipient gout and diseases of the joints. Boiled down again, with *omphacium*, to the consistency of honey, it extracts decayed teeth; and, in combination with a decoction of lupines and the plant chamæleon, it is a marvelous cure for itch in beasts of burden. Fomentations of *amurca* in a raw state (unboiled) are extremely good for gout (Pliny the Elder, XXIII, 37).

Dioscorides proposes also the use of *amorge* for medicinal purposes. Several of his remedies are similar to Elder Pliny’s account "*Amorge* is therapeutic for the bowls, and rubber on with wine, vinegar, or honeyed wine is as effective as lycium (pyxacantha) for toothaches and wounds. It is mixed with medicines that are good for the eyes and for closing pores. Growing old it becomes better. Taken as an infusion it is good for the perineum, the genitals, and ulcerated vulvas. It extracts spoiled teeth, boiled to the consistency of honey with unripe olive oil and smeared around them. It heals scabs on beasts [veterinary] rubbed on with a decoction of lupines and chamaeleon. Used without boiling and new in warm pack it assists those troubled with gout in their feet and joints. Put onto a fleece and applied on those who have dropsy it represses the swelling" (Dioscorides, 1-134 *Amorge*).

Many of the health benefits of OMW have been attributed to the presence of phenolic compounds (Visioli *et al.*, 1995; 1999). OMW is rich in simple and complex phenolic compounds with potent antioxidant properties, which may have a protective action on human health. The most abundant phenolic compounds are hydroxytyrosol and tyrosol with p-hydroxybenzoic, vanillic, caffeic and ferulic acid in less quantity.

The majority of these compounds, depending on their partition coefficients (Kp), end up in wastewater during olive processing, for which reason these wastes may constitute a suitable source of phenolic antioxidants. The olive phenols are amphiphilic in nature and are more soluble in the water than in the oil phase. Due to their low partition coefficients (Kp)[24], only a fraction of the phenols enters the oil phase. In general, the concentration of the phenols in the OMW corresponds to about 53% of the total phenolic content of the olive

[24] The partition coefficient is defined as: $K_p = C_{oil}/C_{water}$, where Coil and Cwater are the equilibrium concentrations of the phenolic compound in the oil and water phase, respectively.

fruit, while the phenolic amount in olive oil is only 1-2% (50-100 μg/g of oil depending on the olive variety), with the rest lost in the olive cake (45%) (Rodis, *et al.*, 2002).

Miscellaneous uses

Amurca was used to seal jars in which the olive oil was stored and jars in which dried figs were kept (Cato, LXIX, XCIX, C; Pliny the Elder, XV, 8). Boiled *amurca* was also used as a means of protecting clothes from moths (Cato, XCVIII) and crude *amurca* as a preservative for dried fruits (Cato, CI, XCVIII, XCVIX). *Amurca* was also used to improve the burning of fire wood (Cato, CXXX). *Amurca* was added also to the brine (NaCl) of green olives to increase their bitter flavor.

Conclusions

The composition of *amurca* remains unclear and, therefore its role is, difficult to assess, though *amurca* does seem to have been a universal remedy against insects, weeds, and plant diseases. Several of the uses of *amurca* are, in the light of recent research, questionable or not exactly applicable for modern day. However, the herbicidal and pesticidal properties of OMW have been confirmed by a large number of research studies. Similarly, it has been confirmed the attitude that the *amurca*, under controlled disposal conditions was beneficial for the soil, as natural fertilizer and low-cost water.

In the quest for better utilization of limited water resources and search for other unexploited water resources, the exploitation of the huge amounts of OMW produced annually is a major challenge. The symbolic character of the myth surrounding the competition between Athena and Poseidon -where the Athenians preferred the olive tree and the Goddess of wisdom who offered it, over the water abundance offered by the God of water- becomes again vivid: wisdom in management seems to be the solution of the ever growing water resources problems internationally, in contrast to water abundance, formerly promised by engineering development (Koutsoyiannis, 2002). In this context, it is worth mentioning that the olive groves around Athens were fertilized by sewage from the city. A canal system was used, and there is evidence of a device for regulating the flow. It is believed that the sewage was sold to farmers (Tisdale and Werner, 1975).

Articles on ancient attitudes towards the environment, while not so uncommon as they used to be, are still something of a rarity. The present study demonstrates how there are crucial areas of the ancient experience that still await systematic exploration, and how this task can be approached most fruitfully through interdisciplinary research.

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Historical Development of Olive Mill Wastewater Production and Management in Crete, Greece: From Minoan Civilisation to Present

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Abstract: Since antiquity, the olive tree has been a traditional cultivation in Crete. Findings presented on this paper provide the evolution of olive oil extraction and the by-product management from *ca.* 3,000 B.C. to present. Based on evidence from remains, photographs, literature, and historic evidence from elderly people, details and flow diagrams for the olive oil production during the Minoan era, Mycenaean era, Roman era, the Arabic to Turkish era, and the 20th century until today are provided. The olive mill wastewater management disposal practices are discussed for the same periods, with estimations for the quantities produced over the last century.

Keywords Historical development; olive mills; olive oil production processes; wastewater management.

Introduction

Olive mill wastewater (OMW) is the liquid by-product derived during the processing of olive seeds for olive oil production. Similar to the olive processing techniques, which were initially developed in the Middle East and later transferred to maritime centres in the Bronze Age (Kiritsakis, 1998), OMW production was initiated in Crete during the Minoan Civilisation, *ca*. 5,000 years ago. Minoans encouraged the production and commerce of olive oil (Di Giovacchino, 2000). Therefore, OMW was possibly produced in remarkably huge -for that period- quantities. However, it is not evident from the literature or other sources that OMW was responsible for any environmental problems since then. Furthermore, it is not clear to identify exactly how the ancestors managed OMW. Consequently, OMW production and management practices have been recorded only for the last fifty years. Even today, due to its nature (high organic load; toxicity; distinctive smell; numerous non-biodegradable substances), OMW is difficult to be managed cost-effectively (Kapellakis *et al.*, 2006).

The aim of this study is to focus on OMW production and management practices in Crete from antiquity until today. Discussion upon the main periods across the history of Crete takes place. These include the Minoan era, the Mycenean era, the Roman era, the period from the Arabic until the Turkish conquest, and the period from the 20th century until today. It should be noted the role of olive oil in the socio-economic structure of Crete through time and the fact that OMW strongly depended on the olive oil production processes. Olive tree reflects to the history of Crete and, despite the low profit per land unit, its cultivation is and will remain a traditional practice in Crete (Region of Crete, 2003).

Olive: From Antiquity to Minoan Crete

Olive tree

The olive tree is amongst the oldest known cultivated trees in the world, with remnants to appear from about 45,000 years ago (Liphschitz *et al.*, 1991). More than 30 species of olive trees are known today (Siggelakis, 1982), however, its origin has been the subject of much debate (Loukas and Krimbas, 1983). Although fossils dating back to the Tertiary period (1 million years ago) prove the existence of an ancestor of the olive tree in Italy (Boskou, 1996), it seems certain that the olive tree, as it is known today, had its origin about 5,000 years ago in the region corresponding to ancient Persia and Mesopotamia and from there it spread to Syria and Palestine (Kiritsakis, 1998; Di Giovacchino, 2000). It was the Phoenicians who were responsible for the spread of the olive tree to Crete (Di Giovacchino, 2000). Crete has undoubtedly been the region which played the most important role in the development of oliviculture. It has been practiced since *ca*. 3,000 B.C., as the main activity during that period was agriculture (Faure, 1976). During the period the Minoan civilisation flourished in Crete, olive cultivation was further expanded.

Olive Oil

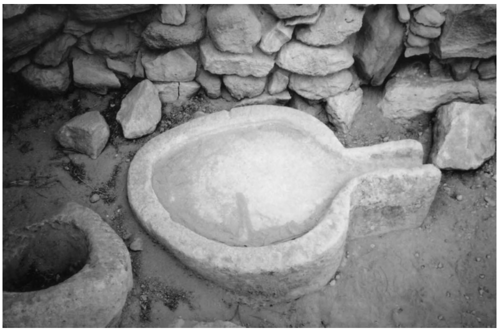
The olive oil has been discovered by the primitive man, in the period when he wandered *barefooted* and *unchitoned*, as he stepped and crushed accidentally on olive seeds fallen into the ground and he noticed that the segregated oil moistened and softened his tough-skinned sole (Sarakomenos, 1930). Based on this incident, he started the collection and crushing of the olives and the segregation of the olive oil (Balatsouras, 1986).

Initially, the olive seeds were placed on a rough plate-stone and one or two persons dragged a heavy stone above them (Bourbou and Bourbos, 1997). This method of olive oil production constitutes the first olive oil production unit. Later on, this unit followed the spread of the olive tree in the ancient world. Olive oil production units have been discovered in the Palestine and they comprised of inclined oil-presses sculptured in rocks (Lampraki, 1999). By that time, seeds were washed with hot water and then were placed for a few days in stone holes. Then seeds were trampled in a rough inclined stone, which had small holes used for olive oil collection (Bourbou and Bourbos, 1997). Similar installations have been found in Syria, Cyprus, and Israel. In the latter location, a remarkable abundance of prehistoric remains have recently been discovered in a parallel to the coast submerged belt (Galili *et al.*, 1997).

Olive Mill Wastewater Production

Minoan era

The Minoan has been the most important and characteristic civilisation across the history of Crete. By the time the Minoan Crete flourished, i.e., between *ca*. 3,000 B.C. to *ca*. 1,650 B.C., the rough inclined stone has been replaced by an inclined stone basin with an outlet (Fig. 1a) or a clay truncated cone bucket with faucet (Fig. 1b). This shift in the process-line resulted in higher olive oil production, adequate to cover the high demand on olive oil (Thompson, 1954), due to the continuous export activities. This demand could explain the numerous olive presses discovered around Crete. Kopaka (1997) referred to a list with more than 40 different structures of presses. Such olive presses have been discovered in all the Minoan Palaces, as well as in the countryside, such as Zakros (Platon, 1955), Praisos (Platon, 1971), Kommos (Kalogeraki, 2002), Phaistos and Vathipetros (Psilakis *et al.*, 2003), Gaydos (Christodoulakos *et al.*, 2000), Mirtos and Palaikastro (Kopaka, 2005), and Sivas (Faure, 1976).



(a)

(b)

Figure 1 The Minoan olive press: (a) A shallow stone basin with an outlet found at the Palace of Phaistos and (b) a clay truncated cone bucket with faucet in the middle, the decanting vat in front of the clay cone, and two storage pots in left and right found at the Palace of Zakros.

Regarding the olive oil production process, the collected seeds were drenched with hot water and crashed in the basin. Through the outlet the olive paste was collected in a small pot. The olive oil then rose to the surface, where it was collected and transferred to storage clay pots (Davaras, 1976; Psilakis *et al.*, 2003). The flow diagram of the olive oil and waste production process during the Minoan civilisation is presented in Figure 2.

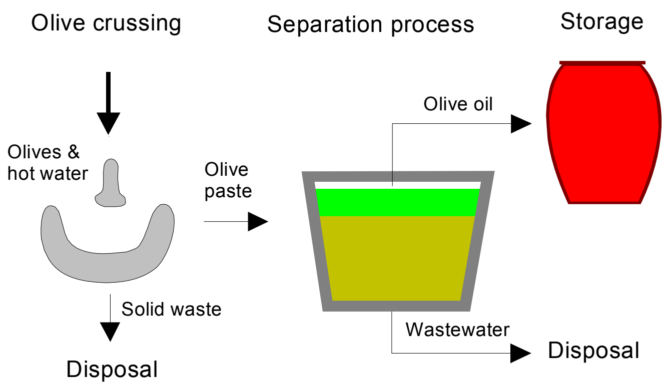


Figure 2 Flow diagram of the olive oil and by-product production in the Minoan Crete.

Mycenean era

Mycenean era in Crete was between *ca*. 1,450 B.C. to *ca*. 1,150 B.C. The process used in olive oil production was similar to that of the Minoan era. However, linguistic indications revealed that woven mats, similar to those used by the Egyptians (Alexakis, 1998), were used in the olive oil production process (Psilakis *et al.*, 2003). According to Faure (1976) and Isager and Skydsgaard (1995), crushed olives were placed in woven mats and squeezed above the settling vats. To the authors' knowledge, mats have not been discovered yet in Crete. However, such mats have been found in Israel (Galili *et al.*, 1997). The flow diagram of this process is presented in Figure 3. During the Hellenistic period, the same olive oil production process was used.

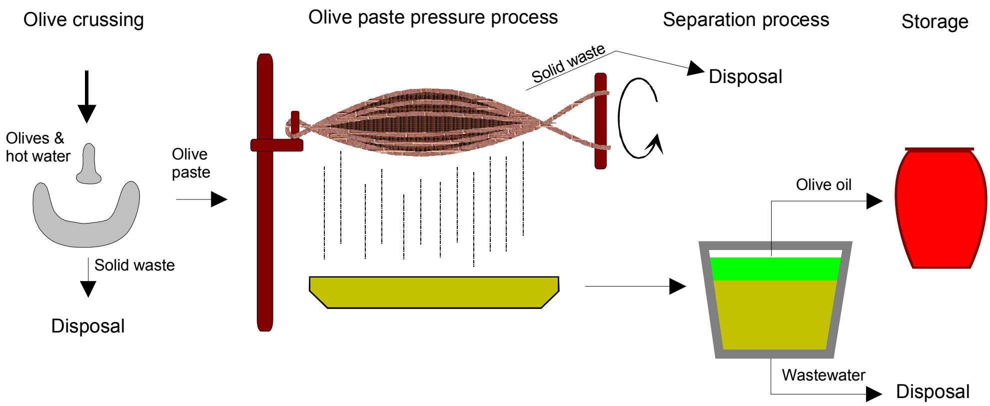


Figure 3 Flow diagram of the olive oil and by-product production in Crete during the Mycenean era.

Roman era

The Romans contributed to the technological development in olive processing by expediting the crushing operation with a millstone crusher, the trapetum (Fig. 4a), and improving the separation system with the introduction of presses (Fig. 4b). The screw press, first used by the Greeks (50 B.C.) and later improved and disseminated by the Romans, represented major progress in olive processing (Di Giovacchino, 2000). The flow diagram of the olive oil and by-product production process is presented in Figure 5.

(a) (b)

Figure 4 The main components of olive oil production during the Roman era: (a) A trapetum, found in Agia Foteini, in the broader area of Phaistos and (b) a base of the screw press, found in Venerato, south from Iraklio.

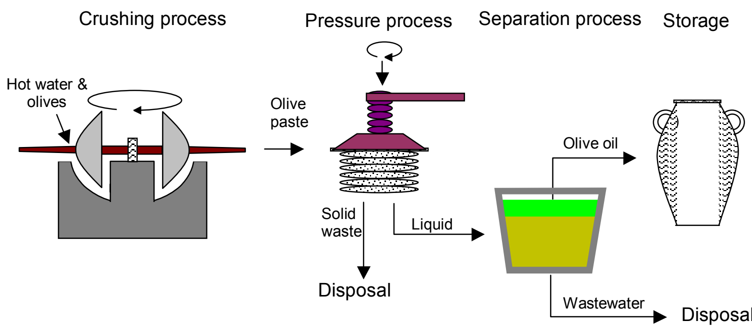


Figure 5 Flow diagram of the olive oil and by-product production in Crete during the Roman era.

Arabic to Turkish era

The fall of the Roman empire, i.e., around the 5th century A.D., lead Crete to its conquest initially by the Arabs and later on by the Byzantines, the Venetians, and the Turks. Very little is known about these periods and their impact on olive oil production in Crete. However, Arabian sources claim that olive oil production in Crete during the Byzantine era must have been very limited and olive oil was imported from Spain and Libya (Tsougarakis, 1990). During the Venetian period, olive oil production was increased, as Venetians used to encourage olive cultivation and oil production in their occupied territories (Tsougarakis, 1990). In fact, olive oil exportation from the Venetian Crete was up to 7,500 tn/yr (Maltezou, 1990), a tremendous quantity for that period by taking into account that the average of Greece for the period 1990-1997 was 117,000 tn/yr (Luchetti, 2000).

Chourmouzis (1842) revealed that during the Turkish conquest, in 1821, year of Greek revolution, there were approximately 2,000 OM in operation in Crete, while in 1832 remained approximately 1,000 OM. In the last census of the 19th century, there were approximately 4,500 OM in Crete, corresponding to an average of 4-5 OM per village. It is worth mentioning that due to a Turkish restriction, which obliged Cretans to offer their land either to Turks or to the monasteries, a significant number of OM operated within monasteries, such as those in Arkadi (pref. of Rethymno; Stauroulakis, 1968) and Odigitria (pref. of Iraklio; Tsiknakis, 1998).

During this long period, the olive oil production process remained almost the same (Balatsouras, 1999). The only change to be monitored was the crushing process. This was developed by the introduction of rotating wheels initially and of animals that rotated them later on, due to the difficulties encountered by the personnel to crush the olives. It should be noted that during the Venetian and Turkish period, the olive crushing process employed by the Minoans was also in use in many occasions, because the OM of that period were controlled by the conquerors and Cretans tried to avoid paying a reward on them (Stathaki-Koumari, 2000).

From the 20th century to present

In the beginning of the 20th century, olive oil production started to increase. The hydraulic press, which represented a large shift in the olive oil production process, was invented in 1795. However, due to lack of electricity, economic resources, and Turkish possession, it was imported to Crete more than 100 years later. Similar to the preceding period, olives were crushed in the rotating wheels by animals (Fig. 6a). The resulted olive paste was placed in woven mats (Fig. 6b), which in turn placed the one above the other in a hydraulic press (Fig. 6c). For better separation of olive oil, the paste was drenched with hot water (Karidis, 1983). After pressure exertion, the liquid phase flowed to a series of settling vats (Fig. 6d). As olive oil was lighter than the wastewater, it rose to the surface and through a hole in the upper side of the vat was poured into another vat, while wastewater was managed in various ways (Geronymakis, 1998; Stathaki-Koumari, 2000). The olive oil collected from the settling vats was then stored into large pots. Storage for long periods resulted in fermentation phenomena and the sedimentation of solids within the pots, the so-called *fetsa* (Psaraki-Belesoti, 1978). The flow diagram of the olive oil and by-product production process is presented in Figure 7.

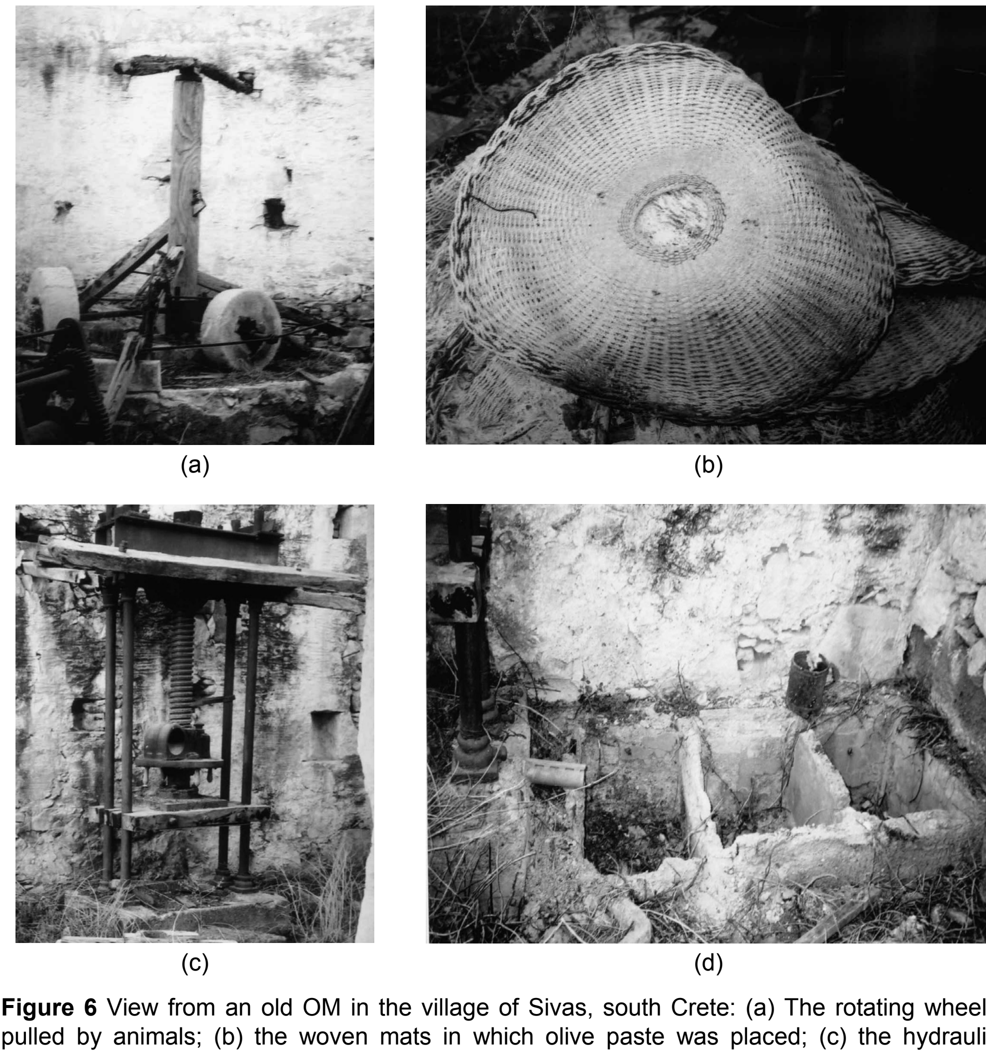


Figure 6 View from an old OM in the village of Sivas, south Crete: (a) The rotating wheels pulled by animals; (b) the woven mats in which olive paste was placed; (c) the hydraulic press; and (d) the series of settling vats used in the separation of olive oil from OMW.

Today, the technological achievements have eliminated the human effort in the production line within the OM. Indeed, in Crete approximately 31,500 people were employed in OM by the end of the 19th century, compared to approximately 1,500 of today, who in turn produce much higher olive oil quantities.

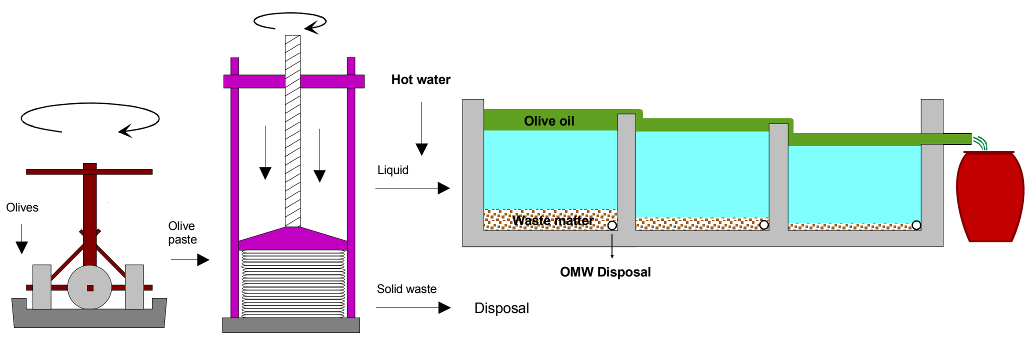


Figure 7 Flow diagram of the olive oil and by-product production in Crete in the 20th century.

The pressure process is now named traditional, as it has been replaced by the modern centrifugation-based systems. These systems are divided into two categories: (a) the three-phase centrifugation systems, in which the three phases are olive oil, dry olive pomace, and OMW, with OMW production being 50% higher than the pressure one and (b) the two-phase centrifugation systems, in which the two phases are olive oil and wet olive pomace (mixture of pomace with OMW), with OMW production being less than the half of that of the pressure one. A typical flow diagram of a modern OM is presented in Figure 8.

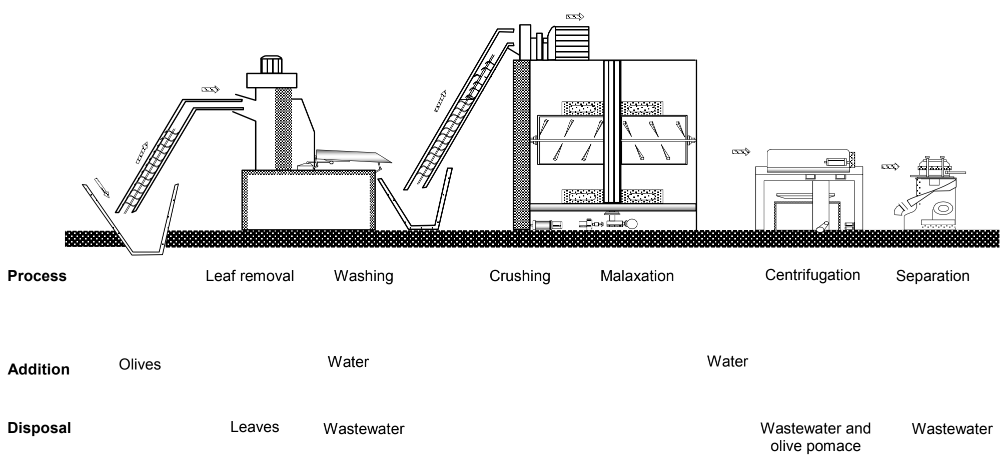


Figure 8 Flow diagram of a modern OM based on centrifugation process.

Olive Mill Wastewater Management

The distribution of the presses in Minoan Crete indicates that OMW production occurred around the island, with a higher density on the coastline, due to the trade of Crete with other maritime centres. Focusing on that, most of OMW production occurred in farmhouses, which were numerous but still undiscovered and/or destroyed and located close to the olive orchards, rather than within the Palaces. This might be due to the preference to carry olive oil rather than olive seeds from the olive orchards in the countryside to the Palaces: In present time olive oil production is 375 L/ha; for a yield of 15% of olive oil, the corresponding amount in olive seeds is 2,500 kg/ha.

By that time, the content of the settling vat was discharged after olive oil collection. The resulted wastewater consisted of leaves and dirt (Sarakomenos, 1930) as well as of a mixture of squeezed olive seeds with water. Since the olives were beaten off the tree and collected by bare hands (Davaras, 1976), the quantity of leaves in the by-product stream was limited. The wastewater was characterised by high toxicity, distinctive smell, and dark red to black colour, and was discharged directly onto the soil. In fact, Balatsouras (1997) insisted that the easiest and cost-effective method to manage OMW in antiquity was its disposal in fallow or arable land, or into ephemeral rivers. Similar findings have been reported by Hadjisavvas (1992), who reported that below the outlet of an olive press in Cyprus many olive pits have been discovered within a layer of blackened soil.

In the cases where olive oil was produced within the Palaces, OMW was probably discharged into the sewerage system, similar to the system used in accidental leakages of olive oil in the storehouses (Alexiou, 1964). This aspect is favoured by OMW's distinctive smell, which, due to inadequate ventilation, could make the atmosphere within the storehouse intolerable, as well as by its oily content that would have been responsible for a slippery floor. In any case, OMW was discharged onto the land or rivers outside the Palaces and the employees of the olive presses have witnessed the negative effects of the cumulative OMW disposal activity.

During the Mycenean and the Roman era, similar management practises to those of the Minoans were employed. The difference lies on the woven mats, as they were permeable for the oil and water pressed, but able to retain the exhausted solid material paste (Isager and Skysdgaard, 1995). Probably, when these mats were cleaned, the remained by-product was washed away and disposed of with the washing water in the soil. It is worth mentioning that there are many authors (i.e., Pliny the Elder; Varro Marcus Terrentius; Marcus Porcius Cato; etc.) who lived during the Roman era and left in their writings detailed information on the potential uses and environmental effects of OMW (Niaounakis and Halvadakis, 2004). On the contrary, the period after the Romans and until the recent years can be characterised by a limited interest on olive oil and OMW management practices, due to the socio-economic conditions imposed by the foreign conquerors in Crete. Therefore, OMW was probably managed according to the previous and/or to next periods.

During the 20th century, more information on OMW management is available. After the pressure process, the exhausted paste was gathered from the edge of the woven mats and transferred from the woven mats to a cavity. This paste was used as fuel matter, as animal forage, in cooking, or sold to olive pomace factories. Regarding the collected OMW from the settling vats, as it still contained a part of olive oil, it was stored either into specific pots or into excavated holes (Fig. 9). After long retention, olive oil was collected from the surface, while *fetsa*, has settled at the bottom. *Fetsa* has been used in the livestock to sheep's protection from ticks. Shepards used to boil the water from the murga and then spread it with a flock of fleece into the sheeps to eliminate ticks (Geronymakis, 1998). Fragkaki (1969) referred that *fetsa* was collected by pedlars, who in turn sold it to soap factories. In the majority of the cases, the remained OMW after storage was discharged untreated outside the OM territories (Markakis, 1998). Through its route, OMW stagnated in many places within the village and ended up either onto nearby fields (Michelakis, 1991) or into ephemeral rivers (Voreadou, 1994).

Different opinions have been recorded about the effect of OMW disposal in the environment. For instance, in the village of Magarikari (pref. of Iraklio, Messara basin), OMW was disposed of into a field with fruit-bearing trees and people have witnessed a high crop production. However, in the village of Sivas, located close to the above mentioned village, people have witnessed that the continuous flow of OMW has resulted in toxic effects on similar trees. In any case, it can be concluded that controlled OMW application can be beneficial to soil fertility, while excessive application might destroy the plantations (Kapellakis *et al.*, 2006).

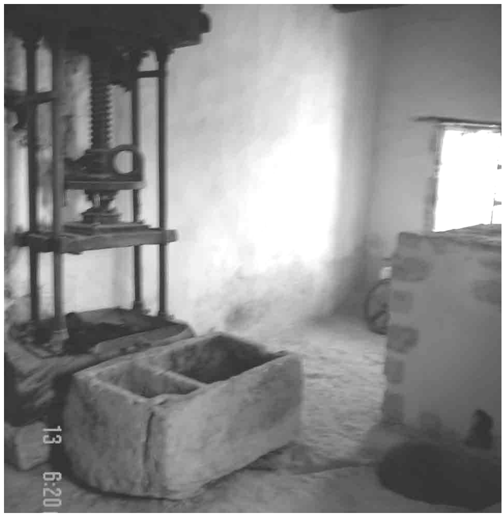


Figure 9 The olive press, the settling vat, and the excavated hole in the ground, used for OMW disposal and remaining olive oil recovery, located in the Monastery of Odigitria.

Public became aggressive against the OM owners and demanded the adoption of effective OMW management practices by the time the environmental degradation became visible. The main reasons which resulted in this degradation are: (a) The industrialization of agriculture, which resulted in an increase in olive oil production worldwide, (b) the conversion of traditional pressure-type olive oil mills (OM) into modern centrifuge-type OM (which corresponds to an 150% increase on OMW), and (c) the dispersed location of a large number of small-sized OM, which has resulted in the expansion of pollution sources (Kapellakis *et al.*, 2006). For comparison purposes, Table 1 refers to OMW production in Crete at various periods. Note that OMW production in the prefecture of Iraklio today is four times higher than the OMW production of Crete in 1948. It should be mentioned that disposal of untreated OMW in the environment was prohibited in 1987. Since then, OMW passes through a grease removal unit and, after being mixed with calcium hydroxide, is stored in evaporation lagoons (Kapellakis *et al.*, 2006). The flow diagram of this management practice is presented in Figure 10.

Conclusion

Since Minoan times, olive oil has always been a cornerstone on the prosperity of Crete. Following olive oil, OMW, the main by-product derived during the olive oil production process, has also been an important issue across the history of the island. Evidence on its production exists, as water has been an essential media to effective olive oil collection. However, it is not clear to identify exactly how the ancestors managed OMW. It is not evident, though, from the literature that OMW was responsible for any environmental problems, although its disguise effects were obvious. Modern scientists and engineers should learn from olive oil production and management practices and technology evolution as these were developed through time in order to solve modern environmental problems.

Table 1 Estimation of diachronic OMW production in Crete and comparison with current values.

Period		Cultivated land (ha)	Ratio OMW/olive oil[c]	Total OMW production (m³)
		(1)	(2)	(3)= 2.5 x 150 x (1) x (2) [d]
1928		29,470[a]	3.25	35,917
1938		35,000[a]	3.25	42,656
1948		40,000[a]	3.25	48,750
Today	Pref. of Iraklio	94,847[b]	5.00	177,838
	Crete	--	5.00	581,000 [e]

[a] Allbaugh (1953).
[b] Ministry of Agriculture (2001).
[c] The pressure process used in this period resulted in 3.25 kgOMW/L of olive oil; Today, the centrifuge process results in 5 kgOMW/L of olive oil.
[d] The figure of 2.5 indicates the production in litres of olive oil per tree and the figure of 150 the average density of olive trees per ha.
[e] Kapellakis *et al.* (2006). The figure has been estimated by the olive oil production.

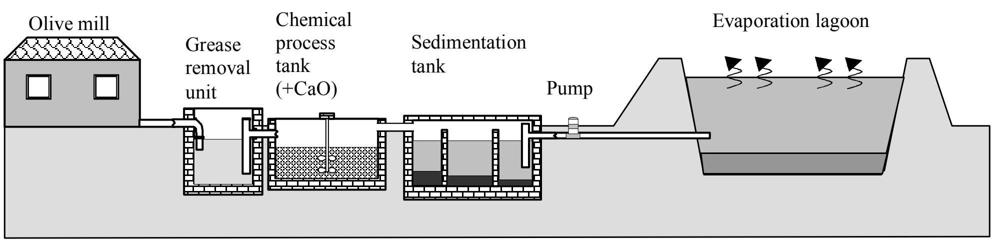


Figure 10 Flow diagram of the current management scheme in Crete (Kapellakis *et al.*, 2006).

Acknowledgements

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Water Resources Technologies (Aqueducts, Cisterns, Dams, Qanats and Karez, and Foggaras)

Conservation and Rehabilitation of Iran's Ancient Bahman Weir

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Abstract: The development of irrigation and agriculture parallels recorded history and facilitated the origins and growth of civilization in most parts of the world. Early human societies endeavoured, as we still do today, to secure a reliable supply of water for drinking, agriculture, washing, transportation, energy production and the many other vital services that this precious resource provides. These societies focused their efforts on devising straightforward and elegant solutions for sequestering and controlling the often-limited sources of water that they knew, directing what they could from rivers and other surface supplies to cities and cultivated areas. In doing so, the ancients introduced hydraulic engineering and water resources management, ensuring them an early and prominent place in what would later be known as civil engineering. Lying at an important continental crossroads, the modern day territory of Iran has hosted several ancient civilizations, including the celebrated Persian empire of classical antiquity. Not surprisingly then, vestiges of past hydraulic engineering can be found throughout the country, predominantly small dams and weirs dating as far back as 3000 BC. Among these antique constructions, the Bahman weir is one of the most famous examples of past ingenuity and an important historical monument. The weir is actually a complex of weirs with an irrigation channel and includes adjacent residential and agricultural areas. It is situated in Fars province in southwest Iran and was built approximately 2500 years ago by the Mesopotamian civilization. This paper introduces the weir and provides a brief historical overview of the monument, commenting on its current condition and the effectiveness of conservation and restoration efforts. It concludes with recommendations for its rehabilitation and preservation as a hydraulic and historical treasure.

Keywords Ancient civilizations; Bahman weir; conservation; irrigation systems; rehabilitation.

Introduction

Prior to the development of civilization, humans lived in close contact with their natural environment and essentially took what they needed from their immediate surroundings, possessing little control over the elements and exerting a small impact on nature. Like many other resources, water was taken where it was found and early bands of hunter-gatherers would be sure not to drift too far from suitable sources while following their prey. The discovery of agriculture and the emergence of sedentary civilization meant that densely populated settlements had to be located, by and large, on the banks of rivers or the shores of lakes. Archaeological evidence and extant literatures clearly testify to this critical dependence on proximity to water. Many ancient scholars noted the importance of building human settlements close to reliable sources of clean water. Among them, the eminent 14th century Arab historian Ibn Khaldûn underscores this importance in simple and unequivocal terms: "In connection with the importation of useful things and conveniences into towns, one must see to a number of matters. There is the water (problem). The place should be on a river, or near plenty of fresh water. The existence of water will be a general convenience to the inhabitants (Khaldûn, 2005)". These conveniences include water for drinking, irrigation, cleaning and a driving force for waterwheels (the indirect harnessing of solar energy) and early hydraulic structures represent a milestone in the long saga of progressive human control over their natural surroundings, a legacy which has become increasingly understood to be mixed.

As alluded to, the introduction of agriculture is considered as the defining moment at which humans adopted a fundamentally settled lifestyle that led to professional specialization, the social division of labour, the emergence of hierarchies and the ensemble of phenomena typically referred to as civilization. Clearly, irrigation is the linchpin of a diet and society based on, and sustained by, crop cultivation. In capturing and taming water, ancient farmers and engineers were preoccupied with issues of storage, distribution, flood control and water quality. In designing and constructing rudimentary hydraulic structures, ancient people would have relied heavily on empirical observation and trial-and-error methods in order to overcome the scarcity of abstract physical representation and mathematical models that their modern counterparts enjoy. When one considers that several aspects of hydraulic design have changed little over the millennia, it becomes easy to appreciate how these ancient ancestors served as trailblazers for modern hydraulics.

The so-called "Fertile Crescent" region of Mesopotamia is where historians place the first known civilization, which arose about 6000 years ago. Given that the ancient Mesopotamian civilizations occupied much of contemporary Iraq, as well as Western Iran, it is no surprise that Iran plays host to hydraulic structures that count among some of the oldest in the world. The Mesopotamia area currently hosts 3% of the world's population but, being an arid land with a annual precipitation of about one third the global average, only enjoys a meagre endowment of 1% of its freshwater resources. Thus, by necessity, a tradition of careful water management has been, and continues to be, an integral part of municipal infrastructure thinking. Ancient civilizations relied on four main categories of hydraulic infrastructure for irrigation: cisterns (above ground, rooftop or subterranean reservoirs), channels, canals, and weirs and dams. Typically, a combination of such structures would be employed in most irrigation systems. In ancient Iran, a multiplicity of canals bringing water to dry areas could be found branching off from major rivers, such as the Tigris in the west and the Hirmand which courses through the southeast of the Iranian plateau. The deployment of small dams and weirs was commonplace and many historical examples can be found throughout the country, from Khorasan province in the northeast to Fars (seat of the old Persian Empire) in the southwest. For comparison and context, Table 1 summarizes some basic information of some well-known ancient dams and weirs in the country.

The construction of extensive and intricate hydraulic infrastructure in ancient times was aimed at improving and adapting the land for human settlement and called for thoughtful site selection while exploiting the best existing water control methods. The careful and intelligent selection of materials such as stone, brick, lime mud and lime plaster, along side due consideration of site characteristics like valley width and the toughness of flanking mountains, were crucial for safeguarding against the stresses generated by lateral pressures. Several concepts and built components were involved in ensuring a viable hydraulic infrastructure. *Water reservoir storage* was used to control the inflow from obstructed rivers during times of flood. *Water reservoir towers* served to regulate pressure when the dam's outlets were opened and *water carrying channels* functioned as the conveyance structures for delivering irrigation water to farms while also providing crucial overflow relief to minimize the risk of structural damage when there was exceptional surplus water in the reservoir.

Table 1 General information of major ancient masonry weir dams in Iran (www.soil-water.com).

Name	Year	River	Province	City	Crest length (m)	Height (m)
Bahman	2500	Ghareh-Aghaj	Fars	near Shiraz	100	8
Gar Gar	1700	Gar Gar	Khuzestan	Shushtar	50	20
Shahpur	1700	Karun	Khuzestan	near Shushtar	200	5
Mizan	1700	Karun	Khuzestan	Shushtar	70	5
Shesh-Taraz	1000	Shesh-Taraz	Khorasan	near Kashmar	35	25
Amir	1000	Kor	Fars	near Shiraz	102	15
Tilkan	1000	Kor	Fars		162	6
Saveh	700	Vafarghan	Markazi	near Saveh	65	33
Kebar	700	Kebar	Qom	near Qom	55	24
Akhlemad	600		Khorasan	Mashhad	14	15
Toroq	400		Khorasan	near Mashhad	82	18
Fariman	400	Fariman	Khorasan	near Mashhad	100	21
Kalat-Naderi	400		Khorasan		84	26
Kerrit	400		Khorasan	near Tabas	35	75
Khaju	360	Zayandeh Rud	Isfahan	Isfahan	133	12
Golestan	300		Khorasan	near Mashhad	100	16

Numerous structures were built for a variety of purposes. *Westerner Hat Tower* facing *Mizan weir* was used for measuring water and the *Bahman weir* for irrigation supply; the *Gar Gar* bridge/obstruction prevented the overflow of water and that might have damaged watermills; *Mahi Bazan* compensated for increasing water pressure so as to maintain high water levels while the *Shahpur Sassanide Castle* served as a center of construction control during ancient times (Azami 2004).

A Short History of Damming

Dam construction enjoys a long history in regions that housed ancient civilizations like Egypt, Mesoptamia and Iran. As such, the Persians are some of the earliest known builders of dams and irrigation systems, with many structures having stood the test of time and lasting, in some cases, thousands of years. Farmers in the foothills of the Zagros Mountains on the eastern fringe of Mesopotamia count among these early Persians who erected some of the world's first hydraulic structures, evident from the eight-thousand year old canals that have been discovered in the region. It is probable that early dams in this area were constructed of brushwood and earth. One type of early dam was the *bridge blocker* that served not only to regulate water and supply irrigation but also to facilitate passage over a natural barrier for both military and civilian purposes. The first extensive irrigation system in Iran dates back to the Achaemenidian and Sassanid dynasties during which, for example, a colossal irrigation network was constructed on the central and eastern plains by Sassanid King Chosroes.

Early Persian dam building was governed by three factors: site location, foundation condition and construction materials. In all cases, dam construction gave particular attention to the unique characteristics of the site (topography, river regime, material availability and the challenges of river diversion during construction). Most of the existing ancient dams were well built, with an earthen core that was reinforced on the upstream face with masonry. The dating of such structures has been assisted by taking into account morphological factors such as stone-facing type and the histories of nearby settlements. A major problem associated dam construction in Iran has been the relative ubiquity of clay and clayey soils. As rain washes these soils from the higher elevations of the watershed, clays often are deposited on riverbeds and in the storage reservoirs of wherever the flow becomes tranquil. Without costly dredging, the accumulation of clay sediments robs these reservoirs of valuable storage capacity (Frye, 1984).

The History and Location of the Bahman Wier

The Bahman weir complex is the cornerstone of one of the oldest irrigation systems in Iran and is still in use, providing water to residents in the Kavar district of Fars province. It was built on the GharehAghaj River and is located 9 km east of the town of Kavar and nearly 60 km south of Shiraz, the capital of Fars province. In various classical texts, the river is sometimes referred to as the Zakan. It is the longest river in Fars province, originating in the mountains west of Shiraz and eventually joining the Mand River which itself empties into the Persian Gulf near the port of Kangan. Fig. 1 shows the current setting of the weir for low and high river discharges. The name Kavar has been employed frequently as an appellation for a village, small town, and district in textbooks pertaining to the early Islamic period in Iran. Examples include references in the *Al-boldan* ("The regions") by Ahmad-ibn-Abu Yaghoob in 909 AD or the *Masalek-ol-mamalek* ("The ways of countries") of Astakhri eight decades later (990 AD) as well as in the *Fars-nameh*, or "Persian Atlas", of Ibn-balkhi.

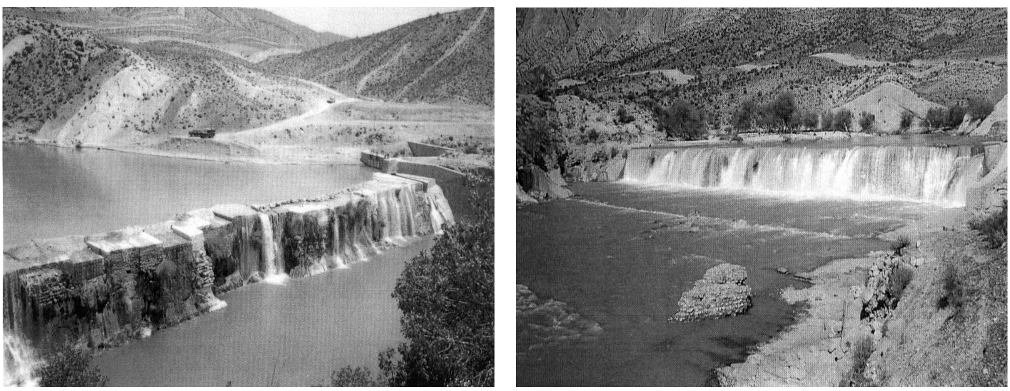

Figure 1 Bahman weir in low (top) and high (bottom) discharge condition.

Curiously, the name of the Bahman weir, despite being a significant ancient monument, though mentioned, is referenced less frequently in historic texts. The exact date of construction remains unknown, but the name betrays an antique origin, perhaps dating as far back as the Achaemenid epoch. There are some historical references indicating that the name of the Bahman weir is a tribute to Bahman, son of Esfandiar, an old Persian hero who is credited with the erection of this structure in order to provide irrigation to the ancient village of Kavar (mentioned in the Nezhat-al-gholoob, a 15th century book by Hamd-ollah Mostofi, Page 119). A descriptive report was prepared by Forsat-al-dowlah Shirazi about the architectural and structural details of the Bahman weir more than a century ago, and presently, detailed studies are being undertaken by various Iranian public entities in order to implement a rehabilitation strategy for this priceless historical monument.

In geological terms, the Bahman weir site is located in folded Zagros structural units consisting of the Pabdeh, Lower Asmari, Upper Asmari and Razak formations. The "Gharreh Aghaj" River valley is carved along the synclinal part of structure with the riverbed eroded into the Razak formation and valley sides which consist of Asmari limestone, rock that is dense and dissected by a number of tectonically releasing joints. The chief discontinuity encountered along the river is the Kavar fault. The anticline core, which is evident on both sides of the river valley as well as other upland area in the vicinity, consists of relatively impervious Pabdeh rock. The site is located on a lime sandstone layer which terminates at a downstream meander. The bedrock foundation of the Bahman weir appears strong and exhibits a sense of aesthetic continuity, supporting the idea that ancient engineers could rely on straightforward visual inspection and site perambulation in the absence of sophisticated contemporary rock mechanics testing. Reviewing the data from the geotechnical investigations, it becomes clear that the original site selection was a good choice and that it was effectively undertaken by relying solely on visible criteria (given that there were not any laboratory or in-situ tests available to the first weir designers as there are today). The investigation was carried out in order to evaluate the quality of materials used to make the weir and included geo-electric studies, subsurface borings and test grouting. Tests revealed significant quality variation of the material comprising the body of the weir and a pronounced decrease in electric resistance from east to west was observed, implying that a greater proportion of lower quality material could be found on the east face of the structure.

The site of Bahman weir happens to lie in a high-risk earthquake zone according to the latest macro-zoning seismology map of Iran. Recent seismic investigations estimate that the probability of occurrence of an earthquake with 0.3g intensity in 50 years is about 50% for a 75-year return period and that the probability of occurrence of an earthquake with 0.4g intensity in 50 years is 10% for a 475-year return period. Given that the structure was built at least 2500 years ago, it must have experienced various earthquakes that have either had epicenters in the immediate area or in neighboring regions during its lifetime and surely the weir has been subjected to vibrations resulting from these. Fortunately, because the main structure of the weir was constructed carefully, it is still in a good state of preservation and functions well today.

Downstream of the weir, there are 19 villages that enjoy irrigation facilitated by an old 7.5 km long channel referred to as the "Great Channel" whose flow is allocated among 151 shares; each share may be as high as 32 l/s of discharge with an average for all shares of 18.3 l/s. Of the total irrigated area of 20,300 ha, 90% (18,200 ha) is devoted to wet framing and the remainder to dry farming. More than 94% of the wet farming area is used for wheat, corn, onion, barley and Lucerne cultivation. Other agricultural products include beetroot, beans, rice, watermelon, melon, garlic, tomato, eggplant and vegetables. The primary fruit products are grape and peach, but other produce such as apricots, pomegranates, flame, peanuts, apples, and olives is also grown. The total gardening area is about 3,013 ha, with 77.5% or 2,300 ha of grape vineyards and 637 ha of peach gardens. More than 3,300 ha of downstream territory are excluded from cultivation each year. According to the Iranian national census of 1994, the demographic composition of the area included 5,471 families with a population of 30,943. The most recent local census (2003) shows that there are 5,985 families with a population of 31,803 (TCE, 2004).

Maintenance and Restoration of the Bahman Weir

When terms such as restoration, reconstruction, preservation, stabilization and conservation are used in discussion of endangered historical monuments, they entail certain implications and significance that depend on the cultural, political and regulatory background. Beyond the monument itself, the surrounding environment usually requires protection to ensure the monument's conservation while at the same time maintaining its primary public functions. The Venetzia Protocol addresses issues pertaining to the demolition of old buildings as well as changes that can alter the aesthetic fit and functional nature of heritage sites and/or their immediate environment (particularly Articles 5 and 6) and calls for conservation and restoration efforts to be conducted by means of all best available techniques (Article 2).

Apart from purely aesthetic or cultural motives, one of the most important incentives for protecting ancient hydraulic structures is the preservation of design values and construction techniques, both for historical interest as well as for transmitting a sense of the evolution of these values and methodologies to future generations. Unfortunately, in addition to all of the stresses that the passage of time itself imposes on historic artifacts, proactive and informed conservation efforts and practices have often waited for implementation in numerous countries that possess a rich legacy of heritage sites in need of protection. Thus, some potentially avoidable damage has often already been sustained. An important first step in achieving the conservation of monuments and historic treasures is to have an accurate inventory of what remains, partially or wholly intact, and a comprehensive description of the current condition of these artifacts and their environments so that timely preventive measures can be initiated in order to halt the advancement of preventable damage and long term restoration strategies that account for the unique characteristics of each site can be appropriately developed.

After deciding upon a particular historical monument for protection and conservation, whether for engineering, cultural, social, political and/or economic reasons, it is necessary to foresee and prevent disturbing factors that could compromise the monument before conservation efforts are in place. There are two basic components to the historical study of ancient monuments: *Material* and *Shape*. Owing to the vulnerability of construction materials (stones and mortar), the shape of the weir has been altered and its uniformity interrupted. The collision of structural elements, such as detached fragments from the main body of the weir, also bears upon the impact analysis pertaining to material integrity and shape deformation. It should be noted that the material, in addition to embodying and conveying knowledge of past construction techniques, is a major determining factor governing the longevity of such a historical artifact. Thus, any prescriptive strategy must recognize that protection of the material against environmental adversities is vital.

When contemplating restoration, it is important to make an inventory of past damage and document any previous restoration efforts. This is often a challenge since most past damage has been caused by multiple factors, some of which remain invisible or unknown. The most apparent stressor is usually assumed to be the dominant cause of harm, but the primary source of deterioration actually depends on time; in some cases, presumably minor factors may eventually govern the nature and extent of disrepair given a sufficient time interval. Patterns of breakdown can be interlinked; a disturbing factor inducing deterioration in one part of the weir can also encourage weakening in other parts of the structure. Thus, alleviating this factor at its source in one part of the structure can automatically avoid dilapidation elsewhere. Impact classification for historical monuments is based on careful evaluation of field observation and testing and damage can be broadly categorized according to whether it arises from internal disturbing factors (IDFs), external disturbing factors (EDFs) and human disturbing factors (HDFs). These factors are influenced by construction conditions, age of the artifact and the nature of surrounding events.

Internal disturbing factors

Internal Distributing Factors (IDFs) are inherited in building materials and usually originate with technical faults such as construction errors and material quality imperfections. It is nearly impossible to distinguish an IDF simply by visual inspection, thus geotechnical investigations are often necessary for their identification. Tests carried out recently at the Bahman weir revealed that foundation materials underlying the crest have sustained considerable damage and manifest aging fractures; however, the material in other parts of the structure appear to be in better condition and seepage through the foundation was negligible. The fact that portions of the weir have held up so well over the centuries is a testament to the skill and intuition of the original builders who selected appropriate (impervious and durable) materials and that the mortar they used has maintained its cohesion. Investigation of a stranded portion of the weir, dislodged downstream from the main body, still exhibited relatively good condition after several centuries. This, and other evidence, supports the notion that the materials comprising the mortar were well selected and that both the mixture of these materials, and the weir construction, were executed with competence.

The investigations also revealed that the strength of the mortar approximately 2 m above the bedrock has diminished, establishing a critical zone that requires special attention. Mortar in this portion of the weir has been undermined and is at risk of complete breakup if pressure fluctuations in this region are too great. The deposition of sediments at the lower left side of the weir attests to differential settling that results from the river's final meander on approach to the construction and points to the existence of vortex flow at its east side. IDF's are classified in three different categories: element faults, geometry faults and human-based factors. An element fault is related to the inherit properties of basic structural components such as foundations, columns, and piers while a geometry fault pertains to construction practice and building execution, typically arising from poor designer skill and lack of builder experience. Since ancient monuments predate the development of numerical analysis and elaborate physical modelling, their design reflects traditional experience, usually meaning that they are "over-designed" in the sense of employing an abundance of construction material to ensure longevity and survivability. In the case of the Bahman weir, it appears that over-design has not been applied uniformly throughout the entire structure. Therefore, some parts are locally over-designed while others suffer from potential geometric faults that render them more apt to incur damage. Human-based factors stem from mistakes in sizing and site selection or the use of unsuitable material. No significant human-based factor faults have thus far been exposed at the Bahman weir.

External disturbing factors

External Disturbing Factors (EDFs) are imposed on the structure from without and tend to result from environmental conditions. Their effects are typically evident on the outside surfaces of the system with the exception of certain events such as earthquakes that can cause deformation in structural frames that are usually hidden from view. EDFs are classified as natural or chemical/electrochemical. Natural EDFs result from continuously acting agents like wind, rain, freeze/thaw cycles and climate extremes and are typically marked by erosion and physical alterations to river morphology that can introduce dynamic stresses that result from new flow variation patterns. Dynamic impacts have been observed at the Bahman weir, where damage at the left side of the structure led to the migration of a large fragment 20 m downstream of the weir. Chemical/electrochemical factors derive from ambient conditions and include chemical reactions introduced by water and moisture that penetrate the structure's masonry as well as excavation by plant roots and algae formation on the weir surface. Botanic activity is present at the Bahman weir as shrub and weed growth is observed both on top and on the faces of the weir structure. Because such activity can weaken the structure over time, it must be monitored and controlled.

Human disturbing factors

Human Disturbing Factors (HDFs) are injuries and damage created by nearby human activity, intentional or unintentional, and include such things such as underground explosions, the disturbance of aquifers, and the erection of new structures. Perhaps the most important HDF is poor management of the site itself. Unfortunately, this has been the case at the Bahman weir where, for example, in order to increase the volume of regulated water, recent structural additions have been made including height increments of the weir crest, the construction of a concrete canal at the left side and cement repairs to exterior surfaces.

Unless well conceived and aimed strictly at reinforcement or preservation, these changes can seriously compromise the historical value the weir.

Hydraulic Structure Scheme

Consulting historical records and contemplating the various alterations to which the Bahman weir has been subjected throughout its history highlights the urgency with which protective and restorative strategies must be implemented. The absence of well-conceived proactive measures would deny global patrimony an intriguing and fabulous hydraulic artifact, one that still serves its originally intended functions today. The point of departure for a long-term strategy is to protect the current form of the weir by stabilizing and preserving its oldest masonry portions.

After this, the potential height increase of the crest needed for providing greater water regulation and irrigation capacity must be evaluated and expansion of irrigation intakes should be undertaken. Construction of an Ojee spillway over the old crest of the weir is proposed in order to minimize excess pressure on main structure and to accommodate a higher upstream reservoir resulting from a height increase. Moreover, the left side of the spillway should be renovated and the smaller irrigating intakes ought to be enlarged. In light of other studies done on the Bahman weir, it seems possible to reconstruct the side spillway of the weir by removing the remaining damaged portions of the previous side spillway, as these possess little historical value, and to construct a new reinforced concrete side spillway whose surface can be covered with masonry in order to maintain visual harmony with the rest of the structure. Considering that during a flood, the height of the water spilled from the weir can reach 2 m, a 1 m height increment will do little to prevent overturning and sliding forces acting on the structure. Thus, it would seem that the proposed height increment for upgrading the level of the upstream lake behind the weir is reasonable (TCE, 2004).

Conclusions

Overall, the Bahman Weir project is an excellent example of how the human quest for environmental control, evident even 2500 years ago, created opportunities and challenges that stimulated the development of construction and material techniques, and necessitated human cooperation. One hopes we will continue to learn and treasure these lessons, both for the present, and for our sense of history.

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Historical Development of the Augustan Aqueduct in Southern Italy: Twenty Centuries of Works from Serino to Naples

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Abstract: The aim of the present study was to investigate the historical development of the Augustan Aqueduct Serino-Naples-Miseno in the Campania Region, in Southern Italy. The Serino aqueduct is not well known because there are no remains of spectacular bridges, but it was a masterpiece of engineering and one of the largest aqueduct systems in the whole Roman Empire. The Serino aqueduct was constructed during the Augustus period of the Roman Empire, probably between 33 and 12 B.C. when Marcus Vipsanius Agrippa was *curator aquarum* in Rome, principally in order to refurnish the Roman fleet of Misenum and secondarily to supply water for the increasing demand of the important commercial harbour of Puteoli as well as drinking water for big cities such as Cumae and Neapolis. The main channel of the Serino aqueduct was approximately 96 km long, and had 7 main branches to towns along its trace such as Nola, Pompeii, Acerra, Herculaneum, Atella, Pausillipon, Nisida, Puteoli, Cumae and Baiae. Since the total length of all the branches was approximately 49 km, the Serino aqueduct complex had a length of around 145 km and therefore it should be considered the largest aqueduct system in the Roman world.

Keywords Miseno; Naples; Piscina Mirabilis; Roman aqueduct; Serino.

Introduction

Ancient Rome is famous all over the world for its aqueducts. As a matter of fact, Rome's water supply system was considered one of the marvels of the ancient world. The aqueducts went wherever Rome went, an outward symbol of all that Rome stood for and all that Rome had to offer (Hodge, 2002). The Romans were not the first to construct aqueducts. In fact, it is well known that the Greeks were the first to realize an aqueduct (Adam, 1988). One of the most famous aqueducts in ancient Greece is the tunnel of Eupalinos for the water supply of Samos (Angelakis *et al.*, 2005). In general, the Roman aqueducts were not built to provide drinking water, nor to promote hygiene, but to supply the bats (Hodge, 2002) or for military aims. Other purposes were the following (Hodge, 2002; Tolle-Kastenbein, 2005): domestic supplies, garden irrigation, aquatic shows, flour mills, decorative fountains and public fountains.

In the historic literature concerning Roman aqueducts, there are two authentic milestones (Panimolle, 1984; Adam, 1988; Hodge, 2002; Tolle-Kastenbein, 2005): *De Aquis Urbis Romae* by Sextus Julius Frontinus and Book VIII of *De Architectura* by Vitruvius Pollo. Sextus Julius Frontinus born probably around 35 A.D. and in 97 A.D. was appointed by

Trajan curator aquarum (water commissioner) of Rome (Panimolle, 1984; Hodge, 2002;). *De Aquis Urbis Romae* was the fruit of his tenure of this post. Vitruviul Pollio lived in the early first century A.D. and his *De Architectura* can be considered the only ancient treatise on architecture to have survived (Hodge, 2002). Nowadays, the popular but inaccurate image is that Roman aqueducts were elevated throughout their entire length on lines of arches. Roman engineers were very practical and therefore whenever possible the aqueduct followed a steady downhill course at or below ground level (Hansen, 2006). The water in the aqueducts descended gently through concrete channels. Multi-tiered viaducts were used to cross low areas; inverted siphons were employed (sparingly) when valleys were particularly deep; tunnels, burrowed through hill too difficult to skirt, were equipped with vertical shafts for inspection and cleaning. Debris cleaned from the tunnels was dumped beside the openings to the vertical shafts. Figure 1 proposes a scheme representing the general path of a whole aqueduct with the basic elements.

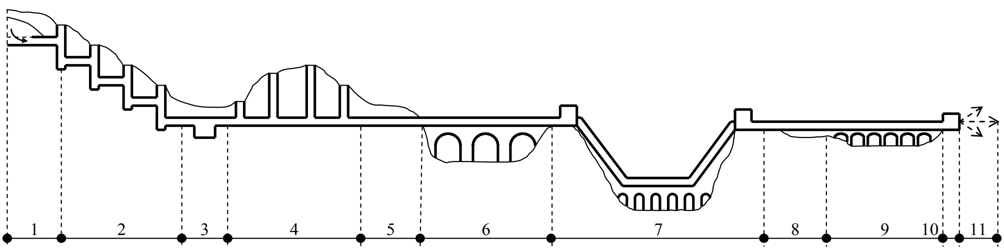

Figure 1 Flow sheet and components of a Roman aqueduct: (1) source – *caput aquae*; (2) steep chutes (dropshafts); (3) settling tank; (4) tunnel and shafts; (5) covered trench; (6) aqueduct bridge; (7) inverted siphon; (8) substruction; (9) arcade; (10) distribution basin/*castellum aquae divisorium*; (11) water distribution system (modified from Passchier and Schram, 2004).

The aim of the present study was to investigate the historical development of the Augustan Aqueduct Serino-Naples-Miseno (shortly "Serino aqueduct") in the Campania Region, in Southern Italy. The Serino aqueduct is not well known because there are no remains of spectacular bridges, but it was a significant piece of engineering and one of the largest aqueduct systems in the whole Roman Empire. Its importance is testified by several bibliographic references concerning specific books of local authors (Pavesio, 1985; Pescatore, 1996; Moscati, 2005; De Biase, 2006) as well as academic studies (Catalano, 2003), historical technical treaties (Giustiniani, 1797; Abate, 1864; Società Veneta, 1885; Sgobbo, 1938), web sites (Potenza, 1996; Nocella and Abbate, 2003; Passchier and Schram 2005), and even a novel (Harris, 2003).

The *caput aquae* of the aqueduct was the Acquaro-Pelosi spring in the village of Serino, in the province of Avellino (the ancient Abellinum). The source, the *Fontis Augustei*, lies at an altitude of 376 meters in a karst aquifer, known as "Terminio-Tuoro", that still today originates several springs (Serino, Cassano Irpino, Baiardo) with a total flowrate greater than 6 m^3/s (De Feo *et al.*, 2005). Nowadays, after two millenniums, the *Fontis Augustei* together with a nearby lower spring at 320 m, the Urciuoli source, still continue to supply clear, fresh and sweet water for the inhabitants of Naples.

Chronology

The Serino aqueduct was constructed during the Augustus period of the Roman Empire, probably between 33 and 12 B.C. when Marcus Vipsanius Agrippa was *curator aquarum* in

Rome, principally in order to refurnish the Roman fleet of Misenum (Miseno) and secondarily to supply water for the increasing demand of the important commercial harbour of *Puteoli* (Pozzuoli) as well as drinking water for big cities such as Cumae (Cuma) and Neapolis (Naples). Rogge (2006) dated back to ca. 35 B.C. linking of Pompeji to the Serino aqueduct, but in our opinion it appears almost impossible. More realistic appears the 27 B.C. suggested by Ohlig (2001) in Jones and Robinson (2005), as a possible arrival of pressurized water from the new Serino aqueduct as a branch of the Campanian aqueduct system.

For a long time, up to 1938, the Serino aqueduct was usually reported as the Claudius aqueduct, being retained that it was realized in the Claudius period (41-54 A.C.). The mistake was due to the discovery in Puteoli, in the 14th century, of big *fistulae plumbee* (lead pipes) on which there was impressed the name of the Emperor Claudius (Moscati, 2005). The enigma was resolved only in the last century, in the '30s, during the excavation for the construction of the new aqueduct of Naples, near the Acquaro-Pelosi spring. During this work, in fact, an important marble epigraph was discovered. The archaeological find gives information on the repairs executed in the period July-November 324 A.C. by Costantinum as well as the name of the cities of the Campania Region served by the repaired aqueduct; in order of importance (decreasing flowrate supplied), they were: Puteoli, Neapolis, Nola, Atella, Cumae, Acerrae, Baiae and *Misenum* (Sgobbo, 1938; Pavesio, 1985; Pezzella, 2002; Potenza, 1996; Catalano, 2003; Moscati, 2005; De Biase, 2006). The repairs are also reported in the *Liber Pontificalis* (Pezzella, 2002).

The marble epigraph, 1.86 x 0.86 x 0.17 m, today is kept in the connection chamber of the Acquaro-Pelosi spring. The inscription was interpreted and integrated by Sgobbo (1938): "*D(omini) N(ostri) Fl(avius) Constantinus maxi(mus) Pius Felix Victor Aug(ustus) et Fl(avius) Iul(ius) Crispus, et Fl(avius) Cl(audius) Constantinus nobiles Cae(saris) Fontis Augustei Aquaeductum longa incuria et vetustate corruptum pro magnificentia liberalitates consuetae sua pecunia refici iusserunt et usui civitatium infrascriptarum reddiderunt dedicante Ceionio Iuliano vi(ro) c(larissimo) Con(sulari) Campaniae curante Pontiano vi(ro) p(erfectissimo) praeposito eiusdem aqua(e)ductus nomina civitatium Puteolana Neapolitana Nolana Atellana Cumana Acerrana Baiana Misenum*". The epigraph reports that the repair works were directed by the *vir perfectissimus* Ponziano, in his function of *praepositus aquaeductus*, which means the curator of water and aqueducts.

Fifteen years after the construction of the epigraph, the Serino aqueduct is mentioned again in a constitution of the Onorio Emperor dating back to December, 28, 339 and addressed to the *praefecto praetorio* of Italy, Valerio Messala (Codex Theodosianus, XV 2.8) (Pezzella, 2002). After the fall of the Roman Empire, the Serino Aqueduct together with the major part of Roman aqueducts went out of service because of the low level of maintenance carried out as well as the devastation as a consequence of the Barbarian invasions (Pavesio, 1985; Moscati, 2005; De Biase, 2006).

In the VI centuries, in fact, Naples was invaded several times by Ostrogoti of Totila and the Serino aqueduct was one of the strategic targets destroyed in order to conquer the city. In particular, Procopio, a Greek historian tells how General Belisario ordered the aqueduct channel out of the Costantinopoli's door of Naples to be broken. A soldier was able to enter in the city using the aqueduct channel and after him, General Belisario together with other 400 soldiers followed. Then, just like Ulysses in Troy, Belisario and his troupe opened the doors of Naples to the rest of his army. Curiously, the same technique was used several years later, in 1442, by Alfonso d'Aragona in his battle against Renato d'Angiò (Pavesio, 1985; De Biase, 2006). Therefore, the aqueduct had a black hole of a millennium in which it was out of service and completely forgotten.

In the period 1532-1553, during the Hispanic domination of Naples, the viceré don Pietro Toledo entrusted Pietro Antonio Lettieri (Tabularius) to investigate the way to increase the supply of drinking water for the city. Lettieri was a technician with expertise in topography and after four years of study, proposed the complete recovery of the Auguestan acqueduct as a possible solution to the problem of water scarcity (Pavesio, 1985; De Biase, 2006). The report written by Pietro Antonio Lettieri was copied for the first time by Giambattista Bolvito and conserved in the archives of Real Corte, and then collected in Archives of P.P. Chierici Regolari Teatini of SS. Apostoli of Naples (Giustiniani, 1797; Pavesio, 1985). Lettieri's project remained on the papers because of its high cost. In that period the *Fontis Augustei* was property of the Prince of Avellino, who earned a lot from the use of water for factories, watermills and irrigation (Pavesio, 1985). Pietro Antonio Lettieri was able to describe the route of the ancient Serino aqueduct (Pavesio, 1985; Moscati, 2005; De Biase, 2006).

Three centuries after the study of Lettieri, another important investigation took place. From 1840 to 1864, architect Antonio Abate, in fact, investigated the route, the works and the places interested by the ancient Augustean aqueduct (Abate, 1864). Other important source of information is the Società Veneta (1885). The Società Veneta was the enterprise entrusted to realize the new aqueduct for the city of Naples. May the 10th, 1885, in the famous Plebiscito square, was a great day for Naples: the people again had the famous water of Serino. However, the water did not come from the *Fontis Augustei* (Acquaro-Pelosi spring) but from the nearby Urciuoli Spring (324 m). This source, in the same period of the Augustean aqueduct Serino-Neapolis-Misenum, was the *caput aquae* for the aqueduct Serino-Beneventum spring (36 km long). In 1936 the water coming from the two sources was joined to significantly increase the flowrate for the city of Naples (2,000-3,000 L/s) (Potenza, 1996).

Route

The main channel of the Serino aqueduct in its route toward Naples and Miseno was approximately 96 km long, and had 7 main branches to towns along its trace such as Nola, Pompeii, Acerra, Herculaneum, Atella, Pausillipon, Nisida, Puteoli, Cumae and Baiae (Fig. 2). The length from Serino (1) to Naples (2) was approximately 78 km long; while, the length from Naples (2) to Miseno (3) was around 18 km. Since the total length of all the branches was approximately 49 km, the Serino aqueduct complex had a length of around 145 km and therefore it should be considered the largest aqueduct system in the Roman world. In fact, the other long aqueducts are Cartagena with 132 km and the Aqua Marcia and the Anio Novus, in Rome, with 91 and 87 km, respectively (Adam, 1988). The ancient route of the Serino aqueduct can be described joining the information coming from the descriptions by Pietro Antonio Lettieri (in Giustiniani, 1797) and Franceco Abate (1864).

From the Acquaro-Pelosi spring in Serino, at 370 meters above sea level, the aqueduct crossed the Sabato river on a bridge to the west to Aiello. It passed below Contrada in a tunnel, then through the plain of Forino through Preturo, Pandola, Tor di Marcello, Castel S Giorgio and Taverna di Lazzaro to a major tunnel below Monte Paterno of 1903 m long towards Sarno. Through Episcopio and Palma it continued to Mura d'Arco where it ran in a double section, one buried and one on arches to Vallone del Monaco where both branches joined again. The following section passed through Torricella, San Gennaro Vesuviano, Piazzolla, Martino, S Maria del Pozzo, La Masseria San Rossio, Masseria la Preziosa and then over a section on arches to Pomigliano d'Arco.

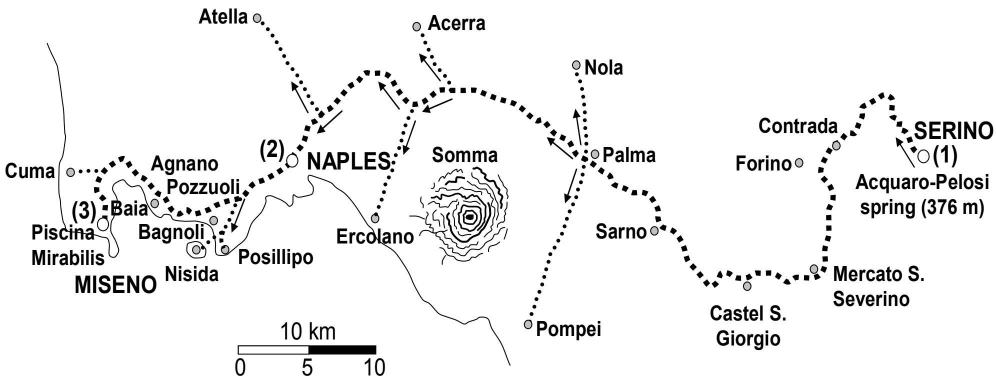

Figure 2 Route of the Augustan aqueduct from Serino to Miseno.

Then through Casalnuovo, Afragola, San Pietro a Paterno to San Giuliano north of Naples where there are remains of an aqueduct bridge (Ponti Rossi). The aqueduct circled Naples below the hills of San Eframo, Santa Maria della Vergine, to Santangelo, where a branch went south to serve the city of Neapolis through Porta di Costantinopoli and San Patrizia. The main channel followed the route through S. Elmo and Chiaia to a tunnel to west of Naples. This is a major road tunnel, the Crypta Neapolitana, 5 m high, 4.5 m wide and 700 m long. It was built by L. Cocceius Auctus, an architect who came from this area and probably worked for Agrippa. The aqueduct does not lie in the tunnel itself, but runs parallel to it at an height of 50 cm from the base of the tunnel on its north side. On the west side of the tunnel, the aqueduct then branched; one branch went south to a junction at the coast, where a branch probably went over a bridge to the island of Nisida, while another passed parallel to but on the north side of another road tunnel, the Grotta Seiano, to serve the large imperial villa at Posilippo (Pausilippon) also known as the Villa Polii after its first owner. The main branch of the Serino aqueduct left the Crypta Neapolitana to the west with a small side branch to the large bath complex of Terme di Agnano. From there, it passed through Pozzuoli with a branch to the city, then along the via Domitiano to circle the Lake of Averno. Here a side branch passed parallel to and at the north side of another road tunnel built by Cocceius to Cuma. The main channel then follows the flank of three craters above Baiae and on the Misenum (Giustiniani, 1797; Abate, 1864; Catalano, 2003; Passchier and Schram, 2005; De Biase, 2006).

The total relief of the aqueduct is 366 m from the source (1) to the Piscina Mirabilis (2) at 10 m altitude, which gives a mean slope of 0.38% (3.81 m/km). The mean slope of the stretch from Serino (1) to Naples (2) (Ponti Rossi at 41.4m) was 0.43% (4.29m/km); while the mean slope from (2) to (3) was 0.17% (1.74 m/km). Along the route, the local slope varied considerably: from 0.016% to 0.73%. The specus of the aqueduct varied in size, but was mostly 0.8 m wide and 1.8 m high (Fig. 3).

The maximum capacity at the upper sections can be estimated in approximately 1,000 L/s, which would be a total of 86,400 m^3/d. Pompeii was one of the towns served by the aqueduct, and the capacity of the branch that ended here in the *castellum aquae* was 42 L/sec (Passchier and Schram, 2005). Ohlig (2001) investigated the connection of the *castellum aquae* with the Serino aqueduct. It was pointed out that a channel outside the town, hitherto interpreted as part of a rather unproductive earlier water supply, was not a water conduit at all, and, moreover, it could be assigned to a more recent date than that of the main water supply channel.

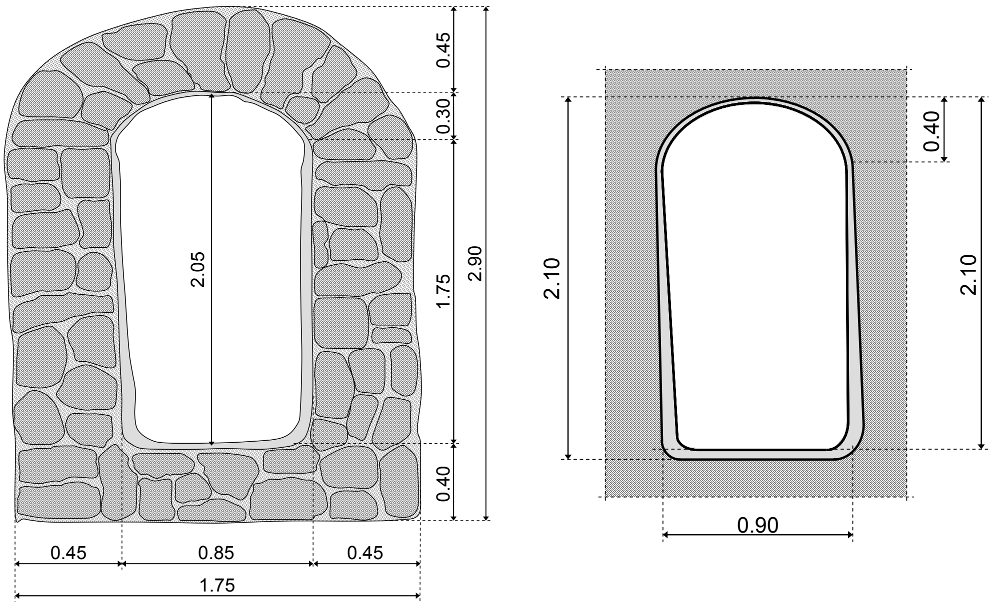

Figure 3 Some specus of Augustan aqueduct channels.

On the other hand, on either side of this supply channel, two layers of lime sediment (sinter) were observed at different levels. Mineralogical and chemical analysis has proved that Pompeii received through this single channel water from two completely different sources, one replacing the other in a later period; the flow of water in the second phase was considerably less than in the first. Analysis of other lime samples, taken from sections of the Serino aqueduct both before and after the junction with the probable branch aqueduct serving Pompeii, gave the following picture. It is very likely that Pompeii first received water via her own aqueduct from the mountains due north east of Avella. The town must have had a long distance water supply, quite some time before the Augustan Age, probably around 80 B.C. When the Serino aqueduct was built under Augustus, it crossed the course of the older Avella aqueduct between the Apennines and Mount Vesuvius, and both aqueducts were united into a single system. The section of the Avella aqueduct, from the point where it crossed the Serino aqueduct onward, continued to serve as a supply channel for Pompeii. The new Avella/Serino aqueduct, apart from serving the imperial fleet at Misenum, also supplied a number of other Campanian towns with water. As a result Pompeii received a smaller amount of water from the new system than it used to get from the original Avella aqueduct.

Works and Places

During the war with Pompeius, Augustus ordered the construction of a harbour complex just west of Puteoli, named Portus Iulius, where an old Greek dam was restored to create an artificial lake, Lacus Lucrinus, which was then connected by a channel to another lake, Lacus Avernus, which was traditionally one of the entrances to the underworld. Later, this harbour was seen as less ideal, because of silting problems, and a new complex was built further west at Misenum, where two lakes were connected to become the basis of the western Mediterranean war fleet. This major naval base needed large quantities of fresh water for the base itself and for the ships, which must have been one of the reasons why Augustus had a new aqueduct built (Passchier and Schram, 2005). The Serino aqueduct filled several cisterns in the section beyond Naples. The main cistern filled by the aqueduct is the Piscina Mirabilis in Bácoli (Misenum) (Adam, 1988; Potenza, 1996; Catalano, 2003; Passchier and Schram, 2005).

The Piscina Mirabilis (Figs. 4 and 5), situated up the hill facing the sea in order to provide the *Classis Praetoria Misenensis*, is a gigantic reservoir 72 m long and 27 m large, which derives its name from the eighteenth century antiquarian tradition, with clear reference to the impressiveness of its plan as well as the remarkable architectonic effect. It is dug in a tufa hill and has two step entrances in the north-west and south-east corners, this latter closed. Forty-eight pillars, arranged on four rows serving as a support to the barrel vault, divide it in five aisles on the long sides and thirteen aisles on the short sides, lending to it the majestic look of a cathedral. The Piscina Mirabilis can be considered one of the biggest Roman cisterns ever known until now with a volumetric capacity of 12.600 m^3 of water. The water coming from Serino flew into it near the north-west entrance. The long wall were realized in *opus reticolatum* (reticular work) with brick bonding courses and by the technique of the tufa stone pillars, both covered with a thick waterproof layer of *opus signinum* (pounded terracotta).

The seventh short aisle, just in the middle of the reservoir, appears embedded in it for about 1 m, with the plane inclined in the direction of an outlet at the south end. It was used as a Piscina limaria for the periodical cleaning of the reservoir. There is a basin of 1.10 m, probably a polishing pool, that is a waste-bath for the maintenance of the cistern, in the floor of the nave The water, through a series of doors opening in the vault along the central nave, was raised through hydraulic engines on the covering terrace of the reservoir, which was also floored with signinum and from there, canalized towards the built-up area. Along the north-west external side, in the course of the first century A.D. were added twelve vault-covered little rooms in *opus reticolatum* with angular brick bonding courses, in the second of which is kept a *signinum* floor with labyrinth-sbaped mosaic *tesserae* and a central white inlaid panel with limestone polychrome tiles, which seems to date back to a more ancient phase (Adam, 1988; Potenza, 1996; Catalano, 2003; Passchier and Schram, 2005).

Close the Piscina Mirabilis, there are two other large cisterns, probably belonging to large villas, the Grotta Dragonaria and Cento Camerelle (Nerone's jail). In Pozzuoli, the aqueduct served several cisterns, notably the Piscina Cardito (55 x 16 m^2) from the second century, and the Piscina Lusciano (35 x 20 m^2) from the first century A.D. In Baiae, a tunnel with two cisterns, known as the Crypta Romana, was filled by the aqueduct (Adam, 1988; Catalano, 2003; Passchier and Schram, 2005).

Conclusions

This paper presented and discussed the historical development of the Augustan aqueduct from Serino to Cape Miseno, in Southern Italy. After a brief introduction on Roman aqueducts, the paper focused on the Serino aqueduct. The topic was discussed relating to three main subjects: chronology, route, works and places. The overall conclusions from the research results can be summarized as: (a) the aqueduct was probably constructed between 33 and 12 B.C. when Marcus Vipsanius Agrippa was *curator aquarum* in Rome; (b) the main channel was approximately 96 km long; (c) the aqueduct had 7 main branches corresponding to approximately 49 km; and (d) the total length of the Serino aqueduct could be around 145 km and therefore it should be considered the largest aqueduct system in the Roman world.

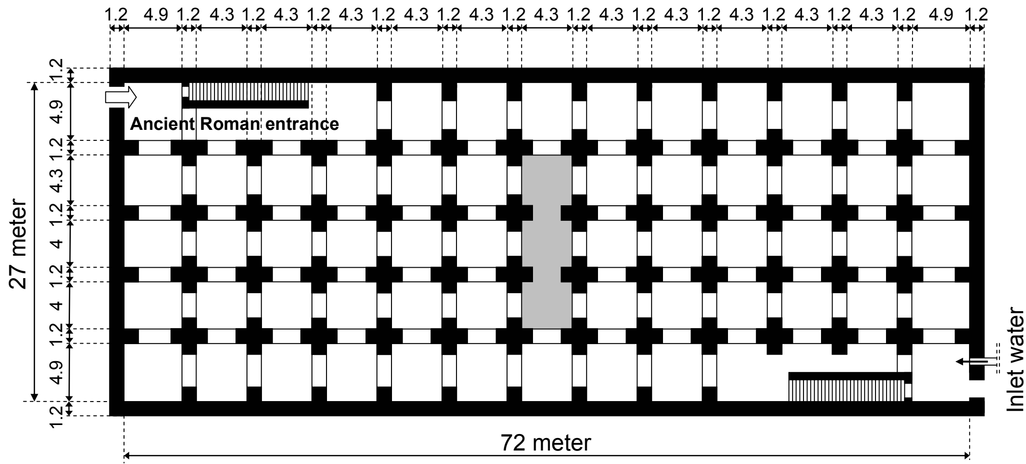

Figure 4 Plant of the Piscina Mirabilis.

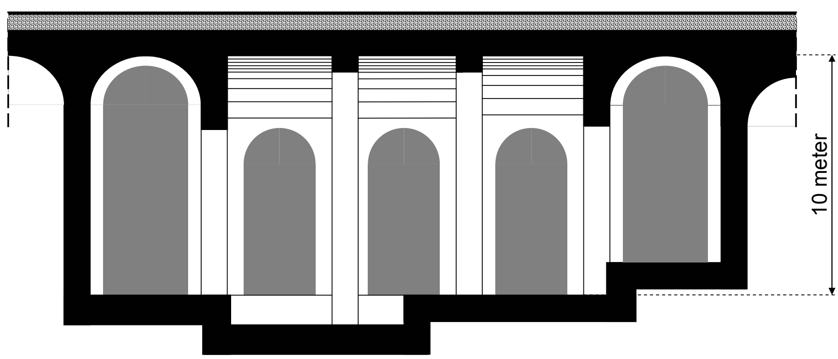

Figure 5 Section of the Piscina Mirabilis.

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A Review of Ancient Roman Water Supply Exploring Techniques of Pressure Reduction

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Abstract: The Ancient Roman Water Supply System still leaves us astonished when admiring the solidity of the ruins of aqueducts surviving around Europe. Some parts of these systems are still in use at present and prove the practical efficiency of Roman hydraulics in the principles acquired from the populations living in the different regions of the Empire. In Pompeii the urban water supply system stands as a clear example of the Roman planning of urban complex networks by using small water towers to serve a limited numbers of users. This allowed to control the derivations and their maintenance and operated a disconnection from the high pressure mains and the low pressure pipes, maintaining a fixed maximum height of water over the final points of discharge. Considering the techniques for pressure reduction as a method to control leakages, this paper examines the ancient Roman water supply system to deduce some applications to modern urban networks built in new housing establishments.

Keywords Low pressure water supply systems; pressure control; Roman water supply.

Introduction

The description of the ancient Roman water supply system is contained in some details in the technical recommendations of the Latin writers: Vitruvius (*De Architectura*, VIII, 1997 translation), Plinio the Elder (*Naturalis Historia, XXXVI,* 1988 translation) and Frontinus (*De Aquaeductu Urbis Romae*, 2004 commentary), *Curator Aquarum* in Rome from 97 A.D. to 106 A.D. The water consumption of Rome couldn't be satisfied by the extraction from private and public wells or rainwater harvesting, so Roman sovereigns resorted to tap fresh springs at the outskirts of the city in the Roman Campagna to bring their freshness to the urban centre.

The first aqueduct to be built was Aqua Appia, in 312 B.C. and ten more followed in 540 years, so that by the time of Frontinus "*curator-ship*", water in Rome was so abundant that he wrote in his report: "With such a quantity of structures dedicated to water, pyramids in comparison seem idle and Greek works, though famous, appear inert" (Op. Cit, Par. 16). Remains are still in place and Roman suburbs as well as in the centre and astonishing views are offered to the traveller (Fig. 1, Aqua Claudia, *Romavecchia*). Taking baths became an important habit in Roman life, regardless of the social provenience, so an increased water supply was needed: ruins of channels or other structures part of the aqueducts exist in all regions of ancient Roman empire (Figs. 2-4; Perkins, 1994).

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Figure 1 Aqua Claudia at Romavecchia, Rome South East outskirts.

Figure 2 Aqueduct of Segovia, Spain.

Figure 3 Pont du Gard, Nimes, France.

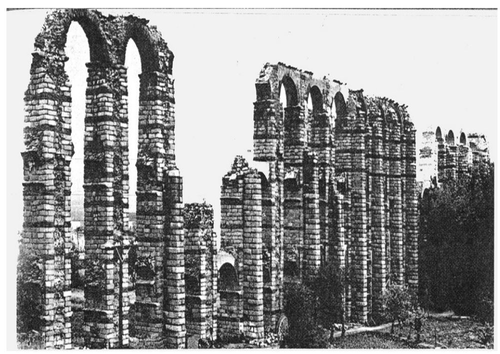

Figure 4 Aqueduct of Merida, Spain.

The construction of the Ancient Roman Aqueduct System is sometimes not different from the modern practice, since modern technologies descend directly from Roman engineering. More over we can learn some useful lessons from those techniques. Considering the urban water supply system of Pompeii, as it will be described later (Richardson, 1989), it can be understood that it is based on the distinction between high pressure areas and low pressure areas. Water conducted from the upstream springs was introduced through pressure pipes into local tanks elevated on pillars so that they could serve a limited number of users.

In this way low pressure areas were disconnected from high pressure mains, so that bursting and leakages could be limited. Looking at the modern techniques aiming to achieve water leakage reduction, pressure containment methods are outlined from IWA in many publications (Thornton, 2003; Brothers, 2005; Thornton *et al.*, 2005). Considering the direct relationship between leakage and internal pressure (Smith, 1999), the local reservoirs acting as a chamber fluctuating in level, with a maximum fixed one, preserve the streets high pressure networks, avoiding an incredible numbers of fittings. Different numbers of customers can be served and reclaimed water tanks can also be added when non potable water will be available and connected to single premises by pumps.

The Roman Water Supply System

The Romans transported water to the cities such as in a “river flow”, in fact they called their channels “Rivus”. A general outline of the components of the Roman water supply system is given in Figure 5.

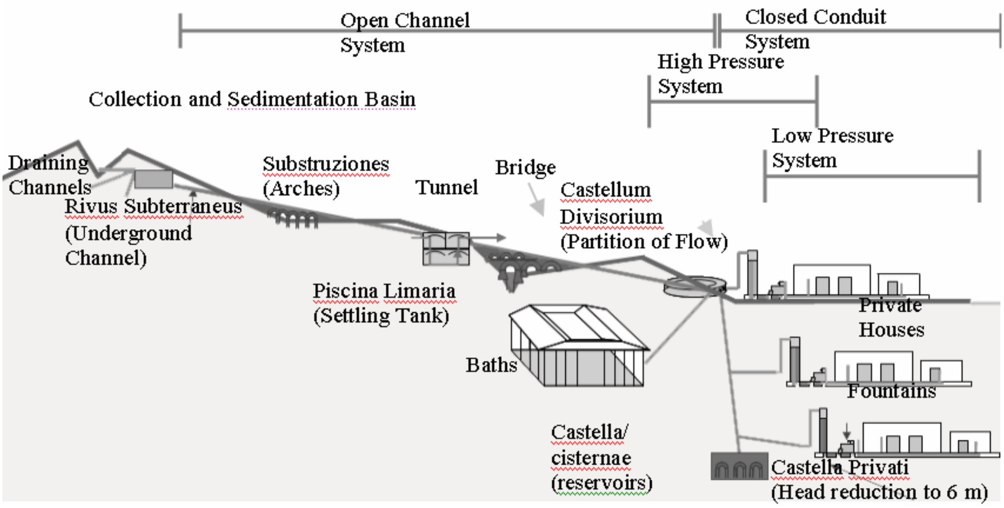

Figure 5 The ancient Roman water supply system.

The building of a new aqueduct started with the search for a spring as described by Vitruvius (Op.Cit, Book VIII, Chapter 4). Sedimentation was achieved in a basin (Mucci, 1995), where water was collected after permeating trough vaults and walls of draining channels in case the spring was not emerging to surface. The arrangements are shown in Figure 6 (Draining channel and basin from Eiffel Aqueduct, Cologne). Water was introduced into channels, whose section was typically rectangular, made with brick masonry or slabs of stone, and sealed with hydraulic cement (Opus Signinum).The cover was a masonry vault or slabs of stone laying in horizontal or roof shape (Corsetti, 1937; Ashby, 1991; Aicher, 1995; Hodge, 2002).

From the spring down to the city the water flowed in an open channel flow, and air was present at all times over the water surface. The slope had to be constant (Vitruvius, Op. Cit, Book 8, Par 6), Vitruvius himself gives a range between 0.0025 and 0.005 m/m Existing aqueducts slopes information can be found in Lanciani (1967), Lugli (1970), and Reina (1917). To maintain a constant slope the channel crossed valleys in siphons with limited slope, whenever this couldn’t be avoided (Hodge, 2002). The characteristics of siphons are described in Figure 7. Two tanks at the inlet and at the outlet of the pressure pipes were built to keep the disconnection with the open channel aqueduct. This was necessary to allow water to go back at almost the same height after passing the valley, since this wouldn’t be possible with the open channel arrangement. The bottom part was horizontal to avoid acceleration and abrupt changes in direction, and stone blocks secured the pressure pipes along the side of the valley.

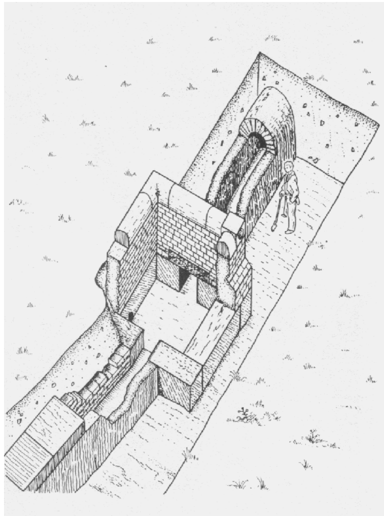

Figure 6 Draining channel and collection basin, Eiffel Aqueduct, Cologne, Germany (Habery, 1972).

The constant slope requirement imposed to the channel to run higher than the ground level, therefore in certain points, it had to be laid over sustaining structures. For considerable heights arches were built and they could lay in different orders, as for bridges (Fig. 3). Sizes and materials of arches varied according to local customs (Fig. 8).

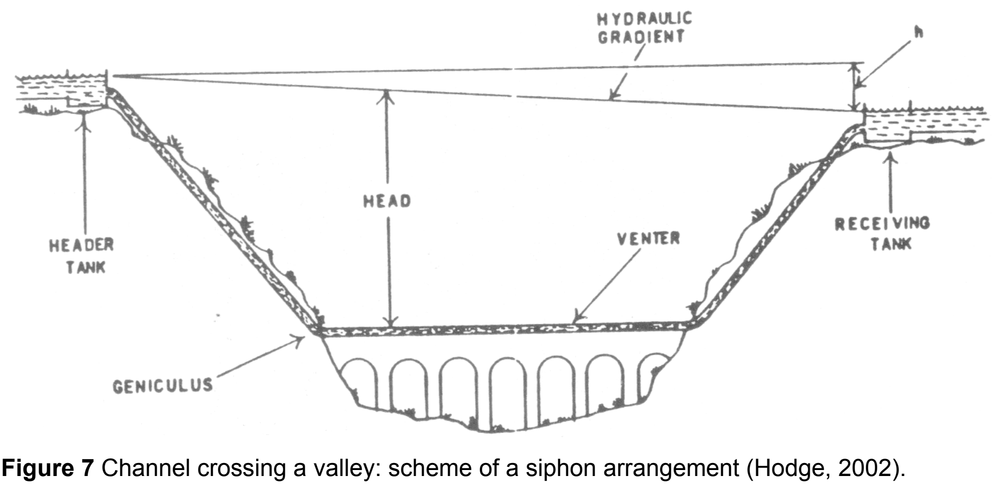

Figure 7 Channel crossing a valley: scheme of a siphon arrangement (Hodge, 2002).

During its course the channel reversed its waters to a so called "*piscina Limaria*". It was a settling tank to allow particulate impurities to settle (Frontinus, Op. Cit., 19, Cagnat, 1916, Pace, 1983). In Figure 9 are reported some arrangements. Once approaching the city the channel flowed into a partitioning tank called "*Castellum Divisorium*" (Perkins, 1994). The tank was subdivided in parts with masonry walls and weir systems (Fig. 10, Pompeii). The partitioning function was planned to introduce the waters into the urban pressure pipes, made of lead, terracotta or wood (Hodge, 2002). The description of the principles governing the operation of the castellum divisorium is given by Vitruvius (Op.Cit, Book 8, chapter 6, par. 1-2).) The best preserved examples are Nimes and Pompei Castella (Richardson, 1989).

(a)

(b)

(c)

(d)

Figure 8 Different shapes and materials of construction of arches: (a) Brick faced concrete, Nero's branch, Rome; (b) brick and stone layers masonry, Taormina, Italy; (c) stone masonry, Aqui Terme, Italy; and (d) stone blocks without mortar, Pont du Gard, Nimes.

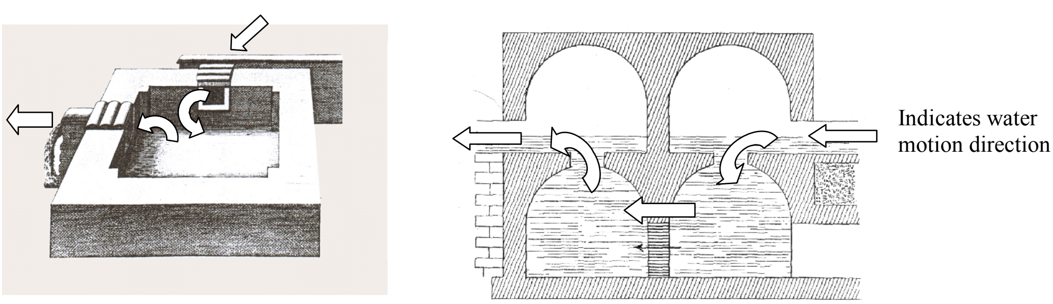

Figure 9 Piscinae Limariae of Aqua Alessandrina, left and Aqua Virgo, right (Adapted from Piranesi and Cagnat).

Figure 10 reports the plan, picture of the façade and view of the inside of Pompei Castellum Divisorium, placed in the highest point of the city, near Porta del Vesuvio.

Figure 10 Castellum Divisorium in Pompeii: Plan, S-E Facade, View of the interior catwalks and partitioning masonry walls.

The pressure pipes served other reservoirs (*Castella*) in the city, as has been reported for the city of Rome. They had a storage function, designed to supply for the fluctuations of demand. Other examples of reservoir in the city had an urban decoration function, such *Nimphei* and *Naumachie* structures (Cagnat, 1916). Ninfei were huge reservoirs with decorated facade displaying niches, statues and water (Fig. 11: Side Ninpheum, Asia Minor and Taormina Naumachia, Sicily). From the castella the water run into high pressure pipes to secondary "*Castella Privati*", small water towers, serving a limited number of public and private users (Hodge, 2002) (Fig. 5). The view of the water towers can still be appreciated when visiting Pompeii ruins.

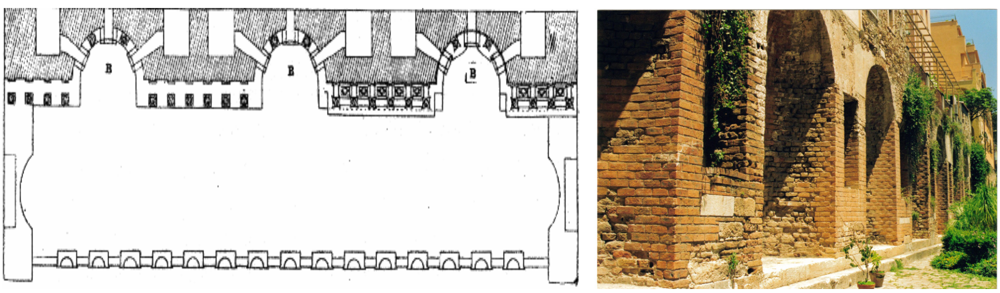

Figure 11 Side Ninpheum plan (Asia Minor) - from Lanckoronsky-and Taormina Naumachia façade (Sicily, Italy).

Pompeii Urban Water Supply System

A clear vision of the urban water supply system by means of water towers is given by Pompeii case study. From the castellum divisorium three mains lead the water to different parts of the city (Richardson, 1989). The water towers (*Castella Privati*, Frontinus, Op. Cit.) were the main feature of the water distribution system. They were lead tanks positioned over brick masonry 6 metres tall pillars, usually built at crossroads and connecting a small number of houses. They fed houses and street fountains, but deep wells extraction was present as well (Fig. 12). The single users paid to derive some amount of water for their own uses (*domus, taberna*). The water was metered with *calices*, bronze orifices (Pace, 1983) connecting the customers pipes to the castellum privatum tank (Fig. 13). In Pompeii case study calices were placed at the bottom of the lead tanks, with pipes running into cavities running in the brick pillars. Minimum size of pipe connected was the *quinaria* pipe, about

2.31 cm in diameter. The lead tank of the water tower acted as a disconnection between system at high pressure and the mains connected downstream.

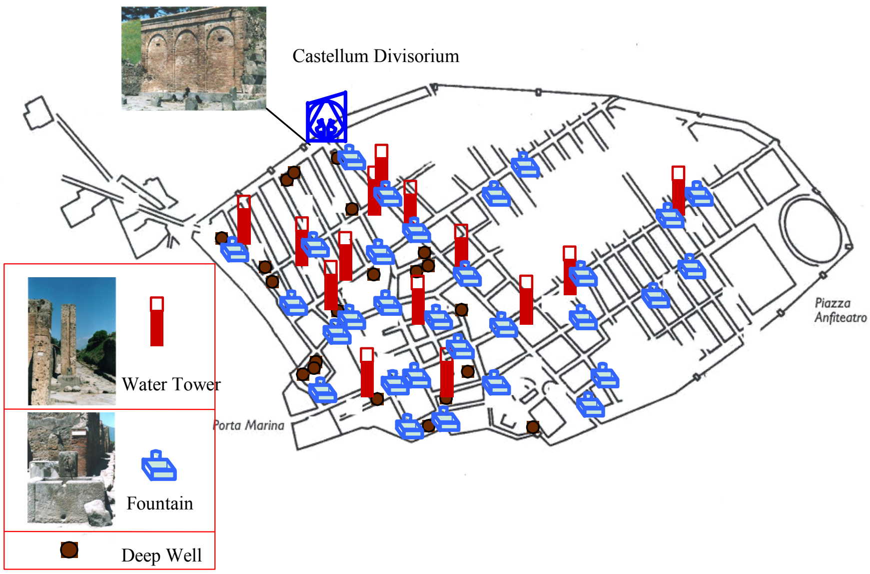

Figure 12 Pompei urban water distribution system: Location of wells, fountains and water towers (Richardson, 1989).

Any of the arrangements fitted elsewhere than in the castellum privatum were against the regulations. The only connection available was through these purpose built water towers, after contacting with the water office personnel and arranging for the consumption (Frontinus, Op.Cit., par. 105 -106). This system of supply clearly shows that water towers could break down the pressure built up in the mains descending from the initial castellum divisorium at the top point of the city. Pressure was regularised in the water towers tanks so that a maximum level of water of about 6 m, without accounting for all the pressure losses in the delivering customer pipes, was maintained "over the tap" (Fig. 14).

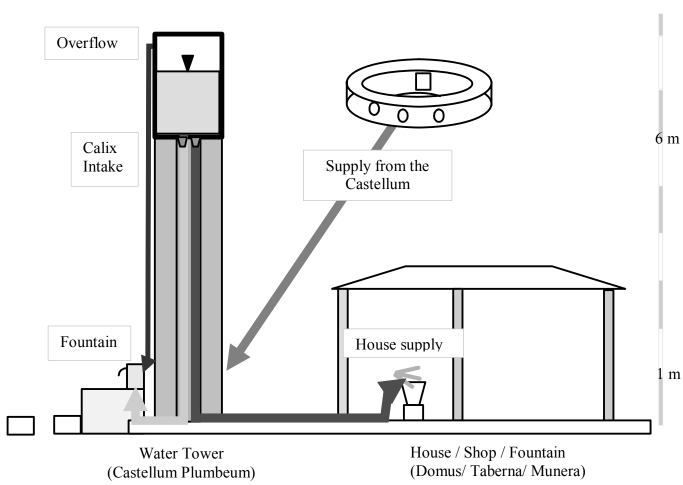

Figure 13 Scheme of Pompei private water supply from water towers.

This method was applied to reduce pressure in the mains, because, although it has recently been demonstrated that Roman lead pipes could bear more internal pressure than they were used for, the Romans were keen on preventing failures and leakages in pipes. In fact pipes were built with lead plates sealed in longitudinal joints and joined with various fittings. Therefore this example of Roman urban water supply system gives some hints on a possible method to reduce internal pressure in water supply mains in newly built housing arrangements.

A Roman Way to Reduce Pressure in Water Supply Mains

The supply system in a new housing arrangement can be based on an in-house or in-area tank, supplying the daily consumptions. The mains leading to single apartments could depart from the local tank situated in an accessible location, so that water could reach the customers taps with dedicated pumps. The main advantage of this arrangement would be that larger diameters and higher pressure pipes laid under streets could run untouched. This could give easy life for repairs, and most of all could create a disconnection between the high pressure network in the roads and the users low pressure systems in houses. The number of junctions fitting into the high pressure loops in the streets would decrease to one per group of users. Moreover it can be made provision for a reclaimed water tank whenever (in the next future?) non potable water will be produced by sewage works to be supplied in a second aqueduct.

Discussion and Conclusions

Taking the inspiration from the Romans practice, the hypothesis of having an in-building potable water tank connected to many users can be considered. Comparing the application of the Roman urban water distribution system to our urban realities, it can be noticed that modern buildings are in many cases higher than the ancient two stories houses, however pumps are available for all sort of conditions and allow many combinations. There is an increasing attention for procedures achieving leakage control, many of them are based on pressure reduction techniques and propose different options. Installing complex devices such as valves in existing networks, can involve increasing of monitoring, maintenance and control work and arises concerns about energy consumption, as well. When using a local tank provision of water some issues such as energy balances, maintenance work, robustness of the system, reliability of the supply, health and safety concerns, have to be examined. The future work can include the possibility to test local small pressure systems by computer modelling for comparison with the valve controlled networks. Some small scale experiments can also be performed for analysing how the local tank system copes with the operation of the modern urban networks. Environmental friendly and robust systems (no complexity of electric-mechanic parts) like the local tank arrangement can in some respect be supported by the future water related techniques improvements.

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Minoan Aqueducts: A Pioneering Technology

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Abstract: In this paper several archaeological, historical and other aspects of aqueducts in Minoan era are reviewed. During the Middle Bronze Age a "cultural explosion", unparalleled in the history of other ancient civilizations, occurred on the island of Crete. One of the salient characteristics of that cultural development was the architectural and hydraulic function of aqueducts used for water supply in "palaces" and cities. In the entire structures of most Minoan "palaces" and cities, nothing is more remarkable than their elaborate water supply systems. The Minoan hydrologists and engineers were aware of some of the basic principles of what we call today principles and practices of water sciences with emphasis on the construction and operation of aqueducts. The description of several of the Minoan aqueducts could justify that Minoans could be considered as pioneers in those technologies.

Key words Aqueducts; Crete; Knossos; Malia; Minoan civilization; Tylissos; Water resources.

Prolegomena

The rainfall regime and consequently the water availability over Greece vary substantially in space. In general, climate is affected during the summer by a subtropical high pressure belt, which results in hot and rainless weather conditions. During winter, the region is dominated by the mid-latitudinal depressions, connected with the westerlies regime, which brings cold weather and rainfall. In Crete the three main mountains (White, Ida, and Dikti mountains) play important role in rainfall and runoff regimes of the Island. Thus, the mean annual rainfall exceeds 1,800 mm in the mountainous areas of western Crete whereas in the eastern regions of the Island it may be as low as 300 mm. It is of interest to point out that the most advanced cultural activities in ancient Greece are located in semiarid areas with the lowest rainfall and thus the poorest water resources; i.e., Knossos, Gortys, Zakros, and Phaestos on Crete with annual rainfall less than 500 mm. The potential evapotranspiration exceeds 2,000 mm all over Crete, with the highest rates in summer months. Thus, irrigation of cultivated areas during summer is absolutely necessary and becomes the most demanding water use.

The above figures apply to the nowdays climatic conditions. Several studies have attempted to reconstruct past climate of the eastern Mediterranean (Issar, 1995; Issar and Makover-Levin, 1996). They concluded on the existence of long cold and humid periods followed by warm and dry ones (Angelakis *et al.*, 2005). For example, Middle Bronze times are characterized by cold and humid conditions. Also, archaeological and other evidence indicate that during the Middle Bronze Age a "cultural explosion", unparalleled in the history of other ancient civilizations, occurred on the island of Crete. However, not only did Minoan Crete establish the critical foundations for almost all modern technological achievements, including water resources technologies (aqueducts, cisterns, wells etc.), but their approaches were remarkably advanced.

It is evident that during the Bronze Age extensive systems and elaborate structures for water supply and sewerage systems, irrigation, and navigation were planned, designed and built to supply the growing population with water for the cities and villages, commerce, and for the irrigated agriculture. Thus, it not by chance that the main technical and hydraulic operations of capture, conveyance, raising and measurement have been practiced in varying forms since *ca*. 3,500 B.C. (Fig. 1). In the Minoan Crete various fundamental technologies such as aqueducts, wells, cisterns, and closed water distribution systems for water supply to the "palaces", cities and villages were very well developed, as did techniques relevant to the recreational use of water.

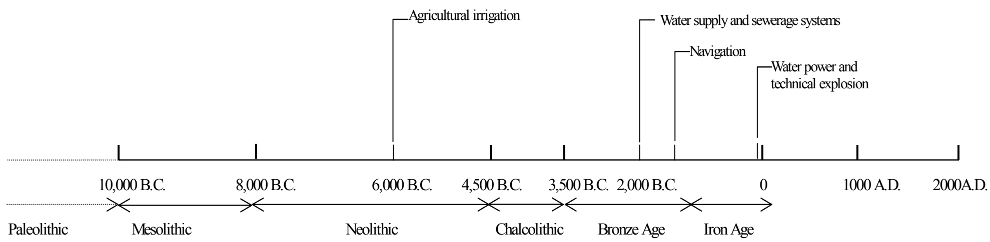

Figure 1 Historical development of water sciences technologies.

Commercial relationships have been known between the Minoans and continental Greece, Egypt, and Syria. There is no doubt that skills in hydraulic and water management had been transferred from Mesopotamia and Syria to Crete by that time. The Minoans not only applied these skills but also they developed them further, especially in urban hydraulics, in the "palaces", the cities and the villages, to a level that was never reached before (Viollet, 2003). In most of Minoan settlements the potable water was dependent on surface springs, rivers, wells and cisterns. The normal reasons an aqueduct was build was to supply the baths (Hodge, 2002). The achievements of this period in dealing with the hygienic and the functional requirements, toilets and baths, and wastewater and urban drainage systems of "palaces" and cities, are supporting this statement (Angelakis *et al*., 2005). However, the water was also used for other purposes, ranging from gardens irrigation to aquatic shows and decorative fountains. A possible second reason for Minoans to build an aqueduct was the civic pride. It seems likely that these technologies had been transferred to continental Greece and then to other European countries by the Minyans, another prehistoric civilization, by *ca*. 1900-1600 B.C., and had since created the so-called Mycenaean civilization. (Angelakis and Spyridakis, 1996a).

The scope of this article is not the exhaustive presentation of what is known today about aqueducts, related technologies and their uses in Minoan Crete. Rather, some characteristic examples in selected fields that chronologically extend from the early Minoan civilization through the end of that era are presented. These examples may justify that Minoans could be considered as the pioneers in the technological development of aqueducts.

Major Aqueducts

In ancient Crete the technology of transporting water to "palaces", cities and villages by aqueducts was very well developed due to the mountainous terrain as early as at the Early Minoan era. Several aqueducts of the Minoan era have been identified so far by Angelakis and Savvakis (unpublished data). Water was transported through the aqueducts by closed or opened pipes (teracotta) and/or opened or covered channels of various dimensions and sections. The main of these aqueducts are in Gournia, Karfi, Knossos (Mavrokolympos), Malia, Mochlos, Minoa, and Tylissos. These technologies were further developed during the Hellenistic and Roman periods in Crete, and were transferred to the continental Greece and other Mediterranean and Near East countries.

Aqueduct of Knossos (Mavrokolybos)

Minoan hydraulic engineers apparently were concerned with the solution of some water engineering problems and were able to provide cities and "palaces" with complete water supply systems. On the basis of their accomplishments it can be assumed that they were, in a sense, aware of the basic hydrostatic law, known today as the *principle of communicating vessels*. It is manifested in the water supply of the Knossos «palace» through pipes and conduits fed by springs; this is supported by the discovery of the Minoan conduit heading towards the Knossos «palace» from Mavrokolybos which suggests a descending and subsequently ascending channel (Evans, 1921-1935; Hutchinson, 1950). However, it appears that Minoans had only a vague understanding of the relationship between flow and friction.

Present knowledge of how Minoan cities were supplied with potable water is mainly acquired from the «palace» of Knossos. The «palace», which was surrounded by a town (with 80,000 inhabitants), lies on the gently sloping banks of the Kairatos river, close to its confluence with a small brook (Viollet, 2003). Evidences for advanced hydraulic structures are apparent in many areas of the "palaces". However, the sources of water and the methods used for supplying the «palace» are only partially understood. Several wells have been discovered in the «palace» area itself, and a single well slightly to the northwest of the Little «palace». The latter, restored to its original depth of about 12.5 m and 1.0 m diameter, continues to furnish an excellent supply of potable water (Evans, 1921-1935).

The Knossos «palace», however, did not solely depend on the water of the wells. There are indications that the water supply system of the «palace» of Minos at Knossos, was initially dependent on the spring water of Mavrokolybos and later on the *Funtana* and the Mt. Juctas (Karidaki and Paradisi) springs. *Funtana* aqueduct, including the Scalani tunnel (1150 m in length), was constructed during the Roman period. Mavrokolybos, a pure limestone spring, is located at a distance of 0.5 km south of the «palace» at an elevation of about 100 m, whereas Knossos lies at an elevation of about 90 m from sea level. The water from the spring of Mavrokolybos was transported to the Knossos «palace» through pipes and conduits. That aqueduct is running along the western edge of the Vlikhia ravine (Evans, 1921-1935). The possible passage of the Mavrokolybos aqueduct is shown in Figure 2. Due to the small distance from the «palace» to the spring, it is possible that a sloping cannel was used as suggested Evans (1921-1935) and Hutchinson (1950).

Water supply in the «palace» was provided through a network of terracotta piping located beneath the «palace» floors. The pipes were constructed in sections of about 60 to 75 cm each. These pipes with their expertly shaped, tightly interlocked sections date from the earliest days of the building and are quite up to modern standards. They imply a practical knowledge of the hydraulic principle that water seeks its own level. The sections of the clay pipes resemble those used in Greece in classical times, though Evans considered the Minoan to have been designed more efficiently; each section was rather strongly tapped toward one end with the objective of increasing the rate of water flow, thus helping to flush any sediment through the pipe (Buffet and Evrard, 1950).

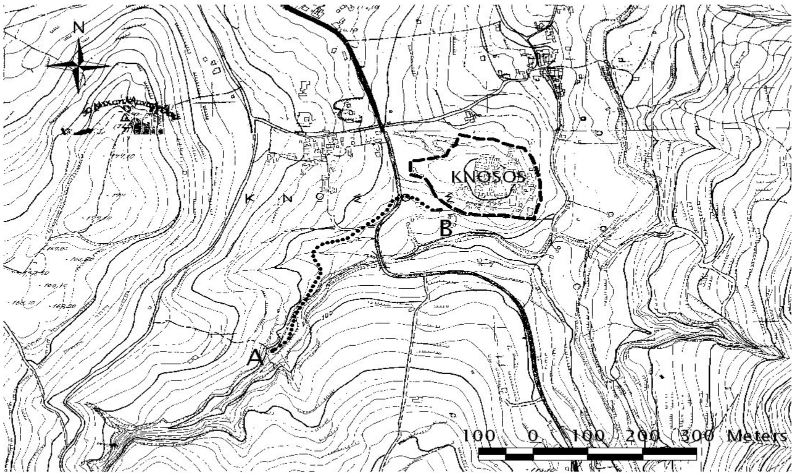

Figure 2 The possible passage of the Mavrokolybos aqueduct (A spring of Mavrokolybos).

Aqueduct of Tylissos

The aqueduct of Tylissos was also developed in the Minoan period. The remnants suggest that part of the aqueduct was constructed from closed pipes and part of it was as curved channel (Fig. 3). Parts of the Tylissos aqueduct are shown in Figure 4; the main conduit at the entrance of the house C (Fig. 4a) and secondary conduits and two cisterns (Fig. 4b). A stone made tank was used for pretreatment of water, mainly for the removal of sediments and/or suspended solids and the main cistern of cylindrical-shaped was used for the storage of water. Finally, a possible layout of the Tylissos aqueduct of a total length of 1.4 km, is shown in Figure 5.

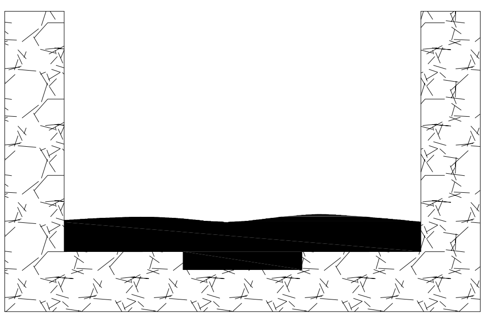

Figure 3 Cross section of water curved stone channel.

Aqueduct of Malia

The Minoan aqueduct was probably using the water of a spring located west of the hilly area of Profitis Elias 'Holly Hillock'. Water was supplied to the «palace» by closed pipes (terracotta pipes) or opened channels. A possible plan of the aqueduct is shown in Figure 6. The total length of the aqueduct up to point B is estimated to be 0.85 and 1.15 km with closed and opened conduit, respectively. A total length of 2.4 km is estimated when the water supply of House A located north of the «palace» and the port of Agia Varvara located northwest of the «palace» is included.

(a) (b)

Figure 4 Parts of the Tylissos aqueduct: (a) central conduit located at the entrance of the three villas and before the little cistern and (b) secondary conduit, small lithic cistern used for the removal of suspended solids of water before its storage into the main cistern.

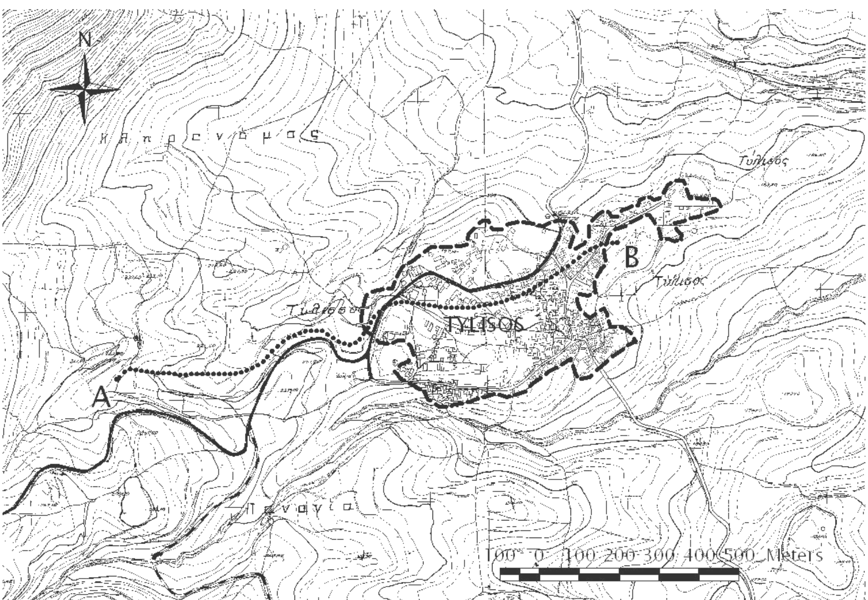

Figure 5 Possible layout of the Tylissos aqueduct (A spring of Agios Mamas).

Epilogue

Crete became the cradle of one of the most important civilization of mankind and the first major civilization in Europe. One of the major achievements of the Minoans was the advanced water management techniques practised in Crete at that time. The advanced water distribution systems in various Minoan "palaces" and settlements is remarkable, because no aqueducts are known before the Minoan era, whilst strong evidence suggests that this technology was developed by Minoans. Thereafter, aqueducts were used by the Mycenaens in continental Greece. In the Minoan «palace» of Knossos terracotta pipes for water distribution have been identified, suggesting that some aqueduct systems should exist. Similar terracotta pipes were found in some other Minoan settlements such as Tilissos, Gournia, and Vathypetro, as well as in Malia.

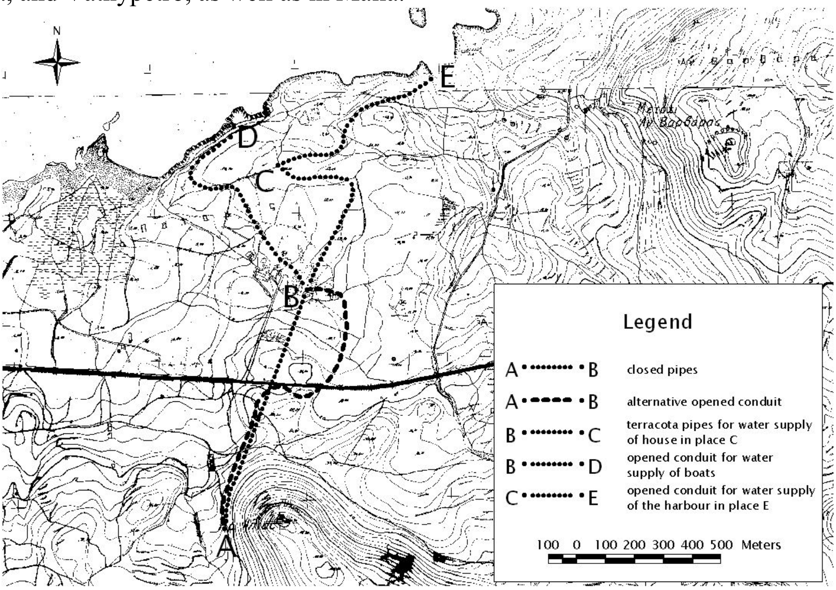

Figure 6 Possible plan of the Malia aqueduct.

Minoan technological developments in water management principles and practices are not known as well as other achievements of the Minoan civilization, such as poetry, philosophy, sciences, politics and visual arts. To put in perspective the ancient water aqueducts discussed in this paper, it is important to examine their relevance to modern times and to harvest some lessons learned. The relevance of ancient works will be examined in terms of the evolution of technology, the technological advances, homeland security, and management principles. The achievements of Minoans in dealing with the aqueducts and functional requirements of water distribution systems can only be compared to modern urban water systems, re-established in Europe and North America from the second half of the 19th century A.D. (Koutsoyiannis *et al*., 2006) until present day. Thus, with a few exceptions, the basis for present day progress in water transfer is clearly not a recent development, but an extension and refinement of the past.

Acknowledgments

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Aqueducts in the Hellenic Area during the Roman Period

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Abstract: Already during the antiquity, societies concerning about the environment and natural resources protection were led them to the construction of admirable technical work. Particularly, during the Roman period, the great interest for the city and the aspiration of covering biotic needs were connected with bright inspirations and maintenance perception in the territorial planning. The erection of great urban centres assembled a long run of population (urbanism) in combination with the technological achievements of the Roman period and, what is more, the Roman emperors need to create long-term projects-monuments, worthy of their fame, led to the manufacture of aqueducts and water supply/wastewater systems in all over the cities of the Roman territory. In the Hellenic area, during the Roman period, due to the extension of cities and the creation of new urban centres, the upgrade of urban landscape and the improvement of living conditions constituted a matter of peak and it was connected with an adequate water supply/wastewater system that was ensured with the manufacture of aqueducts, water towers and underground channels. The investigation of the criteria, which determined engineers' choice for aqueducts run, their methods of reconstruction, the process of reconstruction, the techniques and the materials they used, as these are revealed through the archaeological excavations and the relics of aqueducts' land departments testify the environmental approach and the maintenance perception of the Roman period.

Keywords Aqueduct; Hellenic area; Roman period.

Introduction

During the Roman period important human constructions have been demonstrated, combining mankind's wish to overstep the possible and at the same time, the need for food supplies which would cover their biotic needs. Thus, using the technical experience, functional constructions were created, that were covering the human needs, while, masterpieces were constituted. In Italy, emperors, landowners and the public fund were financing the manufacture of new public works. In inscriptions that have been found, ambassadors or "anthipati" were mentioned as the ones who financed for the erection of aqueducts, fountains, temples, etc.

The network of water supply and sewerage system during the roman period represents one of the bigger achievements in aquatic resources' management; simultaneously, it sparked off the progress of resembling sectors, such as the management of human potential, the conduct of personnel, the management labour, the organization of worksites, and the management of emergency.

Historical View of Aqueduct Technologies

Romans had urban habits and they got through enormous quantities of water supplies that they wastefully consumed in their residences, in the thermes and in rich epavlis, where anavritiria (fountains), swimming-pools, and immense gardens were allocated. Rome allocated 170 public "valaneia" 33 (B.C.), which increased to 856 until the late Roman years, and 14 aqueducts. Due to the fact that aqueducts were manufactured, Rome constituted the unique example of ancient city that its needs in water supply were completely covered. Until the 1st century A.D., it is calculated that 9 aqueducts brought water from the mountains around the city roughly 380,000 m^3/d.

At the same time, aqueducts were manufactured in roughly 200 other cities of the Roman Empire. Athens, Corinthus, Mitilini, Diracheio and Nikopoli were the most famous amongst them. Most of these aqueducts were made of stones, plinths or roman cement that was named "pozzuolana" (crumbled limestone and volcanic dust mixed together). Due to "Pax Romana", trade was flourishing, and the lead import from Spain and other provinces of the Roman Empire, made feasible the wide use of this material for the manufacture of water pipes, which consequently, improved immediately the quality of provided water and the resistibility of aqueducts construction.

Aqueducts construction was known in the Hellenic area. Several water supply and sewerage networks had been revealed in this specific area, even at the prehistoric period. In Knossos, the Minoans transported water by means of earthen pipes, from the regions of Kounaves and Archanes in the aqueduct of the city, and from there, in the residences. The Minies (1450 B.C.) invented an artificial tunnel (katavothra) for draining the Copais Lake. According to Babliakis (1997), the artificial katavothra that Minies constructed was quite the same as later water convection constructions. For the purpose of gathering water from mountains (ydromastefsis), advanced technical methods were used, and shafts, reservoirs and tunnels were erected. Typical examples of water convection works (collection of water with the method of ydragogi) were: (a) the water supply system of Strymi in Thrace (similar to the eypalineio orygma of Samos - Babliakis 1997), composed of tunnels, shafts and reservoirs (late 6th - early 5th B.C.); (b) the Eypalineio orygma at the mountain Ampelos, composed of a tunnel 1,040 m length and 1.80 x 1.80 m cross-section into which, along a water pipeline was created so as to transport the water from springs to the city of Samos (540 or 525 B.C.); (c) the aqueduct of Olynthos at Chalkidiki (late 5th century B.C.); and (d) the two aqueducts of 4th B.C. century in the area of Pangaio, in which the total length of pipes was 20 and 14 km, respectively.

Romans settled in the Hellenic area, participated in the social and economic life of cities and contributed for the accomplishment of public benefit works. In Athens, in Corinthus and in Dyrrachio, the emperor Adrianos manufactured aqueducts, from which, in particular the one of Corinthus, was connected with luxurious krines and baths. Later Alexandros Seviros repaired the aqueduct of Dyrrahio, and Antigonos Efsevis built an aqueduct in the town of Odyssos.

Aqueducts in the Hellenic Area

At 30 B.C., in southern Epirus, Octaves Augustus founded a city, which was called Nikopolis, for people to remember the naval battle of Aktio, which brought victory to Romans. With the purpose of covering the population needs that after a relatively shortly period reached the amount of 300,000 residents, an enormous aqueduct capable to cover the water needs of the city for a period of several months, was manufactured. The aqueduct was

50 km long, in the Filippiada, near the sources of Louros, from where the water was transported to the city of Nikopoli, and at the same time, in the aqueduct of Nymfaio. For the construction of the aqueduct three different types of conductors were used by the craftsmen: (a) usually the water was transported through an underground canal dug in the soft soil, or in certain cases, curved in the hard rock and covered with constructed arces quite impervious to water, with square openings of ventilation and cleaning at intervals; (b) in certain regions, as that one of Kokkinopylo, particularly capable technicians of the roman period were forced to manufacture a tunnel. At this point, it is important for us to mention, the impressive technique that they devised for regions where they were obliged to drive a water tunnel through a mountain. By using fire and water alternatively, they expanded the rock, and they went on to abruptly contract it. As a result they usually caused a crack and partly a detachment. With this way, working in parts and advancing to the interior, they achieved complete drilling; and (c) in order to surmount natural obstacles (i.e., rivers) or to throw a bridge across valleys, as in the area of Agios Georgios, they created arched bridges in which water flowed free (canal bridges), supported by lines of pessaries, built with the characteristic plinths- built walls, and connected with wall- plaster. I would like to emphasize that canal bridges had a specific inclination on the grounds that water rolled regularly into pipes, in the superior department of arches. Lower parts of pessaries were based on pedestals. According to Makris (2004), despite the fact that canal bridges had been manufactured for a specific use (transport of water); nevertheless, they were at the same time narrow and lighter than usual bridges. Pantermalis (1974) characterized these arched bridges, which supported built tubes of aqueducts, genuinely objects of virtue.

During the 2nd century A.D. another aqueduct was erected, in the island of Lesvos, whose relics can somebody visit in a distance of 600 m from Moria, in an area 6 km from Mitilini, as well as in gorges of central Lesvos. It transported water from the sources of the region Agiassos and, specifically, from Megali Limni of Olympus and from other sources, at a total length of roughly 22 km, in the city of Mitilini. For its construction, specialists followed the usual for the Roman architects' technique, the simple and elegant arches, placed in successive levels that ensured the water's transportation. Grey marble pessaries, emanated from the neighboring quarry, were successively placed, and they were linked with three lines of arches, from which, seven arches from the intermediate and one from the lower line, are saved. The artificial channel was found in the top of the bridge and was supported by plinths-built arches. It was calculated that the part of region Moria had a length of about 170 m and a height of 27 m, while it allocated seventeen arches.

In the area of Attica, drought, which had already started from the prehistoric period, led the residents to try, and ultimately find ways for stable water supply. Thereby, they created many aqueducts that drove water in fountains. In Athens and Piraeus, a lot of aqueducts existed, with main, auxiliary or regional operations. For the irrigation of the city, they made underground water- mains tens of thousands meters length or they curved galleries in the rocks already from the prehistoric years. Well known aqueducts was the one of Pelasgoi (at Hymettus), the aqueduct of Thiseas (at Penteli), the Peissistration (2.8 km) -Babliakis (1997) believed it was a water convection construction, and others at the hill of Pnyka, at Thissio and at Loutro.

Under Amalia Street, part of an aqueduct made with the method of arches, came to light, when big worksites were created during the preparation period of the Olympic Games in Athens. What is more, three valaneia appeared, one of them in the riverbed of Iridanos, another one with a lot of cisterns in the contribution of Amalia with Vassilissis Sofias street, and a last one inside the ground of new Museum of Acropolis. In the road of Santarosa, relics of hydraulic systems, with water traps (freata) and cisterns were revealed. They were joined together with underground tunnels, and they functioned as part of a water supply network, from classic, up to late roman period.

In the ancient municipality of Athmonos (Olympic Stadium), water supply was difficult to ensure, because the water horizon was extended in-depth and wells' manufacture, was disadvantageous. During the Roman period (1st - 2nd century A.D.) reserves of water supplies had been obtained by the erection of enormous cisterns in the region (Olympic stage). Inside them water, was transported from surface sources of Kifissia, to the region of Amaroussio, via big earthen water pipes for the water supply of residents and the irrigation of fields. The cisterns at Lassani, (southern side of Peléka), in Artemidos road (Journalistic Village) and in the northeastern and in west accordingly Olympic Stage were big in size; one of them was rectangular in two levels gradient arrangement, (Spyros Louis street, south-western of Stadium) constructed by earthenware inlays that composed the floor mosaic, walls plastered with hydraulic mortar, descendent stairs, and a water trap. Skylardi (2006) assumed that perhaps, these cisterns were accommodated with a lightly elevated roof.

The conductors of water supply, relics of which were discovered throughout the works made for the Olympic installations in Marousi, were manufactured from rings, made from two horseshoe pieces that were adapted the one inside the other. At intervals, square and built shafts had been made, giving the possibility of access for cleaning and controlling conductors.

Perhaps, the most creditable hydraulic achievement in Roman Greece, after the Aharnikos drain at 4th century B.C. is the Adrianeio aqueduct in Athens, which construction began from the emperor Adrianos and was completed by Antonios Efsevis (125- 140 A.D.) (It is known from the sigh curved on the architrave of the entrance in front of the cistern). It is considered as a Greek work, manufactured during the Roman period. It was assembled drinkable water, taken with ydromastefsi from the sources of Parnitha and Kifissia, via conductors of "free flow' with a length of 20-25 km in the cistern which had been built at the area of current Kolonaki, in a depth of 2 m (dimensions 26.10 x 9.10 m and capacity 500 m^3). From that particular cistern water was distributed to the whole city of Athens. Romans, in most of their aqueducts, used to manufacture cisterns near the sources before they begun the transportation of water, so as the principle of communicating vessels was in force, they maintained constant flow and pressure in their aqueducts. The transport of water became from the known vaulted departments that with bent 1:1000 ensured constant flow.

The Adrian ion aqueduct passed from the Municipality of Acharnes, of Metamorphosis, of Maroussi, of N. Ionia, of N. Philadelphia, and Ambelokipi and, as in Nikopoli, it was constituted either by underground built conductors or tunnels carved inside a rock, and constructed land departments (valley bridges), that are preserved till today in the N. Ionia (Kalogreza), in the Olympic Village (two sectors) and elsewhere. Preserved underground departments, exist in Marousi, in the plain, in-depth of 20 m. - manufactured in a rectangular shape, with arched cover, with width of 0.70 m and height of 1.60 m Per 35 m, shafts of cleaning and ventilation were created, square or circular cross-section. It is remarkable that, the aqueduct was made with such a way that would collect the water not only from the initial source, but also from others along its original lining. For this reason supplementary tunnels or smaller aqueducts were created, branches of the water main, which transported water of other springs (Halandri, Kokkinara, Kithara Monomati). A relatively unknown aqueduct was found in Crete, in ancient Lappa (current Argiroupoli, Prefecture of Rethymno) and was dated in Oktavius era. The water from the sources of Kastania and Kollita, one hour long from the settlement, were drained with built tubes in a cistern of 600 m^3 (25 to 6 to 7 m height), manufactured at a high point outside the city. The water cistern provided the city and the thermae (The apartments for the bathers and two other rooms framed a round room with diameter of 18 steps), one of the city's most important structures.

Another one aqueduct is that of Patras that is dated in the Roman period perhaps in the Augustus era and it was the first systematic aqueduct of the city. Close to the village of Romanos stood the sources of "Neromana" of torrent Diakoniaris. There, the Romans, in distance of 10 m from the sources, in the beginning of the gorge, they constructed a wall, with a view to create an artificial lock, part of whose is saved up to today in the base of current manufacture. From there, water, by a stone-built underground tube or through lines of arches, which bridged valleys and ravines, (6.5 km length) was directed in the dense city (its bigger part is saved today under the Byzantine castle). Apart from the central covered tube, branches were also existed that lead to various directions, with smaller cross-section covered ones. Relics of a really strong wall are saved into the riverbed, in a distance of about 20 m from the current cistern and in other places.

Herodis Atticos constructed a monumental drainage in Olympia, Nymfaio (155 A.D.) that supplied with water the sacred area and the surrounding region southern from Alti. It was in the substance a votive offering allocated two cisterns, one oblong rectangular and one semicircular, at a higher level than the first one (externally, the semi circular cistern was used as a high pedestral for the promotion of members of the emperor "oikos" and the family of Herodis).

Conclusions

During the Roman period ambitious constructions were created, with the purpose of promoting the Roman emperors; and, at the same time, covering the needs of province and big urban centres. The issue of permanent water supplies occupied the emperors in particular, who created such an administrative and economic system, that it served and facilitated the construction of water supply and wastewater systems in the hub and the provinces of the Roman territory.

In Greece, the problem of water shortage was already intense from the prehistoric period, and lots of effort was made to find resolution through the erection of technical works. At Roman ages, systematic construction and maintenance of aqueducts and networks of water supply is observed, in the various centres of Greece, using concrete techniques and materials for the construction. This phenomenon was due to the complete incorporation of the Romans in the economic and social life of urban centres and in the sustainable perception of the cities and their various operations, as for example the water supply and the sewerage.

In the Hellenic area, concrete process was used for the aqueducts; techniques and ways of reconstruction were applied, which were legible in most of the constructions of the particular period. At the beginning, they chose the sources that were usually found at a high point, up to hills or mountains. The distance between springs and settlements was of no particular importance, as the craftsmen were in place to overflow natural obstacles and to transport water from great distances. Essential element of an aqueduct was the cisterns, which were constructed: (a) near the source; (b) at a region outside the city; and c) in various points of the urban network. They served the creation of water reserves and guaranteed that the water flow and pressure would be constant.

The prevailing way of gathering water was ydromastefsi (see analysis of this system in Babliakis, 1997), that gave also (a) the possibility to collect water from other sources all along the conductors and (b) the possibility to supply water to other, except the final destination, points, with the creation of sinks. In order to transport water, underground ditches or underground constructed (stoned or with plinths) drivers, tunnels and terrestrial water bridges were used. Ditches were dug in the ground or curved in hard rock and earthen drivers were placed inside them. The underground drivers allocated shafts of cleaning and ventilation.

The tunnels were created (a) by the technique of abruptly expansion- contraction of rocks and the detachment of parts, (b) by digging, or (c) by curving the rock. The canal bridges were built with plinth walls, connected with wall plaster, they were supported by built or marble pessaries and they had arches, usually in their upper part, or in successive levels, which retained the covered channel of water supply. They had bent, allowing the water's free flow, and they also bridged valleys and gorges.

Summarising, we realise that the aqueducts and all the other great works of the times, reflect the memorial of force and the supremacy of the Roman Empire, which thrived in all over the world, and constituted to the historical evidence of maintenance perception of the era. The reflection of Romans on the natural resources of cities is proved exceptionally current today, as it is related to the subjects of priority like the viability of the anthropogenic and natural environment, and the adoption of institutional directions aiming to guarantee a better quality of life.

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Roman Aqueduct and Hydraulic Engineering: Case of Nîmes Aqueduct and its Pont du Gard Bridge

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Abstract: Romans are considered as the greatest aqueduct builders of the ancient world, despite quanta systems were in use in ancient Persia, India, Egypt, and other Middle Eastern countries thousand of years earlier. Based on history documents and civil engineering studies, this paper summarizes hydrology and hydraulics engineering techniques developed by Roman Engineers. The study case is the Nîmes Aqueduct and its Pont du Gard Bridge, the most intact aqueduct bridge remaining today. Despite the existence of superb ruins and conducts' frames, little is known on the hydraulic engineering of these Roman aqueducts and on their water supply and flow rates. This paper explains hydraulic structures and regulations used. It demonstrates the expertise of Roman Engineers on hydraulics of open channel flows.

Keywords Hydraulic; hydrology; Pont du Gard Bridge; regulation; Roman aqueduct.

Introduction

Perhaps more than any other single factor, water determines where cities grow and how they develop. Water-too much, too little, or in the wrong places-can make or break a city's fortunes. Nonetheless, water can to a degree, be controlled, manipulated, and bent to human will (Rinne, 2000).

Aqueducts are man-made conduits for carrying water (Latin *aqua*, "water," and *ducere*, "to lead"). In a more restricted sense, they are structures used to conduct a water stream across a hollow or valley. In modern engineering, "aqueduct" refers to a system of pipes, ditches, canals, tunnels, and supporting structures used to convey water from its source to its main distribution point. Although the Romans are considered the greatest aqueduct builders of the ancient world, quanta systems were in use in ancient Persia, India, Egypt, and other Middle Eastern countries thousand of years earlier. The elaborate systems that served the capital of the Roman Empire and the main cities, however, remain major engineering achievements. Over a period of 500 years -from 312 B.C. to A.D. 226- 11 aqueducts were built to bring water to Rome only from as far away as 92 km (Frontinus, 1925). Their construction was a huge task, often performed by the army under the guidance of military hydraulic engineers. Some of these aqueducts are still in use (Carthage, in Tunisia, and Mons, in France). Roman aqueducts were built throughout the empire, and their arches may still be seen in Greece, Italy, France, Spain (Segovia), North Africa (Cherchel, Algeria), and Asia Minor (Aspendos, Turkey). Roman aqueducts supplied water to cities for public baths and toilets in addition to public fountains (Fabre *et al.*, 1992; Barghouth and Al-Sa`ed, 2006). Water flowed to the city by gravitational force and usually through a series of distribution tanks. Frontinus (1925) reported that water was not generally stored and the excess was used to flush out sewers. Rome's famous fountains were supplied in this way.

The Nîmes aqueduct and its Pont du Gard Bridge

At least 20,000 m^3 of water were brought in daily to the Roman town of Nemausus (Nîmes) via an impressive aqueduct system of 50 km from springs at the Fountaine d'Eure in Uzès. Built by Roman engineers throughout the 1^{st} century A.D., the full aqueduct route had a gradient of 34 cm/km (1/3000), went around the east side of the higher Massif Central, descending only 17 m vertically in its entire length, through a series of some 35 km of tunnels. It snaked its way through the brush, skirting the hills or passing through them by way of underground canals, crossing over valleys through overhead constructions. The Pont du Gard, the most intact Aquaduc Bridge remaining today, spans the Gardon which flows along the bottom of a valley deeply carved in the surrounding plateau. This peaceful creek, where bathing can be so pleasant in summer, can transform itself into a destructive torrent following violent autumnal rains, named "*Gardonade*". When water reached Nimes, it was stored in a large holding tank called a *castellum*, from which it was piped to all parts of the city (Fig. 1 and Pic. 1). A utilities work, le Pont du Gard is also a work of prestige, intended to show the superiority of the Roman civilization, then at the pinnacle of its power and glory (Athena Review, 2004).

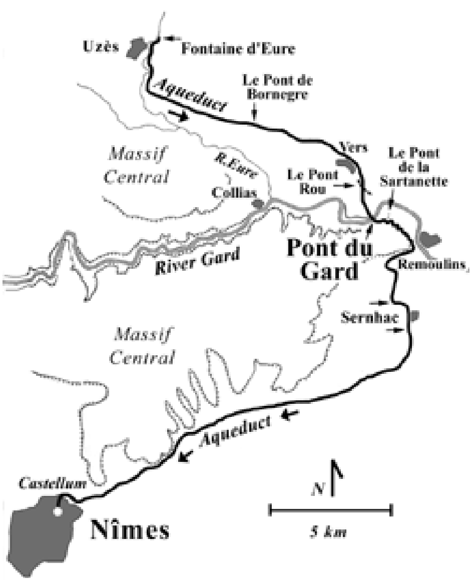


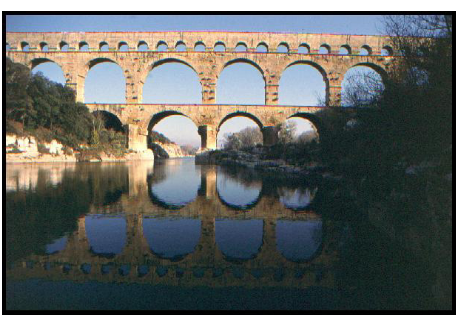
Figure 1 Map of the Roman aqueduct to Nimes (Athena Review, 2004).

Picture 1 Photograph of Nimes castellum divisorium (Schram, 2004).

Admirably integrated into a natural site that has preserved its wild charm, the Pont du Gard fascinates the visitors with its elegance and majesty. Two thousand years after its construction, this ancient edifice is still a veritable masterpiece, as much for the technical prowess involved as for its simple beauty. It attracts more than a million tourists each year; and is the 2^{nd} most visited provincial monument in France. This monument is registered as a World Heritage of Man by UNESCO since 1985. Its classification criteria are : C (i) (iii) (iv), where C=Cultural criteria; (i) to represent a masterpiece of human creative genius; (iii) to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared, and (iv) to be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates significant stage in human history (UNESCO, 2006).

From the 4th century onwards, its maintenance was neglected, and deposits filled up to two thirds of the conduit space. By the 9th century, it became unusable and people of the area started using its stones for their own purposes. However, the majority of the Pont du Gard remains remarkably intact. From the Middle Ages to the 18th century, the aqueduct was used as a conventional bridge to facilitate foot traffic across the river. The pillars of the second level were reduced in width to make more room for traffic, but this jeopardized the stability of the structure. In 1702 the pillars were restored to their original width in order to safeguard the aqueduct. In 1743, a new bridge was built next to the arches of the lower level, so that the road traffic could cross on a purpose-built bridge. The aqueduct was restored in the 18th century, when it become a major tourist sight, and was restored again in the reign of Napoleon III in the mid-19th century. In 1998 the Pont du Gard was hit by major flooding, which caused widespread damage in the area. The road leading up to it and the neighboring facilities were badly damaged, although the aqueduct itself was not seriously harmed (Wikipedia, 2004).

Built on three levels, the Pont is 49 m high and the longest level is 275 m long. The lower level has 6 arches, 142 m long, 6 m thick and 22 m high. The middle level has 11 arches 242 m long, 4 m thick and 20 m high, whereas the upper level has 35 arches 275 m long, 3 m thick and 7 m high. On its first level, it carries a road and at the top of the third level, a water conduit, which is 1.8 m high and 1.2 m wide and has a gradient of 0.4% (Wikipedia, 2004). It was constructed entirely without the use of mortar. The aqueduct's stones -some of which weigh up to 6 tons- are held together with iron clamps. The masonry was lifted into place by block and tackle with a massive human-powered treadmill providing the power for the winch. A complex scaffold was erected to support the aqueduct as it was being built. The face of the aqueduct still bears the mark of its construction, in the form of protruding scaffolding supports and ridges on the piers which supported the semicircular wooden frames on which the arches were constructed. Markings left by the original builders can also be seen, indicating the positions in which the dressed stones were to be placed; for instance, *FRS II* (standing for *frons sinistra II*, or "left front 2") (Athena, 2004). Eloquent pictures let appreciate the technical prowess demonstrated by the Roman engineers (Pics. 2 and 3).



Picture 2 Global overview of Pont du Gard.

Picture 3 Scaffolding supports and upstream cut-water.

Aqueducts Engineering

For most of their length, the early aqueducts were simply channels bored through the rock, from the water intake in the hills almost to the distribution cistern in the city. The depth of the channel below ground varied so as to maintain a constant, very shallow gradient (less than 1/200) throughout the length of the aqueduct; vertical shafts were bored at intervals to provide ventilation and access. Only in the final stretches was the conduit raised on arches, to give a sufficient head for distribution of the water within the city. In order to keep the gradient constant, the aqueducts took a roundabout route, following land contours and heading along spurs which led towards the final city. As time went on, Roman engineers became more daring in the construction of high arches to support the conduits across valleys and plains. Closed pipes were occasionally used to cross valleys by the "inverted siphon" method. But this system (Fig. 2) was costly, as it required lead pipes (lead had to be imported from Spain or Great Britain) and it was difficult to make joints strong enough to withstand the pressure; so arches were far more common (Schram, 2004).

Except where closed pipes were used, the channel in which the water flowed was just over 90 cm wide and about 180 cm high, to allow workers to walk throughout its length - when the water supply had been cut off -for inspection and maintenance. Every now and then there was a sedimentation tank, where the flow of water slowed down and impurities were deposited. When water reached the city, it flowed into huge cisterns *(castella)*, situated on high ground, from which it was distributed through lead pipes to the different areas of the city. Part of the water was for the emperor's use, part of it was sold to rich citizens, who -for a price- could have it piped to their private villas, but much of it was available to the populace through a network of public fountains, which were located at crossroads throughout the city, less than 100 m apart (Rinne, 2000). Despite the existence of superb ruins and conducts' frames, little is known on the hydraulic engineering of these Roman aqueducts and their water supply and flow rates. Some answers may derive from studies of their catchments and hydrology.

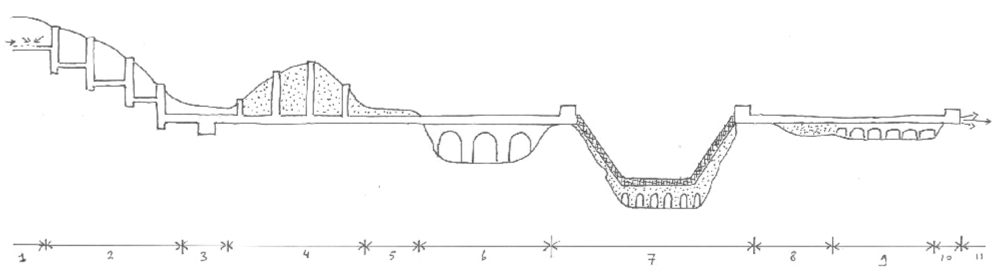


Figure 2 Figure of the Roman Aqueduct water supply system: (1) Source (in this case: infiltration gallery); (2) Steep chutes (in this case: dropshafts); (3) Settling tank; (4) Tunnel and shafts (putei); (5) Covered trench; (6) Aqueduct bridge; (7) (inverted) Siphon; (8) Substruction; (9) Arcade and culverts; (10) Distribution basin/castellum divisorium; (11) Water distribution (in this case with (lead) pipes into the town) (Schram, 2004).

Catchments

There are many ways to get (ground) water into an aqueduct. The most common ones were: spring boxes and well intakes, infiltration galleries, river intakes and dams. The hydrology of some catchments areas supplying Roman aqueducts has been investigated at several locations in France. For example, the 'source de l'Eure' at Uzes supplying the Nimes aqueduct, still in use today, had a catchments area of about 45 km². Flow rate measurements show an average daily discharge of about 29,600 m³/d, with a maximum of 143,400 m³/d and a minimum output of 10,800 m³/d (Fabre *et al.*, 1991). Overall, recent hydrological data show large variations in stream flows. During dry periods, the daily flow was typically less than 10% of the maximum discharge. While the flow rates during Roman times are unknown, it is plausible that hydrological variations were similar to present trends. This suggests that the aqueducts conveyed relatively low flows during dry periods (Leveau, 1991).

Inverted siphon

When a valley was too deep or too big for a bridge, a siphon was built: the pressure forced the water down and up again on the other side, to a level slightly lower than at the inlet. The aqueduct water ran into a distribution tank, often called header basin. A row of parallel (lead) pipes (f.e. 9 ones) came out from the other side, continuing down one side of the valley, crossed the bottom on a so called 'venter' bridge and climbed uphill to the 'receiving' basin from which water continued in the classical way to its destination (Schram, 2004).

Drop structures and stepped cascades

They have been used for over 3,000 years. In particular, Roman engineers designed stepped spillways successfully in Tunisia, Syria, Spain, and Iraq. Although most aqueducts had a mild slope, there were also some steep sections. Three designs of steep sections were commonly used: smooth steep chute, stepped chute, and cascade of dropshafts (Fig. 3) (Chanson, 2004). The latter is most unusual, even in modern times. A dropshaft is a vertical shaft connecting two canals at different heights. Such a structure is commonly used in sewer systems today. Roman dropshafts were characterised by a deep pool and a relatively wide shaft, compared with modern designs. A recent study showed that the Roman dropshaft design was most efficient.

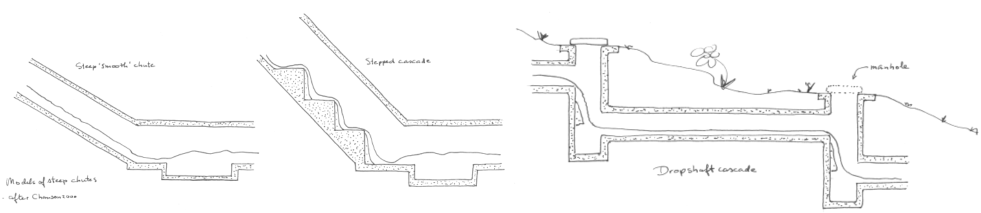


Figure 3 Smooth and stepped chutes, cascade of dropshafts structures.

The Roman hydraulic and civil engineers also devised cascades of dropshafts, i.e., a succession of dropshafts installed inline. The construction of a dropshaft cascade was a very difficult task, with numerous subterranean conduits, connected by vertical shafts, in a steep topography. Even in modern times, the task would be a major engineering challenge. The successful operation of dropshaft cascades for centuries demonstrates sound design and a solid hydraulic experience, if not expertise. Two shapes of dropshafts were typically used, rectangular and circular. At Valdepuentes, Spain, one dropshaft cascade included three shafts with an outlet canal at 90° with the inlet canal direction. Such geometry was rare, although there were possibly five shafts with such a disposition at Montjeu, France. It was a very efficient hydraulic design in terms of energy dissipation. Until recently, it was thought that the dropshafts acted as energy dissipaters and sediment traps. A new re-analysis of Roman dropshaft hydraulics was conducted with physical model tests performed at the University of Queensland, New Zealand. The results demonstrate that the vertical dropshafts could be very efficient energy dissipaters and re-oxygenation structures, with appropriate flow conditions. Most aqueducts were covered along their entire length, limiting the gas transfer at the free-surface and the downstream waters were low in dissolved oxygen content, unless re-oxygenation dropshafts were installed. Steep chutes had a high potential for sediment transport and scour (Chanson, 1998).

Stilling basins

There is little information available on the hydraulics of supercritical flows in Roman aqueducts. Some believe that these aqueducts were designed and operated with sub-critical flows, and that no energy dissipation device was required. However, Roman aqueducts included some very-steep sections (e.g. bed slope up to 78%) operating with supercritical flows. Both 'smooth' chutes and stepped cascades were used. The presence of steep chutes associated with torrential flow regime implied the occurrence of a hydraulic jump at the downstream end. An analysis of tail water flow conditions highlights the presence of unfavourable flow conditions: undular and oscillating jumps. Stilling basins were sometimes introduced to dampen the downstream wave propagation (Chanson, 2003).

Culvert

A culvert is a short conduit to allow stream flows beneath an embankment. The Romans built a number of culverts beneath major roads and aqueducts. An impressive culvert was the multi-cell box culvert underneath the Nimes aqueduct, downstream of Pont du Gard. Unique features of the culvert were a multi-cell design, large size and a modern hydraulic design. The culvert could handle 4.2 m^3/s, almost 12 times the maximum discharge capacity of the Nimes aqueduct. In the barrel, the flow velocities were about 2.5 m/s for a 3 m^3/s flow rate. This structure demonstrates that Roman engineers understood hydrology and runoff, and that they had solid hydraulic design experience (Chanson, 2002a).

Aqueduct Regulation

Regulation basins

Several aqueducts were equipped with regulation basins and sluice gates, installed along the canal. Most of these were equipped with a series of gates and an overflow system. The regulators operated between the source and the city (Schram, 2004).

In pipes, valves and taps are the most common types of regulatory devices. In open channels, gates (or sluices) are more appropriate. The two basic types of sluice gate are the undershoot and overshoot gates. With undershoot, or underflow gate, the outflow is delivered underneath the gate edge. The outflow may be a '*free*' jet or a '*drowned*' flow. In the former case, the jet flow is supercritical (torrential) while the flow upstream of the gate is tranquil (sub-critical). In the latter case, the flow is sub-critical downstream of the gate. At an overshoot, or overflow gate, the water discharges over the upper edge of the sluice. For low tail water levels, the overflow forms a free-falling nape. For high downstream water levels, the jet is drowned. There is a major difference between the hydraulic operation of undershoot and overshoot sluices. With an overshoot gate, a small variation of the upstream water level induces a large change in discharge. At an undershoot gate, a change in upstream water level is associated with a smaller variation in flow rate. For underflow and overflow gates, the relationship between the flow rate (Q) and the upstream water level (d) satisfies respectively:

$Q \propto \sqrt{d_1}$ Undershoot sluice $\quad Q \propto \sqrt{(d_1 - H)^3}$ ` Overshoot sluice

d_1 = upstream water depth; H = weir height.

Practically the overflow gate is commonly used in spillway designs and overflow systems. A small increase in upstream water level induces a large increase in flow rate. An underflow sluice is better used to control the downstream flow rate (Chanson, 2004). Flow regulation devices were a necessity (a) to prevent overflows and unsatisfactory aqueduct operations during wet seasons, (b) to provide optimum flow conditions (minimum energy losses and maximum flow rates), and (c) to supply satisfactorily the city during low-flow seasons. Control structures were a necessity to prevent improper flow operation that could result in major scour, damage, and destruction. During wet periods, large flow rates could overflow the sidewalls, or exert pressures on the rood of covered sections. Overflowing waters could wash away foundations in soft soils. Altogether control of the aqueduct flow was required to prevent damage to the aqueduct and disruption of the water supply. Chanson (1998) highlighted the existence of steep sections. The operation of these chutes was characterised by supercritical (torrential) flow motion. Both upstream and downstream control structures had to be installed. That is, upstream of the steep chute and downstream of the dissipation structure. Supercritical flows can only be controlled from upstream, while sub-critical flows are best controlled from downstream. Sluices and control structures had to be a design feature of the aqueduct. Optimum locations included at the source of the aqueduct, upstream of steep sections, upstream of bridges and tunnels and downstream of flat sections. In term of gate design, in-stream gates, installed in the main aqueduct channel, were undershoot sluices to deliver reasonably constant flow rates. The gates of overflow systems were most likely an overshoot gate type (Chanson, 2002b).

The regulation basin located upstream of the aqueduct-bridge was equipped with an overflow channel and an outlet feeding the bridge canal. Slots for sluice gates were found at the start of the outlet(s) and at the overflow (Fabre *et al.*, 1991). The bridge canal intakes were equipped with an undershoot gate system while the overflow systems were equipped with overshoot gates. For each aqueduct, the sluice gate operations at the canal intake were investigated for flow rates up to the maximum. Hydraulic calculations conducted for the Nimes aqueduct demonstrated that the undershoot gate openings had to be small, between 3 and 12 cm. For larger openings, the flow was not to be affected by the gate presence. This type of operation implied fine gate opening adjustment systems to enable precise flow regulation (Chanson, 2000).

Type of regulation

Water supply operation can be based on two different techniques - on/off (i.e., 100% or 0%), or a dynamic flow regulation. Dynamic flow regulation is commonly used in modern times and it involves a series of operations to respond constantly to user demand. In Roman times, this type of operation would have required an engineer in charge of the regulation, gangs of workmen operating the gates and a good communications system along the aqueduct canal (Chanson, 2002b). At Pont du Gard, it is believed that the regulation system was built to prevent spillage over the bridge canal sidewalls and in the downstream section. Fabre *et al.* (1991) highlighted that the average gradient between Pont-du-Gard and further downstream was very small ($S_o = \sin\theta = 0.007\%$). The very flat geometry created a backwater effect causing higher water levels in the channel for identical flow rates. Indeed the water depth is inversely proportional to the cube of the bed slope (d./. 1/($\sin\theta^3$) where d is the flow depth and θ is the angle between the invert and the horizontal).

There is still some uncertainty regarding operation of the gates. Were the gates operated only under on/off (i.e., 100% or zero flow rate) or were fine adjustments of the gate position performed regularly (e.g. daily), the first type operation requires only one gate opening. Regular inspection and maintenance check are needed only for the overflow channel. In addition, the aqueduct channel had to be cleaned regularly for water sanitation. The simplest procedure was to perform the cleaning when the aqueduct was empty, by flushing some water and the debris up to a pit to clean it. This technique is still used today to clean hydraulic laboratories worldwide. The second type of operation implies a regular transfer of information from the city water engineer to the gate operators, and the suitable adjustment of the gate opening by the caretaker(s). It is conceivable that this operation was done on a daily basis (i.e., daily gate position adjustment). At Nimes (bassin de la Source de l'Eure, and regulator upstream of the Pont du Gard), overflows and the outflow channels were equipped with a double groove system, suggesting two vertical gates at each location. In modern dam outlets, it is common to design two gates. The upstream gate operates fully-open or fully-closed. Its main purposes are to dewater the downstream outlet, allowing maintenance, and to act as a safety gate if the second gate fails. The downstream gate is a regulation gate used to control the downstream water release (Chanson, 2002b).

Frontinus (1925) indicated the need for gangs of maintenance workmen. Outside of the city of Rome, repairs demanded "*prompt attention*". He further classified repair works as either conducted "*without stopping the flow of water, or such as cannot be made without diverting the flow*". Frontinus' statements indicate clearly that the aqueduct flow could be stopped completely, although he added that the aqueduct flow should "*be out of commission as few days as possible*". Bossy *et al.* (2000) showed the existence of several regulation basins along the Nimes aqueduct suggesting the possible interruption of the flow in several locations. They hypothesised further a daily gate operation for a dynamic regulation of the aqueduct flow with water storage at night (Frontinus, 1925).

Aqueducts Evolution through Ages

For centuries, an army of laborers was constantly at work, under the supervision of the *curator aquarum*, extending and repairing the water system. But in the 6th century A.D., as power of the Empire began to decline, the Goths besieged Rome and cut almost all the aqueducts leading into the city (the only one that continued to function was that of the *Aqua Virgo*, which ran entirely underground.). For most of the Middle Ages aqueducts were not used in western Europe, and people returned to getting their water from wells and local rivers.

Modest systems sprang up around monasteries, and, by the 14th century, Bruges (Belgium), with a large population for the time (40,000), had developed a system utilizing one large collecting cistern from which water was pumped, using a wheel with buckets on a chain, through underground conduits to public sites. Major advances in public-water systems since the Renaissance have involved the refinement of pumps and pipe materials. By the late 16th century, London had a system that used five waterwheel pumps fastened under the London Bridge to supply the city, and Paris had a similar device at Pont Neuf that was capable of delivering 454 L/min. Both cities were compelled to bring water from greater distances in the following century. One of the major innovations during the 18th and 19th centuries was the introduction of steam pumps and the improvement of pressurized systems. One benefit of pumping water under pressure was that a system could be built that followed the contours of the land; the earlier free-flowing systems had to maintain certain gradients over varied terrain. Pressurization also created the need for better pipe material.

Wood pipes, banded with metal and protected with asphalt coating, were patented in the United States in 1855 and could withstand pressures up to 12 Kg/cm^2. Before long, however, wood was replaced first by cast iron and then by steel. For large siphons (conduits that draw water from elevated sources under the pressure of siphoning), reinforced concrete became the preferred construction material early in the 20th century. Modern aqueducts, although lacking the arched grandeur of those built by the Romans, greatly surpass the earlier ones in length and in the amount of water that they can carry. Aqueduct systems hundreds of miles long have been built to supply growing urban areas and crop-irrigation projects. The water supply of New York City comes from three main aqueduct systems that can deliver from 50 x 10^7 L of water a day from sources up to 190 km away. The aqueduct system in the state of California, however, is by far the largest in the world. One major project, which has been under construction since 1960, will bring water from the northern part of the state some 960 km south to the Mexican border and is designed to yield 36 x 10^{10} L/yr (Frontinus, 1925).

Conclusion

The Roman engineers who designed and built the major aqueducts in Roman Gaul and Germany were contemporary to Hero of Alexandria who understood the fundamental principles of conservation of mass and of momentum in fluid mechanics. Despite the lack of written evidence, indicating that Roman engineers knew Hero's works, the soundness of design and successful operation of their aqueducts for centuries demonstrated their "savoir-faire" and technical expertise. Catchments and structures used, such as inverted siphon or stepped cascades were presented.

Roman engineers mastered hydraulics of supercritical flows, as they used stilling basins to dampen the downstream wave propagation. The structure of culverts demonstrates that they understood hydrology and runoff. They applied the hydraulic operation of undershoot and overshoot sluices for a precise regulation of the flow of aqueducts, as the bridge canal intakes were equipped with an undershoot gate system while the overflow systems were equipped with overshoot gates. Fine adjustments of the gate position were performed regularly. All these hydraulic systems demonstrate that they had solid hydraulic design experience and master the hydraulics of open channel flows, still in use today.

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Water Management in Minoan Crete, Greece: The Two Cisterns of one Middle Bronze Age Settlement

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Abstract: The two earliest structures of Minoan Crete that may be considered as large cisterns were both built in the first half of the 2nd millennium B.C. (the time of the first Minoan palaces) at Myrtos-Pyrgos (Ierapetra). A considerable feat of engineering and social management, they remain a most unusual attribute of a Minoan settlement, all the more so since the Myrtos river is/was available to supply water at the foot of the hill of Pyrgos. This paper presents these cisterns, briefly, in terms of geology and technology, the history of their use and re-use, and their relevance to understanding the culture and society (at local and regional levels) of Crete in the time of the Old Palaces, as well as their possible contribution to the political and military history of the period. I shall then review possible precursors of, and architectural parallels to, the Pyrgos cisterns at Knossos, Malia and Phaistos (none of which has been proved to be a cistern), and the later history of cisterns in Bronze Age Crete. Since only three others are known (at Archanes, Zakro and Tylissos, of Late Bronze Age date), the two cisterns of Myrtos-Pyrgos are an important addition to our still rudimentary knowledge of how the Bronze Age Cretans managed their water supplies.

Keywords Cisterns; Crete; Middle Bronze Age; Minoan culture; Myrtos-Pyrgos.

Introduction

The small Bronze Age (BA) settlement of the Minoan culture at Myrtos-Pyrgos (Ierapetra) (Fig. 1) on the S coast of Crete had a long, if occasionally intermittent, life from the Early Minoan (EM) II period (*ca.* 2900-2300/2150 B.C.) to the Late Minoan (LM) I (*ca.* 1700/1650-1450), with a few signs of use both before EM II and after LM I. The history of the hilltop settlement, which measures some 90 x 65 m to give an area of somewhat over 0.5 ha, has been divided into four principal phases: Pyrgos I-IV. The third of these (Pyrgos III) belongs to the later part of the period of the Old (or First) Palaces of BA Crete, otherwise known as Protopalatial, and may be dated *ca.* 1800-1700/1650. During Pyrgos III a remarkable group of monumental structures was built for and by the presumably small community centred at this site. Among them are two large plastered cisterns that are the earliest known - and universally recognised as cisterns - from the Minoan culture (Cadogan, 1978; 1992). These water tanks, as I believe they were, represent a considerable, and in one instance perhaps foolhardy, feat of engineering as well as of social management - and remain, since their discovery in the early 1970s, a most unusual attribute of a Minoan settlement, all the more so since the Myrtos river is/was available to supply water at the foot of the Pyrgos hill. One must note, however, that it is just possible, but unlikely I believe, that the smaller Cistern 1, set in a courtyard on the top of the hill, may have been a granary.

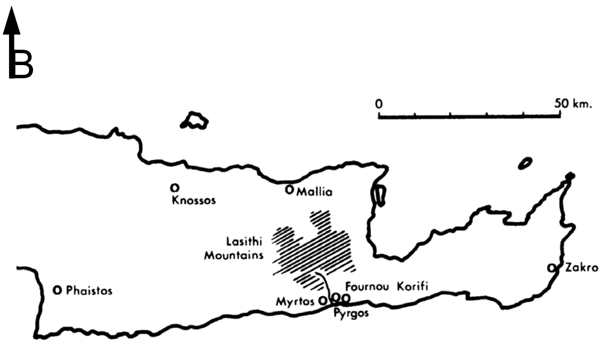

Figure 1 East Crete.

The Two Cisterns

Situation

The hill of Pyrgos rises to 77.63 m a.s.l. immediately to the east of the mouth of the Myrtos river, and across the river from the modern village of Myrtos (to the west). The hill is steep on its SE, S and W sides, but more accessible from the inland-facing N. The top of the hill however, the locus of the Minoan settlement, is steep on all sides, but the summit is relatively flat and was tilled until around 50 years ago.

The hill is formed principally from marl strata interbedded with laminated sands (Gifford, 1992). Given its steepness and permeability, the hilltop location of the Minoan settlement is utterly unsuited for digging wells. The most convenient water supply would have been the Myrtos river below, although its exploitation would have demanded a considerable supply of labour and/or donkeys to bring the water up the hill. Although the river collects water from a large basin on the S side of the Lasithi Mountains, it only flows nowadays down at Myrtos in the rainy winter months. Its apparent drought in the rest of the year may be attributed to the many boreholes and wells that have been dug in the valley for irrigation. We may assume, however, that this was not the case in the past, when the river flowed probably for (nearly) all the year, while wells in the valley floor could have supplied any shortfall. Certainly there was enough water, probably brought by aqueduct from a few km up the valley, to supply a Roman bathing establishment, probably dateable to the 2nd century A.D., immediately to the W of Myrtos village.

When it rains, the precipitation often comes as intense downpours that can cause flash floods in the river, even today. (As for the past, it is noticeable how strongly the upstream quoins were built for a late 19th century bridge crossing the river about 1 km inland.) Similarly on the Pyrgos hill, the rainwater collects suddenly and runs down the slopes vehemently during these storms, eroding the BA buildings that are now exposed through excavation. The rain would have been quite as damaging in BA times.

The cisterns

The two cisterns of Myrtos-Pyrgos (Cadogan, 1992: 203-205, Figs. 28.1-28.2) (Fig. 2) are similar in construction and date. On the evidence of the sherds of ceramic storage jars (that would have been used for collecting the water) found in the bottom of each, their (first) use was in the Pyrgos III phase - or just possibly a little earlier, even late Pyrgos II.

Figure 2 Myrtos-Pyrgos: Cistern 1 is in the lower middle of the picture, Cistern 2 at top.

Both cisterns are circular (but see below on Cistern 2) and have vertical walls and a rounded bottom, where the last drops of water could collect in the concavity. Walls and bottom are coated with white lime plaster 1-2 cm thick. On the cistern bottoms the plaster was applied over a bedding of small river pebbles, on the walls against roughly hewn stone blocks. Neither cistern has evidence of any roofing or of supports (such as stone pillars) for awnings to prevent evaporation. However, it would not have been difficult to stretch awnings over them.

Cistern 1. Cistern 1 (Cadogan, 1978: 71, Fig. 3: D, 74, Fig. 10, 78-79, Figs. 21-22; 1992: 204-208, Figs. 28.1-28.2, 28.5-28.6) is the smaller of the two, measuring about 3.42 m in diameter with a maximum depth, as far as we could estimate (since excavating was dangerous), of 2.48 m to the bottom of the central concavity. This gives a capacity of approx. 22 tonnes. We cannot yet ascertain how stormwater was channelled into this cistern in the Pyrgos III phase, but that would have been fairly easy - indeed it could have flowed there naturally - since the cistern is set some 5 m below the peak of the hill in the flat paved courtyard on the S front of the imposing Country House, which was the central building of the LM I (Pyrgos IV) settlement. As the cistern dates to Pyrgos III, the courtyard was necessarily laid out then - if not yet earlier. In all events, it is older than the Country House. If, as is likely, there was already a Pyrgos III central building on the site of the later Country House (Cadogan, 1997; 2006a), the cistern would have collected stormwater from it. Cistern 1 is, to the best of our knowledge, intact; but we excavated only one quarter of it, for safety reasons. It is just possible that this cistern was in fact a granary (as has been suggested for various round structures at Knossos, Malia and Phaistos [see below]), but improbable. Why? Because, being below the top of the hill with its central building, it would have been hard to stop the water running into it when there was a storm - which would have spoilt the grain.

Cistern 2. Cistern 2 (Cadogan, 1978: 71, Fig. 3: E, 74-75, Fig. 11; 1992, 204-206, Figs. 28.1-28.2, 28.4) is a much larger structure. Far less well preserved, it was excavated completely. Its walls form an irregular circle with a pronounced bulge to the W - and irregular diameter of approx. 5.3 m. As for its height/depth, we do not know if some top courses of stones are missing; but we can say that the cistern was at least 3 m deep. This gives a minimum capacity of approx. 66 tonnes. A number of rectangular and U-section open drains, gutters and spouts, some of them like those from Akrotiri on Thera (Palyvou, 2005: 39-40), could have channelled water off roofs towards and into this cistern: these finds need further study.

Cistern 2 lies some 12 m below the top of the hill at, or very close to, the edge of the settlement. It is partly built into the slope of the hill, and partly would have projected up from it on the downslope side. While it was well placed to receive stormwater coursing down the hill in volume, it was a precarious position to hold such a weight of water. It is not surprising that the cistern broke at some time: the downslope wall fell away, and there is some splaying of the stones that are still in situ at its NW side (the lowest point of the cistern wall), which may be the result of the force of the water spilling out - if, of course, there was water in the cistern at the time of the disaster. This probably happened in Pyrgos III, and certainly before two higher-level walls were built, partly over the ruined wall of the cistern, during LM I (Pyrgos IV).

Immediately upslope from the cistern to the SE and S are two formidable terrace walls that must be of Pyrgos III date, one of them very well preserved (Cadogan, 1978: 75, Fig. 11). These walls had probably both a defensive purpose - to repel attackers at the settlement's most vulnerable point, while providing military cover for the cistern - as well as the structural one of supporting upslope buildings. A few m to the SW, at the end of the principal terrace wall, is a tower-bastion that would also have had a defence function.

Communal and Regional Contexts

In view of the presumed continuing availability of water in the river valley in the MBA, the decision of the Protopalatial "authorities" (whoever they may have been) at, or for, Pyrgos to invest a considerable amount of labour in constructing these two monumental cisterns of a total capacity approaching 90 tonnes, and even setting one of them in an inherently unstable position on the slope of the hill, needs scrutiny.

Explanations may include local causes or relate to regional or island-wide issues, or a combination of such factors. At local level, one could posit perhaps an onslaught of malaria down in the valley. But it would be unlikely then that the mosquitoes could not reach the often static water in the cisterns, while the osteological evidence from the collective tomb at Pyrgos suggests that the males buried there were in good health without much, if any, evidence for malaria (Cadogan, 2006b). It is, however, most probable that these individuals were part of the (healthier) elite of the settlement, and should not be taken as indicative of the health of all the inhabitants.

Alternatively, for reasons unknown, there could have been a shortage of persons to carry the water up the hill, although there were clearly enough people to build the two cisterns. Once they were built, however, and providing ample water facilities in the settlement, a lack of people to bring it up from below would not have been such a difficulty.

These two suggestions, however, do not address the fact that the cisterns were part of a remarkable MBA monumental building programme at Pyrgos, which also included the defence works and the presumed central building as well as continuing use of a collective tomb (that had begun in Pyrgos II). We see here a decision - *unique* in Minoan Crete at the time as well as later - to make a substantial water supply available in a hilltop settlement and provide (virtually) unlimited supplies of a vital commodity. It is an extraordinary reflection of the human resources and decision-making processes of this small settlement that so much could be achieved. This would have had a wide propaganda impact on other settlements in Crete (perhaps leading even to competitive, warlike reactions), while enabling the people of Pyrgos to enjoy the luxury of a self-sufficient abundance of water - a situation that is always something to covet in the Mediterranean.

In this context, one may ask whether there was a differentiation between the two cisterns. Could Cistern 1, set in a courtyard and certainly better, more evenly built, albeit smaller, than Cistern 2, have been used only for the central building on the top of the hill? And was Cistern 2 for everyone else? In view of the unique nature of this group of monuments, there is also the possibility that we should see Pyrgos as somehow primarily a ritual centre rather than simply a settlement (that also happened to have these specific, extremely important structures). If in a hard-to-define way an interpretation on these lines seems probable, then we could imagine ritual uses (also?) for the two cisterns. But what they would have been is equally hard to define.

One other, wider explanation would certainly have had local repercussions: namely, war and defence. *Contra* the widespread view of a *pax Minoica* in BA Crete, evidence is accumulating of war as an important part of the patterns of life, particularly in Protopalatial times, at an inter- and, quite possibly, intra-regional level (Alexiou, 1980; Nowicki, 1999). This seems to have culminated in destructions with fire at a number of settlements at much the same time as the destruction with fire of Pyrgos III - where the tower-bastion and walls were intended to prevent such disasters. In this scenario, the building of the two cisterns at Pyrgos can also partly, or perhaps wholly, be explained as a response to a defence need - the threat of siege? - that did not exist to quite the same degree in other phases of the life of the Minoan settlement.

The Cisterns' Subsequent History

It is apparent during the subsequent Pyrgos IV phase that the social need of water storage on the top of the hill had passed and, we may assume, the inhabitants of Pyrgos now returned to collecting water from the river.

Cistern 2 and its surrounds became a rubbish dump for, principally, LM I (Pyrgos IV) pottery (some of which dates as late as the LM IB pottery in the destruction of the Country House). During this use the two higher-level walls already mentioned were built to form a small L-shaped structure, perhaps as a retaining wall for the rubbish. It is not clear whether this use as a tip should be seen as one of the ritual actions - ritual discarding - that were probably being performed in the settlement (and in particular by the occupants/users of the Country House); but it would be naïve to deny this as a possibility. Rubbish had already fallen down in - or after - the fire destruction that marks the end of the Pyrgos III phase, and would have come mainly, or wholly, from the central building on the top of the hill that was the precursor of the Country House. Perhaps there was ritual discarding to mark the end of that building and the establishment of the new one (the Country House).

Ritual is probably easier to discern with Cistern 1, which was entering a second life as an important part of the design of the Country House. This cistern was now filled to the brim with river pebbles - hard grey limestone *sideropetres* with white veining - and thus had lost any function for storing and supplying water. We may interpret this event as a ritual action, that could have taken place at one go - or over a period of time as people brought up pebbles from the river. If this is what happened, the intention was to mark the end of the one intact cistern as a cistern, and render it useless, by filling it with something that everybody would recognise as coming only from the traditional water source of the community - the river below. Yet the cistern was also highly visible to people approaching the Country House along the raised walk between the S front and the courtyard, or to those looking out over the courtyard either from a balcony which, I believe, was set above the verandah (stoa) on the ground floor of the building, or on coming out of the Country House through its main entrance.

It is important in this regard that Cistern 1 kept its round outline, and its plaster lining would have been visible, as it still was when we excavated 3,500 years later. It would have been clear to the people of Pyrgos IV that its previous use was as a cistern, even if now filled with pebbles that in themselves symbolised a return to the river, the customary source of water for Pyrgos. Following the “earth to earth, ashes to ashes, dust to dust” of the funeral service, perhaps we may sum up the underlying attitude as “pebbles to pebbles”. In this way, these pebbles and the former cistern that held them could have kept the rich memory of the history of the community and the vicissitudes of its water supply - and thus acted, or could be used, as an important tool for social cohesion. The same applies to the long-lived collective tomb at the W corner of the settlement, which continued in use into Pyrgos IV; but, as far as we know, water is not involved there.

If the two MBA cisterns of Pyrgos III were but a passing event in terms of functioning as cisterns, they did have their uses in their Pyrgos IV afterlife. The ruined Cistern 2 was for rubbish; the smaller Cistern 1 became an integral - and ideological - feature of the Country House and perhaps was the best reminder of the antiquity of the hilltop as a site for central buildings. But it may also have had a use as a soakaway for stormwater from the Country House, the central building *par excellence*. Outside its W wall two clay drains were found, sloping down in the direction of the cistern. They are rectangular and had lids - clay tiles - that could be removed for cleaning. The tops of the drain-ends were cut away so that one lid overlapped two drains. Painted on the lids and the drains (at the points where the lids were placed) are single, isolated motifs, of designs that are well known on the LM I pottery of Pyrgos and found notably on small jars used in the collective tomb. The drains are, almost certainly, local products. More than that, they too may have had a symbolic role - through their channelling water from the Country House to what had been the cistern of its predecessor - of uniting in a small way the two central buildings across time, while also alluding to particular iconographic motifs on the pottery that accompanied the dead in the last (Pyrgos IV) phase of use of the tomb - people who had most probably been the elite who used, and/or lived in, the Country House and would have seen Cistern 1 daily.

Early Minoan and Middle Minoan Comparanda

We should review briefly several other wide and/or deep round structures of Middle Minoan (MM) date on Crete that are associated with the Old Palaces of Knossos (4 structures) and Phaistos (4 or perhaps 5): see MacGillivray, 1994: 52; Strasser, 1997; Halstead, 1997; Carinci, 2001. They are broadly contemporary with the Myrtos-Pyrgos cisterns, and comparable in size. Sunk in the ground, they are known as *kouloures* (after a Greek word for something round and hollow). Malia has a set of eight round structures that project above ground, four at least being plastered, and are called silos (Pelon, 1980: 221-226). Their date, however, is problematic. The tendency now is to see them as LM I (Pelon *et al.*, 1992: 178; Driessen and Macdonald, 1997: 185) rather than Protopalatial. At all three sites, however, these structures were set in, or immediately adjacent to, the West Courts of their palaces - apart from one *kouloura* at Knossos that is a short way away, below the later Theatral Area

(Evans, 1935: 51, Fig. 30). They seem to have had design and symbolic connections with the ceremonial/ritual raised walks that are such a striking feature of these courts (Carinci, 2001).

It is generally agreed that the Malia structures were granaries. But how to interpret those at the other two sites is less certain, and seen by all as problematic. Alexiou (1964: 140-141) suggests they were depositories for sacred offerings; Strasser (1997) argues against their being granaries; Halstead (1997) restates the case that they were; Evans (1935, 61-66) suggested that (at Knossos) they were rubbish tips and/or "blind wells for the disposal of surface waters", but not suitable as cisterns since they were not plastered; MacGillivray (1994: 52) inclines towards granaries, and points out that in any event the public may not have had ready access to them; Marinatos (1987: 135-138) also opts for granaries, to be associated with "harvest festivals" in the West Courts; following these and other leads, Carinci (2001) suggests that they were pits for planting trees, the trees having an important function in rituals enacted in the West Courts; but Watrous *et al.* (2004: 288) prefer their use (at Phaistos) as cisterns.

There was also at Knossos the so-called Hypogaeum by the South Front of the later Palace. Incompletely excavated, it is now re-buried and invisible - and also hard to interpret (Momigliano, 1991: 195-198; Wilson, 1994: 38; Belli, 1999). It is apparently a circular domed space cut in the soft natural rock, with a spiral stairway cut into its sides, some 8.32 m in diameter at the bottom and 15 m (or more) deep (Evans, 1921: 104-107, Fig. 74). Evans rejected the idea of its being a cistern, since the sides were not plastered, and thought that it might have been a guard house - or possibly a store pit. Hutchinson (1962: 163-164) was the first to suggest it was a granary. MacGillivray (1994: 54) opts for its having been a cistern. At least it is agreed that, as far as we know, it is of late Prepalatial date (whether EM III or MM IA). These tantalising round buildings provide some help in interpreting the Myrtos-Pyrgos cisterns.

(a) They are all associated with central buildings (if on a far larger scale than that at Pyrgos), and were set in prominent positions in or by the West Courts, with raised walks beside them or leading towards them. Whatever their function(s), whatever they contained, in terms of prestige and display of power - the power of storing valuable commodities, whether foodstuffs or water - they are an important and often underrated feature of the communities that created them. The same holds for our Cistern 1. In its positioning and construction, it was clearly a competitive assertion of power, emulating the larger centres. (But pending further study it is hard - but not totally impossible - to connect the apparently LM I raised walk outside the Country House with the overall original (Pyrgos III) design for this cistern.)

(b) It is clear that having plastered sides is a key factor for positive identification of a cistern, although it cannot exclude use as a granary.

(c) The ritual/ceremonial interpretation of the *kouloures* proposed by Carinci is a helpful lead in considering the role of Cistern 1, notably in its Pyrgos IV afterlife (when it could even have had a bush or flowers growing among the pebbles) but probably equally in its Pyrgos III original use.

(d) But Evans's suggestion of a "blind well" for stormwater is also helpful for Cistern 1, with the drainpipes leading towards it; while his idea of rubbish tips supports our explanation of Cistern 2.

Late Minoan Cisterns

Of LM date are three plastered round structures, of diameter around 5 m, that held water and are usually called cisterns, although two of them may have had other uses besides just storing water. These two, of LM I date, are at Archanes-Tourkoyeitonia (Sakellarakis and Sakellarakis, 1992: 74, 112-115) and in the east wing of the Palace at Zakro (area LXII) (Platon, 1971: 185-191; 1992; Schofield, 1996). The third is of Postpalatial LM IIIA/IIIB date at Tylissos (Vasilakis, 1992). All three have a similar design - which is interesting evidence of the continuity of this plan - with steps leading down into the tank (unlike the Pyrgos cisterns), to give easy access to the water. They are also all plastered on the sides. The two earlier ones, however, do not have plastered bottoms, but are paved, to allow in each case the plentiful ground water to seep in between the stones and fill the cistern. It is not surprising, then, that Platon suggested that the Zakro cistern may have even been a private swimming pool (within the Palace), and the same could well hold for Archanes (where it seems to have been part of the palatial building at Tourkoyeitonia). The Archanes cistern also has an impressive drain to take the overflow. The later cistern at Tylissos is alone in having a plastered bottom: it seems a standard type of cistern collecting the water that was fed into it from above. But, finally, one cannot exclude the possibility that the two earlier LM cisterns also functioned at times as standard cisterns for water storage and distribution.

Conclusions

However we interpret the Knossos, Malia and Phaistos MM round structures, at Myrtos-Pyrgos at least one, and I believe both, of the two MM plastered round tanks functioned originally as cisterns. They are an important addition to the small corpus of Minoan cisterns, as the other certain examples are some centuries later, and to our understanding of how the Bronze Age Cretans managed their water supplies. In view of the presumed water availability during the BA in the Myrtos river below the settlement, it seems most probable that these cisterns were built to cope with unusual conditions, probably war, while having an important social role for the community in making life less arduous by removing the need to go down the hill and up again to fetch a pail of water. We may also discern in these cisterns a symbolic and monumental role in the life of the community, and a competitive display/propaganda role in how it wished to express itself to other contemporary communities through building such rare and remarkable reservoirs among the impressive group of monuments of Pyrgos III. Parallels that come to mind, for the likely combination of the threat of war together with display and monumentality, are the large (rectangular) Hellenistic cisterns in the *agora* - the heart of the community - at Dreros and Lato, to which the Pyrgos cisterns offer a generic resemblance; and for the simultaneously social and symbolic importance (independently of any war factor) of managing water supplies as a way to ensure community cohesion and pride, we can recall the fountain house(s) of the 6th century B.C. Peisistratid rulers of Athens (Camp, 1992: 42-44) - or Francesco Morosini's superb fountain of 1628 in Iraklio: *Ta Liontaria*.

At present, the Myrtos-Pyrgos cisterns remain the earliest cisterns beyond dispute in Crete and are important evidence for social/political - and quite likely military - conditions on the island in the earlier part of the 2nd millennium B.C. That is what waterworks are, in all periods of human history.

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Water Cistern Systems in Greece from Minoan to Hellenistic Period

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Abstract: The lack of adequate water quantity in most Greek islands, since the beginning of their habitation, resulted in the construction of various water reservoir types. In Crete water cisterns have been practiced since the early Minoan era. Since then several types (of rectangular, square and cylindrical-shaped, roofed and roofless, and uncoated or coated internally with impervious material) of cisterns have been developed. However, a significant development appears to have been achieved during the Hellenistic period in all over Greece, with technology which has been extended even to nowadays. Few characteristic examples of Hellenistic cisterns are considered which justify the significance of that technology during that period of Greek history.

Keywords Ammotopos; Ancient Greece; Cistern; Dreros; Hellenistic period; Lato; Orraon; Rainwater.

Introduction

Through the historical development of Greece, because of the frequent water shortages increase, the benefits of water conservation were well understood and the value of rainwater for several use of was grown. Where water is scarce such schemes can be of real value but there are health and environmental risks that need to be tightly managed. Appropriate actions must be taken to protect human health. Thus, the first sand filters and sedimentation tanks seam to have been developed as early as the first water cisterns were used for collecting of rainwater (Sklivaniotis and Angelakis, 2006). Rainwater is defined in this paper as the atmospheric precipitation collected from on ground in impermeable surfaces and stored usually in artificial reservoirs, known as cisterns. This water is used for household purposes such as bathing or washing, dish-washing, laundering, irrigation or other urban uses. The collection and use of rainwater is known since the Minoan era (Cadogan, 2006).

A cistern is essentially a masonry tank, built at ground level or excavated few meters (3-10 m) below it. It is usually fed by rain water and/or fresh water transported by an aqueduct. Sometimes a cistern may be, in effect, a large city reservoir, aqueduct-fed, used for water supply. However, the cistern water was also for rural agricultural or industrial use (Hodge, 2002). Rainwater is normally collected and stored directly from the roofs of buildings or from open impervious surfaces. A cistern is usually a cylindrical, circular or oblong tank, often under the floor of the house. However, there are cisterns of rectangular or square shape. In most cases, the cisterns are equipped with built stairway on one side leading down to the bottom. Their walls are usually coated internally with impervious plaster. The cisterns may most usefully be divided into covered and uncovered, but it is not so easy to categorize them by function.

There are examples of rainwater use systems in many arid and semi-arid countries. Remains of rainwater cisterns, dating from the last 4000 to 5000 of years, are encountered in ancient Greece. Some are well installed and operated for centuries. Most of them were used to collect rainwater and serve as the major source of water supply. However, in a few cases they were used for other purposes, i.e., seasonal regulation of water brought by large conveyance systems. In Greece rainwater harvesting and use has been practiced since the Minoan times, *ca*. 3300-1200 B.C. (Viollet, 2003; Angelakis and Koutsoyiannis, 2003). The earliest known such technology is referred to the very Early Minoan times *ca*. 3300-2200 B.C. Five of such cisterns are known; two in Pyrgos, and Myrtos, one in Zakros palace, one in the city of Archanes, and one in the Houce C in Tylissos. The two plastered cisterns in Pyrgos are the earliest known, and universally recognized as cisterns-from the Minoan culture (Cadogan, 2006). Thereafter, cisterns were developed in Middle and late Minoan periods, such as in Phaestos, Zakros, Chametzi, and Rhizenia (Koutsoyiannis *et al*., 2006). However, during the Hellenistic period the technology of cistern showed further progress. At that period the water supply in several cities all over Greece was dependent entirely on precipitation; the rainwater was collected from the roofs, yards and other open spaces of establishments and cisterns (Angelakis and Spyridakis, 1996).

The scope of this article is not the exhaustive presentation of what is known today about water cistern technologies during the Hellenistic period in Ancient Greece. Rather, some characteristic examples in selected sites are presented supporting that the Greeks could be considered among the pioneers in the technological development of water cisterns.

The City of Dreros

Dreros, a city-state of Classical Greek period, is near modern Neapolis in the eastern Crete. Like the neighboring Lato, it was erected on a saddle between two peaks, on the slope of mount Kadistos (Davaras, 1976). The archaic city had an *agora* (market place) about 30x40m^2 in size, including some moldering steps along the southern side and a retaining wall of the eighth century B.C., and further a huge open cistern

Myers *et al*. (1992) have reported that a cistern, the first and larger cistern ever known is that in the ancient Dreros. It is located in the agora of the city, had a rectangular shape with dimensions of 13.0 x 5.5 x 6.0 m^3 and was used for water supply of the city (Fig. 1). Davaras (1976) was reported that the depth of the cistern is 8 m. At Dreros the average annual atmospheric precipitation is 500 mm and the average cistern capacity 429 m^3; to fill it would require the run-off of a roof or yard area of more than 860 m^2. Of course, this calculation is based upon the cistern being filled only once per year, and would require the inhabitants to live for a year on cisterns-full of water. More on this analyses are reported by Despotakis and Tsagarakis (2006).

The City of Lato

Also, in Lato named after Leto, mother of Apollo and Artemis, a goddess with strong Minoan associations is located in the eastern island; there is no spring at Lato. Thus, the basic water sources were rainwater. North of the little temple is the central cistern, in the agora (city center), which is more or less squared in plan, of side approximately 5m (Apostolakou, 2005). The area of the cistern is of 27.56 m^2 (Myers *et al*., 1992) and its depth is of about 6 m. It was originally covered by a roof supported by two Dorian colons. Its walls are coated internally with impervious plaster and built stairway on one side leads down to the bottom of the cistern. From the location and the size of the cistern, we can only conclude that it was the public cistern of the city (Fig. 2). There are of about 15 more small cisterns. Myers *et al*. (1992) have reported that there is a similarity of that cistern, with the first and larger cistern ever known in the ancient Dreros. It is located in the agora of the city, and was used for water supply of the city.

Figure 1 Remain of the central cistern in the agora of Dreros.

Figure 2 Central cistern in the agora of Lato.

Town of Orraon, Epirus (Ammotopos)

The fortified ancient town of Orraon was founded at the end of *ca*. 4th century B.C., when Alketas was the king of the Molossoi or, at the latest, in the second quarter of that century.

The site and its history are vividly presented at the Guide book "Όρραον" published by the 12th Ephorate of Classical antiquities (Angeli, 2005). The settlement, built on a strategic position, was destroyed by the Romans in 167 B.C., but was subsequently rebuilt and finally was abandoned by its inhabitants, who were forced out to settle down in Nicopolis, after 31 B.C. Many of the houses are still standing two storey high and the street plan network is also well visible. In the town plan twelve narrow parallel streets, in an N-S direction, cross two wider streets. This network forms rectangular oblong town blocks, the insulae, 15 meters wide. A single house usually occupies the full width of each insula. Despite these, the fortification walls, with the bastions and gates, define the area of that impressively well-preserved ancient Greek settlement.

The cistern is situated near the main gate, at the north east part of the town, which is the area with almost the highest altitude. That big public rectangular cistern (Fig. 3) is roofless, in contradiction to the more numerous vaulted cisterns of the classical period, built usually to places where crowds were gathering (e.g., sanctuaries of Epidauros, Delos etc.; many of them, partly curved on the soft rock, have been also found in Piraeus). The place where the cistern is built, at that highest area of the town, reduces to minimum the chances for any kind of natural water flow supply. In addition to that, no traces of aqueducts or equivalent constructions have been discovered up to now. On the other hand, the high amount of rain falling at the west regions of Greece, even during the summer, provided without any doubt the essential water quantities for the cistern. There the rainfall today is much higher than the east regions of Greece and it was also higher in the antiquity, according to the descriptions of ancient writers. An enclosure wall was surrounding the cistern, approx. 2 m away of the edge of its tank and thus a yard was determined. At the middle of the yard's south wall, was placed the antae framed entrance. The height of the stone built enclosure can be estimated three meters approximately, after the amount of its collapsed parts.

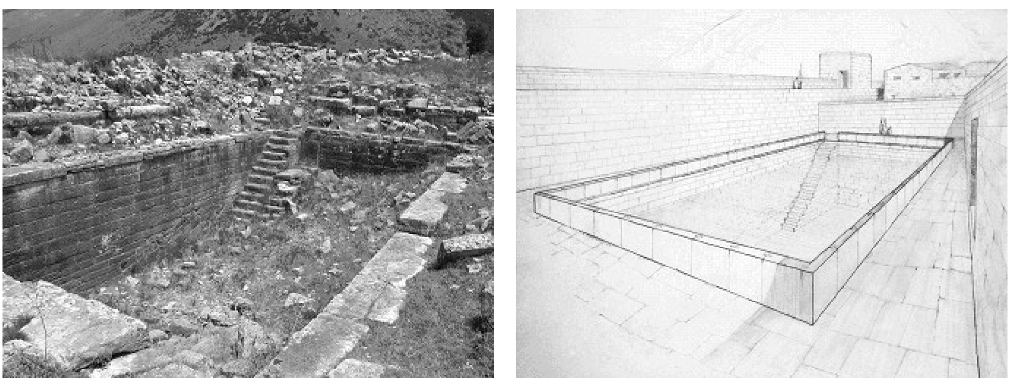

Figure 3 Cistern in the ancient city of Orraon-Epirus (Ammotopos): a. View of the cistern from SW (left) and b. reconstruction from the same side (right), after G.P. Antoniou.

Even though the yard wall is mostly ruined, the cistern itself is perfectly preserved, as well as the straight stair at the northeast corner of the tank. The less elaborated widening of the stair, dated probably in the Roman period, is not as nicely preserved. Furthermore, that widening means that the stair was not only for the access of the bottom -for cleaning the tank- but also for getting water from it, since the level of the water in the cistern was, definitely, varying within the year. The masonry of the cistern's walls is constructed by well formed rectangular stones, made of the local light gray limestone. The very lower parts of the walls are curved on the bedrock, on which is also curved the bottom of the cistern. The edge of the tank's walls was possibly standing higher than the floor of the walking passage, around the cistern forming a kind of parapet (Fig. 3b). The typical form of ancient Greek shrines justifies a conclusion like that. (Travlos: 328, fig 430; Camp, 1984: 22, fig 33; Dukley, 1935-35: 183-184; Glaser, 1983). Moreover there are traces of grooves with iron joints on edge's stones, which suggest the existence of a parapet.

Because of the high enclosure wall, it is concluded that there was care for the hygienic protection of the cistern (preventing of throwing waste or other dirt in it), as well as a kind of controlled access to the tank. Traces of a shrine nearby that could be supplied from the cistern have not been found yet. So it was the cistern itself a kind of arykrene, or was supplying an arykrene. Arykrene (αρυκρήνη) was the kind of shrine from which the water was taken out with a container submerged in the water. The shrines providing natural water flow were called rhookrenes (ροοκρήνες). The first excavations on the site were carried out in 1972, even though Ammotopos (also called Kastri) was well visible during the centuries. The excavation was carried out by Ioulia Vokotopoulou, then director of the 12th Ephorate. In 1975, the University of Ioannina, under the direction of S. Dakaris, in collaboration with the German Archaeological Institute, started the excavation of House 1 in the ancient settlement, which was resumed in 1981. The 12th Ephorate carried out restoration works of the wall masonry of the ancient houses in 1972-1976 and 1981. (Archaeology in Greece, 1976-77; Catling, 1977 – 1978: 3-69). Unfortunately the area around the cistern and the main gate is not excavated yet.

Conclusions

Greek technological developments related to water management principles and practices are not as well known as other achievements of the Greek civilizations, such as poetry, philosophy, sciences, politics and visual arts. The first evidence of the use of water cisterns for water supply in Greek settlements lies in Minoan era. However, that technology was tremendously further developed through history with a peak in the Hellenistic period. To put in perspective the ancient water cisterns discussed in this paper, it is important to examine their relevance to modern times and to harvest some lessons. The achievements of Greeks in dealing with the cisterns and functional requirements of water collection and distribution systems can only be compared to modern urban water systems, re-established in Europe and North America from the second half of the 19th century A.D. (Angelakis and Koutsoyiannis, 2003) until present day. Thus, with a few exceptions, the basis for present day progress in technological development of water cisterns is clearly not a recent development, but an extension and refinement of the past.

Acknowledgements

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Mpourdechtis: Ancient Roofless Cistern Type in Aegina, Greece

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Abstract: The lack of adequate water quantities in most Greek islands, since the beginning of their habitation, resulted the construction of various water reservoir types. In Aegina is being preserved a typical roofless cistern type, Mpourdechtis, which is in use even nowadays. The name Mpourdechtis comes from the colloquial transformation of the word (ομβροδέκτης) - omvro-dechtis which means the place where the rainwater is being gathered. Despite the meaning of the term, most of the surviving mpourdechtes (in plural) combine, until now, the collection of rain water and some kind of natural spring flow. Their structure is mostly consisted by a combination of masonry wall and curved parts of the natural rock underneath, a kind of technique used in many types of ancient and newer cisterns. The irregular shape of mpourdechtes is the result of that constructional method.

Keywords Aegina; Ancient Greece; cistern; Mpourdechtis; rainwater.

Introduction

The lack of adequate water quantities in most Greek islands, since the beginning of their habitation, resulted the construction of various water reservoir types. Many of the small Greek islands in the Aegean Sea can be categorized as arid or semi arid. In Aegina is being preserved a typical uncovered cistern type, Mpourdechtis. The lack of water resources in the Aegina is one of the island's serious problems even today. Tankers carry most of the water to the island from Athens's area.

Mpourdechtis is a very simple cistern, partly excavated below ground level. Most examples embody at the cistern a natural cavity of the rock. Often that natural cavity collected quantities of rainwater, therefore was selected as an impromptu cistern. Quite a few of them are in use even nowadays, since there is still need for water supply in some remote rural areas, mainly for watering sheep and goats. Except the lack of water's network, the cost of water is a significant reason to use Mpourdechtes. The name Mpourdechtis comes from the colloquial transformation of the word (ομβροδέκτης) -omvro-decktis (Faraklas, 1980: 19) which means the place where the rainwater is being gathered. Όμβρος = rain and – δέκτης = the one who accepts-receives. Even though this type of uncovered cistern is much similar with many others, Mpourdechtes are characteristic ones, due to the good condition of their preservation in addition to the continuity of their use. Most of their sites have already been recorded and quoted. (i.e., Welter, 1933; Faraklas, 1980: 19, 55; Stamatis, 1989: 25). On the other hand there is not a detailed study of that cistern type up today. Also this presentation is not an exhaustive examination of Mpourdechtis cistern, but refers on the main aspects of it.

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Historical Remarks

The surviving constructional techniques and evidences are dated in the Hellenistic period. Despite that many sites, where Mpourdechtes are situated, are originally dated much earlier. The combined evaluation of the above remarks could conclude that Mpourdechtes were properly shaped during the Hellenistic period but in many cases an original construction existed before. That earlier and less elaborate form, was possibly a primitive water tank curved on the rock or just exploiting a natural rocky cavity.

The previous hypothesis is also supported by the archaeological finds. At Hellanios' Zeus sanctuary the excavation of the Deutsches Archaeological Institute von Athen, have been found artifacts of various eras. The constructional project of the large retaining walls and the Π plan shape portico –dated at the 2nd cen. B.C. when Aegina was part of the Pergamum Kings' state (Fig. 1; Cult. Assoc. of Pachia Rahi, 2000: 28-29; Welter, 1938)- could have included also the improvement of the two Mpourdechtes. Also at Mpourdechtis area at the centre of the island have been traced evidences of earlier periods (Faraklas, 1980: 55-56).

Sites

The sites where Mpourdechtes are situated are mostly on relatively high altitude places, combining adequate rainfall and natural spring's water flow. In many cases there is high underground water's level. The last criterion, along with spring's water, was definitely more significant. Most Mpourdechtes are constructed next to a natural spring flow or at places where a simple well could be found, instead of being to the spot of the region where the most rainwater is being gathered. Many of the places are next to a small or bigger field or other agricultural and stockbreeding areas (Fig. 2) Generally they are very close to the subject to which they supply water. Due to their small size and respectively small quantity of their water there are not recorded any traces of historic aqueducts leading the water away.

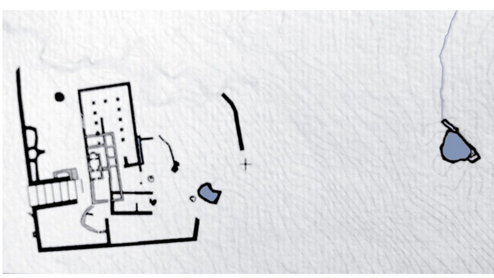

Figure 1 The Mpourdechtes (right) at Hellanion sanctuary.

Figure 2 Fields at "Mpourdechtis" where there are two cisterns.

Water Resources

There were many kinds of water resources for the Mpourdechtes (and in many cases still are!). In most case there was (is) a combination of two or three resources. In the cases where there was more than one water resource, it could be evaluated as primary or secondary, according also to the duration of the water's presence in the cistern. For example the simple rain water gathering provided water for 9~10 months a year. On the other hand the contribution of natural springs' flow or high underground water table, provide water all year round. The Mpourdechtes' water resources have already been mentioned earlier. Briefly they can be categorized as follow:

(a) Gathering of rain water from the surrounding area, on which refers the name of the cistern type. Despite that this resource is being considered secondary, as its contribution is small without the supplying ditches, since in most cases Mpourdechtes are not situated at the lower parts of a flow basin as it should be to obtain greater water amount.
(b) Natural underground spring's flow, coming out of the rocky walls or bottom of the cistern. The cisterns of this type -which most of them are still in use- are supplied mostly from that kind of water resource. Those Mpourdechtes contain enough water quantities all year round.
(c) Well supplying mechanism providing water to the cisterns through the natural rock sides and through their bottom (Figs. 3 and 4), at the places where there is high underground water table. That resource also provides water during the dry summer months.
(d) Natural or partly artificial water supplying ditches leading more water quantities in to the cisterns like a funnel on the ground. These impromptu ditches improve remarkably the efficiency of Mpourdechtes, especially where there is not natural underground water supply. Therefore their contribution is either secondary when there is underground water or primary when there is not.

Figure 3 The ditch of the big cistern at Hellanion sanctuary.

Figure 4 The ditch of the towers' well at Mpourdechtis

Construction

All the surviving Mpourdechtes are made mostly of stone masonry. In many cases this masonry is made out of well curved small or medium size stones. (Figs. 5 and 8) This kind of masonry can be dated in the Hellenistic period, especially the most regular one. On the other hand there are many Mpourdechtes with irregular stone masonry, constructed mostly of larger stones. (Fig. 6, 7) The tidy kind of the irregular stone masonry of the small Mpourdechtis at Hellanio's Zeus sanctuary is similar to Hellenistic constructions on impromptu fortification walls. Beside this structure, most cisterns combine masonry wall higher and at the lower parts curved surfaces of natural rock. This technique was used in many types of ancient and newer cisterns, reducing the need for masonry and the cost as well. Moreover it provides a solid bottom which also keeps the water in the tank. In few Mpourdchtes are still visible curved formations on the rock for improving the fitting of the well formed masonry. Such evidences prove the existence of that kind of wall originally, at cisterns where it has not been preserved (Fig. 7).

Figure 5 The big Mpourdechtis at Hellanion's sanctuary.

Figure 6 The small Mpourdechtis at Hellanion's sanctuary.

The irregular shape of mpourdechtes is the result of that constructional method. (Figs. 5-8 & 1) It is evident that the shape was following the cavities of the natural rock and generally the shape that it could be formed with as less labour as possible. The original upper edges of the cisterns have not been preserved, but, according similar ancient constructions, they can be easily represented. These parts are either missing now, (Fig. 5) or they are partly (Fig. 8) or totally reconstructed (Fig. 7). During the ages of their continuous employment many other changes and repairs have been made. Most of the interventions are impromptu rebuilds of the destructed parts of the ancient masonry (Fig. 7). Despite that in every Mpourdechtis there are still clearly visible ancient constructional parts.

Figure 7 The big cistern at Mpourdechtis area

Figure 8 The small cistern at Mpourdechtis area.

Usage

The usage of Mpourdechtes was mainly rural but has been recorded also some exceptions. Two of them, situated next to the ancient sanctuary of Hellanios Zeus, supplied originally the pilgrims. They are still in use but for stockbreeding purposes. (Fig 7, 1, 2) After that it can be concluded that cisterns of this type were used also for domestic needs, where this kind of water supply was suitable. In that case they probably supplied only small settlements or single farm houses, at relatively high altitude areas. At the towns the water supply was achieved by wells and ordinary cisterns.The sound quality of their construction in addition to their conservation and maintenance through the centuries, have resulted their uninterrupted use until nowadays. The two Mpourdechtes, at the homonymous area, supported -until few years- ago the needs in water supply of the neighbouring monastery of Chrissoleontissa, through a metal pipeline still on site!

Conclusion

Mpourdechtes are protected according the resent archaeological Law, as constructions dated before 1830 (ΦΕΚ 153Α, 2002 Articles 2, 6). A sympathetic restoration, supported by the proper maintenance, will expand their life time and preserve the historic constructions for many more decades. In addition to that, it will improve their efficiency and will provide more water quantities to their owners adding an extra motivation for their continuous maintenance. Beside that, the reuse of surviving Mpourdechtes is totally ecological and supports low water demands in many remote areas without modern water supplying network system. Moreover a detailed investigation of the capabilities on water gathering and supply of such constructions can provide water for the needs of small scale farming and stockbreeding. Modern technology and materials can increase the efficiency of that kind of cisterns and exploit much better quantities of water not used today. Many open large water reservoirs have constructed on many Aegean islands, based on the same concept. Considering the fact that the water supply of Aegina still relies on transportation of water from the mainland with tankers, the reuse of the Mpourdechtes along with the construction of similar cisterns, small or larger, will reduce the dependence of the island on transported water.

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Water Cisterns Survey in Pantelleria Island, Italy

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Abstract: The daily problem of water supply, nowadays as well as in the ancient times, is typical of those regions deeply conditioned by climatic factors or a geomorphological nature in which the scarcity of natural water sources is constant all year round. A particularly good example of human adaptation to a dry environment is that of Pantelleria Island, where water cisterns are widely distributed throughout the territory. The two different types of cisterns identified, bottle-shaped and vaulted roof, can be considered as landscape "markers" useful to recognize the presence and the chronology of archaeological sites. The results of four research campaigns (1999-2002), carried out in selected sample areas, provided useful information on the settlement patterns developed in antiquity on the island, in particular for Punic and Roman times. However, the analyses must consider some problems connected to the reconnaissance of archaeological remains by field-walking. Finally, particular attention will be focused on the Acropolis of San Marco, where stratigraphical excavations can support data.

Keywords Cisterns; Pantelleria; survey; water.

Introduction

The investigation of ancient water cisterns was part of the "Carta Archeologica dell'Isola di Pantelleria" (Archaeological Map of Pantelleria Island) a project begun in 1996 as a joint collaboration between the Archaeology Department of Bologna University and the *Soprintendenza ai BB.CC.AA. di Trapani* under the direction of Prof. M. Tosi and Prof. S. Tusa (Cattani and Tosi,1997; Tusa, 2003). The main aim of the Project was a better understanding of the different occupational phases of the island during its history through the identification, positioning, and analyses of the ancient settlements and other archaeological evidences, in order to provide a useful tool to local authorities for the preservation and the valorization of the cultural resources (Monti, 2001; 2003). One part of the Project was devoted to the study of ancient water supply and underground cisterns mapping (Mantellini, 2000). This paper will attempt to show the results of this investigation and to address some methodological problems, focusing the attention on the bottle-shaped typology and on some interesting areas where the cistern concentration is especially high.

Geographical, Geological and Climatic Settings

Pantelleria is a volcanic island of 83 km² lying along the continental rift system of the Sicily Channel between Sicily and Tunisia (Fig. 1). The geographic coordinates, at the top of Montagna Grande, are 12° 00' 20'' Long. East, 36° 46' 51'' Lat. North. The actual landscape

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is the result of both natural volcanic events and slope terracing made by man in order to obtain a cultivable surface. The last eruption occurred in 1871 although several secondary activities still take place (Belvisi, 1998). Nearly in the center of the island is Montagna Grande (836 m a.s.l.) that overlooks the whole territory, whilst some 40 *cuddie* (from the Arab = hill), dormant volcanic, are spread throughout the island.

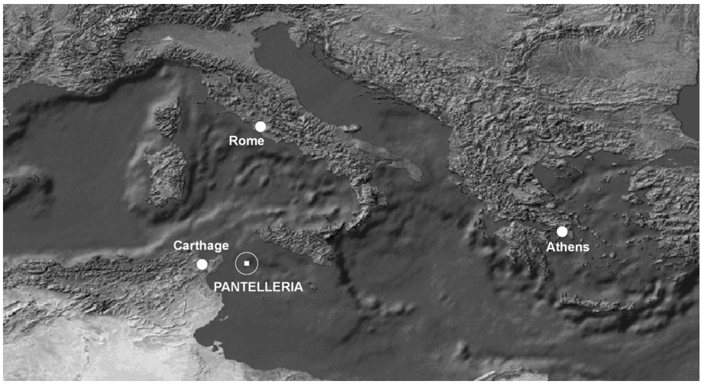

Figure 1 Location of Pantelleria Island in the Mediterranean Sea.

There are only four flat areas, covering a total of 5.42 km² (6.5 % of the whole Island): Ghirlanda, Margana, Monastero and Mueggen (Fig. 2). The second one was used in the 1930's for constructing the airport and gave many archaeological evidences from Punic and Roman periods (Orsi, 1889).

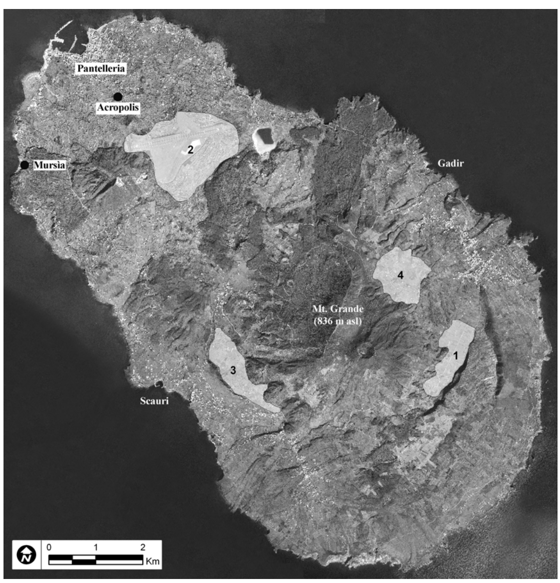

Figure 2 Pantelleria Island: flat areas (1. Ghirlanda; 2. Margana; 3. Monastero; 4. Mueggen) and main archaeological sites.

The climatic factors deeply influenced the economical history of Pantelleria: precipitations reach 415 mm/yr, the annual average temperature is *ca*. 18°C and the wind blows incessantly year round (Table 1).

Table 1 Main climatic factors in the island.

Climatic factor	Average value
Relative Humidity (%)	73.16
Monthly Precipitation (mm)	40,33
Maximum Temperature (°C)	20.33
Minimum Temperature (°C)	14.83
Temperature (°C)	17.58
Wind (knots)	7.80

In spite of the environmental situation, since the first occupation of the island, agriculture has been the main resource, thanks to a massive landscape terracing, a complex dry-farming system, and various specific adaptations to the unique conditions of the island (Barbera, 1998). In this way, for instance, tillage is useful to obtain a cultivable surface, to divide up into parts one parcel and to transform dampness in water whilst the rock-enclosure known as *pantellerian garden* are suitable to shelter fruit trees from the wind (Barbera and La Mantia, 1998). For a specific study on the pantellerian gardens see Brignone (2001).

No springs, rivers or other static water sources are present in Pantelleria, and because of its origin the island is mainly composed of fractured volcanic rocks, where water rapidly runoff to the sea and no consistent water table can form. During the beginning of the Bronze Age (19^{th} - 18^{th} century B.C.) the first inhabitants of Pantelleria solved the problem of water supply by digging artificial wells, locally called *buvire* (Fig. 3), where the coastline is shallow, in particular in the northern side from Cala dell'Alca to Kattibuale (Belvisi, 1998). In Punic times, when Pantelleria was known as *Cossyra* and played an important role as an outpost of Carthage in the middle of the Sicilian Channel, the occupation is witnessed by the main center (Acropolis) placed on the top of San Marco and Santa Teresa hills, urban quarters (Orsi, 1889; Verger, 1966) and many farm-houses scattered over the entire territory (Castellani and Mantellini, 2001; Monti, 2004).

Unfortunately, the continuous terracing transformed the landscape over the centuries, has deeply conditioned the identification of archaeological sites (Monti, 2004) and in many cases the presence of underground cisterns is the only reliable tools to recognize a settlement and to establish a chronology. In fact, whereas walls and houses can disappear with time, underground cisterns survive much better, bearing witness to their ancient builders (Castellani and Mantellini, 2003).

The Survey of Water Cisterns

The investigation was carried out in 24 sample areas across the island (Fig. 3) covering 5.82 km^2 (7 % of total surface) and identifying 675 water cisterns, including both ancient and modern ones. A large part of the cisterns are associated with modern houses, but in other cases identification is proportional to their state of preservation and field explorability. Thus, it has been necessary to complete a full and accurate survey, since traces of ancient cisterns could project only centimeters out of the ground, perhaps abandoned in ancient times, or hidden by briers and vegetation. After identification and numeration, each cistern was located on maps at a 10,000 scale filling a special form including its main characteristics (location, dimensions, typology, supposed chronology, etc.). All data gathered was then included in a digital database to allow fruitful management and elaboration in the main GIS of the Archaeological Map Project.

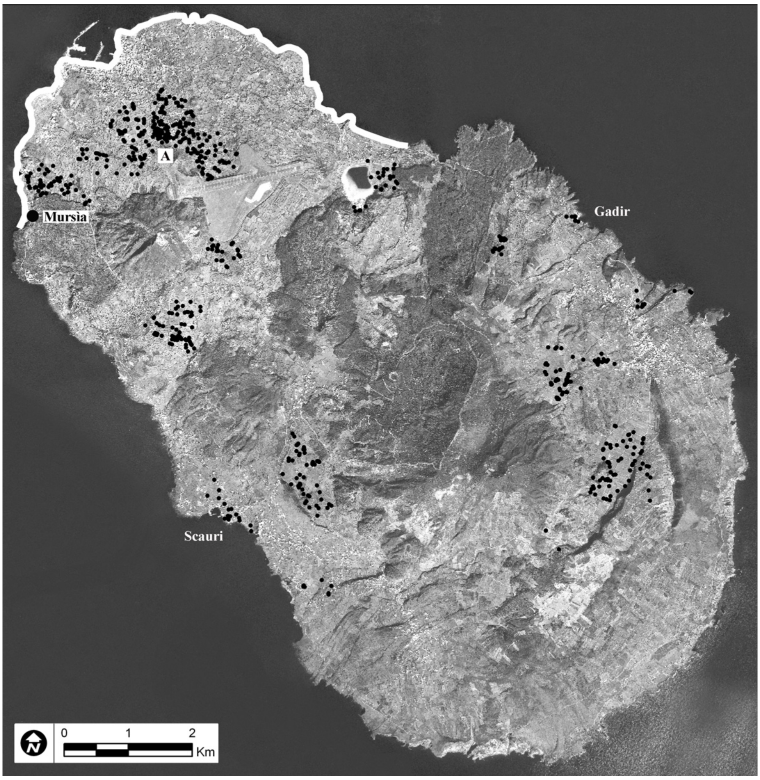

Figure 3 Distributon of buvire (white line) and cisterns (black dots); A = Acropolis.

Wide exploration permitted the development of the cisterns typologies as shown in Table 2. The two dominant diagnostic types became the focus of our study: bottle-shaped and vaulted roof, considering the original bottle-shaped cisterns adapted with the vault roof belonging to the first type. The remaining cisterns were either unclassifiable (each one unverifiable in shape or by local people's information) or of more recent construction. This contemporaneous determination was possible through both physical examination of construction techniques and material, as well as ethnographic sources.

Table 2 Typological classification of cisterns found in Pantelleria.

Cistern Typology	Total	%
Bottle-shaped	274	40.6
Probable Bottle-shaped	48	7.10
Vaulted Roof	189	28.0
Others	27	4.0
Unclassified	137	20.3
Total	675	100.0

Figure 4 Main typologies of water cisterns in Pantelleria: bottle-shaped (left) and vaulted roof (right).

There are many doubts concerning the dating of the vaulted roof type, because the building technique and materials have remained unchanged since Romans times up till today (Castellani and Mantellini, 2003). On the other hand, some conclusions can be made for the bottle shaped typology, since the comparison between Pantelleria and other similar case-studies in the Mediterranean confirm the association of this type to the Punic and Hellenistic tradition (Tolle-Kastenbein, 1993; Bodon et al., 1994; Mezzolani, 1997; Wilson, 1998). Improved dating of the bottle-shape type developed on the Island is possible through the comparative analysis of the results of the field walking survey and the study of finds collected by the Archaeological Map Project. The earlier Punic presence is attributable to the Second half of 7th century B.C. (Bisi, 1970), and the full Punic occupation of Pantelleria occurred since the 4th century B.C., in connection to the strong relationship with Carthage (Cerasetti, 2000; Baldassari and Fontana, 2002). It is represented over the territory by the large presence of scattered farm-houses (Castellani and Mantellini, 2001; Monti, 2003), and it is reasonable that the construction and diffusion of bottle-shaped cisterns also occurred at the same time. The wide distribution of this type on the island confirms the full colonization carried out by Punic people (Castellani and Mantellini, 2001; Castellani and Mantellini, 2003), but it surmised, that also in Roman times, the inhabitants of *Cossyra* continued to live and to construct under Punic traditions, influenced by their proximity to Africa and Carthage (Verger, 1966).

Finally, worth noting is the Acropolis of San Marco, the Punic public center, built on two hills, San Marco and Santa Teresa, divided by a flat saddle of *ca*. 0.5 ha. It represents an excellent case-study because of its historical importance and the remains already remarked by the first scholars working in Pantelleria (Orsi, 1889; Verger, 1966). The historical value of the Acropolis is supported, by the finding of three marble heads, located in the fill of two cisterns, belonging to Julio Cesar, Antonia Minor and Emperor Titus. The survey investigation, extended for several years over 3.3 ha, has reached an amount of 50 cisterns, including those coming from stratigraphical excavation. New discoveries allow more considerations and hypothesis on the exploitation of the area during the centuries (Table 3: last updating in the Summer 2004).

Table 3 Typological division of the cisterns found in the Acropolis.

Area	Bottle shaped	Probable bottle-shaped	Modern vaulted roof	Probable vaulted roof	Unclassified	Total
San Marco hills	18	11	0	0	7	36
Santa Teresa hills	3	3	0	0	2	8
Saddle	2	0	1	0	2	5
Total	23	14	1	0	11	49

The study of the cisterns being on the Acropolis is fundamental for understanding and dating the following occupational phase of this area. The excavation shows the presence of structures and finds belonging to several phases since Late Punic time (4th - 2nd century B.C.) until the Early Middle Ages (Osanna, 2004). The cisterns located here are comparable to those found in Carthage datable to 4th - 2nd century B.C. (Rakob, 1991), and it confirms the chronology previously supposed for the other cisterns identified across the Island. However, the high density of bottle-shaped type on the Acropolis should be viewed in relation to the need of storing a great deal of drinkable water for possible emergences, such as water shortage or military siege. During Hellenistic period the cisterns on the Acropolis were perhaps related to a temple, whilst from the Roman Imperial Age to the Early Middle Ages they were in connection with "elite" house-complexes (Osanna, 2004). The importance of the Acropolis is testified through the presence of the only ancient cisterns system found in Pantelleria (Castellani and Mantellini, 2006). This system has now formed of two cisterns: the upper one probably received water from two gutter-pipes, feeding at least two more cisterns, one still present and one destroyed.

Conclusions

The water harvesting by cisterns was wide spread in the antiquity, in particular in the region under Punic influence, perhaps finding in Pantelleria Island its major expression. Here, in fact, because of environmental and climatic conditions, the water supply is based, since ancient times, on the storage of rainwater. The large presence of bottle-shaped cisterns of Punic-Hellensitic tradition across the whole territory demonstrates the full colonization carried out since the Late Punic period (4th century B.C.). In addition, the vaulted roof typology is difficult to date because it belongs to a building technique unchanged since roman times. However, in both typologies, the construction shows a remarkable skill, which produced functional and durable structures that have withstood the test of time.

Acknowledgments

This paper is dedicated to the memory of Vittorio Castellani, who along with his valued teachings and suggestions nurtured in me his enthusiasm and knowledge of ancient water management. I am grateful to him to having guided me in the first steps of the investigation. For the scientific coordination of the project I would like to mention Maurizio Tosi (University of Bologna) and Sebastiano Tusa (*Soprintendenza del Mare di Palermo*); Massimo Osanna (University of Basilicata) and Thomas Schaefer (University of Tubingen) for allowing me to study the cisterns uncovered during the excavation of the Acropolis. A special thanks to Kevin Donaghy, Andreas Lyrintzis and Sebastian Stride who have kindly reviewed the paper. Last but not least, Lucia and Rosario Di Fresco and their families for their friendship and for supporting the investigation for over ten years.

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Water Storage at Dreros Ancient City of Crete, Greece

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Abstract: Modern applications, hydrology techniques and study of ancient remains can lead to conclusions over water resources management in ancient civilizations. Using GIS, some available hydrological data, studying the remains of Dreros city (3rd century B.C.) and the available bibliographic sources, important information is retrieved concerning how water was collected and stored for using it during dry periods. Using contemporaneous precipitation records it can be concluded that there has not been a change in precipitation levels for the last two millenniums.

Keywords Cistern; climatic change; GIS, Minoan civilisation; water storage; water supply.

Location and History

Dreros is situated near Neapolis in the district of Lassithi, Crete. It is a post-Minoan archaeological site, 16 km. northwest of Agios Nikolaos. It comprises two acropoles with an Archaic agora between them. South of the agora is one of the earliest Greek temples. The Delphinion, as it is called, was dedicated to Apollo Delphinios. Almost the whole of the city and its necropolis have been excavated, confirming that this is a post-Minoan Greek habitation; its inscriptions are in Dorian dialect. Traces of fortifications have been discovered (Wikipedia, 2006). A plan of Dreros city is shown in Figure 1.

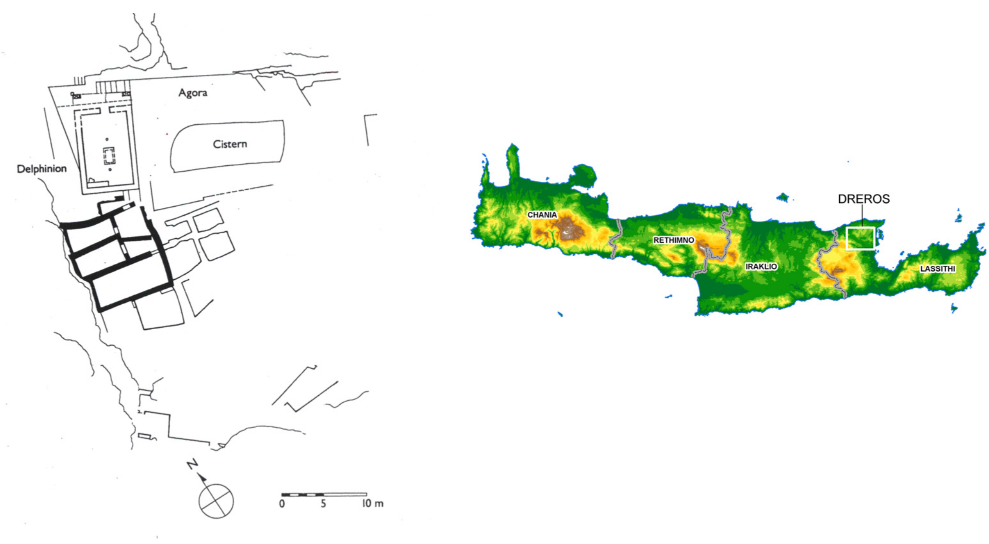

Figure 1 Plan (Van Effenterre, 1992) and location of Dreros city.

The city first became famous in 1885, when an inscribed pillar was found there. It was dated to the end of the 3rd century B.C. Excavations, which started in 1932, have shown that Dreros is one of the typical Archaic cities of Crete, which existed from Late Minoan IIIC to Hellenistic times (Van Effenterre, 1992). Some more fragments were found in the cistern but all archaeologists agree that these were found there after the close wall of the Apollo temple collapsed (McDonald, 1956).

Water Storage at Dreros

The cistern is of rectangular shape (13x5.5x6) of total volume 429 m³ (Van Effenterre, 1992). The walls were reinforced by stone blocks of up to 40 cm length. Today, a large fig-tree has fully covered this cistern making access to it very difficult (Fig. 2). The cistern would be filled up when adequate rain falls was creating surface run off from the paved city. Figure 3 shows a photo of the inner part of the cistern and a close view.

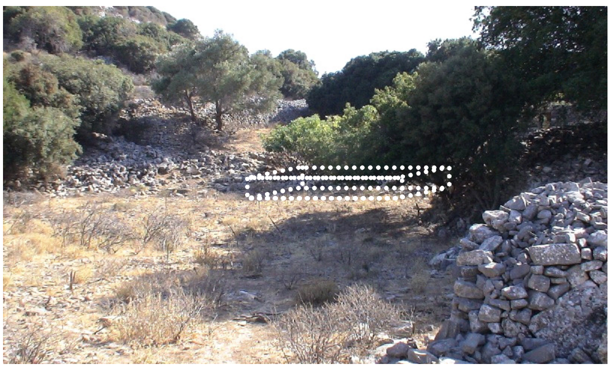

Figure 2 Down side view of the cistern, which is approximately placed. At the clear area was the agora of Dreros.

Figure 3 Inner part of the cistern (left) and close view (right).

Access to lower parts of the cistern was provided by two 80 cm wide stairs. The stairs were built cornered, and adjacent to the cistern walls. Obviously, the stairs were giving easy access to the water when the water level was low. However, the second flight of stairs can only be explained for static purposes of the inner construction, which was most of the time under water. The inner pair of stairs is shown in Figure 4.

Figure 4 Stairs inside the cistern, giving access to the lower water levels of the dry season.

The role of GIS in hydrological analysis

Today's GIS edge technology enables researchers to successfully apply high-accuracy spatial estimation techniques in order to estimate positions, dimensions, water storage volumes and their interrelationships (Burrough, 1983; Despotakis *et al.*, 1992). In many cases 3-D models can be constructed which represent the ground truth for certain hydrological basins, and from which the water volumes from cathment areas and basins can be precisely estimated (Deursen and Kwadijk; 1990, Damoiseaux, 1990).

For this study, we tried to arrive at the precise geometric characteristics of the Dreros ancient city, its reservoir dimensions and the relationships with the surrounding areas. Various spatial data sources were utilised, in combination with GPS measurements to extract the final spatial models for Dreros city. These data sources were heterogeneous, of variable spatial accuracy, extends and scales. To unify them in a common model, we first converted all the sources to digital (GIS-compatible) formats, and then we applied coordinate transformation techniques and spatial analysis methods (raster analysis, area and distances calculations etc). The data sources utilised are summarised as follows: (a) Geological formations, faults, boreholes, rivers from geological and topographic maps at a scale of 1:50,000; (b) terrain elevations, precise basins definitions and local borders from topographic maps 1:5,000; (c) ancient city of Dreros border definitions from 24th Ephorate of prehistoric and Classical Antiquities of Crete; (d) ttopographic maps at a scale of 1:5,000; and (e) aerial orthophotos at a scale of 1:5,000.

Also, precise GPS measurements were used to depict certain positions of the nearest area such as the ancient ruins location, the reservoir, access road and nearest roads location. All the GPS measurements together with the existing digital data sources were referred to the Greek most precise reference system, the EGSA'87 system (x, y, z in 6 degrees - UTM projection, GRS 80 ellipsoid). The GIS results are shown in Figures 5 to 7. The estimated main sub basin area is 1443.7 ha, the local basin area is 2.1 ha. This does not correspond to the runoff surface for the cistern, which is precisely calculated as follows.

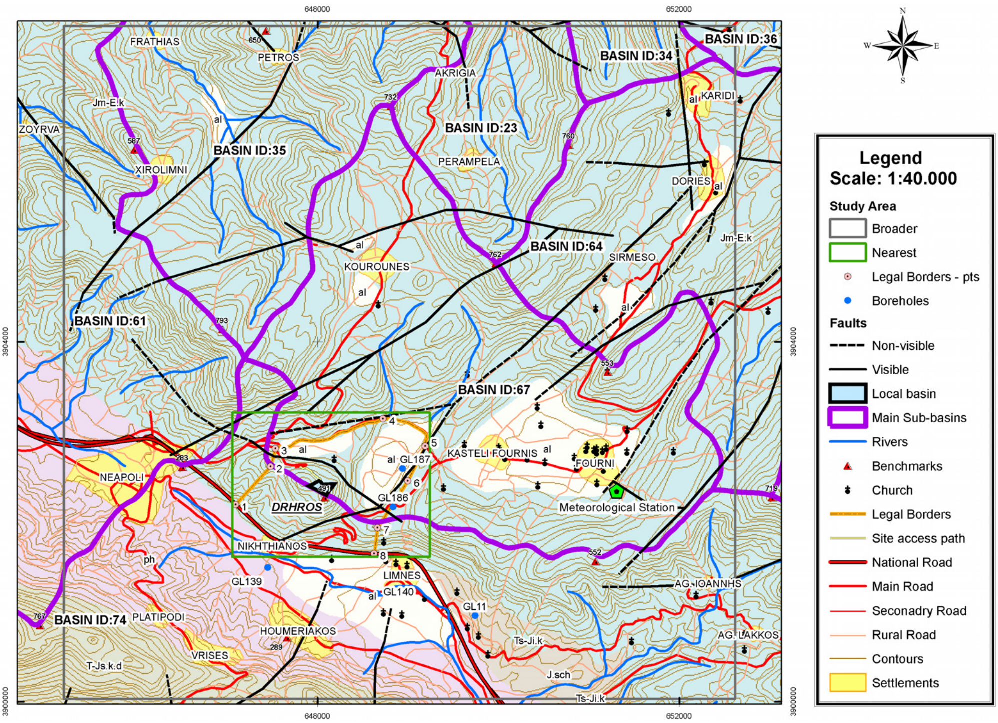

Figure 5 Broader area of Dreros. Main Sub-basin no. 67 (1443.7 ha) is shown.

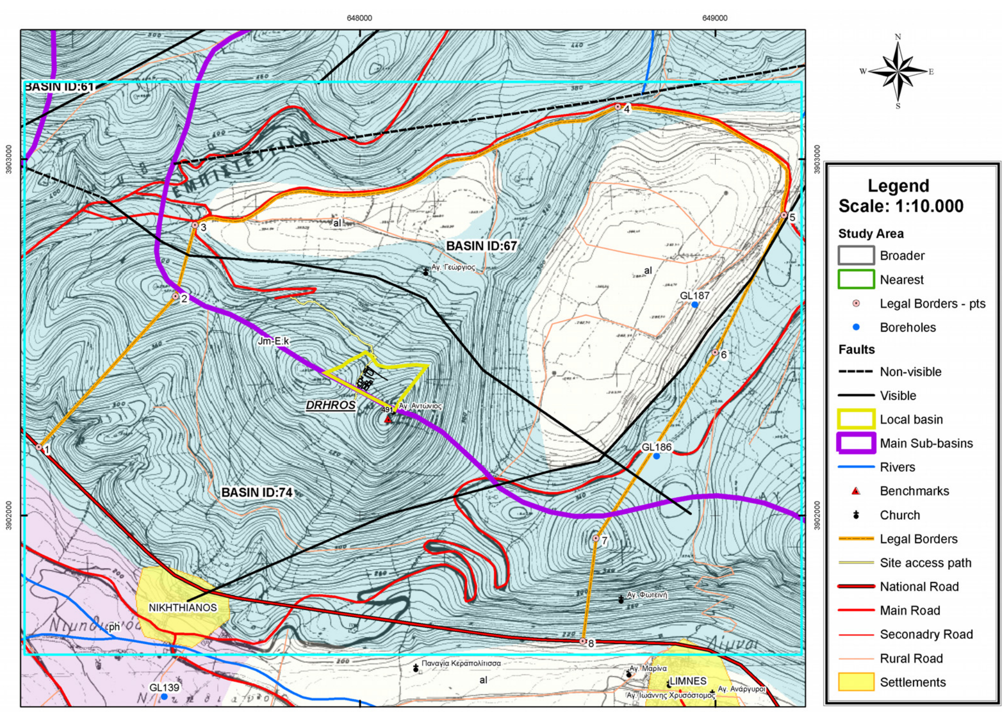

Figure 6 Nearest area of Dreros. Local basin (2.1 ha) is shown.

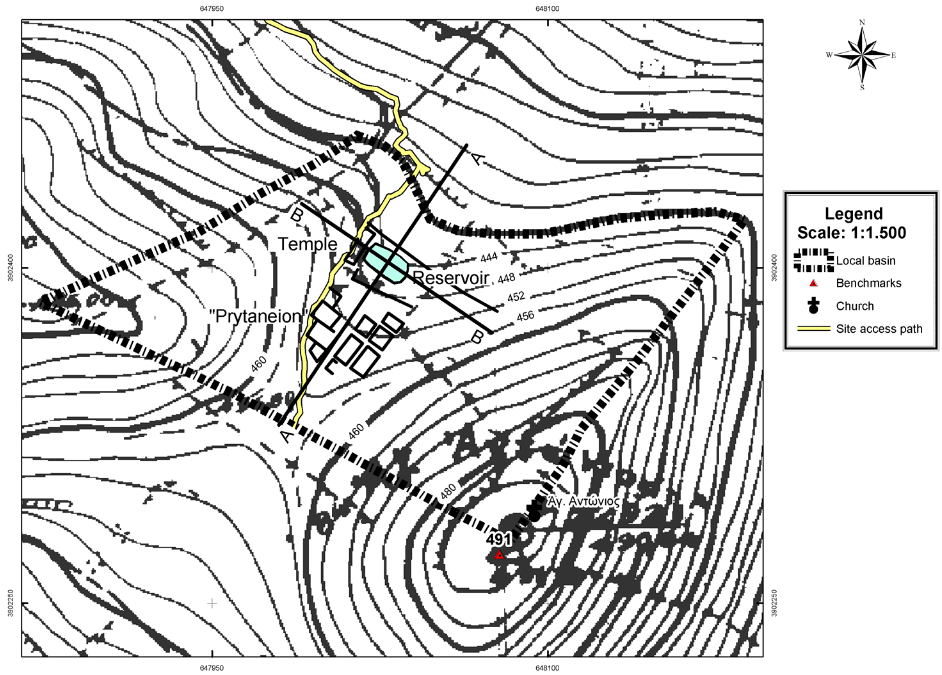

Figure 7 Local basin of Dreros. Location of Reservoir is shown.

In order to calculate the run off surfaces, Figure 7 has been cleared from contours and other information as shown in Figure 8. The effective surface (A), which can be used in a hydrological analysis, consists of 3 surfaces.

$$A = A_1 + A_2 + A_3$$

where,

A_1 = the surface of the cistern (71.5 m²)

A_2 = the surface of the city, including paved roads and assembling areas (1948 m²)

A_3 = the surface of the off city landscape, including planted areas, rocked slides and possibly cultivated land (9466 m²).

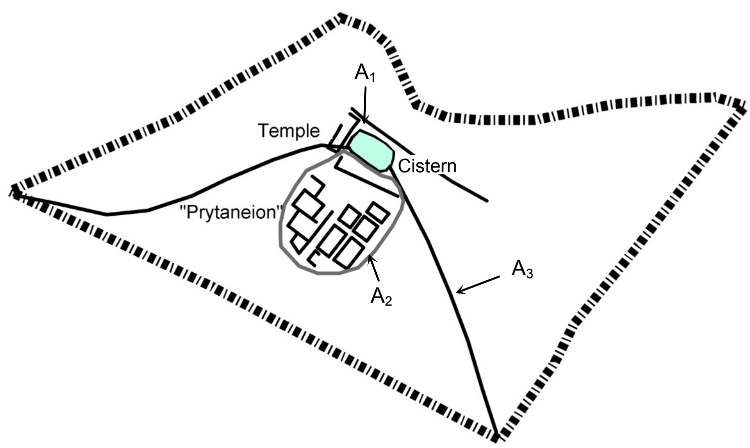

Figure 8 Run off surfaces as exploited from Figure 7.

Cross-sections A-A and B-B as defined in Figure 7 are provided in Figures 9 and 10 respectively.

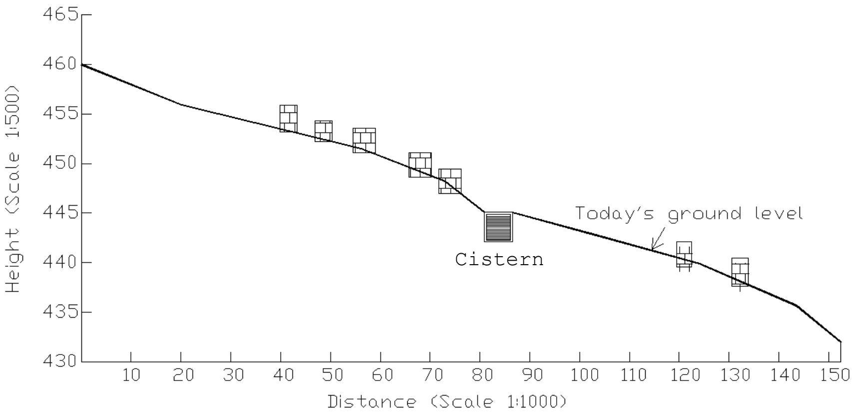

Figure 9 Section A-A.

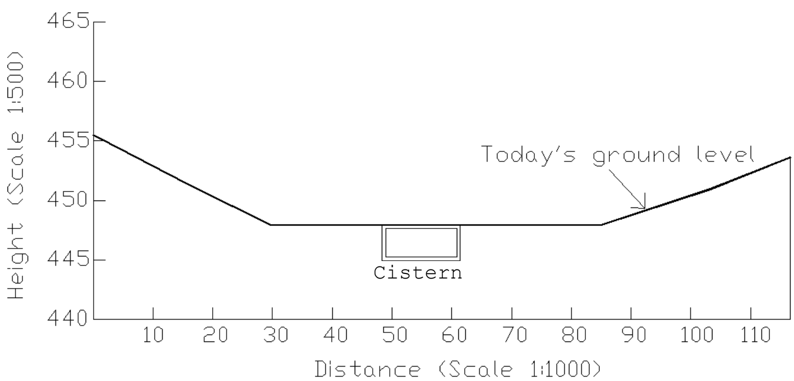

Figure 10 Section B-B.

Hydrological Considerations

Water collection and storage in ancient civilizations was fully dependent on the precipitations and runoff water was collected in the cisterns. This was also done for the Dreros city. An interesting topic of research on which we are working in this paper, is the investigation of the fill-up capacity of the storage cisterns. We suppose that engineers of those periods could design cisterns at volume that would be filled up at the end of the main periods. There is no available data concerning precipitation of those periods, we assume though that rain should be adequate to fill those volumes up. Therefore, we can come to the conclusion that if precipitations of recent years could fill up those cisterns, then there is no significant decrease in precipitations nowadays.

Daily precipitations were inquired for the station of Fourni as shown in Figure 5 (L/W/H: 35°'16/25°20/316) for years 1974-1997 (Fig. 11). According to this, there are years of very limited rainfalls like 1974-1979, while on the other hand there are years with extremely heavy rainfalls. With the available data for those years (1974-97) the average annual precipitation is 486 mm. To calculate the water volumes that will be collected in the cistern after any rainfall (V_i) it will be necessary to investigate separately three components, i.e., the water collected in areas A_1, A_2 and A_3 after a rainfall as follows:

$$V_i = (c_1 \cdot A_1 + c_2 \cdot A_2 + c_3 \cdot A_3) \cdot P_i$$

where,
c_1 = efficiency coefficient for area A_1
c_2 = efficiency coefficient for area A_2
c_3 = efficiency coefficient for area A_3
P_i = the effective rainfall i.

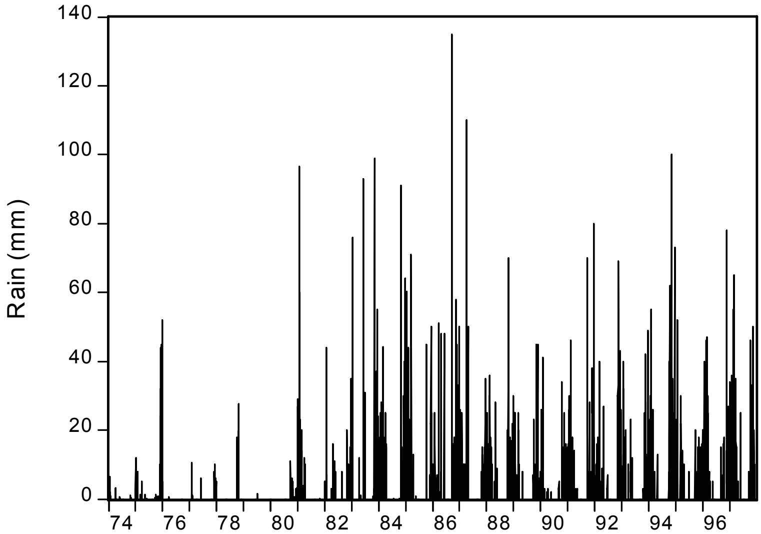

Figure 11 Daily precipitation at the Fourni station from 1974 to 1997.

The annual volume will be the result of ΣV_i. Considering a randomly selected year from the time series data presented in Figure 11, for example 1995. If we consider $c_1 = 0.95$, $c_2 = 0.5$ and $c_3 = 0.15$, then $\Sigma V_{1995} = 1038$ m³ which means that the cistern will be filled up 2.4 times. This is a simplified approach and parameters like rain duration, seepage losses and evaporation should be incorporated but can give the clear idea that the cistern, if it were constructed today, would get filled up at least once.

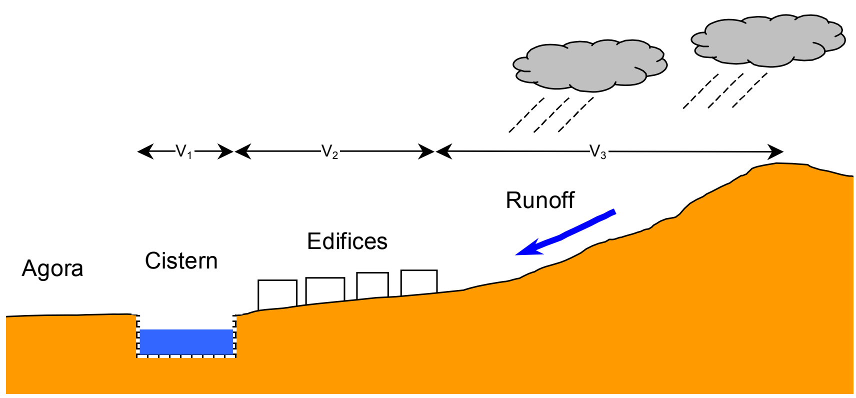

Figure 12 Water flow and storage (not to scale).

Conclusion

The use of modern engineering tools can be of great help in retrieving information captured in ancient cities. Ruins concerning water resources management in ancient civilisations, a common practice has been the collection of surface runoff to a downstream cistern. With the use of GIS and the study of available information we have thrown some light to this water collection plan for Dreros, a post Minoan city in Crete. Modern engineers should further study all this available information and practices. Possible indications for changes in precipitation through time could be retrieved. Consequently possible climatic changes could be confirmed by studying the cistern volumes through whether recent precipitations are adequate or inadequate to fill these volumes.

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Shaduf Systems around Southwest Region of Algeria along the Western Sahara Erg: Gourara and Saoura Areas

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Abstract: Intensive agricultural activity seems to be one of the reasons behind the lowering of the groundwater table. Only a rational use of water for agriculture can help to solve the problem of water. This can be done with an effective contribution of agriculture professionals and scientists. It is advisable to use only natural water flow systems. The deepening of wells is also advisable in order to catch more water and reduce the salt tenure in the water. In the Saoura Valley where land shows a perceptible slope in many places, the use of seguia and draining galleries is recommended because of their relatively low economic exploitation cost. The mechanical use of wells can increase the water flow, but the problem of sand invasion added to the problems of maintenance of water pumps can also disturb the use of such a system. Finally, a major problem still facing local agriculture is sand.

Keywords Ecosystem; Sahara; Shaduf; water.

Introduction

Ancient practices of water harvesting, catchments and distribution had guaranteed for years water supplying to ancient societies. These techniques based on a rational use of water should become part of the local knowledge able to reinforce local identity and trigger harmonious management of the environment. A variety of ancient water systems, such as the foggaras, the "shadufs" - wells with a balance bar, etc. still exist in the southern part of Algeria. Nowadays, the risk of water shortage, due to desertification and degradation of soils depending on global warming and intensive agriculture, is very high. The "shaduf" project, represented through the present paper aims at carrying out archaeological survey of drainage systems following the historical development of settlements, and evaluating the socio economic reasons of their vitality or abandonment. Therefore, foreseeing methods by which the reuse of the traditional water systems is on one hand a fundamental contribution to the water resource management based on the local sustainability, and on the other hand the recovery of aesthetical values of the monuments which are a further resource for people.

Geographical Situation of the Studied Area

Algeria is the second largest country in Africa (2,382,760 km²), it is situated on the southern part of the Mediterranean sea. Algerian climatic map is as diversified as its geographical richness. Its fast growing population has reached 32 million inhabitants in the beginning of the 21st century, with more than 55% living in northern coastal towns, whereas the desert part of the country (80% of the total area) is scarcely inhabited. There are two main geographical areas, an east-west and a narrow northern region, and a much larger Saharan or southern region which is made up of a hot and arid Saharan climate (Fig. 1), with very scarce rainfall.

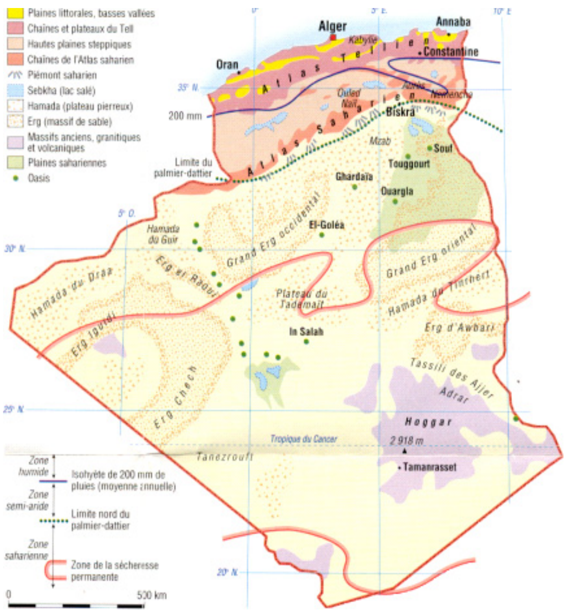

Figure 1 The climatic regions in Algeria.

Area of study

Preliminary field investigations have revealed that there are two distinctive regions were traditional irrigation systems (such as "shaduf", "foggara", etc.), exist. Both of them are located in the south west region of Algeria along the Western Sahara Grand Erg. The first one is situated in Gourara area, in the south around the major city of Adrar (Bisson, 1989). The second one is located in the south west, to the south of the major city of Bechar (Saoura area). This shows the largeness of the area and therefore the difficulty of studying the whole region during the course of this project (Kobori, 1982).

Hydro-Geological Situation

Underground water in the area has two origins: Water coming from humid "Quaternary" period (maximum coming from the Neolithic) and water coming from vanishing quantities of rainfall, which has contributed in maintaining the resources.

Characteristics

Water flow varies from one region to another, although the origin of water is the same, many of the reasons of that difference are geological: (a) ground characteristics, conditioning evaporation and infiltration. The erg (Fig. 2) plays an important role helping infiltration and protecting underground water from evaporation; (b) the difference in geometry of the waterproof underground surface; (c) the volume of the aquifer land which represents one of the major factors contributing to reduce the availability of resources. On the left side of “Saoura river”, the red schist of the upper “Devonian” forms a waterproof barrier for the water reservoir. The level of water depth varied in the mid 1960’s between 0 and 8 m, today some of these wells are dry or in best cases water depth reaches 12 m. Oued Guir (Fig. 3) was interrupted by Djorf Torba dam, which has led to the lowering of the Oued Saoura underground level.

Traditional Waters Catchments Systems in the Saoura

Every shaduf (well) has a flow of about 2 L/s. There are 2,942 wells in total. There are fouggaras in Taghit, Tabelbala, Beni-abbes and in a place called Ouakda which is completely dry now. 86 natural sources with different flows, major ones are situated in Kenadsa, Tabelbala, and Beni-abbes where the water flow was in 1964 27.8 L/s (Roche, 1953; 1973) and in 2000 17 L/s (de Bechar, 2000). There are small dam catchments systems along the slopes. Ksar Moughel dam serves for rain water catchments and for protection from flood water coming from the nearby gardens.

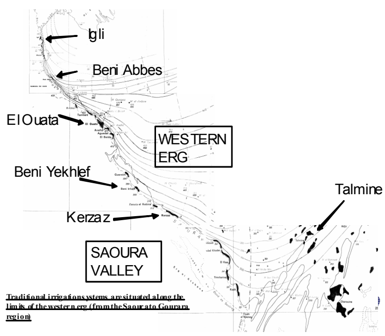

Figure 2 Situation map (Ksour and Shaduf along the Saoura valley).

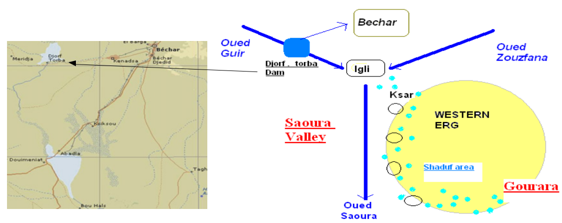

Figure 3 Hydraulic situation in the Saoura region.

Shaduf irrigation system

The irrigation system is presented in Figure 4. This system is usually situated in a strategic location creating at the same time a fully rational use of water and a coherent environmental landscape, reaching a high degree of sustainability (Fig. 5).

Geographic origin of the Shaduf system

Most indicators show that this traditional system comes from the middle eastern area (Egypt, Iran) or through the southern regions of the Sahara (Sudan).

Preliminary case study

Ksar of Taghouzi. Situation: Commune of Talmine, Daira of Charouine, Wilaya of Adrar Commune 17 Ksar, 01 Ksar 1000 Berda. Population: 3000 inhabitants, Zenata origin.

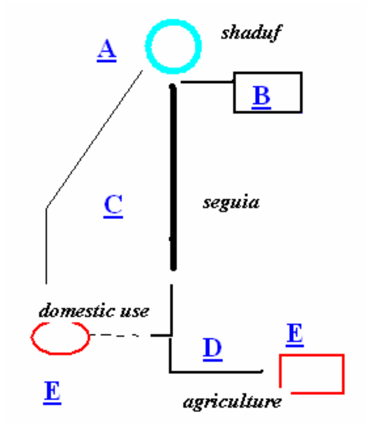

Figure 4 The overall principle of Shaduf utilisation: A. Harvesting; B. Storage (optional); C. Transport; D. Distribution; and E. Use.

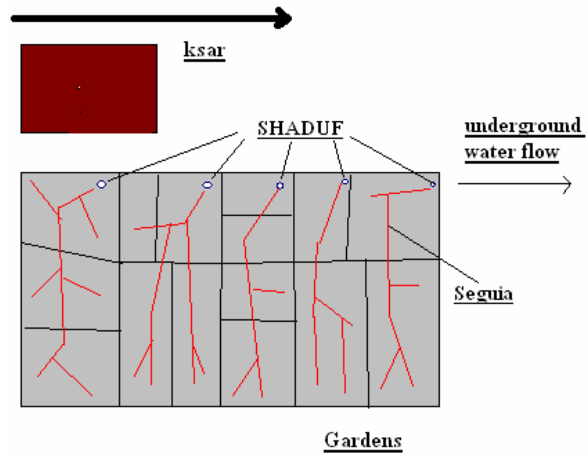

Figure 5 Shaduf eco system (schematic presentation).

Steps towards the creation of an Oasis

These are: (a) Detection of the Berda (low, flat and humid depression on the erg) (Mercadier *et al.*, 1945; Briquet, 1984); (b) palm plants put on the Berda; (c) the sand around the planted area is moved 50 to 60 m away by the use of animals (mainly donkeys) during 2 to 3 years, the plants are then not irrigated for about 30 years; (d) birth of the Agrou = garden (Fig. 6); (e) creation of wells for irrigation, and the edification of the Shaduf (Tanout: name in the area) with its Tihsser = palm trunk (balance); (f) beginning of the Jbid = water extraction from the well; (g) the well is used 6 to 7 times a day (8 m^3/d for an irrigated area of 2 ha through Badou = irrigation canals), each Berda is about 400 m^2 and separated with palm hedges of about 1 m height.

Figure 6 Detection of the depression then the birth of the Oasis (garden).

Some wells are 5 to 6 centuries old and the depth of water level in the 1950’s was 1 m, today it is about 6 m (average loss = 0.1m/yr); (h) several field investigations have revealed that this system appears through divers types (shapes, dimensions, and building materials) and names (Khettara, Naoura, and Khechba); (i) these investigations also showed that the image of a “simple” object is wrong and that this traditional system appears to be rich and complex; (j) the building of this system happened to be a very complex process respecting the environment where it is built in and also the social and cultural identity of their owners; and (k) the typological study is based on the historical development of the system in the visited region, and it concerns: settlement typology, garden systems, space arrangements (built form, annex components, etc.), Shaduf typology, architecture and aesthetic of the object, archaeological development of the system, water specificities.

Different types of Shaduf recorded in the Saoura region

The difference lies in the building of the vertical part of the shaduf, in general 4 types of posts are found: one; two; three; and even four posts. The reasons for those lying behind this diversity are related to: (a) The quantity of water available in the underground. In the same oasis we can find two different types of posts depending on the richness of the water flow coming out of it; and (b) the largeness of an irrigated area can require a big shaduf composed of several posts, knowing that a couple of posts can be used by one balance branch only.

Shaduf building materials and technical diversity

There exist three types of Shaduf:

(a) Multi-post Shaduf, built in adobe (situated in Kerzaz area). Its construction is executed with moulded adobe bricks, set vertically in a crossed manner, the posts are composed with a large base work (approx. 1 m) and narrow top (approx. 0.5 m). The posts (Fig. 7) are joined together with tree branches, which are dried up away from the sun. The incrusted part of wood is covered of animal fat in order to avoid decomposition of the material. The earth material used is composed mostly of silicon, very poor in calcium oxide and practically free of clay. This makes it very stable. However such composition is easily subject to erosion, and needs permanent maintenance.

(b) Two-post Shaduf built of stones (localised in Kerzaz, and Beni Abbes area. This type is relatively rare, it is built of joined stones and their posts can reach 2 m high.

(c) Palm Trunk shaduf, (localised in Taghit). Structurally the principle is the same as the others, simply the timber posts are replaced by palm trunks, not more than 3 m high. These trunks are founded in a large basis made of adobe. This technique has the inconvenient of being of limited height.

Actual and future situation of Shaduf system

There seems to be a certain sense of awareness among the local population. The monumental value is the result of a highly symbolic cultural process. Restoration still takes place as long as there is usefulness or cultural awareness, of course within the availability of financial resources. Infrastructure part (the well) is mostly consolidated with either clay or cement bricks, or concrete (depending on the economic situation of the owner, as long as the level of water in the well is acceptable. Superstructure part (the posts) made of stones and clay or adobe bricks is sometimes restored just for its monumental aspect since the manual shaduf system is not used anymore in most cases and is being replaced by electrical motor pumps.

Figure 7 Shaduf posts types.

Socio-Economic Situation

The historical development of irrigation went through several eras:

(a) Pre colonial era: the adaptation of the berber running laws to Muslim laws have encouraged the individualisation of water property. The oasis paid tribute to nomadic tribes and practised an unfair exchange. The forms of domination already allowed the production of over work. The black African cast was used to irrigate and draw water from wells until when slavery was abolished and it became more and more difficult to find cheap labour.

(b) Colonial era: the move from a nomadic system to a 'pastoral' system led to permanent establishment of nomads. The overwork instead of being paid to the external system is rather kept inside in form of income, this process of keeping the gain inside the local society led to the gradual loss of traditional water systems.

(c) Agricultural revolution: the nationalisation of all the water resources in the Sahara, the creation of equity in the social system, broke the historical domination based organisation and contributed to the gradual loss of the traditional system.

(d) Actual era: The present era: the old social hierarchy is still present in some ksour in the area of Gourara (between the city Adrar and Timimoun), however signals of a social "transformation" are making their way in some other parts due to an evolving administrative management of local population, which used to be isolated and is now regrouped.

Work migration for men out of the Commune limits in newly formed agricultural properties and administrations, and leaving sometimes their ancient local gardening task to women. However, large areas agricultural tasks are still accomplished by men using frequently electrical motor pumps. It seems that traditional systems of water drainage are progressively lost because of 'social progress' rather than an exclusive "technical progress".

Overall reasons of a decline

There is a clear tendency to decline of the Oasis space in general, since its existence depends on a rare resource which is water. It is vanishing because of many reasons, among which are lack of rainfall; evaporation; lack of underground water; sand invasion; and intensive water use leads to salt rising to land upper coats.

Conclusion

The main conclusions that could be drawn from this study are:

(a) Global hydraulic situation. The lack of water resources is due to major changes in the global hydraulic structure (dams, water intakes, 'forages', etc.), climatic changes (less rain), and intensive use (agriculture).

(b) Experiences accomplished and working methods. Use of traditional and local material for the purpose of maintenance, usually coupled with the use of modern building materials (concrete, prefabricated bricks); use of electrical pumps has affected the traditional way of water catchment; the monumental value of the shaduf seems to be a long lasting event, however the hydraulic function is slowly disappearing. This situation is more dramatic in the Saoura then in the Gourara region.

(c) Socio-economic situation. The local society structure is starting to explode, due to run down economic situation. Population is heavily suffering from poverty and there is a lack of public amenities. Women and children are very active in water catchment tasks, whereas men are looking for opportunities of work, sometimes far away from their settlements.

Acknowledgments

I wish to thank first the European Commission and EJTN for their support in this project. Then my special thanks go to the people of Bechar and Adrar (Hydraulic Departments, Bechar University) for the assistance. Finally, I recognize the local people from Saoura and Gourara regions for their help and kindness.

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Archaeological and Written Sources about Water Use and its Technologies in the Medieval Castrum of Montenero Sabino, Italy

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Abstract: Different uses of water have been identified in the surrounding country-side of the medieval castrum of Montenero Sabino among which a complete hydraulic system, which played a key role in the rural community life from the 11th to15th century until 1960. This hydraulic system, typical of the mountainous areas of Mediterranean basin, like in Spain and North Africa, is formed by a horizontal-wheel water mill, for production of oil, flours and meals, a mill pond and 1 km-long mill race whose water came from the natural stream by a diversion due to a rock cut and a brick dam on the natural stream. From an anthropological standpoint the mill and its hydraulic system are a strong symbol of cultural identity for the local community with the castle and the church. It was an important point of aggregation of the entire village, which lived on farming and on rearing of few heads of livestock, in extraordinary continuity with local ancient Roman and Medieval settlements. The present global modernisation tends to dissolve this past, by abandoning "marginal" mountain areas and their traditional crops and customs, which are worthy of preservation as the Montenero Municipality has recently attempted to demand at EU level.

Keywords Rural landscape, horizontal-wheel water mill, irrigation system, medieval castrum, written sources, central Italy.

Introduction

Montenero, a castrum of Sabina located north-eastwards of Rome, is an emblematic example of how a well-preserved medieval mountainous site can provide a lot of information - through archaeological records and historical sources- about the different uses of water in a livestock-rearing and subsistence-agriculture settlement of central Italy that has retained some of those uses from Medieval times to date.

At Montenero, the *Mola*, at the bottom a stream valley, holds a horizontal-wheel water mill, which is connected to a system for water withdrawal, storage and distribution for irrigation. This mill adds to the many that are scattered along the nearby Farfa stream, which linked the *castrum* to the powerful economy of the Farfa Abbey via the Montenero stream. Moreover the Montenero water mill is similar to those which exploited the water of the close Velino river in the Medieval age, after the decline of the Roman sacred use of that water in the so called *Thermae* of Cotilia, the largest shrine in honour of *Vacuna*, the ancient Sabine water-guardian goddess. Mountainous hydraulic systems, such as the Montenero horizontal-

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wheel water mill, are a typical occurrence not only of Medieval central-southern Italy (in the Aterno river valley of Abruzzi, for wool beating; in the Nerina valley of Umbria and in Tuscany, for production of oil, flours & meals), but also of similar human settlements of the Mediterranean basin (especially in Spain and North Africa) (Bazzana, 2003).

The Montenero Castrum

Montenero stands in a humid woody mountainous region, rich in freshwater and groundwater, whose irrigation drainage has favoured constant and widespread human settlements from pre-Roman to present times (Fig. 1).

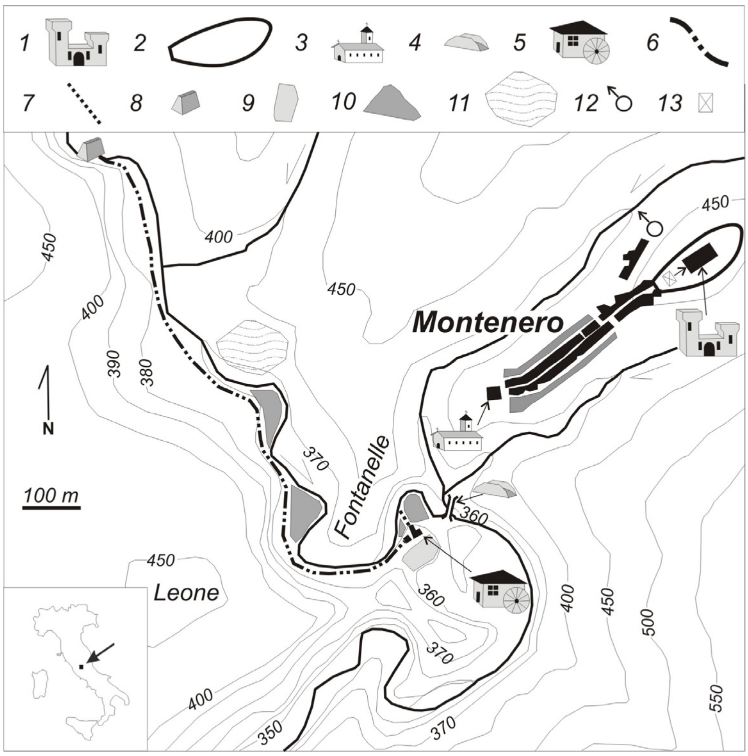

Figure 1 Map of Montenero area and the main medieval buildings or sites: 1- castle; 2- castle walls; 3- church; 4- bridge; 5- water mill; 6- mill race; 7- output mill race; 8- dam; 9- crop field; 10- orchard; 11- hemp field; 12- spring-fountain; 13- castle cistern.

It is a medieval fortified place, well preserved thanks to distance from main roads, but in its past it was better connected to the network of the Farfa stream, then navigable tributary of the Tiber (closely related to the famous Imperial and Benedictine Farfa Abbey), and to the *Salaria* and *Cecilia* ways, which linked the Tyrrhenian area to the Adriatic one. Montenero is a medieval mountaintop castle compound (9th or 11th century) (Fig. 2), having its *raison-d'être* in the natural defence function of water, as it rises at the top of a ridge between two streams, tributaries of the Farfa stream.

In time of danger, rural communities often found shelter in this walled village, as they lived in open-air dwellings at the foot the mountains. These hamlets originated from the ancient Roman *vici*, of which they continued to practise vine and olive growing by using ancient underground water supply conduits. In the Middle Ages, each of these small villages had: a church or parish church (whose names have often been used in the present toponomastics); an isolated mountain settlement, whose dwellers reared livestock and exploited the water resource of a mountain basin (*Lacus Rescanianus* from written sources and also in the present toponomastics); and simple hydraulic works, such as a well that enhanced the value of a mountainous orchard "*cum pomis et arboribus*"; in a donation to the Farfa Abbey in 1038, this well was cited as "*puteum de Capitiniano*") (Di Leo, 2003).

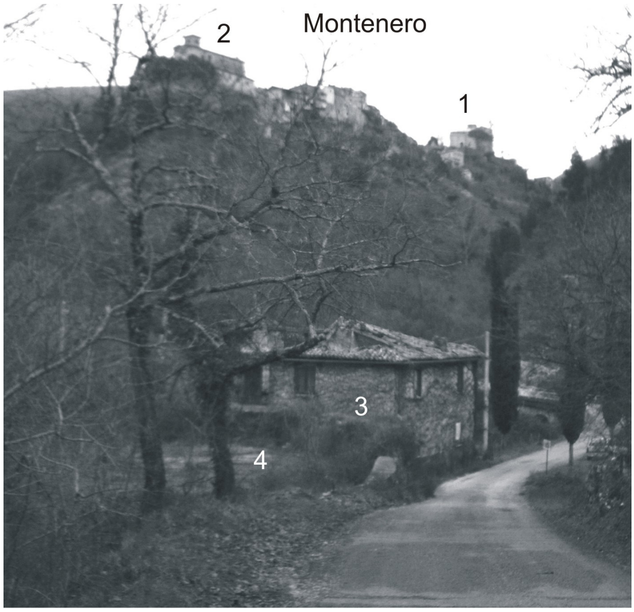

Figure 2 View of Montenero in the background and of the water mill in the foreground. 1- castle; 2- church; 3- mill house; 4- water mill pond.

The first mention of the Montenero toponym (*cacumine Montis Nigri*) leads back to a Papal Bull by Pope Marinus II (944) (Toubert, 1973). In the Bull, the village was reported to be part of the fortified defence network at the border between the Empire and the Pontifical State (*Dominium Petri*), which had been planned by Charles the Great almost two centuries before. Later on Montenero was cited in the "*Regesto Farfense*" (Farfa Abbey register) in 1023 as an unfortified *locum* and in 1038 and 1085 as a *castellum* (fortified castle compound).

Especially during the second period of castle building given rise to the barbarian invasions of the 10th and 11th centuries, each *castrum* responded to the need for *congregare hominess* (i.e. put villagers together) and, consequently, for achieving self-sufficiency (Pani Ermini, 2001). Hence, the *castrum* rose on a defensive rock, had a church and an oven-house and relied on extensive land for farming and grazing (so as to ensure the means of subsistence to its community), as well as a mill, i.e. a cornerstone of the local economy and society.

Uses of Water in the Castrum and in its Territory

Drinking water is reported to have been fed to the castrum by at least one spring (located on the Montenero slope, outside the fortified walls). On the hilltop, a large hypogeal vaulted cistern supplied water to the castle. The cistern, connected by a monolithic manhole cover to the middle of the courtyard, collected rain water (Fig. 1).

Moreover, some pottery fragments of medieval *protomaiolica* were unearthed upon excavations for castle restoration. This pottery, with peculiar decorations, could have been baked in a kiln whose remains are found in the rural area of Montenero called *Pago* (a large ancient Roman settlement, as indicated by its Latin place-name and by many hypogeal hydraulic drainage systems of the Roman age): in fact the *Pago* is still rich in clay and water, both necessary to make pottery and in this area a kiln was certainly active until the last century (Di Leo, 2003). Moreover, the villagers have cultivated orchards on the slopes of the *castrum* hill, using for irrigation rain water by means of terraced technique from Medieval times to date (Fig. 1).

The Montenero Water Mill

In the country-side there is evidence of a complete hydraulic system (Fig. 1), which played a key role in the local community life from the 11th century (based on the Farfa Abbey sources) and 15th century (based on the Renaissance notarial records of Giovanni Salvati) until 1960. This hydraulic system was typical in the mountainous areas of Mediterranean basin in medieval times. It was composed of: downstream, a water mill with horizontal wheel driving a millstone (*Mola*) (Fig. 3), a mill pond (o reservoir basin) (*Refota*) (Fig. 2) withdrawing water via a 1 km-long mill race (*Forma*) (Fig. 1) from the natural stream which was dammed and part of the water has been diverted in to the mill race; upstream a rock cut (*Leva*) (15 m-high and 1 m-wide) from which the stream water, dammed with a brick barrage (*Cascatora*) (Fig. 4), flows in to the mill race, maybe older than medieval time as suggested by the local Roman *villae* and the important local shrine of goddess *Vacuna* (*nemus Vacunae*) at *Leone* (Fig. 1).

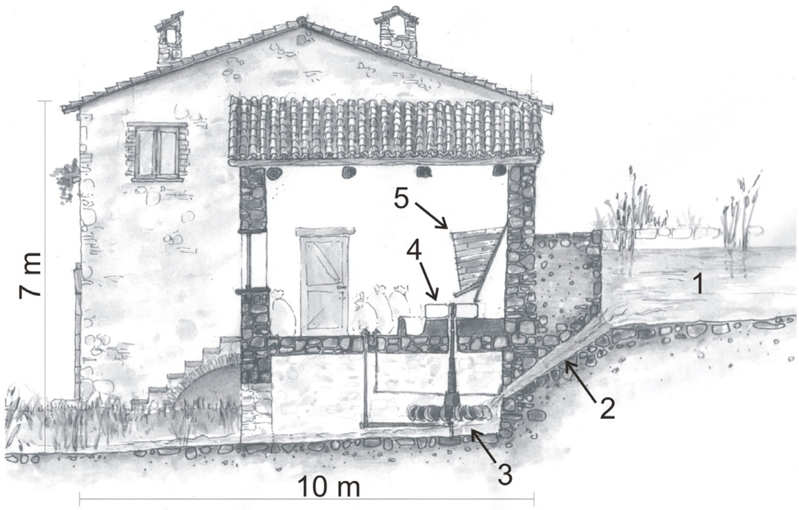

Figure 3 Sketch of Montenero horizontal-wheel water mill: 1- mill pond; 2- water conduit; 3- horizontal-wheel; 4- millstone; 5- hopper (sketch drawn by Anna Rita Farese).

The water of the mill race was also used, by means of a series of sluice gates (*Chiuse*), to irrigate the nearby orchards, among which there were valuable hemp fields, that the owners evaluated so much for eating and dressing as reported from Medieval and Rennaissance sources. The water system is still used nowadays for supplying water for irrigation and human and animal consumption, as demonstrated by the toponym of the area (*Fontanelle*: small fountains).

Figure 4 1- rock cut (Leva) (15 m-high and 1 m-wide) of the mill race; 2- brick dam (Cascatora).

Written Sources about the Mill

In the Middle Ages and in the Renaissance, the mill was central to the rural economy of the *castrum* and its strong symbolic value for the local community survived until the 1960s. The mill had a practical importance for the economy and subsistence of the communities living in the *castrum* and in its surroundings, but it also had a high local political value. Indeed, the landlord of the *castrum* showed his power over the community, by exercising monopoly ownership over the mill: the *dominus loci* imposed exclusive use of his mill and payment of a levy for usage: one sixteenth, one eighteenth or one twenty-fourth of the amount of the milled products. In this connection, in a late 16th century document, a notary (Jacobi) of the nearby Salisano *castrum* drew up a long list of fines for the offence of *maleficia* (i.e. infringement of a rule about the use of the *dominus castri*'s mill). These fines were inflicted onto a considerable number of villagers, including a peasant, on the following grounds: "*Quia macinavit extra castrum*" (the peasant had ground his wheat in a mill that did not fall under the landlord's monopoly). Furthermore, maintenance of the water mill and race system was assigned to farm managers as a mandatory task.

The first documentary evidence of the mill goes back to the end of the 15th century. It is a collection of notarial records of the priest-notary Giovanni Salvati, who lived in the Montenero *castrum* from 1430 to 1495 (Farese, 1997). In these voluminous records the mill is often referred to as a place-name and, in one of the deeds, it is explicitly named as the object of a notarial transaction. This particular deed is a contract for the construction of a bridge (still existing today) crossing the Montenero stream and facilitating access to the mill. The contract, which was dated 21 June 1491 and entered between the *Consiliis* of the *castrum* (i.e. the elected representatives of the community) and the *Magistro* Antonio Lombardo of Mompeo, specified that the bridge should have been built "...*cum lu parapecto alto sino a la cinta et di la largheza della stessa mesura dilla porta dellolivella del* *castello*…" (with a parapet as tall as the safety of people needed and as wide as one of the castle door) (Fig. 5).

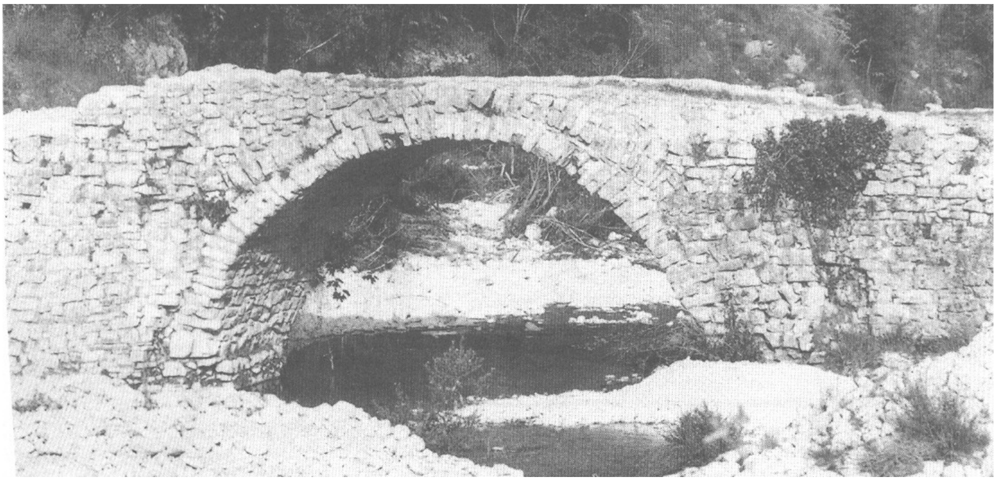

Figure 5 View of the medieval bridge before the 1977 flooding.

Nevertheless, with reasonable certainty, the water mill system was so closely tied to the life of the *castrum* (production of flours & meals and oil) and of its rural population (irrigation of private orchards through the mill race and sluice-gate system) as to have a much more remote origin; in fact, it is likely to have been built during the first period of castle building at Montenero from the 8th to the 9th century. As a matter of fact, as early as in the 11th century, the authoritative Farfa Abbey register mentioned the mill and the *vallem de milo* (present plain of *Mola*, that is, the mill plain) among the donations made by noble families to the powerful Farfa Abbey (in 1085: …*aquimolis, molendinis vel decursibus aquarum*…) among the major resources of the Montenero territory.

The Mill in the Modern Age: Conclusions

In more recent times, the mill was owned by the Marquis Vincentini, relatives of the Orsini, a noble Roman family allied with the Papacy from the Middle Ages to the Renaissance. This family owned, among others, the medieval castle of Montenero that it then sold to private individuals in the late 1970s. The present owner first transformed the mill house into a residence (thus losing its original characters) and then abandoned it. In spite of this, traces of the original ancient structure are still visible: two architectural volumes corresponding to the three processes of grinding: wheat, cereals and olives.

Nonetheless, the relevance of this monument does not lie only in its antiquity. From an anthropological standpoint too the mill and its hydraulic system are a strong symbol of cultural identity for the local mountain community, together with the castle and the church.

At least until the 1960s, the mill was the core of the Montenero rural community life, the driver of the local rural economy, the point of aggregation and of cultural reference of the entire village, which lived on farming and on rearing of few heads of livestock, in extraordinary continuity with local ancient Roman and medieval settlements.

So the mill was unquestionably the engine of the local economy. Today, sadly in decay with respect to the history that it tells, the mill is strongly evocative of a place of work, of rural life, of a not too distant past. The present Italian and global socio-economic modernisation tends to dissolve this past, by abandoning “marginal” mountain areas and their traditional crops and customs. However, this past is worthy of preservation and its value should be enhanced for agri-tourism or as a museal asset of the area and of its inhabitants, as the Montenero Municipality has recently attempted to demand at EU level.

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History of Ancient Dams Located on Kor and Sivand Rivers in Iran

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Abstract: There are several ancient dams and hydraulic structures in Iran. This paper presents history of some of them in south-western Iran. Nine dams on Kor and Sivand rivers in Fars Province and watermills constructed adjacent to the dams are also described. The described dams are Darius dams, Amir dam, Feizabad dam, Tilakan dam, Mawan dam, Hasanabad dam, and Jahanabad dam. Study shows that the ancient Persians had the knowledge of selecting the proper construction site and materials for such hydraulic structures. They also knew how to build stable diversion dams.

Keywords Acient dam; Iran; Kor river.

Introduction

Iran is located in a semi-arid region of the world. Since ancient times, the people and especially the farmers had problems with water shortage. Therefore, they always were trying to find an appropriate solution. Many dams were constructed and underground water tunnels and galleries (Qanat) were excavated by ancient Persians. The traces of some of these projects, which are among the greatest in history, still exist. There are traces of irrigation channels about 6,000 years old in the ruins of Sialak, near Kashan, in central Iran. Cyrus the Great King of Persia, after defeating the Babylonian Army in 539 B.C., built an earth dam for irrigation on Diala, a tributary of Tigris. He ordered excavation of 30 canals for water distribution works. The Persian King Darius the Great (521-485 B.C.) from Achaemenian dynasty built dams on River Kor, south of Persepolis while he was in power (Javan, 1996).

Many people in the region of the Black sea to the Red Sea were subject to the king and had to pay taxes. According to Buske (1995) one of these taxes seemed funny to Herodotus. This was the tax on water right for irrigation. Buske quotes from Herodotus about a plain in Asia which was surrounded by mountains with five defiles and a great river called Aces. This river had been the source of irrigation for people who paid taxes to King Darius. According to Herodotus, the king had caused the clefts of the mountains to be blocked up. He had also placed gates at each cleft and created a Sea in the plain. Javan (1996) believes that the river might be Kor on which six dams were also erected. There are other ancient hydraulic structures for storage and conveyance of water in Iran. Some of them are cited by Javan (1996). Introducing and discussing the various aspects of all of the ancient Persian hydraulic structures is not possible. Many of the ancient Persian hydraulic structures which were located in the Fars Province of Iran are introduced by Javaheri and Javaheri (1999; 2001). In this paper some of them are briefly explained.

Irrigation in Ancient Persia

Field investigations show that since 5,000 years ago, Persians used the Basin Irrigation method to irrigate their farms. Water shortage persuaded ancient Persians to be skillful in water conveyance and distribution from source to plant's root. Whenever they faced a problem, they solved it by inventing new tools. Furrow originally comes from a Persian word PAARO, meaning a place that water can go through it by itself. Old Persians were skillful in raising underground water. They invented an underground conduit Qanat to convey water form wells to surface by gravity. They also used Qanat for drainage. Persians connected a wheel to a bull for uploading the underground water which was named Iranian Wheel in the literature. The famous Greek mathematician Pythagoras explained about this tool after he visited Persia. Ancient Persians dug 2-3 m wells and planted trees in it and directed the surface water to these holes. These holes also reduced the soil water evaporation. The ancient water managers in Persia which were named Mirab(ditch rider) used a kind of watch which that worked with water for irrigation scheduling. Persians used micro irrigation in deserts. They dug a hole and put a jug full of water in it. In Marvdasht and Korbal plains of Fars Province in Iran, farmers had used surface waters obtained from Kor and Sivand rivers. They diverted water from these rivers by several diversion dams which will be described in this paper (Javaheri and Javaheri, 1999).

Description of the Area under Study

The Marvdasht and Korbal plain are located near the city of Shiraz, in Fars province, southwestern Iran (Fig. 1). The average altitude of the area is about 1,590 m. The area is a semi-arid region with an average precipitation of 340 mm/yr. From agricultural and economical aspects, these two plains are very important in Fars province. The ancient palaces of Percepolis and Estakhr city have promoted tourism industry in Marvdasht and Korbal plains. In ancient Persia, the water managers had been the third powerful man in the government ranking. Kor and Sivand rivers are the major rivers of the region. Sivand river flows into Kor river at Pol-e-Khan (Khan bridge) and discharges into Bakhtegan lake. Kor river crosses Shiraz- Marvdasht road at Khan bridge (Fig. 1). In the last 80 km, six diversion dams had been constructed during the past centuries (Fig. 2). The dams were constructed of cut stones with Sarooj mortared joints (lime and ash). These multipurpose dams raise water level in the river and regulate irrigation water to the farm lands, supply the required head for several mills, and act as a bridge between the banks of the river.

Water Mills

According to Javan (1996), the locations of the water mills were chosen in such a way so as to gain a head of 5 to 6 m to prevent damages to the wooden wheels (Fig. 3-4). The general components of water mills consist of a small reservoir upstream of the dam, water tower which could be sealed from inside by stop logs, wooden turbines with wooden axes, two grinding stones with diameter of 1.3 m (the lower one was always fixed while the upper one was driven by the wooden wheel), the feeder tank, the wooden chute, and tailrace canal. At present, these watermills are not functioning.

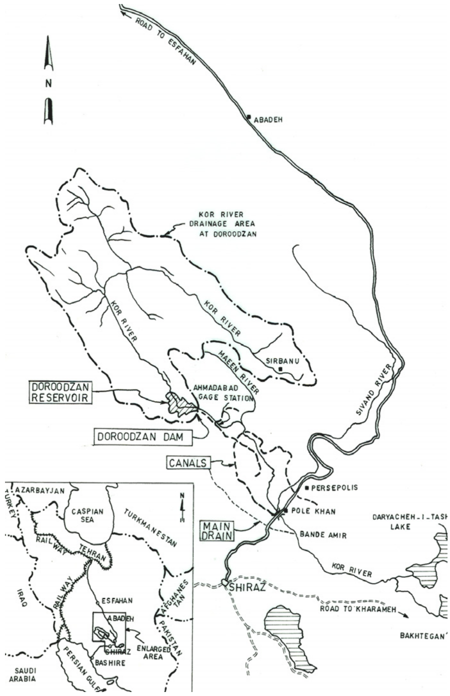

Figure 1 Location map of the area under study.

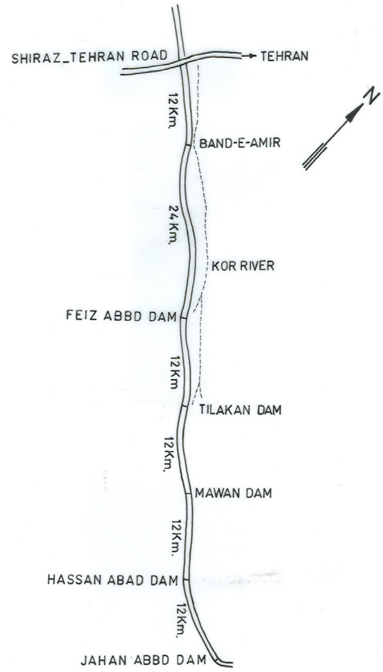

Figure 2 Location of Kor river dams.

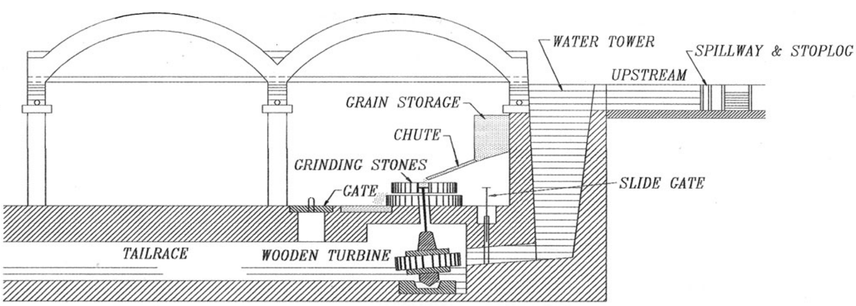

Figure 3 General section of a watermill in ancient Iran.

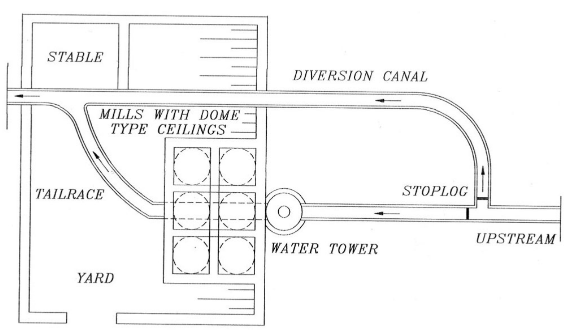

Figure 4 General plan of a watermill in ancient Iran.

Darius dams

About 2,500 years ago, King Darius from Achaemenian dynasty constructed two dams at the upstream of Khan bridge on Kor river and another dam on Sivand river near the Persepolis. The first one was on the left bank of Kor river and was unearthed while Doroodzan dam was under construction in 1970. Doroodzan dam irrigates about 56,000 ha of downstream agricultural lands of Marvdasht Plain. The ancient dam has 2 openings. The length, width, width and height of the openings were 8, 3.5, 2.7, and 2 m, respectively. The second dam was located on the right bank of the Kor river, at the downstream of the first dam, and under the present residential camp. The second dam has a length and width of 75 m, and 5.2 m, including five 1.5 m width offtake openings. The third dam which was a storage dam, was constructed on Sivand river near the ancient city of Estakhr. The remains of Estakhr city still exists. However, some parts of the foundation can be observed at the site. Sivand river was the nearest water resource to the Persepolis. The difference in elevation between the dam and the Persepolis was 10-12 m. Therefore, the dam could convey water to the Persepolis. A canal with a depth of 8 m conveyed a large volume of water to the Persepolis. During the past centuries, the canal was ruined and used by the farmers. Figures 5 and 6 show the ruins of the second and third ancient Darius dams and related hydraulic structures.

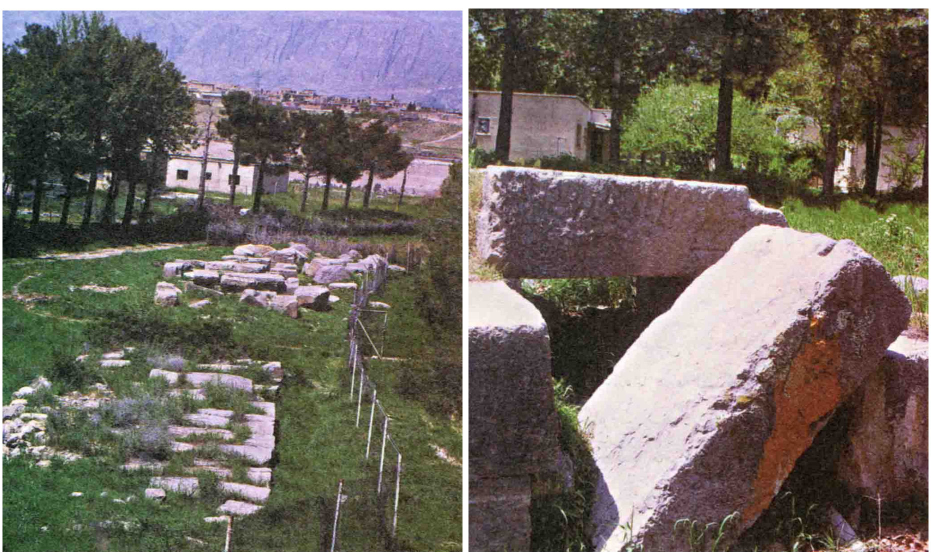

Figure 5 Ruins of the second ancient Darius dam and related diversion structure.

Amir Dam (Band-E-Amir)

This dam which is one of the oldest dams of Iran, is located at 44 km, north east of Shiraz and 20 km downstream of Khan bridge (Figs. 1 and 2). Some historians believe that the dam was erected on Kor river by Achaemenians (about 2,500 years ago), because cut stones from that era were found in the dam foundation (Javan, 1996). However, the King Azadoddoleh Deylami form Al-E-Booyeh dynasty (about 1,050 years ago) rehabilitated the dam. The masonry structure still stands and functions well. It has a height of 15 m from the foundation and a crest length of 119 m.

Figure 6 Ruins of the third ancient Darius dam and related diversion structure.

It has a bridge of arch type with 13 openings. The bridge width is about 6 m. The average width of the openings is 4.5 m while the piers width is 3.5 m. There are 28 watermills along the banks of the river. The other characteristics of this dam are shown in Table 1. A view of Amir dam is shown in Figure 7. There were two bypass canals at the river banks to convey the diverted water. At present, the right bank canal Gavshir Canal can be observed. The average width and depth and capacity of the canal are 9 m, 7 m, and 250 m^3/s, respectively. At present the spillway height is increased by about 1.8 m to increase the amount of diverted water. According to Javan (1996) the minimum dam safety factors for sliding and overturning are 1.3 and 1.8 under earthquake condition. Under flooded condition these two safety factors are equal to 2.4 and 2.5, respectively. Table 1 shows other specifications of the dam.

Table 1 Some of the technical characteristics of the studied dams.

Dam	Unit	Amir	Feizabad	Tilakan	Mawan
Average elevation from the river bed	m	15	5.5	5	1.5
Elevation (a.s.l.)	m	1585.7	1572.8	1568	1563.7
Added height	m	1.5	1.8	1.5	2
Bridge or dam width	m	5.8	4 - 12	7.5	4
Bridge or dam length	m	108	250	180	70
Safety factor for overturning		1.8	2.7	2.4	4.2
Safety factor for sliding		1.3	1.6	1.3	3
Max. below stress	kg/cm^2	1.8	0.9	0.9	0.5
Lane Coeff. (for Piping analysis)		2.8	2	8	3

Figure 7 Amir dam (Band-e-Amir) from downstream and upstream view.

Feizabad Dam

This dam is located at the downstream of Amir dam (23 km) and Khan bridge (36.5 km). This dam was reconstructed by Atabak Chaveli about 700 years ago. There were 22 watermills along this dam. The average length of the dam is 250 m while 200 m of the dam is located in the river. Small canals with 0.3 m depth and 0.5 m width divert water to the mills. The dam width varies from 4 to 12 m. The elevation of the dam was 1572.7 a.s.l. At present the spillway height is increased about 1.8 m. It is interesting that only 40 m of the dam length occupies the river width while the rest is constructed along the river. This was due to two reasons: (a) the small width of the river and existence of watermills and (b) for increasing the flow capacity of the spillway. At the right bank of the dam there is a canal with 1 m depth and 1.5 m width which was constructed on the spillway to convey water to downstream at low flows (flows less than 10 m^3/s). The dam begins to submerge when the river flow reaches 90 m^3/s and is completely submerged at the discharge of 150 m^3/s. According to Zand (2005) the safety factors for sliding and overturning (under earthquake) are about 1.6 and 2.7. The average dam level from the bed was about 5.5 m. Figure 8 shows the pictures of this dam before and after rehabilitation. See Table 1 for more details.

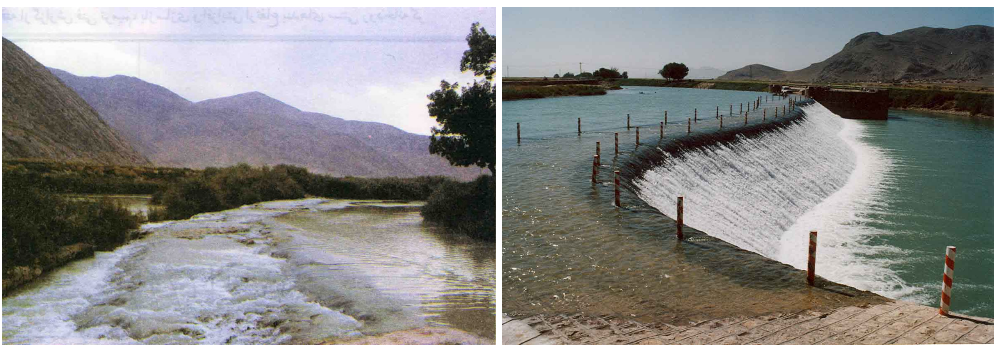

Figure 8 Feizabad dam before and after rehabilitation.

Tilakan Dam

At 14.5 km downstream of Feizabad there is a dam named Tilakan dam. This dam is multipurpose similar to the dams mentioned before. This dam is not submerged for the discharges lower than 80 m^3/s. The upstream and downstream water level will be nearly the same at the discharge of 230 m^3/s. The dam length was about 180 m with 34 openings with 1.7, 2, 2.4, and 3.5 m width. The safety factors for sliding and overturning under earthquake are 1.3 and 2.4 (Zand, 2005). The average dam height from the bed was about 5 m. Figure 9 shows Tilakan dam picture before and after rehabilitation. Figure 10 shows Tilakan dam and the corresponding diverted canals and farms before rehabilitation.

Mawan Dam

Mawan dam is located at 14 km downstream of Tilakan dam. The dam length and width is 70 and 4 m respectively. The plan of this dam is L-shaped. 50 m is perpendicular to the river and 20 m along the river. Water level difference between upstream and downstream face is nearly 1.5 m. According to Zand (2005), from a flow discharge equal to 30 m^3/s, the dam begins to submerge because of the low dam height (1.5 m from the river bed). The estimated safety factors for sliding and overturning under earthquake condition are 3 and 4.2 (Table 1). Figure 11 shows Mawan dam before and after rehabilitation.

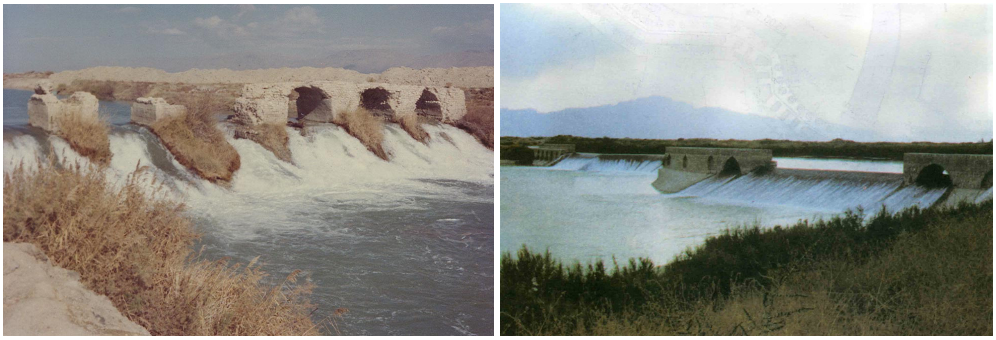

Figure 9 Tilakan dam before and after rehabilitation.

Figure 10 Tilakan dam and the corresponding canals and farms before rehabilitation.

Figure 11 Mawan dam before and after rehabilitation.

Hasanabad and Jahanabad Dams

The last two ancient dams that are located on Kor river are Hasanabad and Jahanabad dams. Hasanabad dam is located at a distance of 12 km at the downstream of Mawan dam while the distance between Hasanabad and Jahanabad is also about 12 km. Hasanabad dam was completely destroyed and a new dam was constructed instead. Jahanabad dam with a length, width and height of 50, 12, and 4-6 m still exists.

Conclusions

At present, the modern storage Doroodzan dam with a capacity of 1 billion m^3 is constructed near the ancient Darius dam. This fact shows that the ancient engineers had enough knowledge in site selection. The estimated dam safety factors also show good knowledge of ancient Persians in designing the safe structures against sliding, overturning and piping, or in other words the principles of stability.

Acknowledgement

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The Ocaña's Qanat and "Fuente Grande": A Cultural Heritage to Preserve

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Abstract: Shallow groundwater collecting systems by horizontal galleries, known by the Arabic voice qanats, have had a large development in Al-Andalus. These systems have been used in order to supply water to cities or irrigated lands, being verified their operating from 20th century until today. Ocaña qanat with Arabian and medieval elements, constitutes an impressive relic due to its 400 m of waterways and magnificent domed chambers. The fact that it is preserved almost in its totally, is owing to that it still contributes to the 20% of the supply to the town of Ocaña (around 600 m³/d) and the careful maintenance on behalf of the Town Council, and perhaps, its connection to the spectacular Fuente Grande, declared a national monument in 1976. Its archaeological, cultural, engineer, architectonic and hydrogeology interest is evident. It trades of a live relic. Its future function, once it won't be necessary to inhabitants supply, is clear: that water comes back again to flow through the pipes, little channels, fonts and troughs of the Fuente Grande, according to UNESCO recommendations, that declared in May 2002 the importance of the protection of this kind of buildings as a monument of world heritage.

Keywords Groundwater; historical water supply; infiltration gallery; qanat.

Introduction

A magnificent qanat (or "*viaje de agua*") with Arabian and medieval elements may be contemplated in the village of Ocaña (Toledo), in the centre of the Iberian Peninsula, 60 km from Madrid. The fact that it is preserved almost in its totally, is owing to that it still contributes to the 20% of the supply (around 600 m³/d) to the town (~6,000 inh.) and the careful maintenance on behalf of the Town Council, and perhaps, its connection to the spectacular Fuente Grande, declared a national monument in 1976. The qanat is included among the superb religious and civil buildings and constructions of Ocaña, a village of historical significance, with Roman paved roads remains and coffins and remains of its occupation during the Arabic period (Matellanes Merchán, 1999).

The "*viaje de agua*" is part of a water supply system that also includes the Fuente Grande, a fountain whose design is attributed to Juan de Herrera (the El Escorial's architect), that was built over the years 1573 to 1578. Its construction is justified by the importance of the village at that period, with a population of 3,000 people that included 300 "*caballeros hijosdalgo*" (lower nobility) and more than 200 priests, monks and nuns (Viñas *et al.*, 1949).

Hydrogeological Framework

To understand the location and operation of the qanats and its elements, we have to consider the regional geology and hydrogeology. Ocaña is located in the so-called “*Mesa de Ocaña*”, an almost horizontal plain of around 1,000 km² that is elevated 100-150 m above its surroundings. A geological cross-section of the border of the Mesa de Ocaña is shown in Figure 1, in which the different lithologies are represented (from base to top): (a) Basal unit mainly composed of gypsum with intercalated marls (Miocene) [layer 5]; (b) Marl-gypsiferous materials [layer 4²] at the base that pass upwardly to marls, marly limestones and limestones (Miocene) [layer 4¹]; most of the collecting galleries cut through these marly calcareous facies; (c) Unit consisting of white-reddish sandstones and limestones (the so-called “*Caliza del Páramo*”, Upper Miocene) [layer 3], located above the water table; and (d) Covering materials, mostly clayey (Pliocene) [layer 2]. The scarps and slopes are covered by cuaternary detrital materials [layer 1].

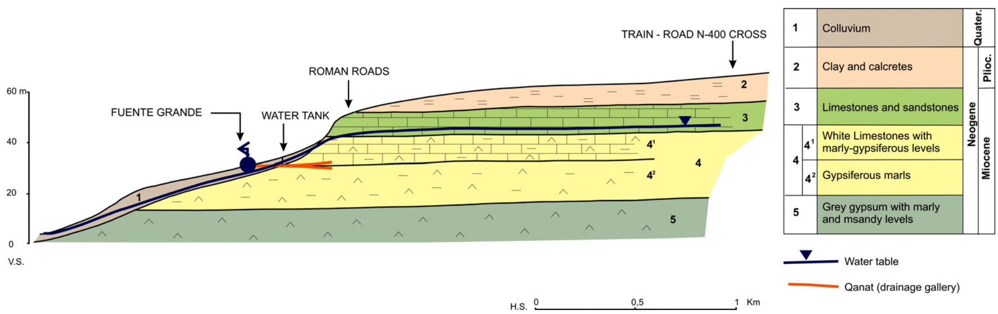

Figure 1 The Fuente Grande of Ocaña delivered the waters supplied by the qanat in function of their quality. The water collected from the gypsiferous marls [4²] was only utilized for washing and livestock drinking. The water collected from the marly limestones was used for human consumption.

Several springs occur at the base of the scarps that limit the plain (“*mesa*”) constituted by the “*Caliza del Páramo*”. They have been used until recent times as source for human and livestock drinking water, and washing and irrigation water. Thus, the village of Ocaña has traditionally made use of them. Also, they have been used for the supply of the Real Sitio of Aranjuez (over 10 km far away) due to the quality of water, better if it is compared to the harder and more sulphated water of Tagus River. The stratigraphical and morphological features and their relationship with the galleries may explain how the Ocaña qanat works. The collecting zones of the galleries are at the marly limestones or the marl-gypsiferous materials indicated above. The NE branch (‘the old gallery’) of the qanat captures waters with conductivity values lower than 1.5 dS/m, hardness of 50º F and about 370 mg/L of dissolved sulphate. In contrast, the SE collecting branch (‘the new gallery’) captures harder waters, with conductivity values up to 3 dS/m, hardness close to 100º F and 800 mg/L of dissolved sulphate. These significant differences in the quality of water reflect the large compositional variations of the materials supplying water, even if differences in depth are small.

The fact that the qanat is collecting two different types of water is the origin of the most outstanding feature of the distribution system: a hydraulic design that keeps the waters unmixed until they reach the Fuente Grande, where they could be delivered in two independent ways through different pipes, troughs and pools. Thus, the best quality water was used for human consumption and the lowest quality water was only utilized for washing and livestock drinking. Water analysis carried out in 2001 and 2004 pointed out the large amount of dissolved nitrate (> 80 mg/L) in the water of both branches. The origin of these high values is the unirrigated and irrigated crops in the valley were the qanat is located at 9 m depth, and a rubbish dump in the left border of that valley.

The Qanat and the Fuente Grande

The Ocaña qanat is an impressive work that evokes the old Roman and Arabic techniques (Fig. 2). It consists of two main galleries with a total length of 400 m. The main transport gallery [point 1] runs in an approximate SW-NE direction. The main access to the waterway is located 125 m from the Fuente Grande in a building with a 200 m³ deposit and a pump system to supply water to the village [point 2]. From that position and going upstream, we find the longest segment [point 3], a lined arched gallery with a section of 1.90 m high and 1.30 m width. There are five aeration wells of conic vertical shape aligned with a spacing of 40 m. They are 7-11 m depth, of square (0.80 m side) internal shape at the ceiling of the main gallery that changes upwards to a circular or polygonal shape. The aeration wells stand out the surface of the terrain as cones with breathing holes and a stone ball on the top which are called "*madamas*" in the local terminology (Fig. 3). Those stone balls are similar to those utilized as ornaments in the Fuente Grande. The positions of these structures allow the course of the galleries to be mapped along the valley (Fig. 4) (López-Camacho *et al.*, 2005).

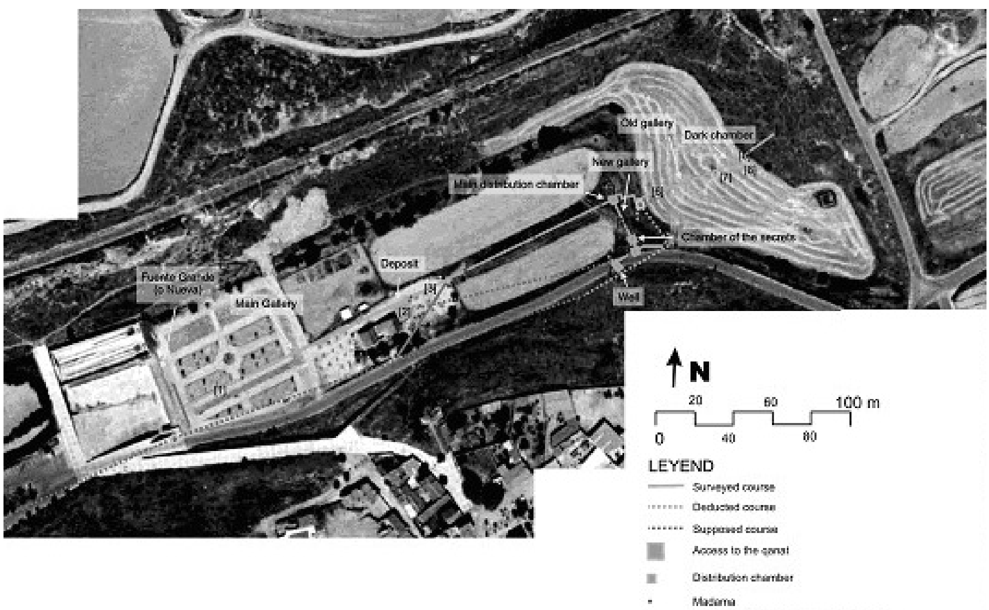

Figure 2 The qanat or "viaje de agua" -with some no accessible galleries and chambers- ends its course at la Fuente Grande, a fountain of Herrerian style built in the 16th century. Location of galleries and chambers are showed in the aerial photo.

The main gallery is rectilinear, starting at the distribution or main chamber [point 5]. This chamber includes the main collection and distribution drain, of 3.30 m side and 4.50 m high, roofed by a barrel vault. The access from outside is direct by an angular staircase built with bricks forming small barrel vaults, revealing a mudejar style. It was the main access before the pump building was built in 1888.

Figure 3 The aeration wells stand out the surface of terrain, as cones with breathing holes and a stone ball on the top which are called “madamas” in the local terminology.

Figure 4 Panoramic view of the valley where the qanat is located. The positions of the “madamas” point out the course of the gallery that ends at Fuente Grande.

As noted above, a peculiar feature of the Ocaña qanat is that the different types of waters do not mix. In the main gallery, the two types of waters are channelled by two gutters (0.16 m high and 0.20-0.30 m width), separated each other by a sidewalk (Fig. 5). Previously, the channelled waters from the two collecting galleries bearing a 90º angle get into the main collecting drain that delivers them separately to the two gutters (Fig. 6).

Figure 5 The main transport gallery, of wide dimensions, is channeling independently the two types of waters: hard water by the left gutter, soft water by the right gutter.

Figure 6 Distribution drain. Note how the two types of water are separated each other.

The old gallery of the qanat [point 6] begins at the distribution chamber and changes abruptly the main course. There, it can be observed an inaccessible chamber from a porthole. Following upstream the course of the gallery, this is progressively getting narrower and increasing the height. Thus, the gallery is 2.50 m high and 0.55 m width just before getting the next chamber [point 7]. That anomalous high is interpreted to be caused by progressively deeper excavation works to connect the main gallery to other structures of the qanat, or alternatively, it can be related to drops of the water table or to errors in the earlier levelings. The chamber [point 7] is smaller than the main distribution chamber and is showing remains of hardwood floor. It constitutes the connection of two branches [point 8], which are similar in dimensions to the later one. This is the oldest surveyed sector of the qanat. Dating performed by thermoluminiscence on bricks yields ages of 620-650 years (middle to end of 16th century). The two branches are very narrow (0.40-0.55 metros wide) and the eastern branch displays some small transversal brick bridges (Fig. 7), which are very unusual in this kind of galleries.

Figure 7 Small transversal brick bridges, regularly spaced along the gallery.

Figure 8 The qanat ends its course at the Fuente Grande, a monumental fountain of Renaissance architecture of herrerian style that was built over the years 1573 to 1578. The fountain stands in a large stone plaza of about 2,000 m² that is closed in its eastern part by a portico of 20 pillars that support a two-way roof.

The modern sector of the quanat was built at the Felipe II times, together with the Fuente Grande fountain. The thermoluminiscence dating on bricks yields ages of 450 years (middle XV century). The brick lining style -the same in the all chambers and galleries, the dimensions of these galleries -more than 1.5 m width, the high capacity of the chambers, and the forced symmetry in the location of chambers and galleries, reflect a rationalist conception. Other 15th century collecting gallery [point 9] departs from the main distribution chamber. That supplies a larger flow, as it is also collecting water from an excavated well. The course of this gallery is very complex: two chambers –the first one with a domed-up groin vault–, two distribution drains and several chambers and galleries that at the present time are closed by walls. The qanat ends its course at the Fuente Grande, a monumental fountain of Renaissance architecture of herrerian style that was built over the years 1573 to 1578. The fountain stands in a large stone plaza of about 2,000 m² (Fig. 8) that is accessed by a ramp and a masonry staircase of two sections. It is closed in its eastern part by a portico of 20 pillars that support a two-way roof. The waters are channeled in such a well-thought out way, that the excess waters from the gutters, troughs and deposits were collected and transported along a gutter excavated in the rock to the outside of the fountain to irrigate the neighborhood crops. The waters from the two gutters of the main gallery were redistributed in the fountain: the water of the best quality flowed via 20 bronze pipes and the water of poor quality was conducted by a stone gutter to a large drinking trough for livestock and two huge washing pools that could be simultaneously used by 300 people.

In this work, we have described the accessible galleries and branches. However, there is evidence of more galleries and works that are inaccessible, remaining their courses and locations unknown. For that reason, surface geophysical techniques are being applied to detect the concealed structures. In this study, the occurrence of both gypsum and water saturated materials recommended the application of the Electrical Resistivity Tomography (ERT) technique. The ERT method is one of the most commonly applied in geophysical survey because of its suitability in detecting walls, cavities and other structures at different depths. The method is based on the measure of the voltage generated by a transmission of current between electrodes placed in the ground. From those data, apparent electrical resistivity may be calculated and used to create sections where the apparent resistivity values are plotted versus the depth, where resistivity variations reflect differences of the materials (including presence of water or voids). Different electrode arrays are possible. Taking into account that the aim of the survey was the detection of horizontal galleries, the dipole-dipole array was chosen among the all possible arrangements since this array gives a good horizontal resolution.

Several test surveys located at places where the water galleries presented well known features (infilling thickness, gallery depth and height) were carried out. The goal of these surveys was to contrast the applicability of the method to the detection of the well known galleries, previously to define a broader survey campaign to locate and map the complete water galleries net. Figure 9 represents two ERT profiles traverse to the gallery. The location of the air-filled galleries are marked by the presence of high resistivity values, circular or slightly elliptic in shape, whereas some low resistivity values of similar shape have been related to the probable occurrence of a water-filled gallery. In a future work, a more extensive ERT survey would be accomplished to accurately delineate the location of waterways and domed chambers.

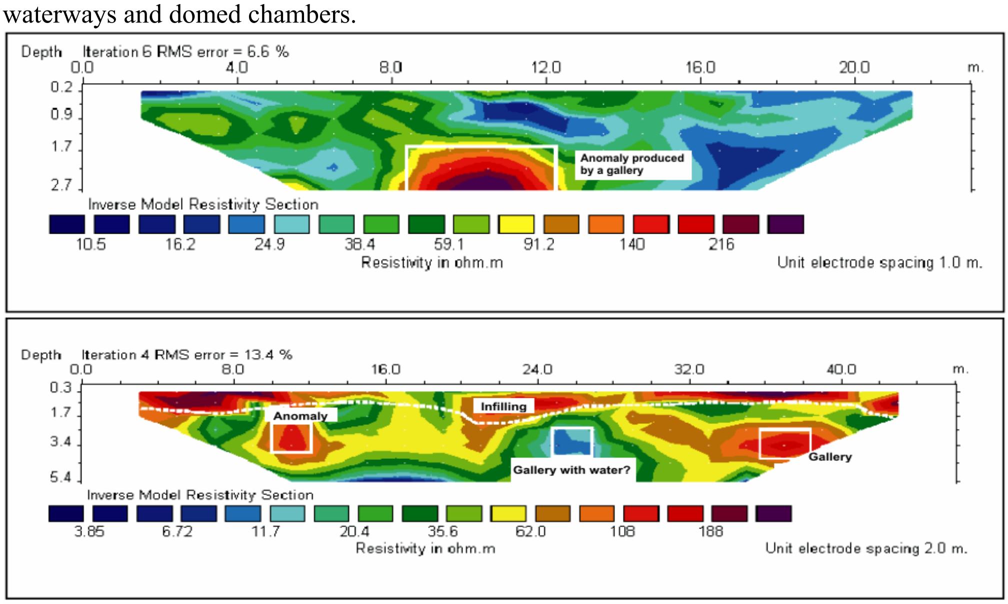

Figure 9 ERT profiles where the location of waterways is shown. First profile corresponds to the rear part of the Fuente Grande, whereas the second one is located near the distribution chamber (See location of profiles in Figure 2).

Acknowledgments

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Abstract: In Kazakhstan, before the present article, only 3 lines of wells (called “karez”, which in Persian means “water uplift”) were known in the area of Sauran (Turkestan oasis) from historical accounts, topographic maps and archaeological surveys. They were considered isolated specimens imported from elsewhere during late medieval times. Only in the years 2002-2004 geoarchaeological and aerial surveys discovered several karez lines in other areas of the Turkestan oasis and, in an area of 20 x 20 km² around Sauran, 261 karez lines developing for 124 km and numbering more than 9,000 wells. The geological, hydrogeological and archaeological context of the karez systems have been studied, together with their mapping and classification, analysis of construction features and elaboration of their data base. A preliminary interpretation of the phenomenon suggests that “karez” are not “qanat” but an original construction based on a local traditional deep knowledge of groundwater dynamics that today have been forgotten. They are man-made springs causing the surface resurgence of water from shallow aquifers not by underground galleries (qanat) but by micro-artesian and gravity pressure. They are not the product of a qanat technology imported during the late Middle Ages, but rather a genial local invention that could have evolved from the end of 1st millennium A.D. as a development of the well-technology of mixed farming-pastoralist communities adapted to desert regions. A preliminary modeling suggests (and some preliminary surveys confirm) that karez must also be present in great number in other desert areas of the Karatau piedmonts, of Semirechie and of other regions of Central Asia (Tarim, Nuratau, Turkmenistan). The discovery has most probably economical significance for modern land reclamation in desert zones.

Keywords Groundwater devices (karez); hydrogeology; Middle Ages; south Kazakhstan.

Background Knowledge about the Karez of the Turkestan Oasis

Groundwater systems consisting of series of aligned wells interconnected by underground galleries have been constructed on desertic sloping piedmonts for more than 2000 years in Middle East (where they are called “qanat”) and during the last 1,000 years in Turkmenistan and Tarim (where they are called “karez”). They are still active today in Iran, Turkmenistan and Tarim.

Historical and ethnographic sources

Information about the existence of karez in the Turkestan oasis is given by the historical account of Wasifi and by the ethnographic account of Dingelshstedt; and a few karez lines are documented on Soviet topographic maps. The XVI century Tadjik writer Makhmud Zainaddin Wasifi, in a passage of “*Amazing Events*”, says that in around 1510 the Muslim sheikh Mir-Arab, religious leader in Bukhara under the Chebanids, offered to the town of Sauran, in the Turkestan oasis, 2 karez lines and a “charbag” (walled garden), “similar to nothing that people traveling all around the world had ever seen neither on land neither on sea” (Boldirev, 1957: 167-168). Wasifi’s account inspired the first archaeological research of the karez of the Turkestan oasis. Groshev (1985) detected 3 karez lines north of the ruins of the medieval town of Sauran (where in reality there is a system of 8 lines) and excavated, down to 4 m, 2 wells (in reality 11) of one of the lines without finding any trace of underground galleries. He interpreted the 3 karez lines as part of the system quoted by Wasifi and, even though facing opposite evidence, didn’t doubt of the presence of underground galleries and the similarity of the Sauran karez with the qanat of the Middle East. Together with Wasifi, the karez of Sauran were interpreted as an exotic rarity imported by an enlightened religious leader during the Late Middle ages.

The second important document (that apparently had not been recovered until now) about the existence of karez in the Turkestan oasis is represented by a few pages of an ethnographic report made in the 1889 by the Russian colonel N Dingelshstedt. Analyzing the irrigation systems of the Turkestan region, Dingelshstedt says that karez exist, had been built more than 250 years ago, and some of them have been continuously restored and are still active. He asserts the presence of 18 active karez systems scattered in several valleys throughout the region; and, following the verbal reports of the local population, quotes the presence of 80 abandoned karez lines in the Sauran region. Like Wasifi, he is astonished by the marvelous characteristics of the karez system and comments: “It is rare to meet such an excellent and convenient system for agriculture. In the area of Turkestan karez are partially functioning today” (Dingelshstedt, 1889: 280-332).

Topographic maps of scale 1/100,000, produced by the cartographic centers of SSSR on the basis of aerial photography, mark the presence, in the Turkestan oasis, of 6-7 karez lines, all located in the Tastaksai-Aksai-Maidantal (TAM) basin; and topographic maps of scale 1/25,000 mark the presence of more than 30 lines in the TAM region and of just a few lines in other valleys. These topographic documents have been available since 1956 but evidently their analysis was not a standard methodological procedure for the archaeological experts of the time or for those of the following 50 years (General Direction of Geodesy and Cartography of SSSR, 1956).

Georchaeological fieldwork

Accurate research about ancient groundwater devices in the Turkestan oasis was implemented during the years 2002-2004 by members of the Laboratory of Geoarchaeology of the Academy of Sciences of KZ in the context of the INTAS project “Geo-archaeological investigations of land use and irrigation works in Kazakhstan in present and in historical times”. Existing maps and aerial surveys proved to be particularly useful from the very beginning in helping the detection of a few karez lines in 5 valleys of the Turkestan oasis and of hundreds of lines in the basin of the Tastaksai, Aksai and Maidantal rivers (TAM) where the medieval town of Sauran is located. Where previous researche individuated just 3 very large tobe surrounded by ancient fields and farms [Karatobe (II-XIII A.D.), Sauran (XII-XVIII A.D.) and Mirtobe (XIV-XVI)] and 3 karez lines north of Sauran (all monuments already quoted in the 1:100,000 topographic maps), geoarchaeological surveys of a sub-rectangular area of 20 x 20 km², located between the Karatau piedmonts and the medieval town of Sauran, found an astonishing archaeological record. Here have been discovered, measured and mapped 7 other mid-size tobe, 104 isolated dwellings (Neolithic camps, Bronze Age, Early Iron Age and Medieval villages), Medieval agricultural fields, farms and canals and, most important, 261 lines of karez that all together sum a total development of 124 km with around 9,000 wells. Most probably these numbers will be increased of 10-15 % by future aerial and field-waking survey of the region. The excavation by accurate methods down to 4 m of one of the wells of the most eastern of the 3 parallel karez lines reaching Sauran (karez 5.2.8) and the study of the profile of 2 wells exposed by erosion on the SE bank of the Maidantal river canyon (karez 7.3.3) didn't find any trace of underground galleries.

Preliminary model

The progression of the research suggested a preliminary model of the karez phenomenon that guided subsequent strategies of investigation. The main hypothesis is that karez do not have artificial underground galleries, i.e., they are not qanat, but are in fact a more complex hydraulic device using a combination of several principles. The complexity of the hydrological principles goes together with the simplicity of the construction, which is realized by minimum labor investment and maximum knowledge and exploitation of natural conditions. The most important considerations supporting such interpretation are outlined here below.

A karez line is not intended, like a qanat, to transport, by gravity and underground galleries, groundwater from a localized aquifer downslope until emergence; but instead to raise by differential pressure the water table along the whole itinerary of the wells. Karez wells are not windows of underground galleries running on a (natural or artificial) impermeable layer (qanat); but, dug down into a water-bearing layer, are mouths through which groundwater is lifted to the surface by the interaction of two principles of water dynamics: hydrostatic pressure and gravity. Because they are dug into a shallow semi-confined aquifer having micro-artesian potential, the wells act as micro-artesian wells. Because they are aligned along a gentle slope and connected though natural horizontal strata of pebble deposits, they work by gravity as a sequence of connected vases making the water resurge from a certain point of the line, depending on the groundwater stock and the season. So, for the functioning of a karez, the region must be endowed with four geological and hydrological preconditions:

(a) localization in a depression where water recharge is favored by the convergence of underground (and eventually surface) waters from neighboring streams.
(b) a geological sedimentary structure made of a first semi-impermeable layer on a second permeable one, the last one bearing a semi-confined aquifer located at a reachable depth;
(c) a convenient drift of the upper sealing of the aquifer, providing differential pressure; and
(d) the inclusion in the first layer of horizontal sand-pebble strata acting as natural galleries between aligned wells.

The first condition provides the water recharge of the system, which in some cases is optimized by artificial devices such as large head-wells applied to the end of an ephemeral distributor. The second and third conditions ensure the functioning of the principle of hydrostatic pressure. The fourth condition ensures the functioning of the principle of gravity. Given these preconditions, the two principles will be both active and will work complementarily in every karez line. Where the first principle of hydrostatic pressure is absent due to the poor impermeability of the first sedimentary layer or by no saturation of the second one, the karez system will anyway work by the second principle through gravity flow well-to-well along the pebble strata. The emphasis on the artesian effect favors the building of clusters of badly aligned wells intended to raise water in situ; the emphasis on the gravity effect favors the building of series of aligned wells intended to raise groundwater levels all along the line. The last case is the most common (Fig. 1). The 4 preconditions discussed above are largely present in the Tastaksai-Aksai-Maidantal (TAM) basin, which constitutes the study polygon of the present communication.

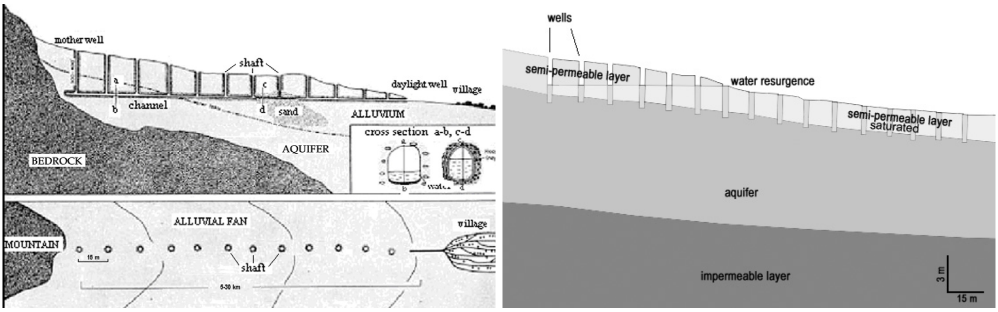

Figure 1 Technical features of qanat (profile and plan, on the left) and of karez (profile, on the right).

Geographical and Hydrogeological Features of the TAM Region

Geography, hydrology, geomorphology

The polygon under study consists of an area of 20 x 20 km² located on the alluvial plain between the southern slopes of the Big Karatau mountains and the right bank of the middle course of the Syrdarya river. The plain of the polygon gently slopes south-south-west between 320 and 200 m a.s.l. with an average incline of 4/1,000 m (0.4%); and is crossed by the delta-like middle-low courses of 3 seasonal streams. It presents the typical desert landscape of the Northern Tienshan region, Karatau district (IV-A-41a), characterized by the light brown desert soils and shrub vegetation of semi-deserts with undulated relief.

The territory of TAM is crossed by the distributaries (mostly dry) of the delta-like middle-low courses of 3 rivers, flowing north-south from the southern Karatau mountains towards the Syrdarya: the Tastaksai on the west, the Maidantal 10-12 km on the east; the Aksai between them. The Tastaksai river is 60 km long and ends just south-west of Sauran. The Maidantal river, 75 km long and the only one that occasionally reaches the Syrdarya, has the biggest surface and groundwater-flow and in fact produced the main geological fundament of the territory. The Aksai river, only 25 km long and ending in front of Karatobe, is by far the least relevant but, because of its central and depressed location, has the middle-low course water-fed by the convergence of the groundwater of the 2 other streams. Apart from some segments of the main canyons of the Tastaksai and Maidantal that present at least a scanty permanent flow all year round, all the other river beds are either totally dry or intermittently active only during springtime. The mid-low courses of the three rivers have complex parallel, diverging and converging branches and, as a whole, constitute three deltas merging part of their groundwater and converging all together in the area of the old towns of Karatobe and Sauran.

Wet climatic phases occurring on a decennial and centennial scale can deeply change the hydrological conditions of the territory, determining much higher water regimes, floods and perennial marshes. The construction during Soviet times of two large reservoirs in the pre-mountain zone on the Tastaksai and Maidantal rivers reduced the hydrological resources of the southern parts of the territory.

The main geomorphological features of the alluvial plain are determined by the characteristics of the distributaries of the three river deltas. They allow us to distinguish, from north to south, three altitudinal bands, which are also endowed with different hydrogeological features and have been concerned by specific water-use technologies (see below: Historical development of water-land use).

(a) The northern band, between 320 and 260 m a.s.l., constituted by the immediate premountain plain sloping by 1%, is longitudinally crossed by single small streams active all year round. It has been the object of very ancient agricultural activities based on the management of mildly active waters through the implementation of small simple comb canals.

(b) The central band, between 260 and 215 m a.s.l., where the river courses acquire delta-like patterns and their distributaries start to converge, has a more anomalous relief of alternating positive forms and depressions. It has very scanty surface waters and has been object of the highest exploitation of groundwater with the highest concentration of karez. A central-upper and central-lower part can be distinguished.

(c) The southern band, between 215 and 200 m a.s.l., located at the final convergence of the 3 deltas, is very flat with poor drainage and wide seasonal marshes. It favored the implementation of drainage canals leading to extensive land reclamation.

These three altitudinal bands are most clearly pronounced along the Aksai river, where they correspond to its segments Karabulak, Aksai and Aksaikarez, Mirdinsai.

Geology and hydrogeology

The geological structure of the centre of the TAM region consists of 350 m of alluvial (and partly aeolian) deposits of unconsolidated materials accumulated on a bedrock substratum. It presents 4 main sedimentary units of different material and origin. The first upper surface layer, 3-5 m thick and of modern and Late Quaternary origin, is composed of a mixture of sand and silt (including circumscribed beds of alluvial pebble deposits), and is divided in 2 strata respectively of 1.5 and 1.5-3.5 m. The second layer, 20 m thick and of middle and upper Quaternary origin, is composed of sand and pebbles, and is divided in two strata of 10 m each. The third layer, 180 m thick and formed during the Neocene and Paleocene periods, is made of clay and is composed of 3 strata of 150, 20 and 10 m. The forth layer goes down to a chalk bedrock: it is 145 m thick, formed during the Cretaceous period, and composed of sand (Fig. 2).

The layer covering the first 3-5 m of the ground surface, made of silt-sand and occasional pebble deposits, is impervious or at least semi-impermeable. The second layer 20 m thick between -5 and -25 m, made of unconsolidated sands and pebbles, is porous and permeable; and, lying on the third layer 180 m thick of impermeable clay, constitutes a semi-confined aquifer. The fourth layer, 145 m thick between -205 and -350, consists of sand and, enclosed between sloping impermeable beds (a clay deposit on the top and a chalk's bedrock on the bottom), constitutes a deep confined aquifer (Karatau artesian basin) with a potential of 50 L/sec.

The geological structure of the two sedimentary layers covering the upper 25 m of the TAM polygon is the most significant for the analysis of the karez technology. The first layer of 3-5 m, semi-impermeable, allows a certain amount of percolation, which reduces water-logging and salinization; moreover the presence in it of strata of pebbles deposits determines a complex network of subsurface water ways. The second layer, located between -5 and -25 m, is water-bearing: it constitutes a confined aquifer that, fed by percolation in the pre-mountain alluvial fans and having a dipping upper sealing, is endowed with hydrostatic pressure and the characters of a micro-artesian basin. The experimental excavation of a well in zone 5.3 determined within 24 hr the raise of the water table of the well from -4 to -3 m.

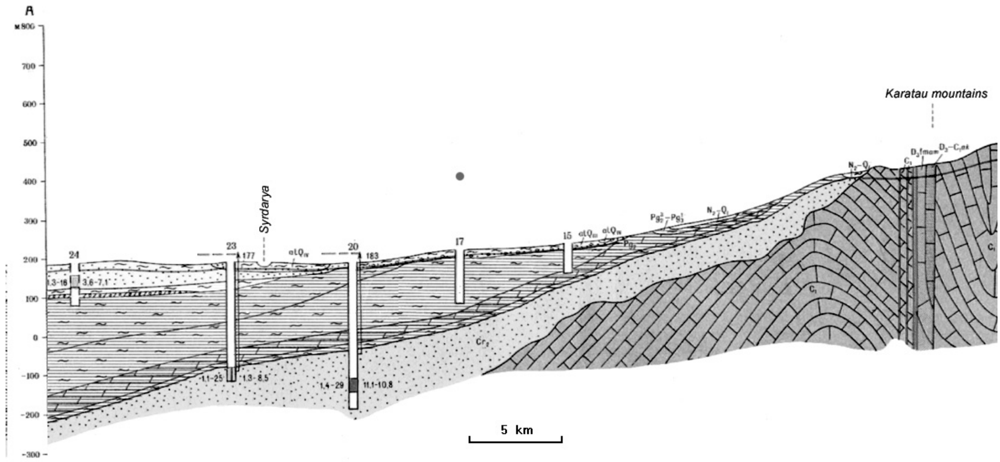

Figure 2 Hydrogeological profile of TAM, Map K-42-2, line A-B. The dot (section 17) corresponds to the centre of the karez complex.

In the TAM region the hydro-geological map K-42-2 and the field-survey of some active wells both record levels of groundwater table between -2.9 and -8 m, with an average of -4 m. It deepens from minus 3-4 m in the northern band to -5 to -6 in the central band and -8 m in the Sauran region; then increases again to minus -4 to 2.5 m when approaching the Syrdarya. The first north-south decrease of the level of the groundwater table depends from the relative sloping of the lower sealing of the aquifer; and its raising in the most southern part of the plain depends from the proximity of the Syrdarya river. Mineralization increases progressively from north to south, going from 0.5 g/L at the upper piedmonts to 1 g/L near Sauran and then up to extremes of 8-12 g/L further south in proximity of the Syrdarya.

The TAM aquifers have complex exchanges with surface waters: in some points they are recharged by percolation and in other points (at the end of dry distributaries, at the bottom of cliffs and in flat depressions) they resurge in the form of seeps, springs and marshes. The main courses of the Tastaksai and Maidantal rivers (respectively zones 1 and 7), intermittently flowing inside canyons 2-4 m deep, are surrounded by lower water tables and present only a few karez lines with simple patterns, i.e., paralleling some segments of the main course. These 2 rivers run on relatively more elevated areas than the Aksai (respectively 5 and 10 m higher), which favor the convergence of their groundwater in the depression of the middle and lower course of the Aksai river located between them. So, it is mainly along the Aksai course that water resurgence happens, more precisely in 2 forms and in 3 segments of its course. It happens in the form of seeps, first order streams (rills) and 1 spring in the segment called Aksai (Aksai depression) located between 260 and 230 m a.s.l. and in the following segment called Aksaikarez (Aksaikarez depression) located between 230 and 215 m a.s.l.; and in the form of marshes further to the south, between 215 and 200 m a.s.l., in the flat plains surrounding the Mirdinsai segment, water-fed by the final fronts of the Tastaksai, Aksai and Maidantal deltas.

Classification of the TAM Karez: Lines, Systems, Zones

In the TAM region 10 cases have been detected of clusters of wells randomly distributed or badly aligned: they can be somehow considered prototypes of karez, intended for the resurgence of groundwater in situ just through the principle of hydrostatic pressure. Apart from these few cases, almost all of the wells are precisely aligned for the exploitation of both principles of hydrostatic pressure and gravity: this is what is called karez and constitutes the subject of the present study.

Wells, clusters of wells and lines of wells are connected with aquifers and the last ones with groundwater flow recharged by surface distributaries. So, the preliminary classification of 7 hydrological zones and of 19 sub-zones of TAM constitutes the basis for the classification of karez lines and systems. By karez zone we intend the specific area where sets of karez lines and systems are concentrated and applied to the same hydrogeological source. By karez line (k-line) we mean any alignment of wells longer than 30 m. By karez system (k-system) we mean a set of karez lines interacting by paralleling or by intersecting each other. An abridged version of the Data Base is shown in Table 1.

Table 1 Data base Table of TAM karez (19 sub-zones and 7 entries).

Zone and sub-zone	Area (m^2)	Number of karez lines	GPS coordinates of the start of the 1° line NW	Total development (m)	Number of individual karez lines	Number of karez systems	Type of karez system: P, I, M**
1.1	Tastaksai	14	67.75919-43.66760	5,835	2	5	P
1.2	course 1,500x 13,000	1	67.751618-43.591487	2,744	1	0	
2.1	Tastaksai	4	67.643688-43.552839	3,487	4	0	
2.2	delta 8,000x2,500	1	67.74136-43.54225	2,940	1	0	
3.1	Aksai springs 1,000 x 300	4	67.8645493-43.6965155	397	1	1	I
4.1	Aksai middle	12	67.83636-43.625422	11,510	1	4*	P
4.2		13	67.81870393-43.59225033	7,312	4	3	P
4.3	2,500x2,500	32	67.84784671-43.62737307	17,963	5	1*	P
5.1	Aksaikarez-	26	67.80491269-43.57230835	7,527	5	3*	M
5.2	Mirdinsai	10	67.778695-43.542262	4,369	1	2	M
5.3		9	67.81412727-43.56357490	2,093	3	3	I
5.4		4	67.80785947-43.53868951	1,170	2	1	P
5.5	5,000x10,000	3	67.78663113-43.49534787	2,351	0	1	M
6.1	Maidantal	30	67.85865670-43.60014463	9,528	1	2*	I
6.2	West	30	67.85273582-43.58337083	15,554	4	5	P
6.3	2,500x8,000	10	67.83181821-43.55636699	7,353	1	3	M
7.1	Maidantal	28	67.97559310-43.66608513	6,129	13	5	P
7.2	East	16	67.88870188-43.58287524	7,531	6	5	P-I
7.3	3,000x20,000	14	67.84797446-43.53780194	8,011	2	3	P-I
Total	176 km^2	261		123804	56	47	

*presence of one mega K-system

**k-system type: Parallel, Interaction, Mixed

Karez zones

The classification of karez zones is based on the consideration of concentration of karez lines applied to the same groundwater source. Different distribution of hydrological and hydrogeological features suggests the individuation of 7 zones. They basically correspond to segments of the 3 rivers: zones 1 and 2 to the Tastaksai course and delta; zones 3-4-5 to the Aksai upper, middle, lower; zones 6-7 to the Maidantal west, east. All together the 7 zones cover an area of 176 km^2, i.e., 44 % of the 20 x 20 km^2 territory that has been surveyed. The consideration of more specific hydrogeological patterns and related concentrations of karez lines suggests the further division of the 7 zones into 19 sub-zones.

Karez lines

A karez line (k-line) consists of any alignment of wells longer than 30 m. In the TAM basin (an area of 20 x 20 km²) have been discovered and recorded a total of 261 k-lines longer than 30 m, making a total development of 123,804 km, which means an average k-line length of 500 m and an average density in the TAM polygon of 250 m of development per km². Their nominal classification is given by the succession of 3 location numbers: code of zone, sub-zone and individual k-line within the sub-zone (i.e., k-line 5.2.1, north of Sauran). Karez lines show different distribution and characters in the 3 altitudinal bands of the plain: northern (pre-mountain band), central, southern. Their highest concentration by absolute number and density happens in the central-upper altitudinal band of the polygon, between 260 and 230 m a.s.l., in zones 4.1-2-3 and 6.1-2.

(a) The northern pre-mountain region (zones 1.1, 3, 7.1) hosts in total just 24 short and simple k-lines: 14 in zone 1.1; 4 in zone 3; 6 in the upper part of zone 7.1.

(b) The central regions, and mainly the ones located in the Aksai depression, characterized by complex relief and convergence of the Tastaksai-Maidantal waters, are the most relevant by number, kilometric development and density of karez constructions. In the Aksai depression concentrations of karez happen in 2 bands, central-upper and central-lower. The central-upper band (zones 4.1-2-3 and 6.1-2) is the most crowded: on an area of 5 x 5 km², are concentrated 117 k-lines (44% of the total) with 61,867 m of development (50% of the total) and 4,237 wells (50 % of the total), making a density of 4.5 karez, 2,474 m of development and 170 wells per km². The central-lower band (zones 5.1, 5.3 and 6.3) is second in importance by number and density of karez,: it covers an area of 5 x 3.5 km², counts 45 k-lines, with a total development of 16,973 m, which means 2.5 k-lines and 970 m of development per km². The other zones of TAM show much lower densities: for example zones 7.1-2-3, third in importance and covering a large area of 3 x 20 km² along the Maidantal course, have only 58 lines, i.e., 0.9 karez and 361 m of development per km².

(c) The southern region (zones 2.1-2, 5.2, 5.5 and 7.3) host few but quite long k-lines.

Karez systems

A karez system (k-system) consists of the interaction of several karez lines longer than 30 m, which can be of 2 types: lines paralleling each other within a distance of less than 50 m, or lines intersecting each other (sharing together one or more wells). Karez systems are named by the code numbers of all its constituent karez (i.e., k-system 5.2.1-8). Sometimes k-systems are of difficult recognition due to the presence of anomalous patterns and/or to the erosion or destruction of some wells. In any case it is not far from reality saying that of the total 261 k-lines of TAM, 56 are isolated k-lines and 205 are grouped into 47 different karez systems. The average area covered by a k-system is of 400 x 700 m, between max values of 400 x 3100 (in zone 4.3) and 1,500 x 2,500 (in zone 6.1) and min values of 40 x 100 (in zone 7.2). In 4 cases (zones 4.1, 4.3, 5.1, 6.1) 2 or more k-systems are interconnected by just few k-lines into a “mega-system” (K-system) of very large proportions, including the almost totality of the k-lines of the zone.

Karez systems are more frequent along the Aksai, both in its segments on the central band most crowded with k-lines (Aksai depression, zones 4 and 6.1-2) and on the southern band characterized by very flat relief (zones 5.2 and 5.5). In zone 4, 47 of the 57 k-lines are grouped into 8 large k-systems counting 4-9 k-lines each; in zones 6.1-2, 55 of the 60 k-lines are grouped into 7 large k-systems of which one puts in interaction up to 16 k-lines; in the flat zones 5.2 and 5.5 all the k-lines are interacting into k-systems.

Instead, along the Tastaksai and Maidantal river courses, the longitudinal development of isolated k-lines is more frequent and k-systems are or very small or totally absent. The Tastaksai lower course (zone 1.2) and delta (zones 2.1-2) don't present any k-system; and in the Eastern Maidantal delta (zone 7), of the total 58 k-lines, 21 are isolated in distant locations and 37 are interacting in 13 small simple k-systems of 2-3 lines.

Depending from the patterns of interaction between k-lines, k-systems can be of 3 different types, made of parallel, intersecting or mix-type interactions. The 3 types occur in different areas, depending from geomorphological features: parallel patterns occur along stream courses; intersecting patterns on areas crossed by complex water distributaries; mix-type patterns on areas transitional between the former two and on very flat areas.

Construction Features of the TAM Karez

Hydrological patterns

The main elements of a karez line are the points of application of its head-well, of its ending-well, and the direction of the line. The head of the k-line, apart from a few exceptional cases (see below pattern 3), starts from the banks or from the end of a distributary which, during wet regimes, will pour water into the head-wells of the k-line as a mean of recharge. The end of a karez line normally happens in connection with small canals directed to fields located in depressions on the sides and beyond the end of the line. On the borders between the central and southern band of the complex, a few cases are detected of k-lines ending in a dry river bed or in a large surface canal directed to the areas of the main towns. Concerning the direction of the k-lines relative to the one of the surface distributary, 4 kinds of direction patterns are present:

(a) Pattern 1 - The k-line parallels the course of the distributary. This is the most common pattern and is found in 14 sub-zones.
(b) Pattern 2 - The k-line departs from one stream course toward the neighboring stream course, in order to catch the groundwater table flowing between them.
(c) Pattern 3 - The k-line cuts transversely the final distributaries of the river delta, following hypsometric lines. Six individual cases have been found.
(d) Pattern 4 - A single k-line is paralleled by 1 or 2 canals totally artificial or carved out from a proximate dry small river bed, starting half way from the beginning of the line. This pattern is very common and characterizes more than half of the karez constructions. The canals are sometimes two in number, positioned on both sides of the k-line. In case of several parallel k-lines, also the canals grow in number and run between them: for example, an exceptional k-system made of 7 parallel k-lines is paralleled by 4 canals (k-system 4.3.2-12). Surface canals paralleling a k-line are considered technical parts of the k-line.

Construction forms

The main construction forms of a karez line are: length, shape and incline of the line of wells; relative distance, shape, dimension of the wells; spoil of the dig, erosion, sedimentation, dept and technical construction of the wells; paralleling surface canals and the much problematic underground galleries; and finally some ergometric esteems.

(a) The length (metric development) of a k-line presents 2 exceptional extremes: a max 3,200 m of k-line 2.1.1 (which also has exceptional hydrological pattern 3) and 3,115 m of k-line 4.3.3 (which is paralleled by 6 other lines); and the min 15-30 m of some scattered k-lines. The length of the other k-lines span between 2,600 and 30 m, averaging 500 m. Long “classic” k-lines measuring between 2,600 (k-line 5.2.1, near Sauran) and 1,400 m number 16, mainly located in the central zones 4, 6.1, 6.2 and a few in 5.2, 7.3. Small k-lines measuring between 30-200 m (sometimes shortened by destruction) are in number of 25 and dispersed everywhere.

(b) The shape of the single k-line shows few variants. The k-line can be unique with straight and bended forms; or can be constituted by a central long segment to which are applied secondary branches (less than 30 m long). Lines with exceptional detours are rarely detected (k-line 7.3.3).

(c) The average incline of the k-lines is of 0.5%, (5 x 1,000): max incline of 1% is found in the northern piedmont zone 3 and in zone 6.1; incline of 0.5 % in the central zones 4, 5.1-4 and 6.2; of 0.1-0.2% in the flattest areas of zones 5.2 and 5.5; no incline at all in karez 2.1.1-4. So, on average, a k-line 500 m long will have a differential altitude of 2.5 m between the head-well and the ending-well.

(d) The relative distance between wells is in most of the cases 15 m and averages 12 m. Exceptional distances of 50 m are detected only in zone 2.1, together with direction pattern 3 (see above: Hydrological patterns, c); long distances of 30 m in zone 7.1; and min distances of 5 m in the short k-lines of zone 1 and in k-lines 5.3.2-3 and 5.5.1.

(e) The shape of the outer and inner rings of the wells is round in all cases (with the exception of few oval-shaped basin-like wells mentioned here below at point f). The plane of the mouth can be or horizontal or, in the case of the presence of a paralleling canal, inclined as if intended to discharge water into it.

(f) The diameter of the inner ring (mouth) of the wells is quite constant averaging 0.8-1 m. The diameter of the outer ring (mound deposit of the spoil of the well) is more anomalous, averaging 6 m, between a max of 12 and a min of 5 in the case of short k-lines or at the end of the k-line. A larger diameter of the outer ring is evidently connected with larger and deeper wells. Like the distance between wells, so the diameter of the outer ring can have different values in different segments of the same line. Sometimes a few wells shaped like oval basins of large dimensions (9 x 12) are located: either at the head of a line applied to the end of a small distributary for favoring an enhanced recharge of the system; or in proximity to a settlement for the application of a water-wheel.

(g) The height of the ring (mound deposit of the spoil of the well) can reach a max of 1 m but is generally quite flattened, the 2 cases being respectively related to bigger or smaller, younger or older and eroded constructions. The same can be said for the 2 cases of pronounced concavity or sedimentation of mouths of wells. The most flattened outer rings and most sedimented mouth-pits are found in the central zones of the complex independently from their diameter and so witnessing their higher antiquity. Three degrees of erosion are detected, pointing to 3 successive generations of karez construction, which is coherent with the stratigraphy of intersecting diachronic k-lines and with the archaeological analysis of other monuments of the archaeological complex (see below: Historical development of water-land use).

(h) The spoil of the dig deposited on the very top of the ring (i.e., the material from the bottom floor where the dig of the well stopped) shows in the absolute majority of cases the presence of pebbles, as if the dig is intended to end in the most permeable stratum.

(i) The technical construction of the mouth of the well can consist of simple digging or in the use of mud or baked bricks for walling the upper 0.5-0.8 m of the mouth. The last case is represented by 20% of the archaeological record and is mainly found in the southern band (zones 5.3, 5.4 and 7.3) in correspondence with the largest, most recent and eventually last generation of karez located in proximity of Late Medieval dwellings.

(j) The archaeological studies implemented up to now, together with the hydro-geological considerations mentioned above, (see par 3.4), provide just an approximate estimation of the depth of the wells. Their depth seems to average 3-4 m, i.e., down to the top of the second water bearing sedimentary layer, or stopping at occasional pebble deposits included in the first semi-impermeable layer.

(k) An open air artificial canal paralleling the middle and lower segments the k-line is found in more than 50% of the cases. 10 cases are found of 2 canals paralleling both sides of the same k-line. In a few exceptional cases consisting of 3-7 k-lines paralleling each other in strict proximity, 2-4 canals are located between the lines (k-system 4.3.2-12) (see above: Hydrological patterns, d). Canals are always connected with wells having an inclined mouth-plane; and, most probably, the middle segment of the k-line where the canal begins corresponds to the starting point of water resurgence.

(l) In the TAM region more than 10 excavations of karez wells have been implemented and none of them found any trace of underground galleries.

(m) If the wells were no more than 3-5 m deep, in principle the construction of the whole 124 km of development of the TAM karez could be implemented in 15-20 years by a medieval brigade of 100 workers.

Archaeological Context of the TAM Karez

Archaeological monuments

Together with the 261 k-lines, the archaeological record found in the TAM study-polygon consists of 3 large medieval towns, 7 medium size tobe, several small ancient villages, kurgans and Kazakh cemeteries, agricultural fields, some open air canals and the remains of a few dams on the Aksaikarez course.

Settlements and cemeteries. In the TAM territory the presence is known of 3 large medieval walled towns surrounded by thousand of farms and fields: Karatobe, I-XIII A.D., 16 ha, surrounded by 3 circles of walls; Sauran, XIII-XVIII centuries A.D., 44 ha, located just 3 km NW of Karatobe and its historical successor; Mirtobe, XIV-XVII centuries A.D., 19 ha, probably the walled garden quoted by Wasifi (see above: Historical and ethnographic sources). Recently discovered have been 7 middle size medieval tobe (3 on the northern piedmonts and 4 in the southern zone 2.1); 104 small isolated settlements (2 Neolithic camps, 2 Bronze and Early Iron settlings and 100 early-mid-late Medieval villages and farms) and 3 clusters of kurgans. Karatobe, Sauran and the 4 mid-size tobe of Kostobe 1-2 and Aktobe-1-2 are located in the southern flattest and marshy areas of TAM, and their water supply depended mainly on the surface canalization of stream waters and on the drainage of marshes. Mirtobe and most of the isolated settlements are located in the dry central band where the water supply could only depend on the implementation of groundwater devices. The 3 walled mid-size tobe and villages located in the pre-mountain zone (I-VIII A.D.) exploited the water of small permanent streams.

Fields. In the TAM territory agricultural activities and fields have been implemented in all 3 altitudinal bands mentioned above (par 3.1 and 5.1), with forms depending from the character of the local water resources and technologies. In the northern piedmonts they developed on terraces paralleling the river course. In the central region they located in depressions at the bottom of karez systems, evidently fed by groundwater resurgence. In the southern region they have been obtained by the drainage of swampy areas.

The morphology of mid-late Medieval fields has been reconstructed from aerial photos and ground surveys. Fields are in general of sub-rectangular shape averaging 1 ha, surrounded by high banks and partitioned by smaller ones into a few internal lots. They often enclose a small tobe and a few wells. Clusters of fields are intersected by small canals of k-lines. Two agricultural techniques are detected: open field and ridge-and-furrow. The first technique consists of the cultivation of flat areas of 1 ha parted into smaller lots for irrigation purposes and/or for hosting different crops. The second technique consists of the structuring of the hectare by 5+5 alternate longitudinal ridges and furrows 1-2 m high, the ridges providing shelter and the furrows providing well sheltered and humid cultivation beds: in that way just 70% of the hectare is cultivated but in an intensive way. The first technique is more diffused in the TAM poorer areas; the ridge-and-furrow technique, more sophisticated and labor consuming, characterizes the fields located around the best water sources and around the big towns of Karatobe and Sauran.

Surface canals. Apart from the canals paralleling the k-lines which are considered a technical part of the k-line (see above: Construction features), open air canals are located in the flattest areas of the southern band of TAM. They are fed by 3 different kinds of water sources interacting into the same hydraulic system, in order of importance river courses, marshes and karez. Six main canals are applied to the lower Tastaksai and to the Aksaikarez rivers (remains of 2 dams have been detected on the course of the Aksaikarez) and sometimes are obtained by reworking dry river beds; others are fed by the drainage of marshy areas surrounding the towns; a few canals also collect waters from karez lines. They all converge to the old towns of Karatobe, Sauran, Kostobe 1-2 and Aktobe 1-2.

Historical development of water-land use: 3 kinds of habitats and technologies

The three altitudinal bands, into which the TAM region has been divided by geomorphological and hydrological considerations, have been concerned by 3 different kinds of water technology and land use, and so represent 3 kinds of historical human habitats.

(a) The northern band consists of the immediate pre-mountain plain crossed by the upper course of the 3 rivers, active all the year around. In this northern habitat waters of active mild streams could be domesticated though very simple comb canals, claiming the land along the river course, which favored the establishment of few small and middle size settlements and kurgans from the earliest times (I A.D.).

(b) The central band presents a more complex relief, moderately flat and quite dry, with rare water resurgence in the form of seeps, ephemeral first order streams and two permanent springs. This central habitat, quite dry and with medium land reclamation potential, could have been colonized only by the exploitation of groundwater sources, i.e., by the creation of artificial springs that, culminating in the karez device, favored the establishment of several small isolated villages.

(c) The southern band has a very flat relief, presenting areas with poor drainage and wide seasonal marshes. This southern habitat saw a very early colonization (I-II centuries B.C.) through the implementation of surface devices like trunk canals applied to river courses and drainage canals for activating and using marshy waters. Moreover, by having very high land reclamation potential, this location favored a large agricultural production, high demographic levels and the development of 2 very large towns and 4 mid-size tobe. The few k-lines that exist in this southern habitat were not intended for irrigation purposes but for the provision of drinking water.

As a whole, the northern and the southern regions, with their easy access to active or marshy waters, saw the earliest development that, in the southern region, resulted in being also much productive and demographically consistent. The chronological attribution of the phases of agricultural colonization of the northern and southern areas is helped by the presence of a rich archaeological context constituted in the north by few medium-size tobe and villages and in the south by the large towns of Karatobe, Kostobe, Aktobe and, later, Sauran, which point to 3 main phases of development. The earliest phase of colonization can be dated to the end of the 1st millennium B.C.; a blossoming phase to the Middle Medieval period followed by a decay during the XIII century A.D. under Mongol domination. After that time, the TAM southern region entered a new process of economical and socio-political development concentrated around only a very large town, Sauran, which integrated into a same hydraulic system the surface and groundwater devices of the southern and central habitats.

Concerning the agricultural colonization of the central dry habitats of TAM, the analysis of ceramic deposits witnesses also here the succession of 3 phases: a starting phase during the late Early Iron or Early Medieval period, and 2 blossoming phases respectively during the middle and late Middle Ages. So, the colonization of the central dry habitat started slightly later than the one of the northern and southern areas, but clearly by the action of independent communities characterized by different techniques of water catchment and of pastoralist and agricultural activity.

Concerning the karez, the date of implementation of the earliest prototypes of k-lines could be quite early but difficult to define. What is possible to say is that some features of the karez lines (the degree of erosion of wells, the stratigraphy of intersecting lines, the complexity of hydrological patterns and the spatial relation with dated settlements) suggest a development in 3 main phases, which partly matches with the tripartite periodization of the development of medieval settlements in the whole TAM archaeological complex. The earliest phase of construction of k-lines (smaller, shorter, simpler and eroded) happened in the Aksai depression of the central band around the end of the 1st millennium A.D. The following second phase sees the spread of the karez technology all over the TAM region with bigger, longer and more complex implementations. The third phase, coinciding with the development of Sauran, sees the construction of the biggest and deepest wells and of walled mouths of wells; and the introduction, mainly in the southern areas of TAM, of new hydrological patterns such as the interaction between karez, surface river beds and canals. This third phase witnesses the integration of underground and surface water devices into a common hydrological system: evidently the TAM populations became politically more integrated during late Medieval times together with their respective hydraulic systems. In any case, water and land conflicts between central and southern inhabitants are testified by ethnographical accounts up to the end of the XIX century.

Preliminary surveys suggest that the three kinds of habitats and water technologies and the 3-fold periodization found in the TAM region characterize the medieval cultures on the whole territory comprised between the Big Karatau range and the Middle Syrdarya river.

Conclusions

Several aspects of the karez construction (par 4) and of their geological and hydrogeological context (par 2) suggest that "karez" are not "qanat". They are an original device for uplifting groundwater not by underground galleries but by other expedients (like hydrostatic pressure) based on a local traditional deep knowledge of groundwater dynamics that today have been forgotten. Their study has most probably scientific significance for the hydro-geological and hydro-engineering sciences and economical significance for modern land reclamation in desert zones. The geo-archaeological discovery in the TAM region of three kinds of habitats and water technologies and of their 3-fold periodization (par 5) provides a model for interpreting the eco-economical conditions and socio-historical development of human cultures in the whole Turkestan oasis.

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The Ancient Qanats of Iran

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Abstract: The technique of extracting ground water by gravity through horizontal glleries with vertical wells was practiced by the old Persians centuries ago. Several Qanats with specific technical characteristics such as ability to prevent wastage by storing water behind under ground dams or running water mills are discussed. Management traditional management and maintenance procedure for Qanat's beneficiaries are discussed too.

Keywords Horizontal gallery; Qanat; vertical well.

Introduction

The archaeological findings reveal that the Iranians had advanced culture and civilization some 7,000 years ago. The cuneiform writing was invented by the Iranians (Persians). In the 3rd millenium B.C. they used to cultivate land and raise livestock. Water has always been a limiting factor in the history of the country. The credit of invention of Qanats and Persian wheel, two types of irrigation system goes to Iranians. According to Herodotus, the Greek historian, the technique of digging Qanats was practiced in the Achamenid's era (550-330 B.C.), some 2,500 years ago. Remains of hydraulic structures such as spillways, water, intakes and reservoirs belonging to pre-achamenids and Assyrians (1,500-600 B.C.) have been discovered. The oldest Qanat sites in the world have been discovered in the north of Iran and dates back to 3000 years ago that is the time when the Arians settled in Iran (Javaheri and Javaheri, 1999).

Qanat in a subterranean horizontal gallery with vertical wells dug along it. The gallery has a slope less than the slope of natural ground surface. The gallery would collect water from the aquifer (wet part) and convey it downstream (dry part). The vertical wells (shafts) are used for air circulation, lighting and removal of the excavated materials (Fig. 1). In Arab countries like Saudi Arabia, Syria and Yemen the name for Qanat is Falej, Aflaj, Fogger. In Northern African States the name Khettava, Mayon, Negoula, Rhettava is used. In China the name Kahriz in used. In Sicil-Italy the word Ingruttati is used for Qanat (Cressy, 1958). About 14% of agricultural products (in Iran) are dependent on irrigation water extracted from Qanats and approximately 10% of the irrigation water (8 billion cubic m) is supplied by Qanat. At present there are about 33,000 operational Qanat in the country. If we consider the average length of each Qanat (horizontal gallery plus the vertical wells) as 10 km, then we will have about 80% of the distance between the earth and the moon excavated beneath the ground surface. This is quite an achievement. Recently the International Center for Qanat and Ancient Hydraulic structures has been established in Yazd, central Iran by UNESCO (Zare, 2005).

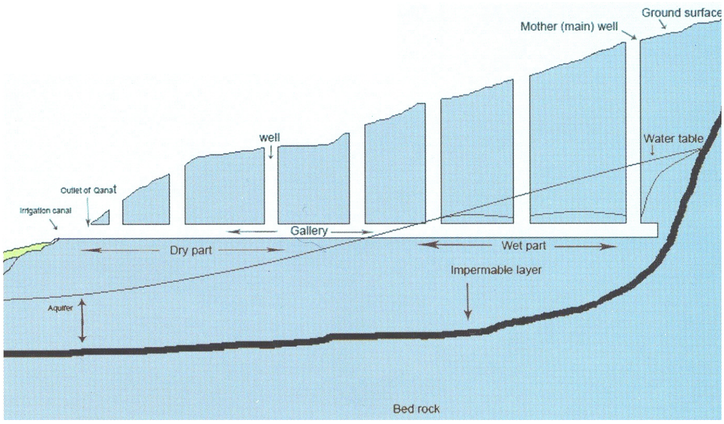

Figure 1 Longitudinal profile of a typical Qanat.

Qanats with Special Characteristics

Qanats with special characteristics are the followings: (a) longest and oldest (Zarch), (b) deepest (Gonabab), (c) with underground water fall (Arvaneh), (d) two horizontal galleries at different levels (Moon), (e) with underground mills (Dehno), and (f) with underground dam (Vazvan).

Zarch Qanat

This Qanat is more than 3,000 years old and some of its vertical wells are dug at Yazd Grand Mosque which is the indication of being in existence before Islam. Some of these wells have square cross section instead of circular or oval shape. These types of wells were dug during Zorastrian (Zarathustra era). This Qanat has three branches of galleries with their outlet discharging at ground surface in the city of Zarch. The characteristics of this Qanat are as follows: Qanat length is 71 km; 2115 vertical wells,; depth of mother well is 85 m; average discharge at the outlet is 150 L/sec; number of owners and drinkers is 800; and area of farms and gardens irrigated is 425 ha.

Traditional management for maintenance and utilizing this Qanat is as follow. A council of 5 members (two from upstream and three from downstream area) are elected by the owners and drinkers during spring season introduce a representative among themselves. This authorized person serves for one year. His duties include collecting annual fees for operation and maintenance of Qanat. He is also a link between the owners and different governmental offices. The council of 5 members (Qanat's council) also elects two water distributor (ditch rider), one at the head spring and the other at Zarch community for a period of one year. He keeps the record of water delivery according to the water rights, irrigation rotation and duration. The irrigation interval is usually 15 days.

Gonabad Qanat (deepest)

Qanat length is 31.13 km. The unique main horizontal gallery has six secondary branches, discharge at the outlet is 150 L/sec, depth of mother well is 300 m and total number of vertical shafts is 405. The vertical wells are of two types: Vertical and shallow wells and Deep and step like wells. The procedure for digging a 300 m deep well was as follows: First a vertical shaft of 70 m deep would be dug and then a relatively hortizontal 3 to 5 m wide canal would be excavated. At the end of this canal the well's wheel could be installed for digging and removing the excavated materials from vertical or stepped wells. The reason for implementing this procedure is that digging a 300 m deep well in more than one stage is that the rope (specially when wet) will be too heavy and must be pulled out by great number of people. The weight of excavated material and the bucket can not be tolerated by the rope too. According to Nasser Ghobadiani (983 A.D.), Bahman one of the ancient kings of Iran, after committing a great sin, he ordered construction of 1,000 Qanats across the country for redeeming his sins. Gonabad Qanat is one of such Qanats (Safinejad, 2000).

Arvaneh Qanat (with waterfalls)

It is believed by local people that this Qanat is the oldest Qanat of Ardestan, central Iran. Three mills existed along this Qanat in the past but no signs of them are available now. One of the specific characteristics of this Qanat is the water distributor's house. From this house the distributors and beneficiaries could guard water. Three out of five shares could be supplied to a depth of 23 m through Porzeh well with a high velocity to an eighteen m deep water fall well (Fig. 2).

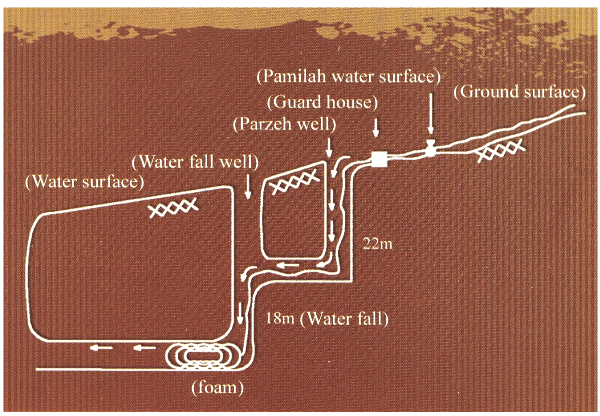

Figure 2 Water fall and water surface in Avaneh Qanat.

Moon Qanat (two stage Qanat)

This Qanat has an upper and lower stage. In each stage water is flowing. The upper stage is 3 m higher than the lower one. Due to the existence of impermeable layer, water can not seep from the upper gallery to the lower one. Some of the characteristics are as follows: Length is 2.5 km, there are 60 wells, water supply discharge is 50 L/sec, area irrigated is 90 ha, and 500 drinkers.

Dehno Qanat (underground mills)

About 700 years ago this 5 km long Qanat with 17 branches was dug by two dedicated brothers. Average discharge at the outlet is 350 L/sec. There are 5 watermills along the horizontal gallery. These mills are installed at a depth of 3 to 5 m and water is conveyed through a 45 m tunnel from Abbasabad to Dehno. Total number of owners and drinkers are 2,000 households.

Vazvan Qanat with underground dam

This Qanat is probably a pre-Islamic one. The construction of this Qanat is attributed to the Sassanids era (about 2,000 years ago). Its mother well is 18 m deep and the length of its horizontal gallery is 1.8 km. The average discharge is 32 L/sec. There are 64 vertical wells along this Qanat. Along the Qanat horizontal gallery three underground dams were constructed and as each one deserted, another dam was constructed. By closing the gates installed on these dams, the people could store water and irrigate their lands during water shortages. The third and largest dam is located at 16 m depth beneath the ground surface. The dam was constructed from bricks, stones and Sarooj cement (a mixture of ash, lime and hair of goat or calf or occasionally white portion of egg). The dam has five openings (Fig. 3). Number of gates is not the same in each row. Size of openings is also different at different levels. The reason for installing different gates with different dimensions at various levels is the fact that the heads and velocities are not the some at all levels. Closure of gates and water storage begins on the 22nd of November each year. Storage duration of water depends on the rainfall. In a wet year storage will end in April. However, during droughts, March 6 will be the end of storage duration. Opening mechanism of gate openings is as explained below: The top five gates will be opened first. After 25 days the second rows of gates (four) will be opened. The procedure will be repeated until water flows naturally (Safinezhad and Dadras, 2000).

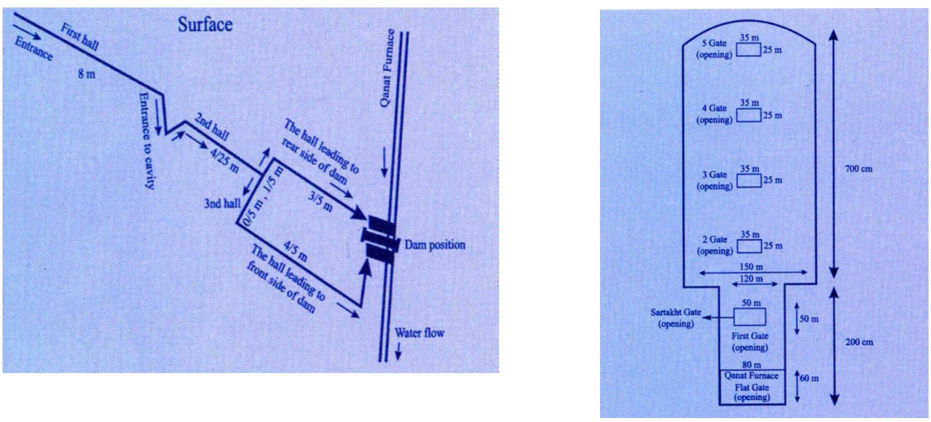

Figure 3 Plan and section of the underground dam in Vazvan Qanat.

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Qanat Invention Puzzle

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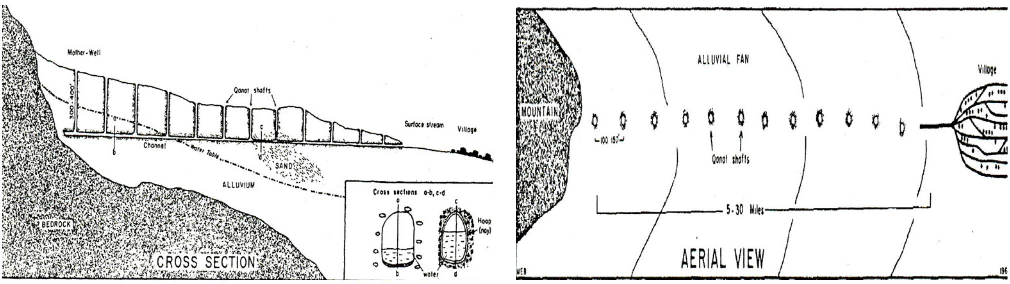
Abstract: There is little documented historical record available on the process of invention of qanat. Henry Goblot, who has stayed in Iran for a long period and has written his doctoral dissertation about qanats of Iran has claimed that mine workers has invented qanat system in the process of draining water out of the mine tunnel by means of a drainage tunnel in north west of Iran Although many hydrologist accepted Goblot idea but some others did not agree with this idea and have introduced other more realistic ideas. In this article several basic ideas about qanat invention are introduced and briefly discussed. This author believes that the idea of consecutive excavation of a contact spring outlet because of discharge depletion after a long drought period is the most probable idea behind qanat invention.

Keywords Iran; Persia; qanat invention; qanat origin.

Introduction

A qanat is a system of water supply consisting of an underground tunnel connected to the surface by a series of shafts which uses gravity to bring water from the water table of the higher elevation lands to the surface of the lower elevation lands. Qanat comes from a Semitic word meaning "to dig", and there are several variations of the name including Karez, Foggara, and Falag, depending on location, in addition, there are numerous differences in spelling (Cressey, 1958). Qanats are usually dug when there is not enough surface water for domestic and agricultural uses. Figures 1a and b shows longitudinal section and plan view of a typical qanat, respectively. English (1968) states that qanats appear to have originated in the vicinity of Armenia (northwest of ancient Iran) more than 2,500 years ago and spreads rapidly throughout south-west Asia and north Africa during Achaemenid (550 to 331 B.C.). Also, Huisman (1972), Bybordi (1974), Goblot (1979), and Beaumont *et al.* (1989) reported that qanats originated from Persia around 3000 B.C. and these ancient systems played an important role in the spread of irrigated agriculture and the establishment of sophisticated settlements throughout dry areas.

Certainly by 209 B.C. qanats were an important feature of the Persian landscape and were described by Polybius during the campaign of Antiochus against Arsaces. In his description, Polybius records how Arsaces tried to destroy the qanats and so cut off water supply in order to halt the advance of Antiochus towards the lost Parthian capital of Hecatoppylos. Lightfoot (2000) stated that qanats, these subterranean, gravity-driven filtration galleries, were transplanted across the Arabian Peninsula first by Persians, and later by others who borrowed their technology. Much scholarly works has been produced to account for their construction in Iran, Oman, and many other countries throughout the world where qanats were eventually built. He showed that fresh evidence collected from 1993-1998 fieldwork in the northern and southern Peninsula offers evidence of distinct pathways of diffusion of qanats technology from Persia across Arabia. Although the method of qanat construction were carried westwards into the Mediterranean and subsequently into Latin America, qanat systems attained maximum development in Iran (Wulff, 1968; Beaumount, 1971). Figure 2 shows the qanat construction procedure in Iran (Huisman, 1972).



(a) (b)

Figure 1 Longitudinal section (a) and aerial view (b) of a typical qanat.

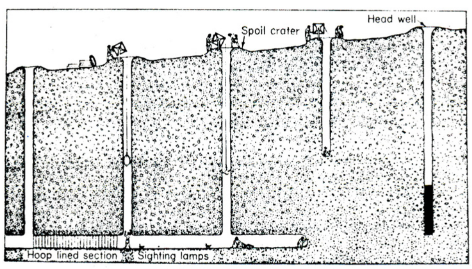


Figure 2 Qanat construction procedure in Iran (Huisman, 1972).

Qanat exists in more than 34 countries in the world (Behnia, 2000), but most are concentrated in present day Iran, which has about 30,000 active systems with total annual discharge of about 9 billion m³. Since Iran has few perennial rivers and surface water resources, many of its communities have depend on qanat water for thousands of years (Saffari, 2005). This unique and environmentally sustainable system has created cultural and natural ecosystems that ideally addressed the specific needs of each community.

Many articles have been published about different aspects of qanat but a few have addressed the subject of qanat invention (Bashir and Muhammad, 2000). Goblot (1979) who has spent a long period of time (more than 20 years) in Iran and has written his doctorate dissertation about qanat has proposed that qanat was invented by mine workers in north part of Iran during the process of draining obtrusive waters collected in the mine tunnel. But he didn't give solid evidence for this claim. One of his evidence is that qanat diggers use tools that are similar to miner’s tools, for example an small shovel and a short handle pick. It is obvious that excavation in a small tunnel needs small tools, so this can not be accepted as a solid evidence for Goblot claim. The main goal of this article is to discuss and evaluate all possible basic ideas of qanat invention.

Qanat Invention Basic Ideas

Several basic ideas about qanat invention has been introduced by different authors (Goblot, 1979; Kobori, 1973; Vellayati, 1995). These basic ideas can be summarized as follows:

Consecutive excavation of a spring outlet after a long drought period idea

The chain of wells associated with a qanat usually runs across relatively flat terrain, though often adjacent to, or even surrounded by, mountains or hills. Qanats commonly tap into shallow aquifers at the base of these hills or mountains. Therefore there is a close relationship between qanats and mountains/hills (Lightfoot, 1996). It is obvious that primitive communities has been established near the springs (at the base of mountains) or besides the rivers. It can be concluded that there may be a close relationship between qanats and springs. Qanat irrigation often expanded coincident with the growth of ancient settlements (Lightfoot, 1996). Smaller settlements, supported originally by perennial surface streams or springs went under pressure of water shortage during drought periods Depletion of spring discharge because of long period of droughts has persuaded the people to excavate the spring outlet and deepen the spring channel in order to get enough water from the spring (Vellayati, 1995). Figure 3a shows the initial stage of channel excavation. At the initial stage the excavated channel could be in form of an open channel. But in the case of continuation of the drought period for a few years, they were obliged to increase the depth of the channel, and in order to prevent collapse of the side walls they had to cover the top of the channel with wood and timber or pieces of stone, and with increasing the depth of the excavated channel eventually made the channel in form of a tunnel to transfer water to lower lands. Figures 3b and 3c show the intermediate and last stages of spring channel excavation. For simplicity of tunnel digging process (breathing, lightening and lifting of the excavated materials) they dug the vertical shafts and carried out the excavated earth materials through the vertical shafts. The final obtained constructed structure which is combination of a nearly horizontal tunnel and vertical shafts is nothing rather than a qanat system. And to the author opinion this is the most probable basic idea of qanat invention. Many qanats of Iran which are operational now especially in the hillside topography have been in form of springs in the past (personal observation and communication with old farmers in Isfahan and Fars provinces of Iran).

Seepage of groundwater into deep diversion channels idea

Diversion dams have a long history in antiquity. Most probably it is a case of independent invention and homologous development in various localities. Goblot (1963) nevertheless sees a certain Iranian influence in this hydraulic structure, as in others, more easily traced, that date to the Achaemenian era. Water level in the river was increased behind diversion dams and transferred to distant areas through diversion channels. In some cases they had to make part of the route in form of tunnels in high elevation areas. In the cases where these tunnels pass through saturated earth materials the digger could see the seepage of water through walls and bottom of the channels. Another possibility is that they might see that even after the cutoff of the water flow at the diversion point flow of water in the diversion tunnel did not cease due to seepage of groundwater into the tunnel. This observation could bring the idea of possibility of transfer of groundwater to the surface of the ground by a tunnel by natural forces (gravity). So this might be the first spark for qanat invention Figure 4 shows the schematic view of a diversion channel and tunnel with cross sections at different points along the diversion channel.

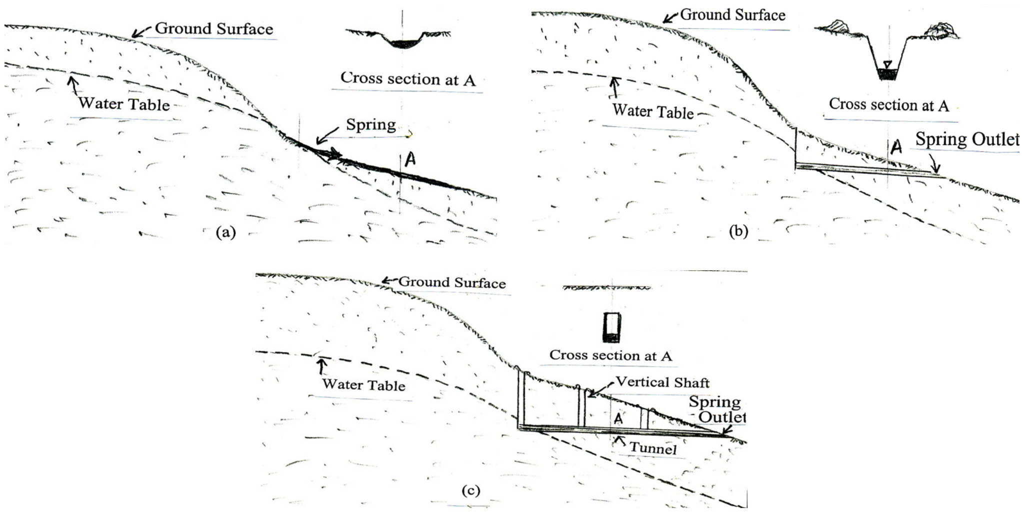


Figure 3 Stages of excavation at the outlet of a contact spring after a long consecutive drought period leading to a qanat system.

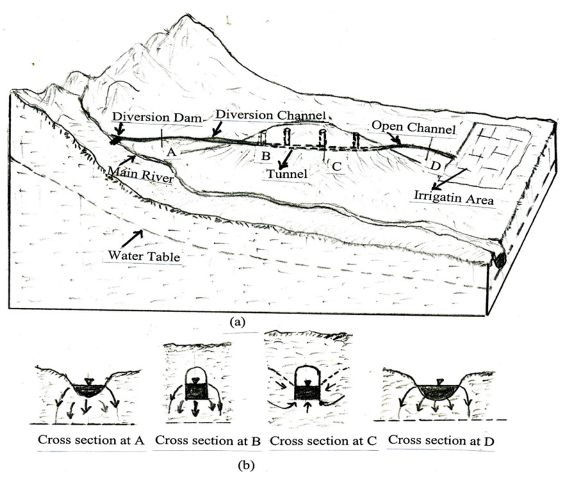


Figure 4 Groundwater seepage into the tunnel portion of a diversion channel leading to a qanat system.

Mine drainage idea

According to Goblot (1979) miners in the mountains of north west of Iran were the first people who dug tunnels to dispose obtrusive water collected in the copper and zinc mines as a result of groundwater seepage into the mine tunnel. The farmers who lived in surrounding area became interested in this method of groundwater production and used the same tools and technique to dig qanats (Fig. 5).

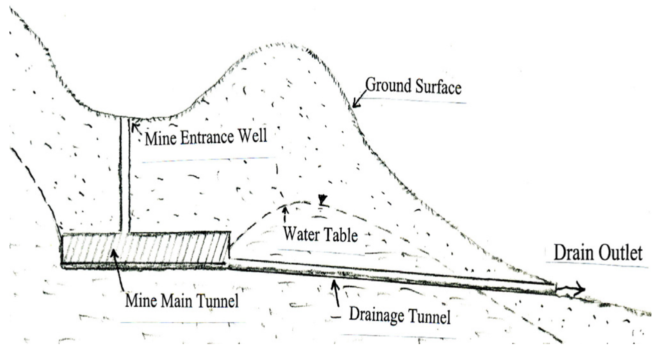


Figure 5 Mine drainage tunnel as an initial pattern for a qanat system.

Many authors have accepted Goblot idea as the most probable basic ideas of qanat invention. But some other authors did not accept his idea (Vellayati, 1995). They claim that since Goblot was a French engineer and France was an industrialized country he insisted to relate qanat invention to mine industry. This author believe that metal mining industry was not so developed and intense in those time (*ca.*500 B.C.) in north west of Iran to need to be drained by tunnels dug in hard rocks of mountain, and the spring discharge depletion and river water diversion channel ideas seems to be more logical and more concordant to conditions of agricultural communities of those time.

Drop in piezometric surface of artesian well idea

Another basic idea of qanat invention is the decrease in water pressure of artesian (flowing) well due to long period of drought. The first action of a curious person is digging a canal for water to flow out of the well (Fig. 6) similar to the case of spring discharge depletion. Consecutive deepening of the canal will make a system similar to a qanat.

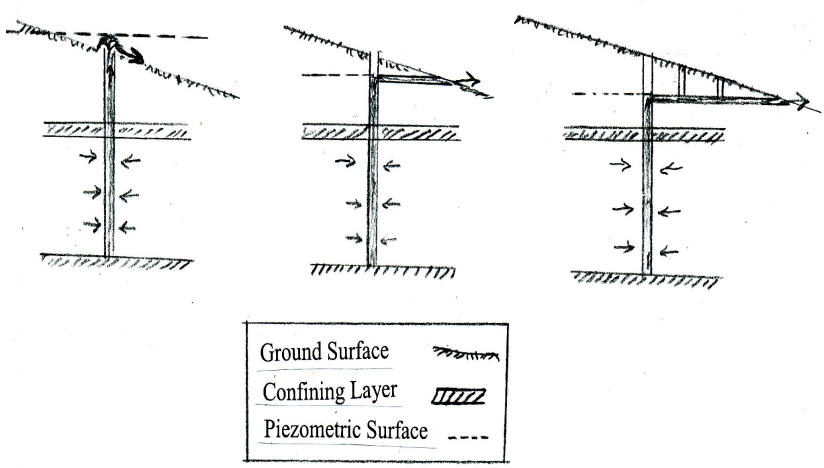


Figure 6 Stages of conducting artesian well discharge to ground surface after consecutive drop in piezometric surface during a long drought period leading to a qanat system.

Spontaneous invention idea

It is also possible that a genius person spontaneously have invented the qanat system. Off course this idea is very hard to believe. But we can not totally ignore it, and this might be the main idea behind qanat invention (Goblot, 1979).

Summary and Conclusion

In this article it is claimed that Goblot (1979) theory of relating qanat invention in Persia to metal mine drainage works is not questionable and there are a few more reasonable theories that are explained here. Based on strength and weakness points of above mentioned basic ideas of qanat invention and considering the natural and technical conditions of the people lived in the time period of qanat invention we can arrange different basic ideas of qanat invention in a descending order of importance as follows: (a) Consecutive excavation of spring outlet after a long drought period idea; (b) seepage of groundwater into deep diversion channels idea; (c) drop in piezometric surface of artesian well idea; (d) mine drainage ideas; and (e) spontaneous invention idea.

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Water Uses (Supply and Irrigation)

Technology and Cult of Water in the Rural Settlements of Sabina, Central Italy, in Roman Times: Irrigation and Groundwater Exploitation and Forest Shrine of Italic Goddess Vacuna

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Abstract: Archaeological surveys conducted in Sabina, about 50 km away from Rome, were - intended to reconstruct the ancient agricultural and pastoral landscape. They identified interesting remains of roman small family farms at Montenero Sabino and Mompeo (province of Rieti), villages located near *Via Salaria* (the "salt way") and the Farfa stream, a tributary of the Tiber River, which in ancient times, both were the main trade routes of central Italy, linking Rome to the Apennines and to the Adriatic coast. There a network of underground channels and tanks, fictile water pipes and pools, at times connected to one another, was found. Many of them are still used today, given the low population growth and the lack of modern industrial development of this area and to its isolation, in spite of its proximity to Rome. Moreover the study area holds a votive stone dedicated to the Sabine-Roman goddess of water *Vacuna,* a multiform Sabine and Central-Italic goddess with many characteristics and functions, known also as *Minerva-Bellona-Victoria*, *Feronia, Caerere*, or as *Angerona-Angitia*. It was related to an agricultural-pastoral shrine for the cult of water whose anthropological relevance still survives in yearly livestock fairs and in the local worship of the Holy Mary of parturients.

Keywords Agricultural landscape; central Italy; drainage tunnel; Roman period; Vacuna goddess of water.

Introduction

In the Mediterranean area water management by means of surface and underground structures has been a long tradition (Castellani and Dragoni, 1997). This tradition, which was shared by many civilisations, reached full maturity in Roman times. However, it was not relinquished after the fall of the Roman Empire. In fact, in the Middle Ages, many attempts were made to keep these water supply systems "up-and-running". In central Italy, both in the study area and in typically rural and peripheral areas, evidence is found of the use of ancient water capture and diversion technologies until the present time.

The study of ancient hydraulic works may provide interesting historical, archaeological and anthropological insights for investigating landscape evolution over time. It may also give useful suggestions on how to reinstate the use of the concept of these ancient pre-industrial water systems in present-day regions experiencing difficulties in finding and managing water resources, because they are economically poor or under desertification, as reported by various international agencies, such as UNESCO and FAO.

Archaeology of the Roman Rural Landscape: *Pagus*, *Vici*, *Villae* and Related Hydraulic Works

Archaeological surveys were carried out 50 km away from Rome with a view to reconstructing the ancient agricultural and pastoral landscape (Fig. 1). The surveys found interesting rural settlements in the area of Montenero Sabino and Mompeo (province of Rieti), extending from the more inland Sabina (poorer and mountainous, with shepherding-based economy) to the richer and more fertile Tiber Sabina to the west.

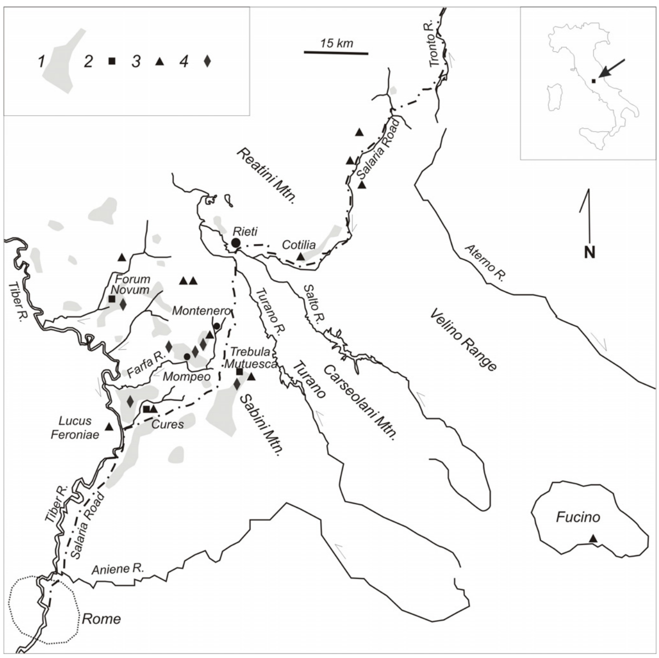

Figure 1 Map and location (in the square) of the archaeological sites examined in this study. (1) area of *villae rusticae*; (2) Sabin pre-roman settlement; (3) findings of Vacuna Goddess (shrine, memorial stone or toponomastic relic); and (4) drainage tunnel (*cuniculi*).

Sparse rural settlements

This hilly area has outcrops of continental and marine deposits of Pleistocene age that consist of clay, sand and calcareous conglomerate. Since the era of the Roman Republic, the area has been renowned for its olive groves (*oleta*) and vineyards (*vineae*) (CATO, *De agri cultura* I, 7; X-XI). Local communities lived in small non-slavery-based family farms (*villae*), which were organised as *vici*. These *vici* (unfortified rural villages of likely pre-Roman and Sabine origin) were united into larger open settlements called *pagi* (from which the surviving local toponym: *Pago*). These administrative units of high vitality and local continuity covered an area which stretched longitudinally from the valley floor (where the *villae* stood) to the heights of nearby reliefs; these heights had low population density and were often used as *pascua* and *silvae* (pastures and woods, like nowadays) by the community. Usually *vici* and *pagi* had one shrine (in the study area: the shrine of *Vacuna* at Leone), which played a centralising and aggregating role for the population scattered in the pre-urban rural area.

The Pago Hydraulic System. The area of the ancient Roman pagus of Montenero corresponds to the present settlements of *Pago*, *S. Andrea*, *Casa Paradiso*, *S. Eleuterio*, *S. Paolo* and *Villa Massa*. In these hamlets, originating from the sparse Roman *vici* (organised into *fundi* and *villae rusticae*), viticulture and oleoculture are still practised. In the area, water supply for irrigation and other uses was ensured by an interesting system of water drainage and abstraction. This system, fairly well preserved, is in part still active and some of its sections are still used for farming. The system may be described as follows: At *S. Paolo* conglomeratic lenses are interbedded with sands and clays, which become dominant downslope near Casa Paradiso. These lenses accommodate aquifers that are perched from the underlying clays and that have been exploited since antiquity as water reserves. This is testified by the widespread systems for water drainage (over 100 m long), withdrawal and storage (tanks and cisterns) of Roman age that are located at Casa Paradiso. Three underground conduits give access to the drainage tunnels (Ranieri, 2004) (Fig. 2).

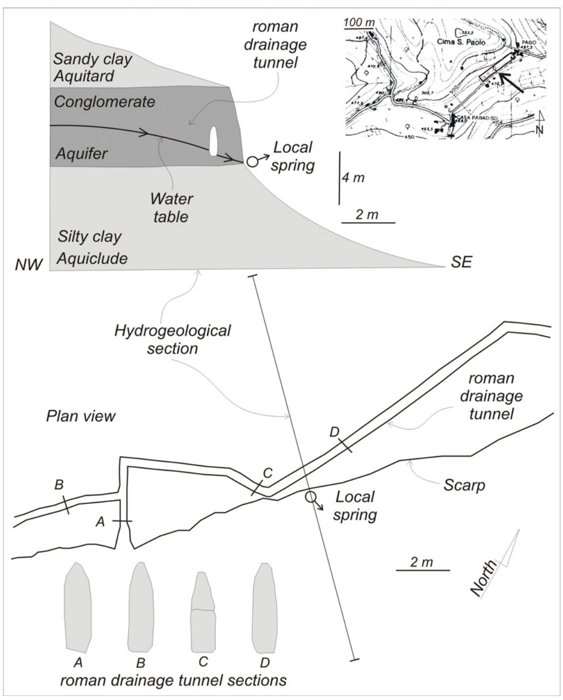

Figure 2 Plan view (partly modified from Ranieri, 2004) (bottom), hydrogeological section (top) and location (top – right) of the Pago tunnel system.

The overall water system is composed of multiple levels. Indeed, about 20 m away, another section of the system (in part still active) lies at a height of approximately 2 m from the main conduit. The drainage tunnels are well preserved and some of its sections are still used today for supplying water for irrigation. The active branch of the drainage system is over 30 m long and lies at an upper level with respect to the main conduits. Access to this branch is via an about 3 m long conduit which then branches off, leading to two different conduits. The first has a length of slightly more than 5 m; advancing farther is blocked by what appears to be a landslide. The second conduit is over 20 m long. Its first 6 m are almost entirely flooded. After advancing for another 20 m, the conduit changes direction again, turning right. In this conduit, too, proceeding farther is hindered by an obstruction. The conduits have an ogival cross-section and are 1.80 m high and 0.6 m wide and they do not seem to have a protective coating of hydraulic mortar (Fig. 3).

Cisterns, tanks and fountains in the Roman fundi at Casa Paradiso. Hypogean conduits for water drainage and capture were usually associated with cisterns or open tanks. Examples of these storage facilities are an about 20 m long structure at *Grotta Ciottina* and a 40 x 3 m² Roman cistern at *Casa Maialini*, both lying near the village of Mompeo. In the area surrounding the cistern, a funerary inscription was also found (probably belonging to the family of the possessor of the *villa rustica*, who must have owned the cistern and the road to the farm). The *Casa Paradiso* hamlet hosts a fairly monumental fountain in conglomerate material, which is likely to have been built on an ancient water storage system and associated conduit of Roman age. However, in a vineyard surveyed during this study, evidence was found of the occurrence, maintenance and continuous use of an interesting system of water drainage, withdrawal and distribution for irrigation purposes (Fig. 4). This system, certainly leading back to the Roman age, must have been made up of one still active below-ground conduit, of one tank for water collection and distribution via fictile *fistulae* (terracotta water pipes, of which relics were found) (Fig. 5), and of a least one small basin.

Figure 3 Roman drainage tunnel about 2 m high from Pago (section D in Figure 2).

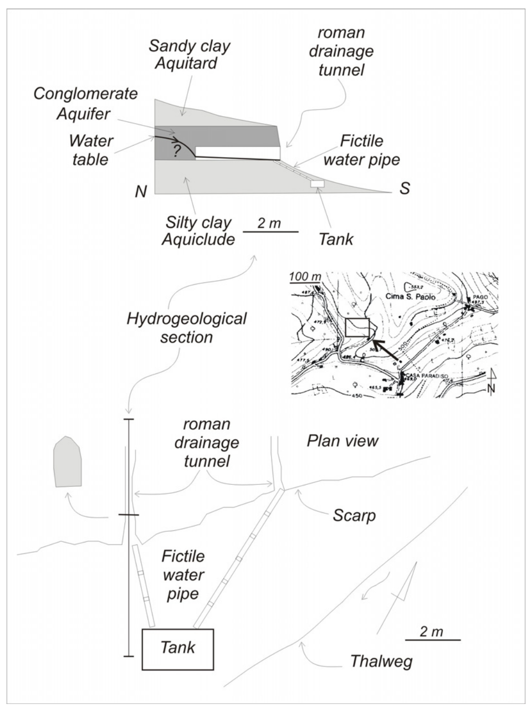

Figure 4 Plan view (bottom), hydrogeological section (top) and location (middle) of the Casa Paradiso drainage tunnel – tank hydraulic system.

At short distance (to the NW, at *Casa Voltafonte*), other archaeological remains were reported in the 1970s: a large cistern (30 x 3 m²) and imposing masonry structures in *opus quadratum*. The architectural and sculptural elements of these structures infer that the *villa* must have had also an impressive *pars dominica*.

Figure 5 30 cm wide and 70 cm long fictile water pipe from Casa Paradiso; the location of its finding is reported in Figure 4.

Other findings nearby Pagus. In the northern area of Pagus another villa was supposedly located on a terraced slope overlooking the *nemus Vacunae* of Leone. The *villa* must have risen in the present-day site known as *Villa massa* (from the late ancient Latin word *massa*, meaning a group of *fundi* making part of a single property). Based on the numerous and scattered archaeological records that have been found so far at the surface, the *villa* is likely to trace back to the Roman age (remarkable moulded or decorated architectural elements, as well as *instrumentum rusticum* like *lapides pedicini* and *arae* which are parts of olive and grape press). The ancient drainage conduits, which are still visible and used in the area, must have supplied water to the *villa*. Another ancient settlement to add to the *vici* of *Pago* is at *Villanette* (toponomastic relic from Latin *villa*), an area with abundant Roman fictile fragments (kitchen pottery, *sigillata-italica* and *aretina* tableware and building ceramics) and with some valuable and inscripted architectural elements coming from its rich *pars dominica*. The periods of use of these *villae* are estimated to range from the Republican age to the 2nd century A.C., thanks also to ancient coins discovered in the area; prominent among them are: one Republican bronze *aes* with a two-faced *Janus* on one side and a ship's prow on the other, and a silver *denarius* of the Imperial age.

Cult of Water in the Montenero Pagus

Cult of water in the Sabina area

Literary sources (Ovid, *Fast.*, 307; Horace, *Ep.*, I, 10; Pliny, *Nat. Hist.*, III, 109) describe *Vacuna* as a typically Sabine and Central-Italic goddess of waters; the Central-Italic area holds many records of this multiform and multifunction deity. The most famous shrine of Latium dedicated to *Vacuna* was recently identified among the impressive ruins of Cotilia, a site rich of water (Alvino and Leggio, 1996; Sensi, 1999). This major archaic sacred place of the cult of water is located uphill of the small lake of Paterno, fed by springs of ice-cold water that has been regarded as salubrious since antiquity. The lake probably matches the well-known *lacus Cutiliense* "*…in quo fluctuatur insula*", a venue inhabited by *Lymphae Commotiles* (goddesses of the island floating in it, driven by the wind as in a supernatural *prodigium*) and the *umbelicus Italiae* ("navel" of Italy), as reported by Varro, Dionysius of Halicarnassus and Pliny the elder; the latter recalled its sacredness as a *temenos* consecrated to Victory in Imperial age and its periodical sacrifical rites. The goddess was also revered at the more important *vicus* of *Trebula Mutuesca*, which *ager* in Roman times must have covered also the peripheral part of the Montenero *pagus*, connected to the much richer flat area of Tiber Sabina by the Montenero stream and the (then navigable) Farfa stream. At *Trebula Mutuesca* (from the archaic italic word *mutusco*: wet, marshy) in the Romanesque church of *Santa Maria della Vittoria*, as the name says, the ancient goddess was worshipped as *Vacuna-Victoria*. It is not by chance that the church was built on pagan worshipping structures (Sabine and then Roman) celebrating such deities of water, as demonstrated by plenty of archaeological material there reused, such as an ancient puteal of a healing-water well (transformed into a baptismal *puteus* in the Christian age) and old drainage tunnels reused as *catacumbae*. Further eastwards, in the more inland Apennines (Turano and Fucino), archaeological evidence is found of the worship of *Feronia -Angitia-Caerere*, an ancient deity of waters and fertility reported also on the banks of the now-drained ancient Fucino lake. A major place of inter-ethnical (Sabine, Latin and Etruscan) worship was located in the southern Sabina, in the Tiber valley, at *Lucus Feroniae*, near *Eretum* and *Cures*; this site, ensuring the fertility of fields and livestock, has been hosting fairs and trades since the protohistorical age.

Also the isolated rural settlement of the Montenero *pagus*, just as the entire Sabina, *Trebula* and the Val Canera area (at least two sacred areas attested) as far as *Cutiliae*, had shrines honouring *Vacuna*. In these shrines local people periodically gathered during festivities, recognising their mutual belonging and identity in the worship of the Sabine goddess of *vacare* ("vacating", as suggested by the poet Horace), who protected absents and ensured their return, who guarded what may disappear (in the frequent and dense fog and flood still characterising this water- and humidity-rich area), who took care of the *vacuum* (temporary vacancy) resulting from separation, journeys, wars and, in a broad and apotropaic sense, from the final departure, which was dreaded upon any disease, as well as in the human and animal experience of parturition, a fundamental factor in that archaic rural society.

The shrine of the Montenero Sabino Pagus: the Fanum Vacunae of Leone

The *Fanum Vacunae* (open-air forest shrine: *fanum* meaning a clearing in the forest that the penetrating light makes sacred) can be traced on the isolated hill of Leone thanks to a number of finds, including remarkable epigraphic material and to some antiquarian sources of the 16th century. The hilltop of Leone still features a clump of oak trees and an enclosure in local limestone which bounds a flat area (Fig. 6). Unfortunately, the technique adopted for building this enclosure cannot be distinguished from those used for the more recent stone walls and substructures found in the fields; nevertheless, these constructions are evocative of the ancient cultural *fanum temenos*. Moreover, this site has a strategic position for the ancient *pagus*, as it is always visible and central with respect to the above-mentioned *vici* and *villae* and is still almost entirely encircled by the waters of a loop in the Montenero ephemeral stream. On this site, country-side inhabitants must have invoked the guardianship of the goddess, as the source of fertility of their mountainous soil and of the health of people and livestock, but also - in a negative sense and as something to be exorcised - as a way of concern about the frequent and ruinous seasonal floods.

The fact that this site was consecrated to the goddess is testified by a votive limestone *cippus* of late Republican-Augustean age, unearthed upon agricultural work and visible in its surroundings until 1996 (Fig. 7), carries an elegant-style epigraph about the positive outcome of a vow that one member of *gens Tossia* made to the goddess, perhaps called with her original divine nomen: *Vacona* instead of *Vacuna*: *Q(uintus) Tossius Q(uinti) [F(ilius)]/Vaconae/D(ono) D(edit)/ L(ibens) M(erito)*. Probably this generic vow could be related to the famous floods happened in the Sabina area on 54 and 23 b.C. reported from ancient sources for two reasons: its classical palaeography and the location of the shrine which dominated the underneath deeply embanked meander of the Montenero stream.

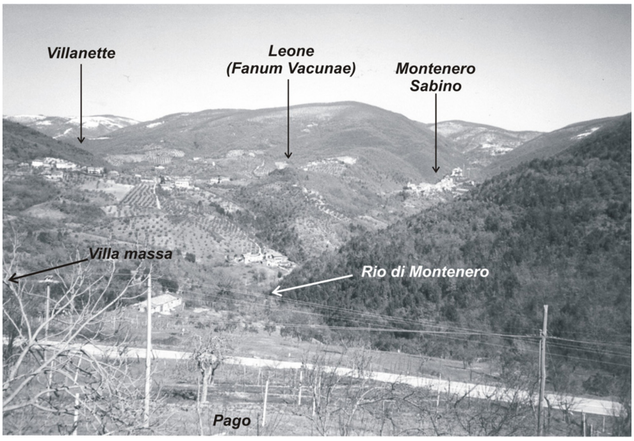

Figure 6 View from Pago of the Leone hill (*Fanum Vacunae*), Montenero Sabino and *Villanette* and *Villa massa* archaeological sites.

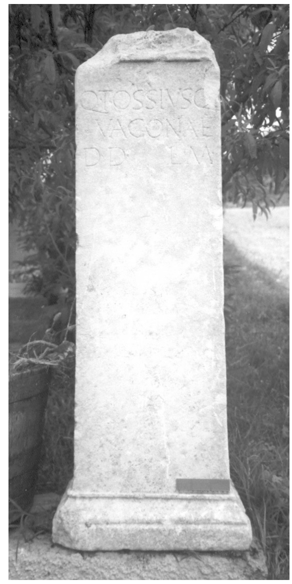

Figure 7 Memorial stone dedicated to *Vacuna* Goddess from Leone site (photo by A. di Leo).

Conclusions

A landscape archaeology study was conducted in the typically rural and mountainous Mediterranean area of Montenero Sabino (central Italy). The study highlighted an outstanding continuity of use of ancient Roman rural structures (underground channels, tanks, fictile water pipes and pools). The study area holds several votive stones dedicated to the Sabine-Roman goddess *Vacuna*. These stones give evidence of a Roman agricultural-pastoral shrine for the cult of water, in which the area was very rich. The anthropological relevance of this cult still survives today in yearly livestock fairs and in the local worship of the Holy Mary for protection of parturients.

This sacred site of Montenero is indeed to be identified with one of the *nemora* (open-air forest shrines) consecrated to the goddess *Vacuna* (deity of *vacuus*, i.e. of vacancy). This is a multiform, typically Sabine and Central-Italic goddess with many characteristics and functions, known as "*Minerva-Bellona-Victoria*", the goddess of safe return from war for the Romans, or as "*Angerona-Angitia*", the goddess of the good outcome of parturition that Central-Italic peoples regarded as a perilous journey the return from which was doubtful. But the worship of this goddess was related above all to the healthy and symbolic properties of water, which is abundant in Sabina and which causes frequent fog; the fog symbolises the disappearance and reappearance of places and people (in situations which were then perceived as dangerous, such as diseases, parturitions, departures also for war) to be exorcised. Therefore, the goddess had to be propitiated with sacred places and shrines located in the woods near springs, lakes and more or less important streams.

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Water Resources of Aitolia and Akarnania, Greece, and their Contribution to the Development of the Society from Classical to Roman Times

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Abstract: Throughout antiquity water resources have played a major part in the development of certain regions in Greece and led people to seek a rational use of subterranean and groundwater and aim at the protection of the land from flooding and corrosion. The main target of technical works that are related to water was economic growth and development of the society, as well as protection of the citizens and their property. This paper refers to the rich water resources of Aitolia and Akarnania during the Classical, Hellenistic and Roman period and documents the archaeological evidence of water management in the region. In addition, we make an attempt to put forward the technical works of ancient times and to point out the importance that is manifested in the planning and building of cities, sewerage, and other constructions for the irrigation or the protection of lands from the corrosion.

Keywords Aitolia; Akarnania; Classical and Roman times; Hellenistic; water resources.

Introduction

Through the study of ancient Greek literature we perceive a tendency of the ancient Greeks to explain though mythology and philosophy the fundamental importance of water resources for the development of cities and culture (Koutsoyannis and Angelakis, 2003). It is not by coincidence the fact that important civilizations flourished in riverside areas, such as the ancient Athenian culture that grew in terrains formatted by the deified rivers Kefessos and Ilissos. Respectively, rivers as Acheloos in Aitoloakarnania and Alfeios in Ilia offered, throughout history, development and prosperity to the inhabitants of Western Greece (Kalavourziotis *et al.*, 2005).

We find references for the outmost importance of water resources in the Minoan culture (2,000-1,400 B.C), with main examples the cities of Knossos and Faistos in Crete (Angelakis and Koutsoyiannis, 2003). The variation in the conditions of watering of the palaces and other establishments depending the seasons and the prevailing hydrological conditions, took great importance in the later construction of water tanks (cisterns) and model sand- refineries of ground water. Also, there has been construction of clay pipes for transportation of spring water, as well as pumping water from wells in the Zakros palace. There are also significant indications for the re-use of water waste for irrigation purposes during the said period (Angelakis and Spyridakis, 1996). Following the Minoan, rose the Mycenaean Civilization (1,600-1,200 B.C). Archaeological research showed that the Mycenaeans managed water

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resources with the purpose of protecting the land and the augmentation of the cultivated land through irrigation. Important technical works of this period are considered to be the Persaia Spring in Mycenae, and the draining works in Kopais Lake. Similar works to the Persaia Spring can be seen in the acropolis of Tiryntha and Athens (Pappas, 1999).

Water Resources in Aitoloakarnania

The prefecture of Aitoloakanarnia is still to this day one of the richest areas regarding water resources. The area is blessed with an abundance of natural water resources that come in many forms and determine the character of the palaeo-environment (Papageorgiou and Steiros, 1991). The region is structured by three rivers: Acheloos, which divides the countryside in two halves (Aitolia to the East and Akarnania to the West), Euenos, which runs down from the Aitolian Mountains and Mornos, which is the natural boundary between Aitolia and the neighboring Fokis to the East. There are also four natural formed lakes, Trichonis being the largest of them, covering 98.6 $km^{2.}$ In addition to that we must take into account the marsh and swamp areas that are known through ancient written sources, such as the marsh/lake system around the ancient city of Oineades.

The dominant role of the river Acheloos is manifested in both mythology and the written ancient sources. Acheloos is described by Homer as second only to Zeus himself and as "father of rivers" "Silver Whirlpool River". According to the myth, the river-God fought against Hercules, competing for the princess Deheaneira, daughter of the Aitolian king Oinea. During the fight Acheloos kept transforming from man to snake and then to bull but finally he acknowledged defeat when one of his horns was broken. The broken horn was given as a wedding present to Hercules and Deheaneira and is often regarded as the "Horn of Abundance". By some this myth is seen, even in ancient times, as the battle between man and the elements of nature, reflecting an effort in the early stages of history to constrain the destructive force of the river by constructing agricultural flood protection hydraulic works (Strabo, Geog. 10.2.19). It might illustrate the efforts of pre-Doric - Mycenean populations to such ends as are known from other areas to the east (Kopais). Unfortunately this theory is yet to be tested, as there is no evidence of such constructions in the lower Aitolian plain.

Another of the myths concerning Acheloos is the tale of his wrath against the Echinades nymphs - the small isles found on the river's delta. Acheloos decided to punish the nymphs by connecting the islands to the mainland (Pausanias, Graeciae descript. 8.24.11). A further interesting tale concerning Acheloos is that of Alkmaion who, after murdering his mother, he received a prophecy from the Oracle of Delphi that he should inhabit the land that was not seen by the sun when the crime was committed. He found this land to be the alluvial plain in the delta of the Acheloos River. The last two myths signify that the ancient Greeks were fully aware of many aspects of the hydrological cycle and its mechanisms such as the alluvial process (Pausanias, Graeciae descript. 8.24.8, Thucydides, Hist. 2.102).

The populous of Aitoloakarnania, located in the periphery of the ancient world and cut off to the east by the rough mountain range of Pindos, with little natural ports to disrupt the arduous coastline to the west, was nevertheless able to develop a remarkable civilization, which flourished during the Hellenistic period. The Aitolians and the Akarnanians developed a pioneering model of governing -the Aitolian League and the Akarnanian Koinon respectively- which comprised a representative federation system with equal rights for all the participating city-states. This civilization left impressive, well-preserved remains all over its territory, mainly cities built with the ippodamion system (grid-planed) and fortified with strong stone walls (Oiniades, Pleuron, Kalydon, Stratos, Palairos to name but a few).

The region is not particularly explored in terms of archaeological excavations. The archeological research consists mainly in salvage excavations by the Archaeological Service and secondarily by (smaller scale) systematic excavation by some universities or Archeological Institutes (University of Athens: Oiniades excavation, University of Ioannina: Thermon, Maurikas, DAI Berlin: Stratos, Palairos projects, Arch. Inst. Denmark: Kalydon project.). Only recently three major archaeological sites of the area were included in phase three of the Community Support Framework, improving the level of research and development in the field. Nevertheless the works are still in progress, so the archaeological data are not conclusive or published yet. Judging from the documented archaeological material gathered, there appears to be a close relation between the archaeological data and the effort towards the natural resources management. Time and time again the archaeological research has brought to light small or larger scale works that testify the systematic use of technology in relation to water resources. Besides, the basic requirement for the creation of any kind of installation is the existence and access to potable water.

Archaeological Evidence of Water Management

During the Classical, the Hellenistic and the Roman period, through the archaeological data, we can see five different kinds of water resources use in Aitolia and Akarnania. The three said periods constitute several centuries of history, from the 5th century B.C. to the 1st century A.D. Nevertheless we must take into account a breaking point in the history of the region, that of the sea fight of Aktion and the building of the Nikopolis by Octavian Augustus and the migration of the people to the new city. The different categories are related to the use of water for personal needs (drinking or cleansing), drainage (waste water) or protection from flooding and it can be divided as follows: (a) systems of water supply/fountains-springs-cisterns; (b) baths-sanitary facilities; (c) large technical works: setout of streambeds/dams; (d) water drainage in theatrical installations (open air theatres); and (e) ports/shipyards.

Systems of water supply

The main evidence of fountain/spring construction are:

(a) Peristeri Trichonidas- location *Moutsiara*. Water source constructed in a Π-shape, by local limestone, with the isodomic building system. Original height is estimated 3 m and width 5,45m. water was sprigged out by two square shaped openings. Nowadays it is partially destructed. (Papapostolou, 1982).

(b) Kainourgio-location *Sorobou*. Water source known as *Veinovrysi*. Built in the isodomic system. Still in use today. (Stavropoulou-Gatsi 1994).

(c) Thermon - sanctuary of Apollo. Monumental water spring, built in the secret sanctuary and political center of the Aitolian League. It is built with rectangular stone tiles, in the isodomic system, also Π-shaped. The south shank ends up in a well-built stone waterspout, which can be seen for several meters and can be found in other parts of the enclosed sanctuary. Due to its central position in the sanctuary and the neighboring of the temples of Apollo and Artemis - right between the temples and the *stoes* of the "Agora"- it is most probable that the spring were used for ceremonial or religious purposes.

The evidence of cistern construction are:

(a) Pleuron (Aitolia). Monumental cistern of very large dimensions, carved in the natural limestone. Three walls separate the cistern in four compartments. The bottom of the construction is accessible by a stone lades in the west side (Fig. 1). In the ancient city there is a number of smaller cisterns, also curved in the limestone, for water collection. It is not yet how these containers were filled. Taking into consideration the arid character of the area this must have been accomplished either by an aqueduct through the neighboring ravine, or by a system of rainwater collection by the city's roofs.

Figure 1 View of Ancient Pleuron in Aitolia.

(b) Pelegriniatza (Akarnania). Built cistern with a stone ladder whose steps come out from the inside of the exterior walls. The well-set construction is circular, 9.60 m in diameter, built with rectangular limestones, in the pseudo-isodomic system. Traces of hydraulic plaster, used for insulation, are still visible. (Heuzey, 1856).

(c) Archondochori- location Kastri. Square water reserve partially carved in the natural rock.

(d) Naupaktos, location Ovriolakka. Two small cisterns were located during salvage excavation. The cisterns are found under the remains of a private building, dating back to the 1st century B.C. (Papapostolou, 1978).

The major water pipes/canals are:

(a) Thyrreion

(i) Kousa property. During salvage excavation, part of a water canal was revealed. The canal was 1.50 m long, with walls 0.15 m wide (dimensions of the opening in the interior: 0.30 x 0.30 m^2), and it was covered by limestone slates. It is possible that the canal is part of the ancient city's water system. According to the locals the same canal has been detected in other locations and can be traced back to an area called *Paliovrisi* or *Pegadia* (translates Old-Fountain or Wells respectively) (Stavropoulou-Gatsi, 1998).

(ii) Tsabatopoulou property. During excavation in 1996 an important part of the city's ceramic water Pipe was revealed. The clay sections are of 0.35 m in diameter and 0.75 m of maximum length. The ends of the clay sections are isolated/joined with plaster while the inside of the pipes are covered with a thick layer of salts (Stavropoulou-Gatsi, 1998).

(b) Alikyrna. While constructing a new road, part of a built canal and a posterior building was revealed (Dekoulakou, 1972).

(c) Naupaktos

(i) Mpotsari & Messenion str. Part of a Hellenistic period support/paparet wall was located and part of a large draining sewer covered with slabs, directed to the sea (from North to South) (Saranti, 1998).

(ii) Farmaki & Tsoni str. Building remains of Hellenistic period were discovered. The building consists of eight rooms. Through the semi-covered room X3 run a small slab-covered canal which ended up in a rectangular shallow reservoir (Saranti, 1997).

(iii) Farmaki & Bardakoula str. A Hellenistic period building with a large slab-covered sewer/draining canal was found. The canal it was crossed by another in the East. A well was also found in the area (Kolonas and Saranti, 1994).

(iv) Farmaki & Tsabella str. Residential remains of early Hellenistic period were uncovered with storage spaces and floors of small pebbles and plaster. a long drainage canal was found on the north (Aleksopoulou, 1988a).

(v) Megalomata area. The area is inside the city walls. Part of a built canal running from east to west was found. (Aleksopoulou, 1988b). Megalomata: name of a Byzantine/Turkish fountain still in use today. On the façade of the construction there is ancient material (rectangular stone blocks)- probably part of the spring dates in the ancient period (still in situ). There is a possible connection of the fountain to the watering system of the ancient city.

The major wells are at: (a) Nafpaktos. Farmaki & Bardakoula str. A Hellenistic period building with a large slab-covered sewer/draining canal was found. In the west part of the building a well (with built walls) was also found (Kolonas and Saranti, 1994) and (b) Thyrreion. Location *Paliovrisi* or *Pegadia*: the existence of two ancient wells with built walls was verified. According to attestations there is also an ancient spring (Stavropoulou-Gatsi, 1998).

The major baths are at:

(a) Alikyrna - St. Thomas: Great Roman Baths. A roman bath complex with very good level of conservation was revealed (Petropoulos, 2004; Katsaros, 2004). The walls of the main building are still visible in a great high and the rest of the spaces are well preserved: hypocausts, small water reservoirs with marble walls, piping and draining system. There is a question whether the baths were built to serve the needs of the citizens of the nearby city (Alikyrna) or were used by the travelers of the *via publica* that led from Nafpaktos to Nikopolis to the north (parts of the paved roman road have been located in the forefoot of mount Arakunthos and was still in use during the Turkish occupation period).

(b) Nafpaktos: (i) Public baths of roman period. Hypocausts and built bathtubs were found (Kolonas, 1983); (ii) parts of roman baths (Kolonas, 1983); (iii) Roman baths with mosaic floors and water pool with marble walls (piscine) (Petsas, 1971); (iv) parts of roman baths (Papapostolou, 1981); and (v) parts of roman baths - hypocausts and air pipes (Sarandi, 1997).

Evidence of technical works: Setout of streambeds/dumps

The major are:

(a) Nafpaktos: Ska stream. Near the Aphrodite settlement a strong supporting wall for the setout of the streambed was located, -2.65m in depth under the current street level. It is built by large uneven limestone blocks roughly worked - mostly on the west face of the wall. As the excavator reports: “ the wall was probably used for the setout of the course of the Ska stream, which lies, even today, near Plastera str. Parts of the same wall have been located in two other places in Plastera str, to the north and to the south” (Aleksopoulou, 1992; Kolonas-Saranti 1995).

(b) Alyzia: Varnakas stream- the dam at “Glosses”. The dam at Glosses is an ancient technical structure, probably unique at its kind in Greece. It is located at the entrance of a step ravine, blocking the force of the stream, just before it reaches the plain of Alyzia. The structure measures 10.5 m height and 25.3 m in length and it is built by 14 rows of stone blocks (with average dimensions 1.5 x 1.0 x 1.0 m^3) that form a sloping front (about 45°). According to Murrey (1982), it is possible that its construction is related to the theory of Plato "of the creation of springs", which was developed in the middle of 4th century B.C., a period during which flourished the nearby city Alyzia. In the "Laws" (Νόμοι) there are indications that Plato even had knowledge of the area - there is the possibility that he stopped in Alyzia on his way to Syracuse. Murrey claims that the dam was connected to the enrichment of the water tables and the protection of the precious land of the plain from destructive floods and it dates to the Hellenistic period (end of 4th- beginning of 3rd century B.C.). It should be noted that the dam was not that effective to its function and it was soon filled by the drifting material of the stream. According to Knauss (2002), the structure was used as a "laundry", a facility for the cleaning and purging of the wool that came from the life stock, or as a watermill. So, it was not constructed for the objective of collecting/storing water but for the rising and the precipitation of water aiming at producing dynamic energy. Knauss dates the structure - somehow arbitrarily- to the Mycenaean period. It is questionable whether such a technical work would be worth the effort merely for the creation of an artificial waterfall, if we take into account the rough and steep terrain of the territory. Dating the construction is another issue, given the difficulty of dating a wall merely by the way it is built, especially in the western part of Greece, where there seems to be a tradition of following ancient (archaic) techniques. Nevertheless it is not unlikely that the construction was used in two different periods of antiquity, one of which being the Hellenistic era.

Theatres

Ancient Greek theatres constitute spaces with a high level capacity of rainwater collection, due to their shape and their open-air character. The fan-shaped formation of the *koilon (cavea)* - where the seats of the spectators are located- and the stairs leading to the upper levels facilitate the concentration of water and direct them to the orchestra of the theatre. The ancient writer Vitruvius in his book *De Architectura*, despite the fact that he analyses the technical issues on the construction of theatres, he doesn't mention a system of drainage. Nevertheless, such a system was provided and used widely, as we know by the surviving examples of theatres. The simplest solution to prevent the orchestra from flooding was to create a shaft at its periphery, at the base of the *koilon*.

In the case of Aitoloakarnania such structures are located at two well-known and fully excavated theatres of the area, those of Stratos and Oiniades. These two akarnanian cities were built in key-points, controlling the course of the river Acheloos. Oiniades controlled its debouchments and Stratos, the mighty capital of Akarnania and centre of the Akarnanian League, the upper course of the river. The ancient city of Stratos is built on the west bank of the river and is fortified with strong walls 7,500 m of total length, which enclose three hill ridges. The theatre is built in between the two hills to the east, next to the ancient agora (Schwandner, 2000/2001). The koilon is built by local green-brown sandstone, while the construction of the orchestra and of the first row of seats was made by limestone from the nearby quarries of Lepenou (Figs. 2 and 3).

The drainage of the rainwater is achieved by a semi-circular channel that follows the perimeter of the orchestra and is covered by turns with limestone slabs. A characteristic of the channel is that its west side ends at a "blind-spot", carved in the soft natural rock bed, while its floor has a gradient declination to the east. At the east end of the semicircle the channel becomes subterranean and continuous North-Northwest under the stage building. In the north of the stage there is a very strong and well built retaining wall that also defines one of the city roads, one level down. The drainage from the theatre ends up at the base of the retaining wall and from there on to a larger draining channel, under the stone pavement of the road. The course of both the drainage and the road to the south is yet to be discovered by excavation, but it is most probable that it takes advantage of the declension of the hillside.

Figure 2 View of Ancient theatre of Stratos.

Figure 3 Stratos, the ancient theatre: the orchestra.

What can be seen in the construction of the semi-circular drainage of the orchestra is the logic in which the ancient builders worked. Showing extreme skill and practicality they created a shaft with a gradient to the west side, in order to drain the rain water to just one and not both sides of the theatre. The erection of the sustaining wall and the thoroughness in the construction demonstrate the diligence of the builders in issues of drainage in connection to the stability of the whole structure (Fig. 4).

Figure 4 Stratos, the drainage of the orchestra.

The same more or less solution is followed in the ancient theatre of the other Akarnanian city, Oiniades. The main difference lies in the fact that most of this theater's cavea is chiseled in the hillside's bedrock and is only partially built. In this case too a drainage is created in the perimeter of the orchestra, with a "blind spot" at the east end and a gradient towards the west (Gogos, 2003), (Fig. 5). The channel is covered with limestone slabs and continues its course between the west *parodos* and the stage and ends up south, out of the theater's grounds. This is a much simpler construction that nevertheless follows the same principle. Rain water is channeled to one exit point using inclination on the bottom of the shaft. These two examples refer to theatres located in cities with abundance in water resources. There is a question however whether rain water gathered in such constructions as ancient theaters could be used or stored in case of warfare or whatever was its use - if any - in arid locations.

Dockyards

A very well preserved example of ancient dockyards is also located in the city of Oiniades. The construction is very impressive, since most of it is chiseled off the limestone rock and originally could house up to six ships. The *neorion* is found next to the mouth of the city's north port. The reason it is mentioned here is that it makes an eloquent example of water-use as a criteria for the location of a city at a particular area.

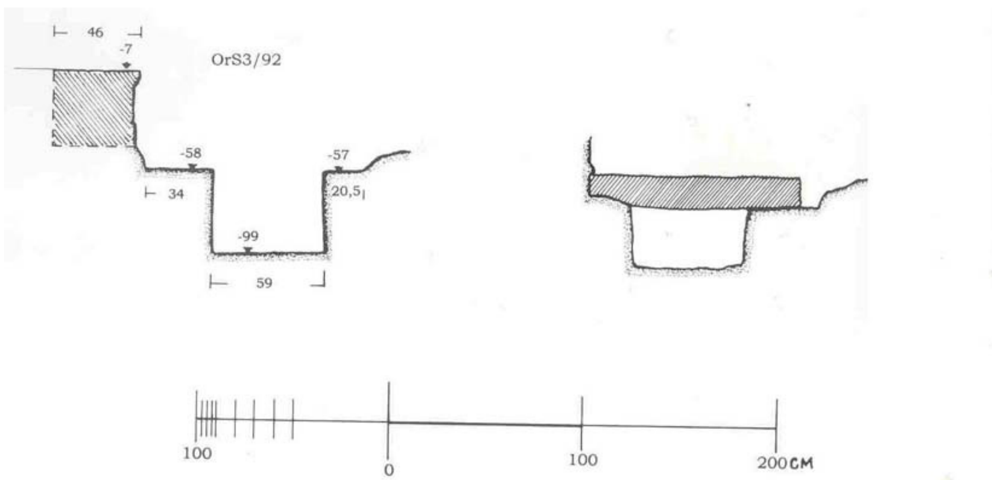

Figure 5 Cross section of the orchestra drainage (Gogos, 2003).

Nowadays the city of Oiniades is nothing but a rock hill in the middle of a rich plain, somewhat 20 km inland. The city in its prime, however, was on the shore side and a naval force, having both the sea and the river Acheloos working on its advantage (Strabo, Geogr. 10.2.20). Thucydides (Hist. 2.102.2) comments on the city's defenses, saying that during wintertime it was impossible to march against the city with an army, since the river's waters circled around the city creating a lake («περιλιμνάζων»), making passage impossible («άπορον ποιεί υπό του ύδατος»). In summertime - when most warfare was conducted - the conditions didn't get much better for an invading army, since the surrounding lake became a swamp. The Achelloos River might have stolen the city away from the sea, but there was a time that it sustained and protected the city and its people as much as the strong stone walls did. The dockyards of Oiniadae stand as a reminder of the nature's forces and the benefits of working with nature and not against it.

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Water Supply in Athens, Greece

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Abstract: Athens has suffered from a lack of adequate water resources throughout the ages. As a result of the constant increase of demand, the raw water supply system has developed into a very complex and demanding system that requires highly specialized operational procedures. This paper provides a brief overview of Athens's raw water system and discusses the operational challenges that are presented and proposed.

Keywords Athens; resources; supply; water.

Introduction

Athens has been plagued with a dearth of water resources since the ancient times. It was said that the Athenians were punished with a lack of water from the moment they selected the goddess Athena over Poseidon, as their patron god. Athena had offered the Athenians the olive tree as a gift, while Poseidon offered a spring of fresh water. The Athenians found the olive tree more useful than the spring and named their city Athens in the honor of her. Poseidon in a fit of rage cursed Athens to suffer from lack of water throughout the ages.

Aside from myth, the greater area of Athens is one of the driest areas of mainland Greece. The average yearly rainfall is between 350-400 mm, whereas in the Western areas of the country, yearly rainfall exceeds 1.200 mm. Athens is a sprawling city with over 4,000,000 inhabitants, close to 40% of the entire population of Greece, and it is a Herculean task to meet its water supply needs (Nestorides, 2005). Athens Water Supply and Sewerage Company (EYDAP s.a.) is the water service provider for the greater area of Athens and is the largest water company in Greece. It has over 1,900,000 counted customers and supplies the city with an average of 1 Mm^3/d.

The water supply system of Athens developed gradually, as demand for water increased. The consumption of the city of Athens has steadily increased throughout the years. Figure 1 shows the evolution of the water consumption in Athens. Exceptions to this rule are only during the years of WWII, as well as, the two periods of severe drought in the early 1980's and 1990's, when EYDAP drastically increased the cost per m^3, in order to regulate consumption. In recent years, Athens' water demand has leveled off and has remained relatively constant (Nasikas, 2003). Today, EYDAP maintains a complex network of interconnecting aqueducts closed to 500 km in length, in order to bring raw water to the area of Athens from a distance of over 200 km away. Three man-made reservoirs, one natural lake and a complex system of groundwater wells provide the raw water source for Athens.

Description of the Raw Water Supply System

The raw water sources of Athens are predominantly surface water sources. In periods of drought, EYDAP also utilizes its underground water reserves. Figure 2 depicts the water supply system along with the reservoirs and the ways of bringing the water to Athens.

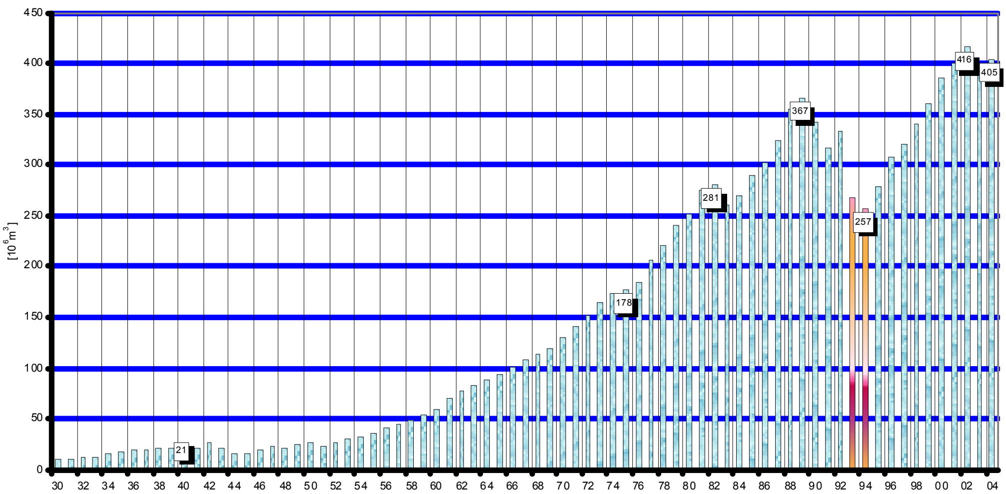

Figure 1 The evolution of the water consumption.

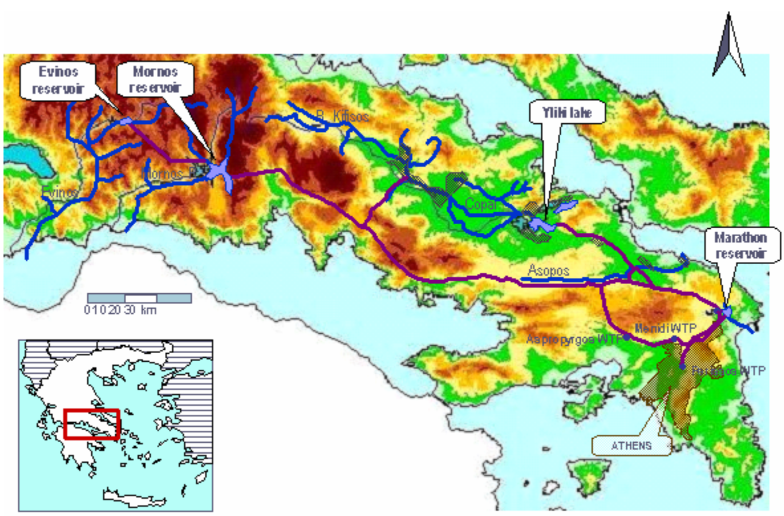

Figure 2 Raw water supply system: Main components and evolution.

Surface water reserves

The surface water reserves of Athens are comprised of the Mornos, Evinos, and Marathon reservoirs and the natural lake of Yliki. The total reserves amount of water is estimated to be 1,560 Mm³, while the total surface area of the four watersheds is 3,517 km² (Design Conglomerate of Maheras Offices; Hydroexigiantiki Design firm; and others, 2005). Table 1 gives the area of the four basins, which the reservoirs belong, the average annual rainfall, the reservoir surface and capacity and the average annual runoff. The Evinos is the newest reservoir and was completed in 2002. This reservoir contributed substantially to the increase of surface water reserves. It also has permitted EYDAP to operate its aqueducts with greater reliability and economy.

Table 1 The characteristics of the four reservoirs supplying water to the Athens greater area.

Surface Resources	Runoff basin surface (km^2)	Reservoir surface (km^2)	Useful storage capacity (Mm^3)	Average yearly runoff (Mm^3)	Average annual height of rain (mm)
Mornos Reservoir	586	18.5	630	235	950
Evinos Reservoir	352	3.5	112	278	1000
Yliki Lake	2,460	24.5	584	295	650
Marathon Reservoir	119	2.4	34	14	700
Total			1,360	822	

Groundwater reserves

EYDAP operates 83 fully equipped groundwater wells, which are located along the external raw water aqueduct system. In Table 2, one can see the installed power for the 83 wells, the daily discharge capacity and the safe quantity of perennial water abstraction.

Table 2 The characteristics of the groundwater reserves.

Underground resources	Number of equipped wells	Installed power (HP)	Daily discharge capacity (Mm^3/d)	Safe quantity of perennial water abstraction (Mm^3/yr)
Total	83	19,130	0.57	70 - 125

External aqueduct system

Raw water is brought to Athens via two main aqueduct systems: the Mornos-Evinos aqueduct and the Yliki aqueduct. These primary aqueducts are interconnected with each other, as well as, connected to groundwater wells, through series of secondary and auxiliary aqueducts. The length of aqueducts, are given in Table 3.

Table 3 The length of aqueducts.

Aqueducts	Length (km)
Primary	311
Connecting	105
Auxiliaries	80
Total	496

The Evinos-Mornos Aqueduct system is a gravity flow system with a maximum flow capacity of 20 m^3/sec. It is comprised of 16 tunnels with a total length of about 100 km, 12 inverted siphons with a total length of 7.2 km, and 15 open canals of varying sections, with a total length of 111.7 km. It also has 18 flow regulating structures and five major energy dissipation works. In recent years, EYDAP has also constructed 5 small hydroelectric plants along the Evinos-Mornos aqueduct system with a total yearly energy production of 35.6 GWh. The Yliki aqueduct system operates with the aid of pumping stations with installed power of 70 MW and has a maximum flow capacity of 7.5 m^3/sec. The entire aqueduct system has a length of over 60 km. Tunnels make up for 13.5 km of the system and the rest of the aqueduct is comprised of a combination of open channel sections and pressure pipelines. Along these aqueduct systems EYDAP also provides bulk water supplies to over 15 local municipalities with the help of small water treatment facilities and auxiliary aqueduct systems.

The average yearly yield (measured at the source) of the total raw water resource system is estimated to range from 440 to 570 Mm^3 of water depending on the usage policy of underground water reserves. This average yearly yield ensures proper usage of the water resources and guarantees that they will not be exhausted. Athens has high quality raw water sources, due to the remote mountainous location of its major reservoirs. Only water from the natural lake of Yliki is influenced to a minor degree, by agricultural activities. Water quality at all water sources is closely monitored by EYDAP and far exceeds the limits set by European Union standards.

Water Treatment Plants

Water from all raw water sources is conveyed to EYDAP's four water treatment plants with a maximum combined treatment capacity of over 1.9 Mm^3/d. Table 4 gives the nominal capacity, the maximum capacity and the storage volume of the four treatment plants.

Table 4 The characteristics of the four water treatment plants.

Water treatment plant	Nominal capacity (Mm^3/d)	Maximum capacity (Mm^3/d)	Storage volume (hm^3)
Perissos	0.45	0.60	0.21
Menidi	0.60	0.85	0.28
Kiourka	0.20	0.30	0.06
Mandra	0.20	0.22	0.05
Total	1.45	1.97	0.60

Operational Characteristics and Problem Areas

The raw water supply system is characterized by its complexity, the vast geographic distribution of raw water sources and aqueducts, the great distance between raw water sources and demand centers, the large water losses of the Yliki Lake (due to the carstic limestone lake bed), the high operational cost of the Yliki aqueduct system, the limited flow capacity of portions of the aqueduct system, and the lack of adequate water reserves close to Athens in order to deal with the constant fluctuations of demand.

Under normal conditions with adequate water reserves, EYDAP predominantly uses the Evinos-Mornos system, which operates at a low cost given the gravity flow of the aqueduct. The Yliki and groundwater well system operate seasonally (usually during the summer months) to supplement water demand and to maximize the performance of the external aqueduct system. The Yliki and groundwater system operate at maximum levels, despite the high cost involved with the operation of these resources, only during periods of drought when water reserves of Mornos and Evinos are low. Given the complexity of the system, EYDAP operates the raw water aqueducts with a team of high trained technical personnel and the use of state-of the-art SCADA and Management Information Systems.

Water Resource Management

One of the most challenging aspects of operating this raw water supply system is deciding which water source to use so as to maximize aqueduct performance, ensure long term water resource availability, at the least possible operational cost. Preserving high water quality, minimizing energy usage and environmental issues are also factored in to the operational equation. The water resources management decisions are supported by high level decision support tools, developed by EYDAP in cooperation with the National Technical University of Athens (NTUA, 2002).

The decision support system gives answers to questions regarding: (a) Maximum yield from any given water resources as a function of current meteorological conditions and existing water reserves; (b) water resource management policy decisions to ensure the abstraction of the determined water quantity; (c) the actual and optimum cost of each water resource management policy decision; (d) projections of water resource availability for future periods as a function of historic and current rainfall and inflow data; (e) the future consequences on water resource reserves of a given water resource management decision or the operation of new works; (f) the capability of the raw water system to adequately cover future company expansion; and (g) the consequences of sustained periods of low rainfall on raw water reserves.

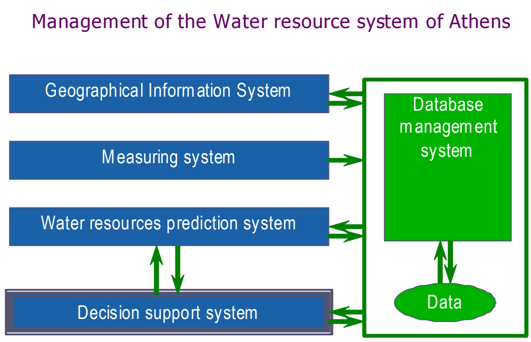

Figure 3 The basic modules of the water resources management decision support system.

Basic modules of the water resources management decision support system

The basic modules are: (a) Geographic Information System (G.I.S.) providing the visual representation of the external aqueduct system; (b) measuring System collecting meteorological and hydrological data (i.e., rainfall, stream inflow, etc.); (c) Water Resource Prediction System which simulates reservoir inflows, evaporation and other losses, and predicts water resource availability; and (d) Decision Support System which takes into account all of the above data and optimizes the performance of the raw water supply system.

Conclusions

The raw water supply system of Athens is exceptionally complex, covers a vast geographical region and requires highly specialized operational procedures. The incorporation of the Evinos reservoir has greatly improved water reserves and increased the potential of the entire system. The danger of severe water shortage has diminished and EYDAP has now focused its energy on the upgrade and the flow capacity increase of the raw water aqueducts and pumping stations. New works are necessary to improve aqueduct reliability and to lower operational costs. EYDAP's experience in high - level operational procedures has led to the development of Decision Support Tools that are presently at the cutting edge of water resource management technology.

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Water Supply of the Cities in Ancient China

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Abstract: Water-supply facilities have a long history in China. Historical records show that the level of development of a city depended highly on sufficiency of water. Past research has shown that highly developed water-supply facilities existed in ancient China, and the prosperous periods in Chinese history all had comprehensive water-supply planning and reasonable choice of water source. This paper introduces and analyzes the highly comprehensive water system planning, water-supply facilities and the evolution of water-supply technology of cities in ancient China. The discussion includes water-supply system consisted of pipeline system and cleaning measures in City of Yangcheng (of Eastern Zhou Dynasty), and the choice of water source and history of water-supply development of ancient Cities of Chang'an (modern Xi'an) and Beijing. The paper also sums up the main methods and achievements in water-supply of cities in ancient China, and the experience that are applicable in modern city planning and water-supply technology.

Keywords Ancient city; city planning; water supply facilities.

Introduction

Water supplies of the cities in ancient times were mainly for satisfying lives, production, navigation, irrigation, landscape, fire control, etc. It was required that water used in daily life and production to have good quality and stable amount. Water for these purposes usually came from wells and springs, or sometimes rivers and lakes. Water used for navigation, irrigation and fire-control purposes had a relatively lower standard. It usually came from developed city water system. City water systems in ancient times were very important facilities that ensured the use of water within the city. They generally consisted of natural rivers, lakes, artificial trenches, channels, pools. Also, pipe systems used for water supply were discovered in archeological excavations.

Water is the bloodline of a city. Development of a city cannot be without water supply for even the tiniest moment. Water shortage is severely problematic for modern city development. As of today, out of about 600 cities in China, the number of cities that have water shortage problems already passed 400. The questions of how to ensure water for development and how to supply water in a sustainable fashion have become global focuses. In a situation like this, looking back to the history of water-supply in ancient times and summarizing the experience of opening water sources in ancient cities would be very meaningful.

Background on Water Supplies of Cities in Ancient Times

Water supply facilities of the city of Yangcheng in eastern Zhou dynasty[1]

City of Yangcheng of Eastern Zhou Dynasty was located in the town of Gaocheng in Dengfeng Prefecture, Henan Province[2]. It was an important western military base of the States of Zheng (in Spring-Autumn Period) and Han (in Warring-States Period). The underground water-supply pipelines were important discoveries in recent archeological excavations. They serve as realistic (opposed to recorded) proofs, which are uncommon, to the research of underground water-supply facilities in ancient China. Since Yangcheng city was built on a slope with relatively higher elevation, for water-supply purposes within the city, jointed clay pipes were installed underground, transferring water into the city from outside. The pipelines were equipped with cleaning pools and valve trenches. This is a relatively complete water-supply system of Eastern Zhou Dynasty discovered so far (An, 1992).

The clay pipelines were installed from north to south, into well-dug sockets in the stone layer. About 500 m of pipelines had already been discovered (Fig. 1), in which a T-shape joint was found every 30~50 m. The south end was connected to a storing pool, which stores the water transferred from the north side (in higher elevation). The storing pool was also dug in the stone layer. The shape was an east-to-west rectangle with large top (opening), small bottom, narrow east side and a broad west side. The four walls were installed neatly in order. The opening of the pool was 14.6 m long, the west end was 4.52 m wide, and the east end was 4.2 m wide. The bottom of the pool was 13.25 m long, the west end was 3.75 m wide, and the east end was 3.25 m wide. The west end of the pool was 2.2 m deep, and the east end was 1.5 m deep. The bottom of the pool was covered by pebbles with diameters of 0.4~0.5 m (Fig. 2). The pebbles might be used for sediments in the water to precipitate. The pebbles were installed in lines, with about 6~12 cm of space in between each line.

Figure 1 Water-supply pipelines of Yangcheng (Yang, 1985).

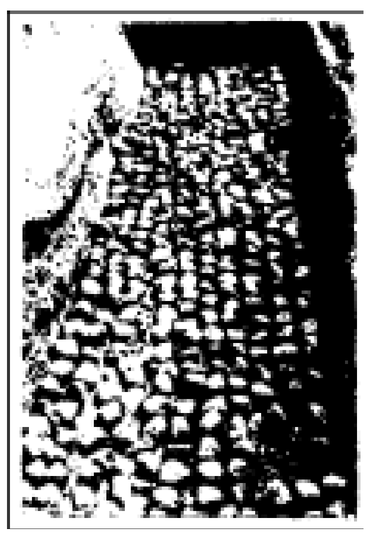

Figure 2 Storing pool of Yangcheng (Yang, 1985).

[1] Refer to Appendix I for a table of the dynasties and their corresponding years (in B.C. and A.D.).
[2] Refer to Appendix II for a map of the provinces of modern China.

In the bottom of the center of the eastern wall of the storing pool, there was a small culvert on the slope, with a length of 3.8 m. The west mouth of the culvert was 0.4 m higher than the east mouth. The height of the culvert was 0.21~0.98 m, the width of the bottom of the culvert was 0.2~0.7 m. At the bottom of the culvert, 11 joints of clay pipelines were installed from the storing pool towards the east, each joint was broad on one end and narrow on the other end, 0.6 m long. The broad end had a diameter of 0.17~0.18 m, and the narrow end had a diameter of 0.13~0.14 m. The thickness of the pipeline was about 2~3 cm. At the joints, narrow ends are installed into broad to about 4~6 cm. Since the purpose of the pipelines in the culvert was transferring water to the east, all the joints were set in the same direction: broad end heading west, narrow end heading east (Yang, 1985).

Next to the east end of the culvert there was a "valve trench." (Fig. 3) This was made by digging a lateral square trench and a lateral circular trench in the stone layer. The square trench was at the west side. Its each side was 1.35 m, and it was 1.7 m deep. The circular trench was at the east side. Its diameter was 1.1 m, and it was 1.85 m deep. The pipelines from the culvert extended to where the two trenches connect. There were obvious marks left from grinding and colliding, meaning this opening might be used to release water and block water with something (which created the marks). This explains that the two trenches might be used when blocking and releasing water, similar to modern tap water valves.

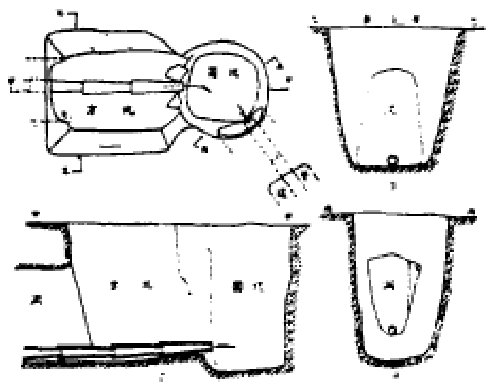

Figure 3 The "valve trench" (Henan Province Artifacts Research Institute, 1982).

Under the southeastern side of the valve trench, there was a 0.7 m long, 1.03 m high, 0.3~0.54 m wide arch-shaped culvert dug towards southeast. Connecting to the culvert, continue going southeast, there was an exposed trench that was 0.25~0.6 m wide at top, 0.25~0.35 m wide at bottom, 0.14~1.76 m deep. The bottom parts of the culvert and the trench were both installed with jointed pipelines. After the pipelines were installed, the trench was covered by soil and the pipelines became underground pipelines. 61 joints of this section of pipelines have been discovered, with 32.6 m remaining underground (Henan Province Artifacts Research Institute, 1982). The entire water-supply system of Yangcheng was reasonably planned and cleverly designed. It is important realistic information for the research of water-supply of cities in ancient China.

Rise and fall of the water source in Chang'an

In 206 B.C., Liu Bang established the Han Dynasty and name Chang'an the capital city. Chang'an of Han was located at the northwestern side of modern city of Xi'an. The city was in Guanzhong Plain with Weihe River crossing the north side. With the tributaries of Weihe

River covers most of the city, at the time it was said that “Chang’an was surrounded by eight waters (rivers)”. At the south of Chang’an, there was the prosperous Ba and Shu (modern Sichuan Province); at the north of Chang’an, there were the profits from foreign tribes. The defense of the surroundings had always been strong (Wu, 1995). Therefore many dynasties named Chang’an the capital. From Western Zhou Dynasty to Tang Dynasty, a total of 10 dynasties named Chang’an the capital in a 1062-year span (Dong, 1988).City of Chang’an in Han Dynasty was established on the base of the palaces of Qin Dynasty. The old palace-wide water-supply system was put in use. In the beginning years of Han Dynasty, water-supply in Chang’an was adequate. Wu Emperor (7th emperor of Han) rapidly expand the size of the capital. Water-supply then became insufficient. Therefore the Kunming Reservoir was dug. For a long time, the purpose of Kunming Reservoir was said to be for military training for upcoming battles against the Kunming State in Yunnan. In fact, the main purpose of the reservoir was to serve as a source of water in Chang’an (Liu, 1988).

Huang (1958) made a map of water-transfer channels of Chang’an in Han Dynasty (Fig. 4) after a series of research. He also deeply investigated the city water system. The water in Kunming reservoir originated from Jiaoshui River. *The Book of Water (Annotation)* recorded that there was a stone tablet built at the point where Jiaoshui River enters Kunming Reservoir. The purpose of the tablet was for blocking/transferring water into the reservoir. In flood season, extra water from Jiaoshui River could flow over the tablet into Fengshui River, thus protecting Kunming Reservoir from the flood. Kunming Reservoir supplied water to downstream through channels in the east side and the north side. The one in the east was called Old Kunming Channel, built specifically for supplying water to canals. The one in the north was called Kunming Reservoir Water, built specifically for supplying water within the city. There was another adjusting reservoir connected to Kunming Reservoir Water before it enters the city. The water was divided into two distributaries after this: one to the north into the palace heading for Weihe River, one to the northeast into the city (Xiong and Guo, 1989).

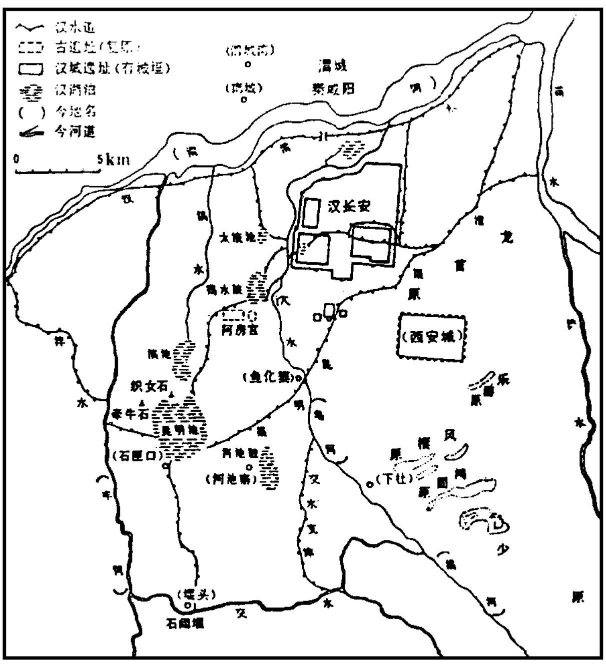

Figure 4 Map of channels around Chang’an in Han Dynasty (Huang, 1958).

Wu (1995) gave an approximate figure of the capacity of Kunming Reservoir at 35.497 Mm^3, which is equivalent to a medium-size modern reservoir. Kunming Reservoir and it channels ensures water-supply in Chang'an for the rest of the Han Dynasty. At the end of Han Dynasty, Chang'an was severely damaged due to numerous civil wars. The channels were also destroyed. Water in the city was not suitable for drinking due to salinization. This was one of the key reasons that Sui and Tang Dynasties went seeking new locations for the capital. The north and east sides of the new capital were surrounded by rivers. The selection of location was closely related to water source. Water source of the new capital and the city development was planned simultaneously. City of Daxing[3] was built in 583 A.D., and at the about same time, three channels-Longshou, Yong'an, Qingming-were built and put in use. These channels solved the problem of city water-supply.

At the end of Tang Dynasty, a powerful warlord named Zhu Quanzhong forced the emperor to move the capital to Luoyang (in Henan Province). Chang'an was again rampaged in a series of civil wars. Although the following dynasties all had put effort to restore the city, the size of Chang'an never reach even 1/6 of the original size during Tang Dynasty. The water-transfer systems from Sui and Tang Dynasties were all ruined, and the channels were mostly abandoned. Wells became the only source of drinking water within the city. In 1014 A.D., Longshou channel was restored to transfer due to severe salinazaion of well water. The channel was in use until the end of Jin Dynasty, when it was again abandoned. During 1264~1294 A.D., Longshou channel was repaired twice to supply water for the entire city. It was abandoned again in mid-Yuan Dynasty. At the beginning of Ming Dynasty, Longshou channel was again restored due to salinization of well water. Yong'an and Qingming channels were never used after Tang Dynasty, and were replaced by Tongji channel, built in 1465 A.D. Most of the channels outside of the city were the old channels from Tang Dynasties. From then on, east side of the city relied on Longshou channel, and west side relied on Tongji channel. The two channels supplied water for the entire Chang'an. Hundreds of years later, Qianlong emperor built the modern Xi'an City, and the two channels were abandoned since then (Huang, 1958).

The water source of Chang'an is summarized as above. Building channels to transfer water into the city and establishing fluent city water system not only supplied water to the city, but also satisfied the needs of navigation, fire-control, landscape, defense, drainage, etc. This is important experience from water-supply of cities in ancient times.

History of water supply in Beijing

The City of Beijing has a long history. In the Warring-States Period, it was then called Ji, which was the capital of Yan State. From Qin Dynasty to Tang Dynasty, Ji had always been an important military base and capital of feudal states and prefectures. In 936 A.D., Taizong Emperor of Liao Dynasty(The Kitan Empire) named Ji the second-capital of the empire and then rename it Nanjing (Southern Capital) or Yanjing. In 1153 A.D., Jin Dyanasty (The Jurchen Empire) moved its capital to Yanjing and renamed it Zhongdu (Central Capital). Since then, Beijing became center of power of Imperial China for more than 700 years (Chen, 1991).

According to *The Book of Water*, the first effort put into solving water source problem was made in the Three-Kingdom Period. A general of Wei Kingdom named Liu Jing transferred water from Yongding River into City of Ji for irrigation purposes (Cai, 1987).

[3] Daxing is the name of capital of Sui Dynasty; the name "Chang'an" was again used in Tang Dynasty.

Although this was a simple agricultural project for food supply of military, it had great impact on upcoming water source problems in Beijing.

Before Yuan Dynasty (The Mongol Empire), the city of Beijing was close to Lianhua (Lotus) Reservoir watershed. Sources of water in the city were wells and transferring surface water from Lianhua Reservoir. Lianhua Reservoir was originally an underground spring and was called Xi Hu (the West Lake) (Duan, 1989). According to *The Book of Water (Annotation)*, the flow from the east side of the reservoir was Xima channel and enters Ji city from the south gate (of City of Ji in Northern Wei Dynasty). After Jin Dynasty moved its capital here, Xima channel was planned as part of the city, crossing the imperial palace. It became an important water source in the palace (Fig. 5) (Hou, 1979). City of Zhongdu expanded rapidly and the population reached one million. Need of water increased rapidly with population, and Lianhua Reservoir quickly became insufficient. Xishan Spring extraction was started to solve the problem. Cai (1987) analyzed that during Jin Dynasty, there might be channels located upstream of Lianhua Reservoir that transferred water from Xishan.

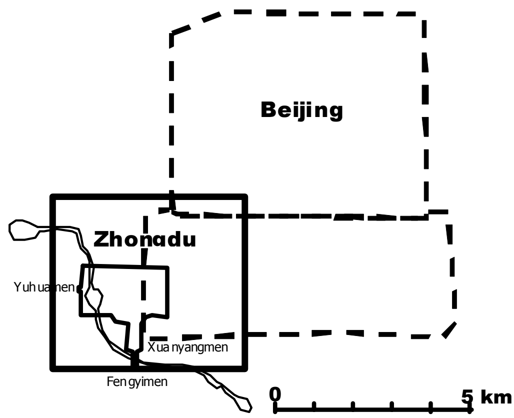

Figure 5 Channels into the palace of Zhongdu (Hou, 1979).

The capital of Yuan Dynasty, Dadu (Great Capital), was located northeast to Zhongdu, moving from Lianhua Reservoir watershed to Gaoliang River watershed. The reason of moving was that Zhongdu was severely damaged in times of war, and the palaces were in ruins. The other, and an more important reason was for abundant water resource (Chen, 1991). Since then, under the clever design of Liu Bingzhong and his pupil, Guo Shoujing, The construction of Dadu was completed in 1285 A.D., spending 18 years. The selection of location for Dadu was closely related to water-supply and transportation purposes. Gaoliang River watershed could provide much greater amount of water than Lianhua Reservoir watershed. Also, water from Baifu and Xishan Springs was transferred into Gaoliang River few years later. Water-supply and water-transport needs were met.

Jinshui River outside of Dadu was dug in Yuan Dynasty. It collects spring water from Yuquan Mountain and entered the city through Heyimen Gate (now Xizhimen). This water specifically served the imperial palace. For controlling the quality, no mixing with other water source was allowed. Independent troughs were bridged where Jinshui River must cross other channels. According to legal documents from Yuan Dynasty, bathing, washing, dumping and livestock drinking were all prohibited. Navigation canal was also constructed in Zhongdu in Jin Dynasty. But because water source could not be guaranteed, the canal was not effective. In Yuan Dynasty, Baifu Spring water was transferred to fill the canal. The entire project was completed in 1292 A.D. Cargo ships and boats can directly enter the city through the canal. The canal was named Tonghui River, and is still in use. Baifu Spring water transfer project was one of the most innovative solutions to water source problems in the history of Beijing (Hou, 1979).

In Ming Dynasty, the canal stopped flowing due to lack or repair. In Early Ming, reconstruction of Beijing damaged the old canal system. The old canals were planned as part of the imperial palace (Forbidden City), therefore cargo ships were never be able to enter the city (Fig. 6). The palace-only channel, Jinshui River, was also abandoned. There were efforts made to restore Tonghui River channel in Ming Dynasty, but none of them were effective due to lack of water source (Zheng, 1985). Water-supply in the city could only rely on spring water from Yuquan Mountain. Spring water was collected at Wengshan Lake (now Kunming Lake) and transferred into Jishuitan Reservoir within the city. Then the water was divided into two distributaries: one into Forbidden City, and one into Tonghui River (canal). Therefore, the water supplied within Ming imperial palace was no different from water used in the canal. This was very different from the scenario in Jin and Yuan Dynasties. But the situation remained unchanged since then (Hou, 1979).

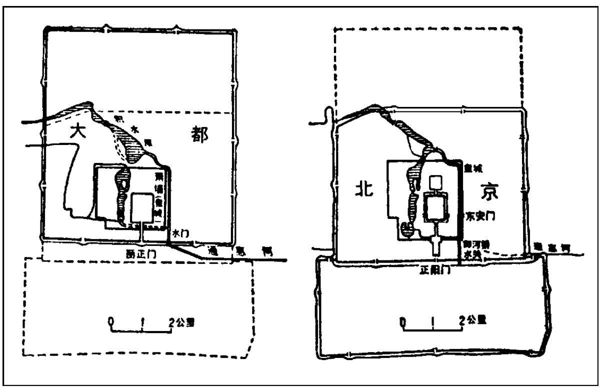

Figure 6 A comparison of Dadu (left) and Ming-Dynasty Beijing (right) (Hou, 1979).

Water channels in Beijing in Qing Dynasty were mainly old channels left from Ming Dynasty. During Kangxi Reign (1662~1722), Tonghui River was used for transportation purposes. A channel at the east side of Beijing was opened for small cargo ships to enter the city. But lack of water source was still the main problem for transportation. In Qianlong Reign (1736~1795), the government finally decided to manage the water channels at the west of Beijing for landscape and transportation purposes. The first step was to utilize Wengshan Mountain as a site for landscape garden. Second, deepening Wengshan Lake, construct a levee at the east side to block streamflow from Yuquan Mountain, thus creating a much larger lake-modern Kunming Lake. Wengshan Mountain then was renamed Wanshoushan Mountain. The east levee significantly raises the water level and the capacity of Kunming Lake, making Kunming Lake the first artificial reservoir of Beijing. Situation regarding water source was much improved since then (Zheng, 1985).

Within City of Beijing, citizens had been using wells to draw groundwater for daily life uses for generations. The alleys in Beijing are called "hutong," meaning "well" in Mongolian. In Dadu of Yuan Dynasty, the wells were dug in the alleys, and the alleys were named after the wells. Therefore "hutong" has the meaning of "alley." City of Beijing was reconstructed in Ming and Qing Dynasty. Many hutongs were left without a well. According to contemporary records from Yuan, Ming and Qing Dynasties, water quality in the wells had been low due to salinization. Low water quality led to two results: water was supplied in three levels of quality (washing, cooking, drinking), and selling water became a profession in Beijing (Duan, 1989).

Main Methods of Water Supply of Cities in Ancient China

From the rise and fall of water source of Xi'an (Chang'an) and Beijing in history, it can be concluded that rise and fall of a city is closely related to water supply. The movements of two ancient capitals were both related to lack of water source and to seek new water source. From water-supply of cities in ancient China, one can gain precious experience and information for modern city planning and development. Main methods of water-supply of cities in ancient China can be summarized as follows.

Drawing water from wells

Drawing water from wells was an important method of water-supply in ancient China. Under the sanitation conditions in ancient China, even if there are multiple sources of water in a city, well water was always the top choice for drinking water for its stable quality. The first well found in archeological research in China was located in Hemudu Ruins (in Zhejiang Province), built approximately 5,700 years ago. The well was made by more than 200 circular wood pillars, and had a simple pavilion structure. This was a comprehensive wooden well structure. History of wells in Central Plains of China began about 4,000 years ago. Although it began later than the south, but in terms of technology, the north was ahead. The ancient wells in Central Plains have larger diameter and a deeper bottom. For example, two wells found in Handan, Henan Province were 2.1 m wide (in diameter) and 7.7 m deep; a well found in Xiangfen, Shanxi Province was more than 3 m wide and about 13~15 m deep (Fang, 1986).

In Xia, Shang and Zhou Dynasties, the use of wells was very common. The wells were mainly made of soil, such as Shang-Dynasty wells found in Yanshi and Zhengzhou of Henan Province. By Eastern Zhou Dynasty, use of wells grew even more. At some places the wells were densely distributed. For example, in Jinan Ruins in Hubei Province, in a 1,000 x 60 m^2 area, 256 wells were present; in Ji City Ruins (southwest of modern Beijing), concentration of wells was as high as 4 wells in 6 m^2. During Eastern Zhou Dynasty, wells were mostly made of clay. Well technology had also much improved. Since Qin and Han Dynasties, wells and city development had been more closely related. Besides soil and clay, bricks and rocks were used to build wells. Ancient wells still can be found in many of the cities in China today.

Transferring water through canals

Ancient cities usually follows the rule "stay away from dry lands at high elevation; stay away from water at low elevation." Considering the geographical and flooding conditions, the cities could not be built too close to water. Therefore canals must be built to transfer water into the cities. For example, Longshou channel of Chang'an, Jinshui River of Dadu, etc. Another well-known example was Jinshui River Project in Chengdu (Capital of Sichuan Province) in Tang Dynasty. The project transferred water from Minjiang River. Water entered the city from the west, crossed the entire city, and made water-use convenient for the citizens. According to historical documents, Chengdu citizens used Jinshui River water to bath, drink, irrigate, wash, etc. Jinshui River in Chengdu was repaired and harnessed in every dynasty after Tang, and was still effective after 1949 (Xiong and Guo, 1989).

Storing water by building dams

Building dams and levees to block and store water in rivers and form large capacity reservoirs was an important method for solving problems regarding city water source. Kunming Reservoir of Chang'an of Han Dynasty, Qianjinjie Reservoir of Luoyang of Han and Jin Dynasties, West Lake of Hangzhou of Tang and Song Dynasties, and Kunming Lake of Beijing of Qing Dynasty were all well-known examples. Other than these, some cities artificially dug large pools to store water from springs or rivers and used it as a supplemental source of water, such as Daming Lake in Jinan, Shandong Province. Reservoirs could not only serve as sources of water, but also manage floods and be effective in flood defence.

Delivering water by wagons

No matter how developed the city water systems were in ancient China, modern tap water pipeline networks were impossible to achieve back then. A well in each household was also an impossible scenario. Therefore selling and delivering water became a profession. This is an important supplemental method of water-supply in cities, especially when canals were abandoned in certain times in history. In Ming and Qing Dynasties, although Jinshui River was abandoned, the imperial palace still used spring water from Yuquan Mountain. Spring water was carried by royal water wagons and delivered to Forbidden City. This showed how important that water wagons were in water-supply of cities in Ancient China.

Methods that guaranteed water quality

Quality of drinking water can directly influence the users' health. For this reason, people in every dynasty have paid attention to maintain water quality. Independent troughs bridged in Jinshui River canal of Dadu mentioned before was an example of maintaining water quality. This method was widely used in ancient China. Generally, water was used without any treatment because water sources were usually protected from pollution. In some cities that water at the sources was muddy in the first place, "purifying troughs" (similar to modern deposition pools) were built to purify the water. For example, In Northern Song Dynasty, Jinshui River of Chengdu was equipped with purifying troughs for sediments to deposit before the water entered the city. Also, large amount of sediments were present in water in some areas. Residents of these areas knew that stirring after putting alum in water can quickly purify the water. This is the same mechanism as modern coagulation process.

Conclusion

The main experience from water-supply in ancient cities is to discover and open new water sources according to geography of the place. From examples of Xi'an and Beijing, it can be concluded that as long as the problem regarding water source was solved, city development would be rapid and smooth. On the other hand, if the problem could not be solved, then development would be limited. Methods and facilities of water-supply and controlling water quality in the cities of ancient China were significant achievements, which are worthwhile for us to learn and use as reference in modern city planning.

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[4] "Chubanshe" is the Chinese phrase for "Press."

[5] "Jianghan" refers to modern Hubei Province.

Appendix I Table of Dynasties and Periods.

Dynasties/Periods	**Years**
Prehistoric Times	1.7 million years ~ the 21st century B.C.
Xia (Hsia)	21st ~ 16th century B.C.
Shang	16th ~ 11th century B.C.
Zhou (Chou)	Western Zhou (11th century B.C. ~ 771 B.C.) Eastern Zhou - Spring and Autumn Period (770 B.C. ~ 476 B.C.) - Warring-States Period (476 B.C. ~ 221 B.C.)
Qin (Chin)	221 B.C. ~ 206 B.C.
Han	Western Han (206 B.C. ~ 24 A.D.) Eastern Han (25 ~ 220)
Three Kingdoms Period	Wei (220 ~ 265) Shu Han (221 ~ 263) Wu (229 ~ 280)
Jin (Tsin)	Western Jin (265 ~ 316) Eastern Jin (317 ~ 420)
Northern and Southern Dynasties	Northern Dynasties - Northern Wei (386 ~ 534) - Eastern Wei (534 ~ 550) - Western Wei (535 ~ 556) - Northern Qi (550 ~ 577) - Northern Zhou (557 ~ 581) Southern Dynasties - Song (420 ~ 479) - Qi (479 ~ 502) - Liang (502 ~ 557) - Chen (557 ~ 589)
Sui	581 ~ 618
Tang	618 ~ 907
Five Dynasties and Ten States	Five Dynasties - Later Liang (907 ~ 923) - Later Tang (923 ~ 936) - Later Jin (936 ~ 946) - Later Han (947 ~ 951) - Later Zhou (951 ~ 960) Ten States (902 ~ 979)
Song (Sung)	Northern Song (960 ~ 1127) Southern Song (1127 ~ 1279)
Liao (Kitan Empire)	916 ~ 1125
Jin (Kin) (Jurchen Empire)	1115 ~ 1234
Yuan (Mongol Empire)	1271 ~ 1368
Ming	1368 ~ 1644
Qing (Ching) (Manchu Empire)	1644 ~ 1911
Republic of China	1912 ~ 1949
People's Republic of China	1949 ~ Present

Appendix II Map of Chinese Provinces.

Iran: Past Progressive Civilization in Water Management and Supply

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Abstract: Iran is one of the ancient civilizations with a rich history regarding management of water resources in the world. Because of the dry condition, low precipitation and insufficiency of water, there was development of various techniques in water supply and different organizations in water management. Some of the techniques for surface water management included dam and reservoir construction, named “band”, irrigation methods and networks, and water harvesting systems, such as “ab-anbar”, etc. Techniques for groundwater utilization were also numerous. They consisted of drilling wells, inventing the “Qanat”, “Kii”, etc. The traditional organizations concerning with water management were named “Boneh”, “Haraseh”, “Sahra”, “Khish”, etc. and were established for managing surface and ground water by approving local regulations about water utilization for humans, agriculture or livestock. The main aim of this paper is to describe some of these traditional techniques of water management and supply in Iran.

Keywords Arid region; Iran; water scarcity.

Introduction

For thousands of years, water shortage has been the most important problem in Iran. Iran is Located on the arid belt of the world with an average precipitation of about 240 mm/yr, i.e., approximately one third of the world average precipitation of 840 mm per year (Ahmadi, 1995). Additionally, this amount of precipitation is not uniform spatially or temporally and there is high variation among different regions of the country, such as the Anzali region with over 2,000 mm and Yazd with less than 50 mm/yr. Moreover, except the northern and western country strips (north of Alborz and west of Zagros Mountains) which have enough precipitation, eastern and central parts of Iran have a long dry season during a year (Mahdavi, 1998). In these regions there isn’t enough water for humans, agriculture and livestock uses, which forced the population to mange and use the available amounts very cautiously. The genius inhabitants of these regions developed several efficient approaches to gain, supply and use water since 3,000 to 5,000 year ago (Kardavani, 1988). Some of these approaches, such as “Qanat”, were exported form Iran to other countries. As a result, water and its scarcity constitute an important aspect of the Iranian culture and history. Water has been present in all aspects of human life of the Iranian whose beliefs, customs and ceremonies are linked to water. The objective of this paper is to review the ancient water management systems and the attempts of past people to gain, supply and use of water in Iran.

Iran as an Arid Country

Iran is located approximately between 25° to 45° N, and 44° to 64° E. Because of specific geographic and topographic conditions most part of Iran have arid and semi-arid climate. The extensive central part of Iran has the precipitation of less than 100mm per year and the average amount of precipitation in Iran is about 240 mm/yr. Average amount of evaporation in arid regions of Iran is over than 5,000 mm/yr. In semi-arid regions humid season is about January to April and dry season is about May to December, though in arid regions the dry season is longer than it. Except the northern and western parts of Iran, there are only a few perennial rivers in eastern and central parts of country, and most of rivers are temporal. In these rivers there is no flow at dry seasons that may include 6 to 10 months of year. In these regions precipitation mostly has high variation spatially and temporally, which often occurs during the intense heavy rainfalls in one or a few days during the year, that cause to flood and destruction of natural resources and human constructions. These temporal rivers finally enter to saline areas, lakes and marshes as low quality and unusable water. Growth of population and demand for water has accelerated desertification and land degradation and has led to destruction of water resources and deterioration its quality in recent decades. Some problems in arid regions regarding to water scarcity include depletion of water table because of excessive withdrawal of groundwater from aquifers, increase of water and soil salinity levels due to over exploitation of deep wells and desertification, and increase in disease. But how the past humans combat with these problems?

Water Resources in Iran

According to available information total amount of precipitation of Iran is about 400 billions m^3/yr, which 320 billions m^3 occur in mountains and 80 billions m^3 occur in plains. Major part of this water is unusable and flow over land and reaches to Persian Golf in south, Caspian Sea in north and interior lakes and saline playas and evaporates from dams and lakes. With regard to problems such as water shortage, drought and salinity, people from olden times have attempted to adapt with difficulties of life in arid regions by inventing some techniques and establishing some managing systems for water dividing all over the country. Techniques which applied in different regions were nearly similar such as Qanat (kariz) system, water reservoir, icehouse, water mill, water dam, bridge, etc. Although traditional water resources managing systems were basically alike, there were some differences among terms, rules and approaches in ancient communities in different parts of Iran. Some of these systems were named as Boneh, Haraseh, Sahra, Khish, and so many local terms such these. These systems were linked to water and land management (Safinezhad, 1989).

Techniques for Water Resources Management

Surface water management

There were some techniques for surface water managing in ancient times in Iran that have been invented to combat water scarcity. Most of these techniques were developed based on gathering and supplying water at humid season or at rainfall, rainstorm or snow occurrence. In arid regions a few rainfalls may happen during a year and because of difficult conditions, such as high temperature that cause evaporation, salinization and contamination, it is essential that this limit water gather and supply for humans, irrigation, and livestock uses.

Some of gathering and supplying techniques that have been used since antiquary times introduce as below:

(a) Dam construction. Dam which has been called as “BAND” in Persian is a construction that prevents or regulates water flow in a river and causes to reserve water for use in dry seasons. According to available documents Iran is one of the pioneer ancient civilizations in dam construction (Fig. 1). There are some old small and big dams or their relics in well selected valleys in different parts of Iran that show high ability of predecessors in this field (Kardavani, 1988). Some of these antiquary dams are consist of: (i) Bahman dam or “Band-e-Bahman”; in south part of Iran, Fars province, that has been constructed about 2,000 years ago in Achaemenian era; (ii) Amir dam or “Band-e-Amir”; in the north east of Shiraz, Fars province, which has been constructed on the “Kor” river about 1,000 years ago; (iii) Sāveh dam or “Band-e-Saveh”; in the central part of Iran, north of the Markazi province that has been built at about 700 years ago in Ilkhanian era; and (iv) Farimān dam or “Band-e-Fariman”; in the north east of Iran, Khorasan province, which has been constructed about 1,000 years ago.

Figure 1 Pictures from four ancient Dam in Iran (www.soil-water.com).

(b) Āb-Anbār. In arid and semi-arid regions because of high temperature in dry seasons that occur in 6 to 10 months of a year, amount of evaporation is very high. As a result reducing the evaporation from water surface is very important to supply water in reservoirs or pounds. One of the oldest techniques to preserve surface or ground water that has been using in arid and semi-arid regions of Iran is a domical house which is built over a reservoir or pound in a specific place of a desert or near the residential areas (Fig. 2). This construction reduces the evaporation strongly and the water remains there for a long time. This water often is used for drinking and livestock (www.soil-water.com).

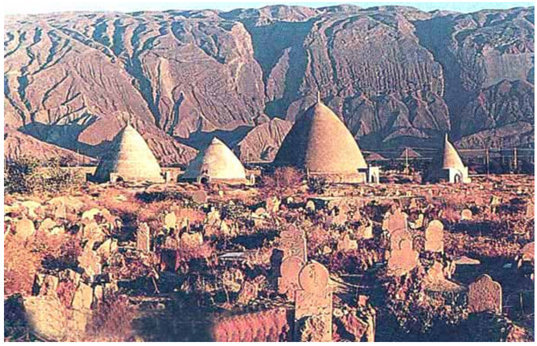

Figure 2 Āb-Anbār in arid regions of Iran (www.soil-water.com).

(c) Reservoire. In arid and semi-arid regions there are many temporal rivers that are often dry and water flow is limited to few days during the year. These rivers reach to saline plains or enter to saline marsh lands commonly and would be unusable. From olden times farmers have made the reservoirs using simple traditional tools to store water and use it for irrigation or livestock (Safinezhad, 1989).

(d) Band Sār. One of the antiquarian ways to use ephemeral flood water in arid and semi-arid regions of Iran was building a diversion barrier opposite the flood flow that named as "BAND SĀR". This construction conduct water into arable lands and using this water farmers have been planted various crops such cotton, watermelon, and grape in this lands. At present with regard to some problems of this method, construction of "BAND SĀR" is limited to some parts of Iran as complementary irrigation in farm lands. However this method has some advantages, for example farmers use the sediments of the flood water as fertiliser in farm lands to enrich soil with minerals (Kardavani, 1988).

(e) Bridge. There are a lot of bridges throughout Iran. Some of these bridges are technically noticeable because of their specific design. These bridges have been constructed for multi purpose such as regulating the river flow when a flood occurred, control the velocity and volume of water and reduce turbulence of river, addition to main object of its construction to pass across the river. Tow famous bridges in Iran are "Si-o-se Pol" and "Pol-e-Khaju" in Isfahan, over the "Zayandeh Rud" river, which have been designed by "Shekh Bahaei", the well-known Iranian architect, about 400 years ago in "Safavieh" era (Fig. 3).

Figure 3 Ancient "Si-O-Se Pol" bridge in Isfahan.

Ground water management

Iran is one of the ancient pioneer civilizations in ground water management and utilization. There are some miscellaneous techniques which have been invented and developed during the time. Some of these techniques such "Qanat" system spread throughout the world from Iran. Because of arid climate and shortage of surface water in arid and semi-arid regions, ground water has been had an important role in humans life of Iranian. Some of techniques in ground water exploitation are describe as below:

Qanat system. Qanat system is the masterpiece of ancient Iranian people in ground water utilization since about 3,000 to 5,000 years ago (Ministry of Energy, 1975; Behnia, 1981; Kardavani, 1988). Lightfoot (1996) defines Qanat as "a form of subterranean aqueduct or subsurface canal engineered to collect groundwater and direct it through a gently sloping underground conduit to surface canals which provide water to agricultural fields." A Qanat system is consisted of an underground tunnel, a master or mother well, some vertical shafts, and a storage pond at its out let (Fig. 4). According to available evidences and literatures, this technology spread throughout the world from Iran, and it is documented that Qanat system exists and applies in over than 34 countries (Behnia, 1981). Qanat has been spread toward Nineveh about the 7th century B.C.; during the period 550-331 B.C., concurrent to extensive Achaemenian Empire in Iran (Persia) that was extended from the Indus to the Nile (India, Pakistan, UA Emirates, Bahrain, Iraq, Palestine, and Turkey), Qanat diffuse over this empire. To the west, Qanats were extended from Mesopotamia to the shores of the Mediterranean, as well as southward into parts of Egypt, Tunisia, Sahara, Morocco, Libya, and Algeria. To the east of Iran (Persia), Qanat spread toward Afghanistan, the Silk Route oasis settlements of central Asia, and Chinese Turkistan (i.e., Turpan). During Roman-Byzantine era (64 B.C. to 660 A.D.), Qanat system were expanded to Syria and Jordan, and then spread toward Europe, Luxembourg, North Africa and Cyprus, Sicily, Spain, the Canary Islands, Spain, Germany, France, England, and Czechoslovakia and even western Mexico, in the Atacama regions of Peru, and Chile at Nazca and Pica, and north of America at Hawaii Islands and southern California (Behnia, 1981; www.waterhistory.com).

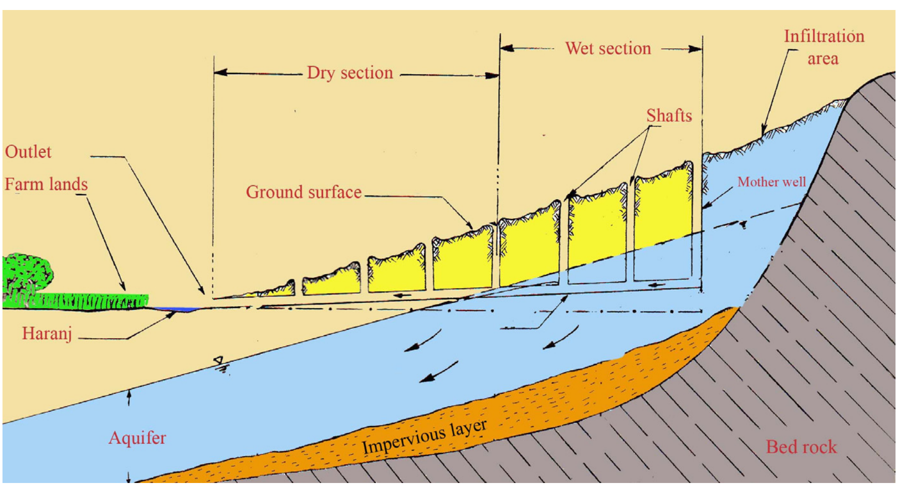

Figure 4 General cross section of a Qanat.

Qanat system has been called as various names in different regions such Qunat, Qonant, Khanat, Kariz, Karez, Falaj, Afalaj, etc. (Behnia, 1981). There are about 32,500 Qanats with the discharge about 7.5 billion m^3/yr (www.iranhydrology.com), although there were over than 50000 Qanats in the past, but most of them have been out of use during the time. At present it seems that some of damaged Qanats have been repaired and renovated (Kardavani, 1988). Difficulties in maintenance and cleaning of Qanat and socio-economic problems, threat Qanat sustainability on the long term (Wessels and Hoogeveen, 2001). Some of the well-known Qanats in different regions of Iran are introduced as below: (i) Zavareh Qanat, with 350 m depth of master well, dating back to about 5,000 years ago (www.destinationiran.com); (ii) Bidokht Qanat, in Gonabad region with 2,500 years oldness, with 350 m depth of mother well, and discharge of 150 L/sec (Behnia, 1981); (c) Keykhosro Qanat, in Bejestan region with 70 km long of under ground tunnel and 400m depth of master well (Behnia, 1981); (d) Kerman Qanat, in Kerman region with 40km long of under ground tunnel, discharge of 20 L/sec and 120 m depth of master well (Safinezhad, 1978); (e) Chogha Zanbil Qanat and water refinery installation with antiquity of at least 3,250 years (www.destinationiran.com); (f) Sadr-Abad Qanat, in Yazd province with 70 km length (Behnia, 1981); (g) Shahrud Qanat, in Semnan province with depth of 60m in mother well and discharge of 250 L/sec (Behnia, 1981); and (h) Arvaneh Qanat and tow floor Mun Qanat in Isfahan province (Behnia, 1981).

Kii System. Kii system in not famous as well as Qanat, although it seems that be older than Qanat system. Kii has been constructed for irrigation purpose in central parts of Iran, around the Isfahan region, in areas that the water table was near the ground surface, about 1 m depth. In this area farmers have begun to excavate the lower parts of the ground horizontally toward the higher parts as an open channel until they have reached to water table; then they have enlarged this channel to a suitable size. Finally the main hole of Kii has been expanded and deepened sufficiently in order to supply enough volume of water. Ground water, flow within this channel and convey to irrigation area, because the level of water table is near the surface. Although construction of this system is simple and quick, it has very important limitations that cause to abolish kii system in recent times. Problems such as drought and constructing of wells that lead to depletion of water table, maintenance difficulties, and high evaporation from water surface in open channel limit the efficiency of this system. Nowadays, using new techniques to improve Kii efficiency, this system can be used as a cost-effective approach to ground water exploitation (Kardavani, 1988).

Well excavation. Well excavation is an old way to water exploitation all over the world. Well is defined as “any artificial excavation constructed for the purpose of exploring for or producing ground water” (www.edwardsaquifer.net). For thousands years, in arid and semi-arid regions, shallow wells have been dug by simple means to access and use groundwater (Fig. 5). These wells have been used for irrigation, human, and livestock. Wells for human were very important in desert areas. Many oasis, ancient roads and caravanserais have been constructed near the water resources such as wells. At present, there are a lot of shallow and deep wells throughout of Iran which provide about 30 billion m^3/yr (www.moe.ir).

Springs. Spring is defined as “a place where ground water flows naturally from a rock or the soil into the land surface or into a body of surface water, which its occurrence depends on the nature and relationship of rocks, especially permeable and impermeable strata, on the position of the water table, and on the topography” (www.edwardsauifer.net). There are about 20,000 springs in Iran that provide over than 6.5 billion m^3/yr. Some of these springs are more famous than other because of their water yield, position, or their history such as Bagh-e-fin spring in Kashan region, Shahmirzad spring in Semnan province, and Tagh-e-bostan spring in Kermanshah province. Springs water use mainly for human, livestock and irrigation. Some problems which restrict utilization of springs are tectonic (earthquakes), drought, contamination, and their salinity in desert areas. However springs provide a significant part of high quality usable water yearly and it is essential that more efforts be done to improve management of springs and prevent them from contamination by roofing and pipe-laying their water to villages and towns (Kardavani, 1988).

Figure 5 Women are taking up water from a well.

Tillage on water table. Ancient inhabitants of arid deserts in central parts of Iran such as Kashan region have invented an efficient way to till some crops over the sandy areas and sand domes. In these areas water table is near the ground surface. Ancient inhabitants of deserts found that they can reach to water table by digging a shallow hole and plant some crops such water-melon there. Seeds that planted near the water table, utilize groundwater to grow. Growing small plant, farmer fills the hole with sands and organic manure until the plant grow completely and the hole fill up. In this method the plant only uses groundwater during the growing stages and don't need to irrigating at all. This method is very useful in desert areas which use from ground water for tillage in unsuitable conditions, which intelligently invented by deserts ancient residents since thousands years ago (Kardavani, 1988).

Conclusion

Iran history is corresponding to water history; Iranian settlements have been exposed to water scarcity during the time. Hence they have adapted to this problem by inventing some techniques and establishing some water managing systems that are single in kind, creative, intelligently, and artistic which some of these techniques spread throughout the world. An Iranian (Persian) proverb says: "need is the mother of invention".

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Fragments from History of Water Supply for Bratislava, the Capital of Slovakia

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Abstract: This paper describes the development of water supply in Bratislava city, Slovakia, which is closely associated with its history. The oldest well which was found at the historical centre of Bratislava is dated back to the Iron Age. The next noteworthy finding is a preserved Roman well, which was part of the castello Gerulata military base, constructed probably at the end of 1st century. In the historical part, 69 wells dated back to the Middle Ages were found; the oldest ones are from 12th century. In this paper, the technology and the materials used in their construction are presented. In the 15th century, construction of public wells, called fountains, started on the squares and markets of this mediaeval town; some of them are well-preserved to these days. The water supplied from these fountains was conveyed from springs at the foot of the Carpathian mountains by pipelines from different materials -wood, lead. On the Main Square, ceramic pipelines from the 18th century were found. To the history of water supply belongs a pump tower; this part of water supply system of Bratislava castle was built thanks to district administrator Pavol Pálffy in the 17th century and the pump machine was constructed by the master Wolfgang Kempelen in 18th century.

Keywords Fountain; pipeline; water supply; well.

Introduction

The area of today's Bratislava bounded by Carpathian hooks through which Danube passes became an important strategic place as we can see from a number of archaeological finds of a settlements dated into a later stone age. In addition to transcontinental water trade route the river provided the inhabitants with a source of fine drinking water in quaternary fluvial deposits that was taken from wells. One of the oldest remaining wells on the territory of today's Bratislava originates from times of the Roman Empire's northern borderline building up and is dated to 1st to 2nd century A.D.

A sophisticated defense of the Roman Empire's borderline Limes Romanus on the central Danube at 1st-4th century includes outposts of military units whose task was not only to defend the Empire against raids of enemy tribes from the North of Danube but also, both in peacetimes and wartimes, to protect, control and inspect trade and supply routes. Two main routes considered transcontinental because of their importance and length - Amber Road and Danube Road - crossed just in the area of Bratislava Passage. One of the Limes fortified points - antic Gerulata - was built in Bratislava-Rusovce.

Well Technology

Roman sense of sophisticated decision on a settlement location in terms of nature, transport and economy is demonstrated by this place. The last term is important as a quality arable land, grazing land, large wood and water sources and quality drinking water from sophisticated wells are available in this area.

The best-preserved sight in today's Rusovce is a quadratic building, the premises of a museum. Its dimensions are 30 x 30 m^2 with an external wall wide up to 2,4 m. A turrical building stands on 12 columns with an asymmetrically oriented well in the middle. The stone well has a diamond ground plan 2,0 x 2,0 m^2, 7,0 m depth and time-to-time water appears there. Masonry of the well is 50 - 60 cm wide and consists of secondary used outlined stones formally used as gravestones. Remains of a wooden frame documenting the technology of construction were found at the bottom of the well (Fig.1).

Figure 1 Roman well - Gerulata. Stone well built probably in 1st-2nd century.

At the Great Moravian Empire period a roost of Bratislava performed not only military duties but also it played an important role as an administrative and ecclesial center. Footings of sacral and civic buildings and even remains of Slavonian well were found in the historical town center. The 14th century is considered as a zenith of urban development of towns in our territory and Bratislava is not an exemption. It is worth to notice that the creation of most of the wells dates to 14th-15th century, but some of them were built at the turn of 12th-13th century. Building of wells was closely connected with an expansion and architectural development of towns. A concentration of people (and even animals) probably raised higher needs of hygiene both in private premises and probably on public spaces exposed to a high attack of contaminations namely at times of fairs as well (in the 15th century there were 98 fair days per year). In 15th century Bratislava had 4600 up to 4800 inhabitants and 7000 at the end of 16th century. Most of Bratislava's wells originate from 14th-15th century. Foundation of public wells on squares and market places is dated from this period.

Medieval wells of Bratislava are built from a quarry stone placed in rows either dry, on clay or the stone with quality mortar with high whitewash content. In some parts of the historical town heart wells were sunk into a compact ground. Since 17th century, bricks have been used for their construction together with stone. Above a ground level the wells had to be protected against contamination. Protective constructions are mostly documented iconographically and by historical reports. The protective constructions consisted of: (a) an above ground level. (b) a wooden cover, grill and (c) a canopy - open or closed. Bodies of wells were terminated above the ground level by a continuation of a shell construction but also by other type of construction or material, namely bricks, square stones (sandstone) bonded by a mortar and a stone or wooden rings. A gothic and late renaissance construction was successfully reconstructed from a refill of a well at Devín.

Outlined wood in square form is a part of the construction in the bottom of the well. The bottom is created by a filtering system of a gravel layer and a lower sand layer. In many cases a wooden construction was found in the bottom part what seems to be related to a well deepening under an existing footing bottom. The bottom of the well at Devin had a hexagonal shape. In times of their function wells were cleaned and deepened. After their destruction they could be secondary used as sumps or cesspools.

Water was drawn manually by different means. If a water table was not deep a bucket on a rope or a rod was dipped, deeper water table was reached by a pulley by means of two buckets where on the one end of the rope/chain there was a full bucket and on the other end an empty one. A winch with a crank used for manual pumping could be connected with a pedal wheel driven by animals. Many medieval scientists were interested in a simplification of water drawing. A manuscript from the beginning of 15th century (*De ingeneis* by an Italian gadgeteer Mariano Taccolu) was preserved together with his sketches of drawing devices. Remains of such a wooden device from 15th-16th century were found in one of the wells in Bratislava.

Other Water Supply Technologies

At the time of M. Terezia's rule a castle was reconstructed and changed into a luxurious royal residence. In the 18th century, within a framework of reconstruction according to proposals of J.W. Kempellen, native of Bratislava, secretary and an advisor of Court Chamber, a separate water piping system was built for the castle residence. A well on a Danube embankment in the middle of a decagonal building with a system of horse-powered pressure pumps was a part of the system. This building was called "Water Tower". A tunnel with stairs in which a copper piping was placed run to it. According to archive records the system provided the Castle with one bucket of water to a level of about 70 m every 1.5 minute. This sophisticated facility had been in operation until a fire of the Castle in 1811. After a renovation of outbuildings the water piping had been operational again together with newly built pipelines around the Castle until 1887. It was in operation for 125 years and was closed when the objects were connected to the town water supply.

Some 100 years before opening of the first Bratislava waterworks -in the second half of the 18th century- the water supply and sewage systems had started to change because of Danube regulation and building of a sewer system and water piping. There were 11 squares in the town with wells and fountains supplied with water by wooden and metal piping from surrounding hill slopes of Malé Karpaty. Despite water distribution by pipelines, public wells did not lose their function. Many of them were enriched by "aesthetic dimension" and converted into fountains that served as a source of potable water even in 19th century (Figs. 2 and 3). A complex piping network is known from 19th century but its building began in 16th and 17th century. Originally the piping was made of wood by tub makers, a plumbeous one started to be used later. Both types were used for a long time. We can mention records from 1837 when the wooden piping near Michalská gate was replaced by a plumbeous one.

Wooden pipes were made from straight tree trunks with a crust. Pines were used mostly but fir or oak were suitable for this purpose as well. Their outer diameter was 30 cm and their length was 4-5 m. Trees were chopped down and drilled during winter so as to give the wood a time to mature. The transport from forest had to be very careful in order to prevent damage of the trunks. The trunks with crust were chopped in a desired length and after jigging on a tripod they were drilled by a rotary bit. The wooden pipes were connected by copper, bronze or later iron rings. Their profile widened conically and narrower ends were inserted into wider ones. The internal pipe diameter was about 60-80 mm. The piping was bedded in a depth of 1-1.5 m that protected them against mechanical damage and freeze.

There were raising complaints about the quality of drinking water in a growing town when the public wells and fountains failed to cover needs of potable and supply water. An idea of pipeline and waterworks building had been on the agenda of the City Council of Bratislava since 1868. The Council asked an English expert, building advisor John Moor, to present a project of a water piping. Moor proposed to get water from a drain consisting of a perforated piping overlaid by gravel, sand, rocks and rubble that could be led above the town. According to the Council Moore's proposal did not guarantee the required water quality and the project was rejected.

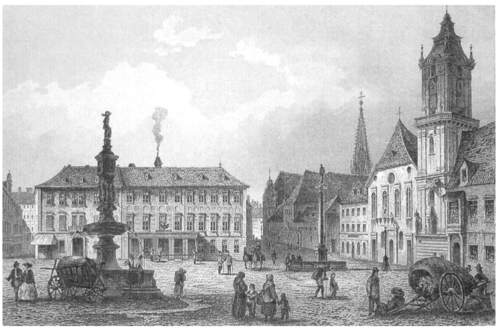

Figure 2 Main Square. A tube well is mentioned in 1439. In 1572 a stonemason M. Lutringer built the fountain of Roland on its place. It was supplied by water from the Heilgenbrunn spring.

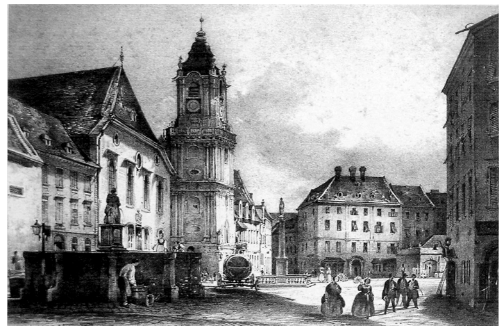

Figure 3 Františkánske square. Rohrkasten - a fountain or a town well with a balance beam. It was supplied by water from springs on roots of vineyards through wooden or later plumbeous pipelines (15th century).

The Council posed high requirements on the water quality but on the other hand it did not want to build the waterworks at the town's expenses considering the building quite risky. A further contractor had to build the waterworks at his own expenses. Finally, in 1883 the town concluded a contract with a company C. Corte Ltd. that began the waterworks building on August 1884 and on 1st February 1886 started to supply inhabitants with water. A former equipment of the waterworks consisted of a well in alluvial Danube fluvial deposits on an island of Sihoť (formally Käsmacher, Äugelhaufen), a siphon tube, a pumping station, 2 water reservoirs near the castle (Oslí vrch) and a range pipe. The contract with Corte Company guaranteed the town an excellent quality of water not risking any financial loss connected with building up of the water piping with a title to redeem the waterworks any times it wished. Since the waterworks grew away well, the Council of Bratislava redeemed it on 1st February 1894.

Conclusions

In the past, people were aware of the importance of water in life and based their settlements mainly on locations with sufficient water resources. Since this territory had sufficiency of both surface and ground water, we can find there archeological findings of settlements dated into a later stone age. Advantageous natural conditions of the territory and sufficiency of surface and ground water led the Romans and to found there their encampment Gerulata. They knew they needed water for transportation, drinking and hygiene, as proved by findings not only of a well but also of canalization. Population living on this territory used drinking water from wells that were built in the Danube alluvial fluvial deposits and from springs on mountainsides. Sufficiency of quality drinking water ensured a development of the territory and did not compel to save water and transport it on long distances as Egyptians, Romans or Greeks were forced to. The development of the town and the castle, and the higher requirements on the quantity of drinking and supply water led to a supply of the inhabitants by wells and fountains, later by smaller water piping bringing to the town water from mountain springs, that was carried to the castle by pressure pumps powered by horses, and finally by real waterworks in 1886.

Acknowledgements

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Overview of the History of Water Resources and Irrigation Management in the Near East Region

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Abstract: The Near East region extends from Turkey in the north to Somalia in the south and from Mauritania in the west to Afghanistan in the east. It is characterized by aridity and scarcity of water which explains its dependence on irrigation since ancestral times. The aim of this paper is to give a brief overview of the history of water management and irrigation developments in the region, based on remnants and bibliographical research, with a focus on ancient water management techniques and ingenious irrigated agriculture practices, including the use of non conventional water resources. The implications and impacts of these techniques on modern management of water resources and irrigated agriculture are also discussed.

Introduction

In general terms, irrigation can be defined as the artificial supply of water to supplement natural precipitation -or substitute for it- for the purpose of agricultural production. In the Near East region, irrigation has been vital for as far back as history can go, making it the origin, or at least one of the origins, of irrigation practice and its diffusion to the rest of the world. The rise -and at times decline- of the different civilizations that lived in the region was related to water harnessing. Irrigated agriculture provided economic prosperity, social stability and military powers.

The early developments evolved gradually with time and provided the foundations for today's water technologies not only in the region but throughout the world. The historic heritage and the lessons learned provide a wealth of experience for the sustainable management of water resources today and in future generations.

Irrigated Agriculture Historical Developments

In many part of the region, ruins and historical remnants of ancient water structures and irrigation schemes, dating back to 2,000-5,500 B.C., can still be found. It is believed that elaborate water diversion structures and irrigation schemes (by the standards of those days) were developed and used in Egypt and Mesopotamia, as far back as 5,000 B.C. The methods invented were refined with time and became gradually adopted by the surrounding regions, particularly North Africa and the Mediterranean.

The practice of irrigated agriculture

According to many references, the major first civilizations that developed on the basis of irrigated agriculture were in the Near East region, particularly Egypt and Mesopotamia. The peoples of these civilizations were the first to learn that, among the tasks needed for growing crops and ensuring food production, the provision of water was a vital one. This constituted the first steps of harnessing water resources for irrigation which became later a technology underlying the success of the greatest civilizations of the Region.

Anthropological studies have revealed that the oldest irrigated agriculture in the Near East Region was practiced in Egypt some 5,000 years B.C., and is as old as the practice of agriculture itself. Ancient Egyptians built large flat basins for growing crops along the Nile river banks. At the peak of floods, water was naturally diverted into these basins where it was stored in the fields for 40 to 60 days. The technique was rather primitive and passive as it depended on the Nile flood fluctuations, but allowed the production of winter crops (Brittanica, 2006). The system was later refined and gave rise to basin irrigation, a productive adaptation of the natural rise and fall of the river. Farmers constructed networks of earthen banks, some parallel to the river and some perpendicular to it, forming basins of various sizes. Regulated sluices would direct floodwater into a basin, where it would sit for a month or so until the soil was saturated. Then the remaining water would be drained off to a basin down-gradient or to a nearby canal, and the farmers of the drained plot would plant their crops (Goblot, 1963).

Similar techniques have also been used in Mesopotamia, some 3,000-5,000 years B.C. Compared to Ancient Egypt, Mesopotamia was supplied by the Tigris and the Euphrates which were much smaller than the Nile. The arable lands were very flat with the problems of poor drainage and soil quality, important flooding and excess of salts. The Euphrates bed, being higher than that of the Tigris, provided a natural gradient for irrigation and drainage schemes: the Euphrates water was used as supply, whereas the Tigris River provided a drain (Waterhistory, 2006). The flooded lands in between were used for growing crops.

In North Africa region, as in Egypt, Iran and Iraq, water management and irrigation practices are considered very ancient techniques. It is believed that development of irrigation in North Africa have extended from Mesopotamia and Egypt to the Mediterranean under the Carthaginian (Phoenician) some eight centuries before Christ and then to the south under the Roman Empire (146-439 B.C.). The focus of water management by the Romans in the region was on harnessing existing water sources and rainfall water collection. Some of the structures developed have been preserved and are still used nowadays for domestic and irrigation purposes; they include: (a) Dams built with blocks of masonry established in wadi beds, with one of the sides left open as a derivation canal to serve irrigated lands; (b) reservoirs and cisterns filled by rainwater drained from mountains. These reservoirs were very numerous and at times had very important storage capacity; (c) canals and aquaducts for transporting natural sources of water as one of the Roman ingenious practices; and (d) dams in dry stones, generally near mountains to divert water for irrigation.

During the early Islamic period, prosperity of the Abbasid Dynasty, headquartered in Baghdad (762-1258 A.D.), was partly related to water and irrigation management which concerned the renovation and extension of all existing irrigation schemes. Irrigation water was carried from the Euphrates at five separate points and led in parallel canals across the plains to the south of Baghdad (Waterhistory, 2006). In the 12th century, salinization problems increased and canals were silted because of the lack of maintenance. This, coupled with natural catastrophes particularly massive floods which shifted the courses of both the Tigris and the Euphrates, destroying most supply structures, contributed to the decline of the dynasty.

A similar trend followed in North of Africa between the 8th and the 13th centuries A.D., with intensive development of water and irrigation structures to boost agricultural production. Some of these structures are still functional today and include water lifting devices (noria or saniya, dulab, Diou or Dlou, Gargaz or shaduf), aquaducts, cisterns and qanats, as elaborated below.

Irrigation water infrastructure-Surface water diversion, conveyance and storage systems

The first major irrigation project in Egypt was built about *ca*. 3,100 B.C., during the reign of Menes, founder of the First Egyptian Dynasty (Brittanica, 2006). By *ca*. 2,100 B.C., several ingenious systems for irrigation were in use in Egypt, including one with about 20 km of canal that diverted Nile floodwaters to lake Moeris (Brittanica, 2006). The oldest dam in the region, named Sadd Al-Kafara, was built on "Wadi Al-Garawi" during the period of the Third or Fourth Dynasties of Pharaohs, i.e., between *ca*. 2686 and 498 B.C. (Murray, 1947; Garbrecht, 1984), but it was washed out by floods before it was ever used. Across the Red Sea, the oldest dam in the Arabian Peninsula, Marib Dam, in Yemen today, was built about *ca*. 500-600 B.C.

In Mesopotamia, very large weirs and diversion dams were built, to create reservoirs and to supply canals that carried water over considerable distances across flat areas. The scale of their irrigation was larger than in Egypt, and Mesopotamian irrigation was active and based on water interception. It is believed that the oldest technique of surface water management by building diversion dams was first realized in Mesopotamia. Irrigated agriculture in Mesopotamia has been practiced for more than *ca.* 5,000 years. The City of Eridu, located about 22 km south of Nasiriya and 40 km south west of the traditional site of the Garden of Eden (Mughair), is believed to be one of the first villages of Mesopotamia that grew into cities as a result of irrigated agriculture development (Fig. 1). The region flourished later on during the period of the Babylonian dynasty, especially under the rule of the famous King Hamourabi (*ca.* 1792-1750 B.C.) The well known Hanging Gardens of Babylon - one of the Seven Wonders of the World - are believed to have been built during the Neo-Babylonian Dynasty, under the king Nebuchadnezzar (*ca*. 604 -562 B.C.)

Figure 1 Ruins of Eridu, Iraq (Atlas, 2006).

The Solomon's Pools in Bethlehem, Palestine, are three large catchment reservoirs of around 160,000 m³ each, built with stone and masonry between *ca*. 2000 B.C. and 30 B.C. in two stages. Ancient aquaducts used to collect water from the springs of Wadi Arab and Wadi Biyar and carry it to the pools. Some of the springs with channels are still in operation and are used for irrigation.

Water diversion devices for irrigation and other purposes have been used in various locations in the region, particularly Egypt, Yemen, Iraq, Iran and North Africa. In Egypt, the Al-Kafara dam was located 30 km south of the current Cairo, between "Wadi Al-Hof" and "Wadi Al-Garawi". Its construction required the excavation and transport of approximately 100,000 m^3 of rock and rubble (Garbrecht, 1984), for an estimated capacity of 600,000 m^3 of water (Smith, 1971). In Yemen; the oldest dam was built near Marib, the ancient Sabaean capital, in *ca*. 500-600 B.C. Constructed in masonry over a length of about 500 m (Brittanica, 2006), the dam had the objective of holding back some of the annual flood waters of Wadi Dhâna and to divert them into two canal distribution systems of irrigation use.

In North Africa, at the beginning of the 12th century, several terraces and dry stone dams were constructed to divert surface water to be used for irrigation, notably in arid regions. In Madeira Island (Cyprus) about 1.5 km network of irrigation channels carried spring water down from nearby mountains. Paths and steps were built alongside the man-made water channels for maintenance purposes. In Lapta (Lapithos), many springs from the Besparmak Mountains flowed noisily along irrigation channels to supply the surrounding gardens and groves of citrus and olive. The Kamares aquaduct was built in the 18th century on the outskirts of Larnaca for domestic and irrigation purposes.

The exact date of the invention of early diversion dams is not well known, but it is clear that the technique started in the Near East region. Early civilizations had a clear distinction between storage and diversion dams. The latter seems to have a long history in Yemen and explains the early water and irrigation management philosophy. It was preceded by early irrigated agriculture production that relied on natural floods events during rainy seasons.

Groundwater mobilization systems

The Persians started constructing elaborate systems for extracting groundwater in the dry mountain basins of Iran and in western Persia, northern Mesopotamia and eastern Turkey, about 2,500 years ago (English, 1968). The system consisted of tapping groundwater by a series of wells, 20 to 30 m apart, connected at their bottoms by a tunnel with controlled slope (Fig. 2). The upstream wells tap groundwater and the series of all wells represents points of entrance for excavation and maintenance workers.

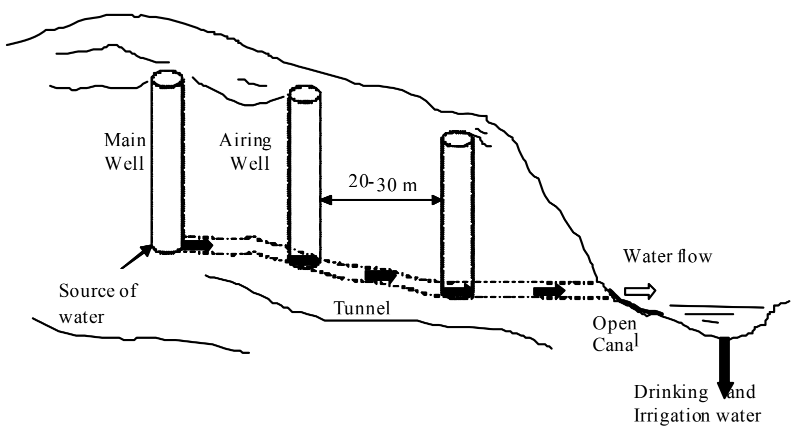

Figure 2 Principle of qanat conception (Ward, 1968).

This technique has the advantage of using milder slopes than surface canals and preventing evaporation losses; but the main advantage reside in taping groundwater without lifting devices. The system, termed “qanat”, system induced prosperity of water users by developing irrigated agriculture. It also allowed the creation of numerous oases in desert areas. The history of qanat diffusion from Persian origin to other countries of the region can be summarized as follows (Brittanica, 2006): (a) During the period 550-331 B.C., when Persian rule extended from the Indus to the Nile, qanat technology spread throughout the empire (Brittanica, 2006). The rulers provided a major incentive for qanat builders and their heirs by allowing them to retain profits from newly constructed units for five generations. As a result, the system expanded westward from Mesopotamia to the Mediterranean, southward into parts of Egypt and east of Persia in Afghanistan, the Silk Road, oases settlements of central Asia, and Chinese Turkistan (English, 1997); (b) during Roman-Byzantine era (64 B.C. to 660 A.D.), large numbers of qanats were constructed in Syria and Jordan. The Romans also used qanats as subterranean parts of aquaducts, as witnessed by still examples of “qanat-aquaduct” system in Tunisia and Turkey; and (c) the expansion of Islam provided another major diffusion of the technology, spreading qanats westward across North Africa and into Cyprus and Sicily. The technology of qanat was rapidly spread throughout the Middle East and North Africa under different names, but the basic principles remained the same (Box 1).

Box 1: Development and spreading of qanat systems

The “Qanat” technique is still in use in Iran for various purposes including irrigation. Out of an estimated total of 40,000 units, 70% are operating particularly in Bam, Yazd and Isfahan. Many other units have collapsed as a result of neglect and earthquakes, such in Baravat and Bam. The principle of qanat has been established up to 2,000 years ago in the Arabian Peninsula under the name of “Falaj, plural Aflaj”. The systems provided ancient Arabians with permanent and stable water for drinking and food production. Their number dwindled with time, with some units still operational today. Several existing oases, such as those of Mahdah, Oman, depended entirely on this system for their water needs. The social structure and water rights in these isolated communities were closely linked to the need for managing and maintaining these systems in an optimal manner. In Saudi Arabia, there is evidence that a Falaj once saved the city of Jeddah from a Portuguese invasion in 1516 A.D. The 16 km Falaj supplied the town with all water needs during the invasion. In the United Arab Emirates, the well-preserved Al-Mualla falaj around Al Ain city dates back to the Iron Age. The majority of Aflaj in the Arabian Peninsula existed where Oman lies today with an estimated number of 11,000 units out of which some 4,000 were major ones, constantly flowing and constituting the main source of water. Today they deliver around 900 Mm^3/yr of water, representing 70% of the country’s total water use and irrigating 55% of the total farm lands under irrigation. In Afghanistan the systems, termed “Kareezes”, are still widely used, with about 6,500 units supplying 168,000 ha of land (7% of the total irrigated area). Similarly, Persian wheels still supply water for drinking purposes and for irrigating about 12,000 ha of land (FAO, 2006). In Syria, qanats have been used to irrigate fields and gardens for centuries, particularly around the cities of Damascus, Selemiya, Palmyra, Qadeym, and Taibe. The diversity of qanat types seems to reflect their origins, but it is certain that many of the systems were first constructed during the Roman-Byzantine era (64 B.C. to 630 A.D.) The large number of aquaducts and wells, many of which are still in use, generally improved irrigation techniques and expanded arable land (Lightfoot, 2003). Today, Syria has a total of 239 qanat galleries, but only 12% still flow and most are gradually drying up. In Jordan, the technologies of qanats and cisterns have also been used since ancient times, particularly the Roman-Byzantine era. In the Jordan Valley 6 qanats were rehabilitated in the 1920s and used for irrigating about 600 ha. In the early 1960s, farmers in the region began installing diesel-pumped wells which resulted in drying up all qanats by 1970. In the West Bank of Palestine, since more than 2,000 years, farmers have irrigated terraces of olive trees, vineyards, and orchards with water tapped from some 250 qanats crossing through the hills on the eastern shores of the Mediterranean. Today these terraces and tunnels are largely abandoned. In North Africa, the qanat system was introduced after the Arab Expansion and became widely adopted by the 13th century. Called “Foggara” or “Damous” in Tunisia, it has been used in El Guettar region (Orbatta Mountain) to irrigate small oases and in the north, near Tunis, for irrigation and domestic use. In Algeria, the system termed “foggara” has been widely used for irrigation, particularly in the south west, for more than 600 years. The installed systems provided water for irrigating more than 25,000 ha of oases in the region of Ouled Said in Adrar. Many of these systems have dried out and sustainability of the few remaining ones will depend on their maintenance and the level of groundwater. In Morocco, the system, called “Khettara”, was introduced in many localities, particularly around the city of Marrakech and the Tafilalt region. In the latter, the network provided domestic water for the ancient city of Sijilmassa and for irrigating about 3,000 ha (Lightfoot and Miller, 1996). Many systems continued operating for much of the northern oasis until the early 1970s. Today, only 19 khettaras with 90 km of network are still supplying 12 localities. The qanats of southern Morocco (Marrakech and Tafilalet) and southern Algeria represent the greatest development of this technology outside the Persian area (Brittanica, 2006). It is worth mentioning that a wealth of knowledge on groundwater abstraction was written back in the 10th century A.D. by the Persian scientist Karaji. His book titled “The Extraction of Hidden Waters” deals with the techniques of groundwater exploration and is in general agreement with modern understanding of the subject (Waterhistory, 2006).

Water conservation systems

Throughout the highlands of the Near East region, ancient farmers have laboriously constructed small terraced fields by filling horizontal plots with soil behind stone walls. The terraces allowed storing direct precipitation and runoff from upstream for use by crops. In a second stage of technological development, the fields are watered by complicated systems of open channels and wooden aquaducts leading from nearby rivers or tributary streams. Later on, intricate irrigation systems were developed, by dividing the terraced fields into small shallow basins that were irrigated in turn.

This technique, consisting of rock-walled bench terraces and diversion of rainfall water, has been used in Lebanon nearly 3,000 years ago, for irrigating the famous forests of cedar. Similarly, Yemen is well known for its ancient terraces that facilitate the successful cultivation of crops on very steep terrain (Fig. 3). Throughout North Africa, inhabitants have developed elaborate systems for harvesting rainfall water to irrigate trees. The “Djessure” technique, built in runoff courses in Tunisia, is an example of such systems that is still widely used today and allows growing olive and other tree species in areas where rainfall is less than 250 mm/yr.

Figure 3 Terraces in Yemen.

Another ingenious system of water conservation in agriculture, believed to have originated in North Africa, is the “pot-watering” or “jar irrigation”. It consists of burying a water-filled clay jar near a tree seedling so that water potential gradient across the jar wall allows moisture movement to provide water for the plant roots. The system is still used today to grow trees for fixing sand dunes in the Tafilalet region, south of Morocco.

Water lifting devices

The Egyptian “shaduf” and the water wheel or “noria” or “sania” are probably among the earliest devices for lifting water to be used for irrigation and domestic water supply. The shaduf (Fig. 4) consisted of a bucket - leather bag in ancient times - balanced with a counterweight that served for lifting water from the Nile river. In North Africa, a similar technique (called locally Diou or Dlou) was developed in the beginning of the 12th century (Joffe, 1992). It consists of a leather bag connected to a rope that serves for lifting water from wells. The system was refined later on with the introduction of a pulley and animal traction for lifting water from deep wells. It is still used widely today for providing drinking water and irrigating small land plots close to wells. The device was also diffused to the Arabian Peninsula.

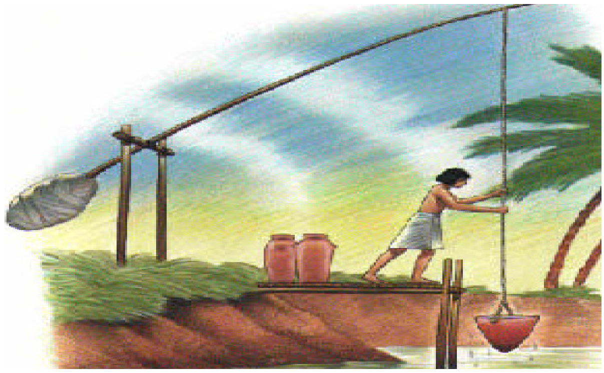

Figure 4 Egyptian Shaduf (Waterhistory, 2006).

The Noria or Egyptian Wheel (Fig. 5) is thought to be the first vertical water wheel and was invented by the Romans around *ca* 600-700 B.C. It consists of a wooden wheel powered by water and fitted with buckets that lift water for irrigating nearby lands. The diffusion of the noria is typically associated with the Arab civilization and the animal-powered noria is considered as the high symbol of the Islamic imprint upon irrigation technology. The hydraulic wheel was first built in Fez, Morocco, in the 13th century (Cohn, 1933) then spread to other parts of North Africa. Waterwheels powered by camels have been used in Afghanistan and elsewhere in the region to lift water for irrigation and domestic use (Fig. 6). A limited number of these units is still in use today. In Sudan ox-powered system, as a simple irrigation device, has been used for centuries and continues nowadays.

Figure 5 Noria in Hama, Syria (Angelfire, 2006).

Figure 6 Camel powered water wheel, Afghanistan (Hindunet, 2006).

A different version of the noria is the Persian Wheel the date of its invention is not well known. It consists of an endless series of pots of unequal weight turned over two pulleys (Angelfire, 2006) and is therefore classified as a pump rather than a water wheel. The water wheel, in its different versions, constitutes the ancestor of water pumps and modern hydropower systems the principle of which is to extract power from the flow of water. The shortage of labour during the Middle Ages made machines, such as the water wheel, cost effective. The water wheel remained competitive with the steam engine well into the

Industrial Revolution (Wikipedia, 2006). The system used for lifting water to irrigate the Hanging Gardens of Babylon remains a mystery, although Greek historians describe it as consisting of something similar to an Archimedes' screw or of chain pumps, each consisting of two large wheels, powered by slaves.

Water regulations

The first known regulations related to water date back to the era of the Babylonian King Hammurabi (1792-1750 B.C), with the elaboration of a code of law based on previous Sumerian laws. Considering the importance of farmers' cooperation as critical in irrigation management, to ensure a fair distribution of water and to avoid conflicts, the Code introduced three main concepts related to irrigation water management: (a) Proportional distribution whereby the farmer receives water in proportion to the amount of land he works; (b) definition of an individual farmer's responsibility towards the whole community, by safeguarding the sections of public canals that lie on his property, accepting community rules such as water turns and liability for damages caused to neighbours owing to negligence or malice; and (c) water apportionment and policing of irrigation arrangements as a collective responsibility of beneficiary farmers. These concepts constituted the foundations of irrigation development in the region, and although some of them have been neglected during certain periods of time, many countries are returning to them today as a way of ensuring good management through farmers' participation.

These early water-related regulations were followed by a wealth of other laws, at times very elaborate and complex, throughout the region. As an incentive to encourage the construction of agricultural hydraulic works, the Romans (*ca*. 146-438 B.C.) allowed the lands that bear such works to be transmitted to the heirs of the persons who constructed them. Similarly, during the period *ca*. 550-331 B.C., the Persian rulers encouraged by law qanat builders by allowing their heirs to retain profits from newly constructed units for five generations.

Water distribution and monitoring devices

Because of the link between the Nile's flow level and the population's well-being, the ancient Egyptians developed a system for monitoring the Nile flow in many points along the Nile River. The system (Nilometer) consisted of marking the level of water and comparing it with those of previous years, thus allowing predictions with some accuracy of the following year's high mark. At least 20 "nilometers" were spaced along the river, and the maximum level of each year's flood was recorded in the palace and temple archives (Worldwatch, 2006). The early version of the system consisted of marked flights of stairs and has been used for thousands of years (Fig. 7). It is not much different from the principle of today's river staff gauging.

At the beginning of the 13th century, Ibn Shabbat (*ca.* 1221-1285 A.D.), a Tunisian distinguished historian, magistrate and engineer invented an elaborate system for water distribution in the Tozeur Great River. The system is still operating and well maintained. In Algeria, a system termed "Kassria" was used to distribute the flow of water from foggaras in an equitable way; the system is still operational in several oases. Many other ingenious water distribution systems and regulations, dating to several centuries back, are widely used for managing perennial and flood waters throughout the Middle-East and North Africa Region.

Figure 7 Nilometer on Elephantine Island, Aswan (Waterhistory, 2006).

Irrigation with Non Conventional Water Resources

There are no historical records of the use of saline and brackish water for irrigation in the early civilizations of the Near East. Nevertheless, the loss to salinization of large areas of agricultural lands in Mesopotamia and other parts of the region provides an indication that saline waters were used for agricultural production. It is very likely that, when available, such low quality water has been used especially under the shortage of good quality water such as during drought periods.

There is also no historic indication however on the use of human wastes in the region. In the absence of sewage facilities, it is likely that such wastes were disposed in open lands and water courses, thus contributing to soil fertility. Remnants of the first sewerage systems in the region have been found in the Roman ruins, as Roman cities had regular systems of drains running under the streets and carrying storm water and sewage. Individual and public toilets have also been found.

A few centuries later, there was renewal interest in the construction of storm sewers, mostly in the form of open channels or street gutters in cities. The development of municipal water supply systems and household plumbing brought about flush toilets and the beginning of modern sewer systems. In the beginning of the 20^{th} century, septic tanks were introduced as a means of treating domestic sewage from individual households both in suburban and rural areas in the Near East Region. The construction of sewage treatment facilities started around the same time.

The concept of treating and recycling sewage effluent, as known today, is recent in most Near East countries. However, untreated sewage has been used around old inland cities, such as Damascus, Fez and Marrakech, for several centuries (Bazza, 2003). The wastes were dumped into rivers where they mixed with fresh water and were used in the outskirts of cities for irrigating fruit trees and vegetables.

The interest in using municipal wastewater grew in recent years in all Near East countries as a result of freshwater shortage but also for environmental concerns. The number of wastewater treatment plants has grown rapidly over the last few years and continues to hike in many countries. However, the high cost of sewerage systems and treatment plants are hindering the generalization of these technologies to all population of the region. As a result, the picture of wastewater treatment and reuse is very heterogeneous, ranging from discharge -and at times even direct use- of raw sewage to high level quality treated effluent. The situation is likely to improve gradually with improvement in economic and social development, greater shortage of freshwater and increased awareness on health and environment.

Conclusions

As witnessed by historical and archaeological records, irrigation has been practiced in the Near East Region for more than *ca*. 5,000 years. In fact, harnessing water resources and mastering their use were the backbones of development and prosperity of most early civilizations in the region. Dependence on irrigation for food production, social stability and power gradually improved the knowledge of early civilizations to manage water for agricultural use. The earliest irrigation practice seems to have started in Egypt, with flood water from the Nile River, before gradually evolving to the use of water lifters powered by humans, animals and the flow of water. The technique of artificial irrigation was later on introduced in Mesopotamia and Iran, at least *ca.* 3500 ago, before spreading to different neighboring regions, particularly westward to North Africa and the Mediterranean.

While there is no doubt that irrigation development greatly enhanced economic development, attempts to evaluate the technical performance and impacts of ancient water technologies in the region reveal that the task is very complex. The infrastructure and its evolution with time indicate that the degree of hydraulic genius was high during all historic periods. Water management was based on simple rules of physics and the devices developed were labour intensive but they constituted the basic foundations for the technologies of today.

The traditional structures and practices for water management obeyed to certain criteria specific to the regions of their application. For instance, qanats were constructed essentially in regions receiving between 100 and 300 mm as average annual precipitation and all qanats were found below the 500 mm isohyet line. Moreover, the structure and practices were compatible with water resources sustainability as compared with today's technologies. This is particularly true when comparing the impact of qanats on groundwater with the use of pumps and tube wells. In fact, groundwater overdraft through pumping is the major cause for the abandonment of qanats in most parts of the region. However, the practice of irrigation in old times has not always been without risk for agricultural lands, as witnessed by the loss to salinization of large areas in Mesopotamia and other parts of the region.

Collective water management is another main characteristic of ancient civilizations in the region. This was probably due to the fact that water structures and practices were labour intensive and beyond the capacity of individuals. Today, governments are attempting to go back to collective management, through the involvement and active participation of farmers. The role of governments was detrimental in ancient civilizations for developing water resources for all uses, particularly agriculture, by providing incentives to beneficiary populations and establishing and enforcing well adapted regulations. The technological developments over time constituted unavoidable stages for reaching the current level of know-how and should not be ignored. Unfortunately, it is not often that modern management takes into account the lessons learned and the wisdom of managing natural resources developed and accumulated by our ancestors.

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Water Supply at Ancient Mesa Verde

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Abstract: 4,000 year-old reservoir sites at Mesa Verde, Colorado were analyzed by the author using field research paleohydrologic techniques over an 11-year period. The research demonstrates the advanced engineering skills and hydrologic acumen of the Ancestral Puebloans. In an arid environment, these resourceful people created and maintained water supply reservoirs that were used for up to 350 years. The Ancestral Puebloans were able to harvest water where modern engineers would say there is none.

Keywords Ancient reservoirs; dredging; Mesa Verde; sediment; water harvesting.

Introduction

Established by Congress in 1906, Mesa Verde National Park (MVNP) is a 21,000-hectare national treasure in southwestern Colorado (Fig. 1). In 1978, the United Nations designated the park as a World Heritage Site (Ferguson, 1996). In 1999, the National Geographic Society ranked the park number six on its list of world wonders. In 2004, the American Society of Civil Engineers designated the four reservoirs as a National Historic Civil Engineering Landmark, one of only 230 such landmarks.

The park contains close to 5,000 archaeological sites awaiting further study (Wright, 2006). About three dozen sites are open to the public. The Ancestral Puebloans of Mesa Verde, sometimes referred to by archaeologists as the Anasazi, were able to plan, build, and operate public works projects in southwestern Colorado more than 1,000 years ago (Wright, 2006). The evidence they left behind has provided proof of civil engineering achievements that spanned hundreds of years (Fig. 2). This field evidence rests in canyon bottoms and on mesa-tops of MVNP, archaeological sites that were reservoirs for storage of domestic-use water (Smith and Zubrow 1999). The four reservoirs we explored, analyzed, and documented are identified in Table 1. Early Americans created viable and active settlements in the Mesa Verde area over a 750-year period, from about 550-1300 A.D. (Table 2). The research related to reservoirs has identified the 750-1180 A.D. period with reservoir building and operation. Archaeologists have divided the overall 750-year time span into distinct periods for study purposes, with the Pueblo I and II periods best representing the time of the four Mesa Verde reservoirs (Wright, 2006).

The Ancestral Puebloans had no written language, did not have bronze, iron, or steel; and did not use the wheel, although they did use stone to good advantage. As a result, American history books tend to underrate them in terms of technical capabilities and social organization. However, the Ancestral Puebloans had rudimentary knowledge of hydrological phenomena, water transport, and storage (Wright, 2006).

Figure 1 Location of the Mesa Verde.

Figure 2 Archaeological site at the Mesa Verde.

Table 1 Mesa Verde reservoirs.

Structure	Identification	Location	Time span (A.D.)
Morefield	5MV1931	Morefield Canyon	750-1100
Far View	5MV833	Chapin Mesa	950-1180
Sagebrush	5MV1936	Unnamed Mesa	950-1100
Box Elder	5MV4505	Prater Canyon	800-950

Table 2 Time periods of Mesa Verde.

Period	Time span (A.D.)
Basketmaker III	550-750
Pueblo I	750-900
Pueblo II	900-1100
Pueblo III	1100-1300

To build reservoirs, they also had good organizational capabilities; otherwise, their large public works efforts requiring major and continuous operation and maintenance work would not have been possible. Their wise use of water and land provided for community development. Study of two canyon-bottom reservoirs, Morefield and Box Elder in Morefield and Prater Canyons, respectively, showed enough similarities to prove that prehistoric technology transfer existed between the canyons as early as about 800 A.D.. Later, in the 10^{th} century, other Pueblo II people, living on mesa-tops rather than the canyon bottoms as with the first two reservoirs, constructed two additional reservoirs that modern engineers would have judged to be ill-directed and bound for failure, but they provided much-needed water (Wright, 2006).

Puebloan water handling

The field research performed on the four archaeological sites provided evidence of an uncanny ancient ability to harvest water using transient ground surface impermeable characteristics, operational canals (Smith and Zubrow, 1999), sporadic runoff capture, water storage vessels, and elementary sediment dredging techniques. In creating Morefield Reservoir, the Mesa Verdeans first excavated a pond on the valley-bottom to reach the periodic shallow water table and capture infrequent storm runoff. The stored runoff carried sediment that needed to be periodically dredged and cast to the side using crude tools. Over time, the pond bottom rose in elevation and the excavated sediment was accumulated at the edges. Because dredging did not remove all the sediment during each cleaning, it was not long until the pond bottom began to rise in elevation and take the form of a mound into which water would no longer flow by gravity. The Mesa Verdeans determined that water could be diverted from the canyon bottom into a delivery canal leading to the rising pond, but sediment deposits still had to be regularly cleaned out and cast to the side, forming berms. By 1100 A.D., this process brought the Morefield Reservoir up in elevation some 6 meters (m) above the original pond bottom of 350 years earlier (Fig. 3).

Figure 3 The Morefield Reservoir.

Not only did the public works of the Mesa Verdeans have to withstand drainage basin forest fires and floods, they were also subjected to a regular upstream relocation of their point of diversion. This was done to gain elevation advantage for gravity flow to the rising reservoir pool. Concurrent with the relocation of the point of diversion of the inlet canal, the Mesa Verdeans would raise the canal elevation along its alignment to keep up with the rising elevation of the water system, creating a tadpole image. Eventually, the canal, at the proper grade, was on an elevated berm. Box Elder Reservoir was constructed a short time later in much the same manner as Morefield Reservoir, relying first on groundwater and then diverted surface water. However, on the mesa-tops, Far View and Sagebrush Reservoirs were built where modern engineers would opine that the structures were sure to be failures because of runoff (Wright, 2006).

There were no natural drainage basins for either, and the natural soil surface had a high infiltration rate. What the Ancestral Puebloans had learned, however, was that the soil contained enough silt and clay particles that when the soil was puddled, the silt and clay migrated to the surface, creating a highly impervious soil surface. Nearby areas that were subjected to busy foot traffic, such as well-travelled paths, the environs of pueblos, and upslope agricultural fields, would create runoff from even small rainfalls (WWE, 1998). Realizing even only 0.25 ha of such impervious surface could generate a substantial volume of runoff from only a couple cm of intense rainfall, the Ancestral Puebloans began harvesting water. Interceptor ditches needed to route the limited mesa-top water runoff to their newly created depressions for storage resulted in Far View Reservoir and Sagebrush Reservoir (Figs. 4 and 5). All of the reservoirs have enough similarities to identify the application of successful public works technology transfer from canyon bottom to mesa-top, from settlement to settlement, and from generation to generation, a remarkable achievement.

Figure 4 An interceptor ditch.

Figure 5 The Far View reservoir.

The Paleohydrological Investigation

Webster's Third International Dictionary defines paleohydrology as "the study of ancient use and handling of water." Our research at Mesa Verde has been aimed at that definition. Designed to be easily implemented and effective, the fieldwork had to fit within the strict field protocol the park service has developed to protect this treasure house of archaeological sites. Fortunately, we had the assistance of park archaeological professionals Linda Towle, Larry Nordby, and Cynthia Williams, and Chief Ranger Charlie Peterson. After the initial field study exploration trip, Dr. Jack Smith, former chief archaeologist of MVNP, joined the research team as scientific advisor. Smith was instrumental in ensuring that engineering and hydrologic findings were interpreted in a manner consistent with Mesa Verde's long and rich history of scientific research. Using science and engineering over an 11-year period, many specialists allowed our research team to conduct a wide variety of technical investigations. The analyses typically applied at each reservoir site included procedures that, when integrated, would elucidate the purpose and function of each site and provide evidence as to how the site was developed, how and when it was used, and the likely characteristics of operation and maintenance. We applied standard water resources and civil engineering methodologies to the archaeological sites in a painstaking manner; we followed the facts as they were defined, to study water use and water handling by ancient people. Our basic conclusions about each considered reservoir are summarized in the following sections.

Morefield reservoir

While Morefield Reservoir began as a hand-dug pond in the canyon thalweg on a mesa-top to capture seasonal groundwater, a subsequent supply to the reservoir was surface water carried by a stone-lined canal. There was a regular and well-defined series of canals, one above the other in the excavated wall. Sediment from the upstream drainage basin was carried to Morefield Reservoir, sometimes at a high rate. Total volume of sediment carried into Morefield Reservoir was about 1,200 cubic meters (Wright *et al.*, 2001). Abandonment of Morefield Reservoir likely occurred when dredging became too inefficient or when the Morefield people began thinking about moving to cliff dwellings. The dredged sediment used for the Morefield dam embankments was a mixture of clay, silt, and fine sand, which created a nearly impervious berm area. We found that sand deposits were cast over the top of the berm.

Based on potsherd analyses and carbon dating, Morefield Reservoir was used for approximately 350 years, during the 750-1100 A.D. period of the Pueblo I and II people (Wright, 2006). Over the 350-year life of the reservoir, there were about 21 instances of measurable sand to sandy clay deposition that represented canyon flooding and 14 instances of thin, continuous layers of charcoal representing forest fires. Prehistoric agricultural fields and occasional forest fires in Morefield basin likely allowed enough runoff for Morefield Reservoir to store up to 450,000 L of water at one time.

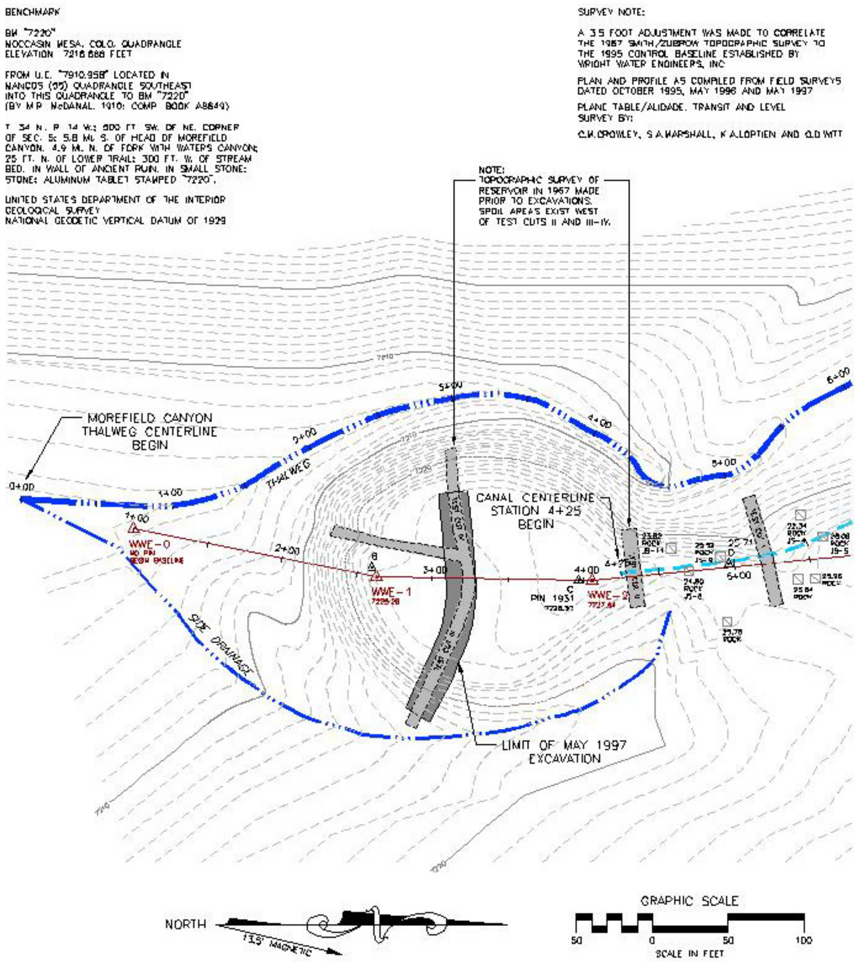

Figure 6 The Morefield Reservoir.

Far View reservoir

Far View reservoir was a mesa-top reservoir initiated in about 950 A.D. for the purpose of occasionally storing domestic water. Groundwater was not a water source for Far View Reservoir. The water source was primarily from occasional surface runoff and melting of the spring snow pack in the reservoir. An old route running from Far View Reservoir southward down Chapin Mesa toward the park headquarters or Cliff Palace was not irrigation ditch, as had been thought. The route was likely an early park service roadway. There was no ancient irrigation ditch known as Far View Ditch, such as was portrayed by *National Geographic Magazine*. The three stone perimeter walls of Far View Reservoir were for retaining dredged sediment. One wall is buried under the surrounding embankment.

The 4-hectare area (water gathering basin) lying two km north of Far View Reservoir was an agricultural field during the Pueblo II period. As a result, rainfall-runoff characteristics caused surface runoff on the average of several times each year. Runoff water was likely carried to Far View Reservoir via a foot-packed trail, and later a canal, to the agricultural field. However, local packed areas would also have provided water runoff. The high-status stone stairway leading into Far View Reservoir is one of only several known to exist in the park. Another is at the nearby Pipe Shrine House. The stairway at Far View Reservoir is not an essential part of an ancient water storage facility; however, it provided good access from the embankment to the potential water body. We were not able to adequately explain the enigmatic circular structure, excavated by Al Lancaster, southwest of the reservoir that had been thought to be the early intake where sediment would settle (Fig. 7) (Lancaster,1969). The purpose and function of Far View Reservoir from 950-1180 A.D. was for periodic domestic water storage. Much of the time it would have had no water and, therefore, it provided an unreliable source of water for the early inhabitants.

Figure 7 The circular stone stairway.

Sagebrush reservoir

Sagebrush Reservoir also served a Pueblo II water storage function from about 950-1100 A.D. Sagebrush Reservoir lies in a canyon bottom and consists of an enclosure defined by a stone-faced earthen embankment on its southwest, south and east sides. The opening in the northwest wall of Sagebrush Reservoir was an entranceway to the reservoir; it did not serve to convey water.

Most of the sherds from Sagebrush Reservoir were from jars, with a few bowls. No dippers, mugs, or other shapes were recognized. Maize pollen was found in layers within the reservoir and from the area between the two walls at a depth of 43 to 50 cm, the only pollen sample tested from the berm fill. The Sagebrush Reservoir structure ceased functioning as a reservoir prior to the area abandonment by late Pueblo II or early Pueblo III occupants of the adjacent mesa-top. The uppermost layer in the reservoir is not water deposited, but it does contain evidence of human activity such as sherds and a metate fragment. Sagebrush Reservoir served as a useful water supply during its period of operation, providing stored water on the average of perhaps 5 or 6 times per year (WPI, 2002).

Box Elder reservoir

Box Elder Reservoir is a 4-meter-high mound containing about 4,300 m^3 of sediment that represents the remains of a Pueblo I/early Pueblo II reservoir. Our team determined the reservoir began as an excavated pond for accessing groundwater in the Prater Canyon floor adjacent to, and lower than, the thalweg. The time was likely 800 A.D., or earlier. The canyon bottom terraces were gently sloping all the way to the canyon thalweg.

Sediment flowed into the pond from time to time, which by that time had been excavated. As the water table lowered over time, the pond was deepened; finally to an elevation of 2,200 m. Water was also collected from agricultural fields. The sediment contained maize pollen from upstream agricultural fields. Over time, the pond bottom began to grow in elevation, and the water table was only periodically available in the pond bottom. The east bank of the reservoir was opened to the canyon thalweg for intermittent flows. Later, because the pond bottom rose in elevation, the pond required a diversion canal from the Prater Canyon runoff for water supply. Sediment was continually deposited in the reservoir, and it was regularly dredged to help form the U-shaped berm.

Many reservoir sub-phases occurred over time as the reservoir bottom rose in elevation about 6 m and the excavated material was used to create a berm. With each later phase, the inlet diversion canal was rebuilt and its point of diversion was extended upstream. Over a long period of time (~150 years), the reservoir became elevated, the canal became longer, and the work required for operation and maintenance became greater for every liter of water stored. In the final stages of the reservoir, during the early Pueblo II period, the diversion canal from the thalweg of Prater Canyon was abandoned and filling of the reservoir was shifted exclusively to the two minor tributary gulches that infrequently flowed from west to east down the canyon wall and from the agricultural fields. This phenomenon is evidenced by the higher elevation sediment deposits lying on the west portion of the mound. Limited use of the storage site might have existed beyond 950 A.D., but not very long. After abandonment of the reservoir, the sloping surface of the reservoir sediments experienced some west to east erosion.

Supplementing the reservoir water supply was the likely use of excavations in the canyon bottom floor that reached the water table, though no evidence exists. Even today, areas exist with occasional, rather shallow water tables as evidenced by occasional lush vegetation adjacent to the Prater Canyon thalweg and historic homestead water wells of modest depths. Box Elder Reservoir would have been able to store water about five or six times per year from the Prater Canyon watershed as it existed during the Pueblo I period. This is more than adequate to justify the human effort in building and maintaining the water supply structure. People continued to live near Box Elder Reservoir after its abandonment (WPI, 2002).

Comparing the Canyon-bottom and Mesa-Top reservoirs

The two mesa-top reservoirs were commenced some 150 to 200 years after the two valley-bottom reservoirs. It is likely that the mesa-top dwellers recognized the hydrological acumen of their neighbors to the east by some 8 km, even though they did not have any natural drainage basins to yield water to their structures. It would have been evident to the mesa-top people that water runoff could be carried and directed in open ditches to the reservoir. The mesa-tops were covered with wind-deposited soils rich in silt and clay, but with some sand fractions.

Maintenance of the reservoirs by dredging of sediments was common to all four reservoirs. All had nearby pueblo settlements within walking distance, and ceramic jars had been utilized for water transport (Fig. 8). At Morefield Reservoir, 91% of the classifiable potsherds came from jars, mostly utilitarian Pueblo II San Juan Whiteware (Smith and Zubrow, 1999). At Box Elder, 94% were from jars, mostly from Early Pueblo Gray (WPI, 2002). Reservoir building and operation required considerable time and effort, with an extraordinary organizational skill to keep workers on the job. As the reservoirs got older, higher, and more difficult to operate, the labor input per liter of water stored and used increased. For this reason, one could imagine that the inhabitants would finally abandon a particular site and turn more to groundwater in the valley-bottom alluvium and the use of a few natural springs such as at Balcony House or the internal seepage at Cliff Palace. Later at Mesa Verde, the worst drought periods within the dendroclimatic record, going all the way back to about 500 A.D. at Mesa Verde, ran from 1135 to 1180 A.D. (Dean and Robinson, 1977). It was so widespread that even the central United States still bears the scars; in eastern Colorado, along the South Platte River, drought-induced sand dunes that originated in the mid-12th century still exist. Then, another drought struck from 1275 to 1300 A.D. (Dean and Robinson, 1977). Irrefutable evidence in the reservoir sediments tells us that these water operations were continuous, over a period of 350 years, and tells us of the remarkable achievements in social structure organization and community development that existed. For otherwise, how could people be expected to operate, dredge, and maintain such huge public works projects over a span of 15 to 20 generations? Little credit is given to the early Americans of the southwest and Mesa Verde for their ability to build, maintain, and operate big projects where organizational skills and technology transfer were essential.

Figure 8 A ceramic jar.

Acknowledgments

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Irrigation in the Indus Basin: A History of Unsustainability?

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Abstract: The Indus basin civilization (3000-1500 B.C.) is thought to have collapsed both because the Indus river shifted its course, and due to unchecked salinization of the irrigated land. This latter problem is recognised as a major obstacle to irrigated systems' sustainability. Though modern irrigation practices in the Indus basin do not have to worry about the river shifting its course, a priority concern should be the increasing salt profile. Though efforts have been made to deal with the problem since the 1960s, the net result is still an increasing salt balance. This paper explores what it means to manage risk, and then applies these insights to a narrative history of the Indus basin. Particular focus is placed on the modern management of irrigation in the basin since its actions will shape how irrigation is managed in the future. A key lesson to derive is that given the short-term nature of decision-making in the basin, any significant change has to address the political reality whereby politicians exert influence over water allocations in order to safeguard their political lives.

Keywords Indus basin; irrigation; risk; salinity; sustainability.

Introduction

A key feature of irrigation is its expansionist tendencies. Countries that rely on irrigation for their agricultural production, and economic growth, tend to want to maximise their ability to reap the benefits by expanding the area under irrigation. Most development loans for irrigation focus on increasing the irrigable area by capturing and delivering more water to more land. However, although it is perhaps understandable that countries want to maximise their agricultural and economic returns, the emphasis on increasing irrigated area is often detrimental to productivity in the long term. This is because they are focusing on irrigation's positive results, and ignoring its negative consequences-waterlogging and salinization. Given many countries' dependency on irrigated agriculture, it would appear foolhardy to ignore the system's inherent risks. Yet, it is common for countries to do so.

Whilst the productivity benefits of irrigation are well established, there has also long been an awareness that the advantages come with a price (Mulcahy, 1983). Questions about the sustainability of irrigation practices have been raised recently (e.g. by Khan *et al*., 2006) and a re-evaluation of the cost-benefit balance of irrigation has recently been called for by Hillel and Vlek (2005) who pose the simple but highly pertinent question 'Is irrigation sustainable, and if so, where, how, and under what conditions?'

The Indus basin has a long history of irrigation stretching back more than 4,000 years to the Mohenjodaro and Harappa civilizations. Does the existence of irrigation for so many years in the Indus basin mean that the system has found a way to deal with the risks inherent in irrigation? This paper will explore this question by first examining what it means to manage risk, and then apply the approach to the Indus basin's history. Particular interest will be paid to the modern management of irrigation in the basin since its actions will shape how irrigation is managed in the future in the Indus basin.

Managing Risk

The risk management literature tells us that every system has some inherent risk of failure that will threaten the system's sustainability. Therefore, it is wise to tackle this risk upfront before a failure occurs, in order to ensure the system's longevity. However, most systems are managed in ways that ignore these risks, and tend to be caught off-guard when an event causes a breakdown.

Risks are often ignored because short-term benefits are traded off against problems that may happen in the future. As time passes and the system functions without a crisis occurring, people involved in the system begin to believe that the system is infallible and fall into a 'blissful ignorance'. This ignorance may be a deliberate construct in which managers refuse to acknowledge that risks exist, or an unintended result of a lack of knowledge.

When a crisis does occur, the response is often reactive, dealing only with the immediate causes of the event rather than a full evaluation of the underlying issues and tackling of the accompanying risks. Consequently, the system is 'managed' in such a way that it lurches from crisis to crisis until it fails completely. In some cases the events that signal system failure are not specific events but actions that wear the system down over time. If we take this notion that every system carrying its own risk of failure as part of its make-up, it would suggest that irrigation systems also carry inherent risks.

Irrigation is essentially about controlling the amount of time soil is in contact with water. Being able to control this interaction at will leads to considerable positive benefits vis-à-vis a society's ability to develop agricultural products. In agricultural societies this has implications for their economic and social stability and longevity.

Irrigation also has negative consequences that usually stem from excessive use of water over time. This is aside from the environmental and social impacts arising from the infrastructure needed to control the water used for irrigation. The negative consequences are waterlogging and salinization. The primary cause is inadequate drainage. If excess water cannot drain away from the soil once it has been applied, it collects below the surface, raising the water table over time, leading to the soil becoming waterlogged. Since soil and water both naturally contain mineral salts, the application of water increases the amount of salts being applied to the soil. If the water remains stagnant in the soil, when it evaporates, salts leach out causing salinization. In both cases, the irrigated area eventually is unable to support agriculture. A related issue is the amount of water applied to the soil to begin with. If less water is applied, less needs to be drained away. Salts present naturally in soil and water, when concentration exceeds limits that are productive, aesthetic or environmental needs for society, land or water is considered salinised. Natural salinity is called primary salinity, whereas salt concentration increases due to human intervention called secondary salinity (Prathapar *et al.*, 2005).

Irrigated agriculture is a major human activity that leads to secondary salinity of land and water. The risk to the system from waterlogging and salinization is that they drive irrigable land out of production, and threaten the system's sustainability. Approximately 25% of irrigated land worldwide is currently salt affected to the extent that agricultural productivity is affected. Currently, 223,000 ha of irrigated land is going out of production each year. The obvious consequence is the collapse of irrigated agriculture in a society, and depending on its reliance on agriculture, it can lead to a societal collapse. Managing this risk means developing an irrigation system that applies only the water needed for crop production to the soil, and has good drainage to take excess water away.

Michel (1972) recognised that providing artificial irrigation systems need artificial drainage systems to be sustainable. However, the focus is often on providing the storage and distribution systems, and postponing the drainage systems because the effects are not evident until much later even though we know that the ultimate cost will be much higher. Because the first two components often overrun, even if drainage is included, investment is limited because of budgetary constraints.

In order to explore in more detail how the development of irrigated agriculture is often pursued in spite of rather than in full knowledge of the risk profile, we turn to an historical case study. The following section traces the history of irrigated agriculture in the Indus basin as a precursor to drawing out those aspects of irrigation practice which compromise sustainable food production and damage local ecosystems. We structure our narrative history by dominant governance systems.

Sustaining Irrigation in the Indus Basin

Today the Indus basin is home to 140 million people in Pakistan and contains two million farms. It also contains the largest contiguous irrigation system in the world with 16 million ha receiving approx. 172 km^3 of high quality river water annually. (Prathapar *et al.*, 2005)

Although there is a lack of a continuous history of irrigation in the Indus basin, we know that it is one of the oldest agricultural production systems in the Indian subcontinent. Annual floods have shaped agricultural development for more than 4 millennia. Pastoralism was the main form of livelihood because of space and unreliable rainfall, technical innovations that increased water availability have been vital to the region's agricultural history (Gilmartin, 1994).

The people of the Indus basin prospered on the foundations of an agriculture based system on irrigation and fertility, maintained by silt-bearing floods (Hawkes 1973). Wheat and six-row barley were grown, as were melon seeds, oil crops like sesame and mustard, and dates (petrified dates have been found in archaeological excavations in the valley). As for vegetables, the only apparent source was the field pea. The earliest traces of cotton known anywhere in the world have been found in the valley (Wheeler 1966).

Mohenjodaro and Harappa Period (Indus Civilization)

Harrapa was an Indus Valley urban centre of the second millennium B.C. It lay in what is now Punjab Province, Pakistan, on an old bed of the River Ravi. It provided the first clues to the ancient Indus Valley civilizations. The Harappa culture was part of a continuing evolution of the Vedic culture which had developed on the banks of Saraswati River. Harappan urban form, with its characteristic grid pattern, has also been correlated with various other functional requirements of a city, such as drainage, sewage disposal and transport systems. Though trade was important to the economy, so was agriculture. A variety of crops were grown including grain (Wheeler, 1976).

Located in modern-day Sindh, Pakistan, next to the Indus, Mohenjodaro is probably the best known Indus Valley site. Here a great bathhouse, uniform buildings and weights, hidden drains and other hallmarks of the civilization were discovered in the 1920s. Almost all houses had a form of bathroom with a pipe leading down either into storage jars or cisterns or into covered brick street sewers. The sewers had manhole covers, and sometimes flowed into storage pits. It is not known where the waste eventually wound up, but these cities would have been far cleaner than almost any before the modern period.

Nearing the end of the Indus Valley Civilization, the cities began to wither and the strong economy slowly deteriorated. It was most likely the intermittent floods that tore apart and put and end to this civilization. Floods wiped out the irrigation system that supplied water to the crops, and many of the buildings were smothered. The people lost their drive to keep the cities orderly and prosperous. The constant flooding simply broke their morale as a proud people of such an advanced civilization. If it is true that the Aryans invaded the Indus Valley at the time when the civilization was withering, it was no wonder that they had no trouble forcing the people of the Indus out of the area. But, it is certain that these people were powerful, determined, and advanced; easily seen through their strong willed and successful economy (Wheeler, 1966: 76-9). Their culture suffered as a result of a series of floods and droughts, and from the changing of the river's course and their civilization declined. Some climatic change may have resulted in the exploitation of the alluvial flood plains like the Indus which led to an increase in agricultural production.

Possehl (1997) questions previous hypotheses including Wheeler’s floods and proposes that there was no general collapse or eclipse, just a process of de-urbanisation and shift eastwards of the population. Other hypotheses concerning the collapse of the early Indus civilizations have proposed eco-disasters arising from overexpansion of population causing deforestation and agricultural abuse (Saier, 2004).

Mughal Period

The introduction of the Persian wheel between the 13th and 16th centuries allowed animal power to be harnessed to draw well water, and encouraged large-scale migration and agricultural settlement in central Punjab. Similarly, as inundation canals were built they influenced local agricultural production, opening areas that would not be dependent upon the rivers’ flooding, because more regular irrigation was possible. Inundation canal building during this period was not simply about technical innovation, but was also linked to political imperatives of rule. Though some canals existed under Mughal times, local rulers used inundation canals to consolidate their power as the Mughal empire declined in the late 18th and early 19th centuries.

Wescoat (1991) describes how perennial canal systems developed in Kashmir during the 8th century, and in Punjab and Sind during 13-16th centuries. Brief periods of large scale irrigation were punctuated by military conquests, court intrigues and frequent political restructuring. During periods of instability and decentralisation, well irrigation was used. By the mid-1800s, the only significant canal irrigation was provided by small inundation canals serving the floodplain areas along the Sutlej river, and the middle and lower Indus river. Well-fed irrigation was predominant mainly in the foothills where the water table was within 100 feet of the surface (Michel, 1972).

British Period

The British conquered Sind and Punjab provinces in the 1830s and 1840s and formally annexed Punjab in 1849 when they began to transform irrigation practices through new technologies. British irrigation policy prioritised returns on investments and protection against famine as guiding principles of investment. From the second half of the 19th century, British canal building took on a distinctive political and ideological significance with the aims of settling communities and strengthening imperial control (Gilmartin, 1994).

Because the Indus is one of the heavier silt-bearing river systems in the world, irrigation development had to contend with annual silt clearing to keep canals operational. When statute labour, *chher*, was outlawed under the British in 1870, the Sind provincial government realised that 25 percent of its revenues were going to pay for labour to do annual canal clearances (Gilmartin, 1994). In the 1880s the British started constructing interlinked irrigation canals that would eventually make millions of acres accessible for agricultural production, and settlement (Table 1).

Table 1 Development of irrigated area (x10^6 acres) (Gilmartin, 1994).

	1880s	1918	1940s
Punjab	1.32	9.06	14.0
Sind	1.5	3.16	4.5

Pakistani Period

In 1989, Pakistan's net irrigated area was 16.22 million ha and 78 percent of its arable land was irrigated. By 1995, Pakistan's net irrigated area was 17.2 million ha and 80 percent of arable land was irrigated. Groundwater currently provides over 40 percent of total crop water requirements in the densely populated province of Punjab, producing 90 percent of the country's food. The number of wells in this province has increased from barely a few thousand in 1960 to half a million in 2000 (Shah *et al.,* 2003).

The Tarbela dam (completed mid-1970s) is already silting up, with increasing water and power demands there is growing pressure for more dams (Westcoat, 1991). Surface irrigation and drainage problems have stimulated massive groundwater development involving hundreds of thousands of public and private tube wells. Many parts of Pakistan use fixed scheduling to provide water - the quantity is consistent, and the timing pre-determined (Sarwar and Perry, 2002).

A History of Unsustainability?

As described above, although it is unclear why the early Indus Valley civilizations collapsed, there is evidence for both river bed migration and salinization being contributory factors. Our primary focus hereon however is to trace more recent history which illustrates an inability to manage risk highlighted in our opening section. A pursuit of the services provided by water resources (primarily irrigation) has increased the overall vulnerability of the system to shocks and extreme events.

There is little doubt that irrigation in the Indus basin has disturbed the hydrologic equilibrium between recharge and discharge of groundwater (Prathapar *et al.,* 2005). Seepage from the canals, distributaries and watercourses, and deep percolation from irrigated lands have increased the natural recharge rates.

Several authors have pointed out that modern irrigation technology has been used in the Indus basin without anticipating its ecological impact, and that modern communities are now having to pay the price (e.g., Michel, 1972). British rule focused on extending the command area so that new regions could be settled and taxed, as well as resettling discharged soldiers, relieving over-crowded areas, creating a Punjab granary to offset famine elsewhere, and in Sind province increasing cotton production. Cropping patterns at this time were dominated by wheat and cotton that spread water thinly. Sugarcane production was limited; and rice discouraged until the water tables rose.

As early as 1859, close to the Western Jumna Canal in the Ganges basin, there were waterlogging and salinity problems but it was not until 1925 that the problem was given wider recognition with the establishment of the Waterlogging Enquiry Committee. Even then, irrigation was not seen as the cause, but other infrastructure that interfered with surface runoff. It was also suggested at the time that the Punjab was simply in a 'rainy cycle'; this despite the fact that the Lower Chenab Canal which had opened in 1892 had serious waterlogging problems by 1908. There was also a strong anti-drainage lobby that regarded high water tables as advantageous because it helped operate hundreds of Persian wheels and allowed the water to be utilised during the dry season. By 1949 water tables had risen close to the surface and even intersected with surface waters during the latter part of the summer (*kharif*) growing season. The average water table rise has ranged between 0.6-1.0 ft/yr since modern irrigation practices were introduced. By 1959, of the 23 million acres annually irrigated and producing at least one crop, 5 million were seriously damaged by waterlogging or salinity, and between 50-100,000 acres were being affected each year, many passing out of crop production altogether. In the worst districts in the Rechna Doab, 40-50% of cultivated land was severely damaged. Pakistan's groundwater and reclamation programmes are extremely complex and efforts to offset the undesirable consequences of surface irrigation are costly. Between 1965-75, the plans would cost US$1.1 billion which is more than the cost of building Tarbela dam (Michel, 1972).

As Michel points out (p263) "The lure of adding new acreage was still strong, and few were interested in reclamation when lost acreage could be replaced elsewhere" even though the costs of bringing water to new land was higher, and the soil quality poorer. Farmers responded by growing rice where the land was waterlogged and where it was salinised they grew only one crop or to reduce the amount of water used. However, as gross area cultivated increased, so less water was available to flush the salts out of the soil, which made the situation worse and lead to salt accumulation until land had to be abandoned. Lessons from elsewhere were not sought out or adopted and "there is no evidence that anyone, even within the same political jurisdiction, really learned from, or paid attention to, experience with waterlogging and salinity" (Michel, 1972: 265)

Most of today's water problems in the Indus region began during colonial period - salinity, drainage, inadequate water pricing, poor maintenance, provincial conflict, ineffective bureaucratic organisation etc. For example, water pricing has often been promoted as a way of improving water efficiency and system maintenance, but governmental inability to introduce it stems back to colonial times when it was repeatedly considered and then dropped for political and practical reasons. More than 100 years later circumstances still do not favour water pricing reforms. Many existing systems are well overdue for rehabilitation and renovation, raising a real challenge for moving to a more sustainable water management regime. (Sarwar and Perry, 2002).

Indeed, the frequency with which water management problems return and the sluggishness with which solutions have been implemented appear to be unaffected by modernity. As Westcoat (1991, p392) mused "the sobering lesson from the colonial period is that a problem may be well understood, and potential solutions may be well known, but it may take decades or centuries before the problem can be resolved." This reflection is echoed by Michel (1972: 272) who commented that "What amazes me about the history of agriculture is that the lessons of field cropping in semiarid margins have to be learned again and again, from place to place and from time to time." Given what we know about the cumulative effects of irrigation in inducing high water tables and surface salinity there is a real danger that these same fields may cease production a second time for reasons of declining fertility, waterlogging, and salinity.

Conclusions

As noted above, risks are an inherent part of any system and are particularly characteristic of large scale, highly connected systems. Whilst we cannot expect ancient societies to have applied modern approaches to understanding and mitigating against risk, we can expect both communities and governance bodies to learn from the past. Such learning can, however, be utilised in two ways. It can be incorporated into an understanding of how the resource can be better exploited, or it can be used as evidence for how management of the resource is limited in its capacity to generate benefit from the resource.

The dangers of a 'command and control' approach to irrigation in the Indus basin have been articulated elsewhere (Faruqee, 1996). Whilst our analysis supports Faruque's critique, we only partially concur with his conclusions. Although incentive, or market-based policies are an additional, and often effective, tool to achieve change, they still emerge from a management paradigm premised on a full and complete understanding of how the socio-natural system works. Such an understanding is, at any one point in time, risk reducing, often to the point of absurdity.

This study has shown that, despite four thousand years of irrigation experience, the Indus basin has continued to suffer from the negative impacts of poor irrigation system management. By taking a long term historical perspective we are able to demonstrate that, in the case of irrigation in the Indus valley, the future is like the past in that the risks of irrigation are not adequately mitigated for. But is this failing due to ignorance (a lack of knowledge or incapacity to learn), an inability to intervene in appropriate ways (lack of resources), or wilful convenience (a lack of political will to fully address the totality of the problem)?

Our own interpretation of this repeated inability to learn from the past is that successive regimes has two elements. Firstly we conjecture that the incumbent societies have not handled the accompanying risks. Though there have been advances in technology and understanding of how water impacts soil through irrigation, and large amounts of money have poured in to develop the irrigation system, the risks have not been addressed properly. It has been a case of either ignoring the risks, or doing too little too late. A key lesson to derive is that given the relatively short-term nature of decision-making in the basin, any significant change has to address the political reality whereby politicians exert influence over water policy. Political cycles do not well match the timescales of those drivers which upset the best laid plans.

Secondly, we argue that irrigation itself has an organizing effect on society, economy and governance. The allocation of water rights, scheduling of water use, construction, maintenance and defence of infrastructure from hostile neighbours, are all forces at work within hydraulic societies. This thesis, more elegantly laid out by Karl August Wittfogel (1957), premises that while irrigation can be carried out by small groups on an informal basis, it is more efficient and leads to greater growth if there is central management. Large scale, centrally managed systems are poor at responding to change and rely on command and control management styles to legitimize planning and intervention.

These tensions between the benefits and costs of coordination, collaboration and scale characterise many water management systems. We should be concerned that the lessons of the past appear not to have been learned in the Indus valley. But equally we should be optimistic that we are better armed than ever to create new realities which decouple some of the socio-natural couplings which create seemingly impassable challenges to more sustainable use of water resources.

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Analysis of the Water Supply System of the City of Apamea Using Actual Knowledge in Fluid Mechanics: Hydraulic System in the North-eastern Area of the City, in the Byzantine Period

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Abstract: In this paper, the flow of water in several elements of the water supply system of the city of Apamea is simulated. The studied elements were used in the 6th century A.D. (Byzantine period). These simulations allow a modern point of view analysis of the water supply system, in terms of water flow rate, energy loss, etc. This analysis provides a quantitative description of the water supply system of the city, supplementing the field observations.

Keywords Apamea; computational fluid dynamics; hydraulics; water supply.

Introduction

Capital of the Roman province of Syria Secunda, Apamea reached a real prosperity during the 5th and 6th centuries A.D. until Persian Wars and dramatic earthquakes made the city weak and vulnerable to the Arabic conquest in 638. A famous feature of the city is the Cardo Maximus, a 1,850 m long street with porticoes intersecting the town from North to South. The only known water supply of the city is an aqueduct, used from 47/48 A.D. until the 7th century at least, and bringing water into the town from a spring located 80 km from Apamea (Balty, 1987; 2000). Excavations in the north-eastern area of the city, where the aqueduct goes into the town, were performed in the last four years by the team of Prof. Viviers from the University of Brussels. They revealed at least four main periods of (re)construction, characterized by different water systems (Viviers and Vokaer, 2004). The latest one was built at the end of the 4th century A.D. or the beginning of the 5th and was used until the 7th century. This fourth period is itself divided in four sub-periods by the archaeologists.

The Romans had a remarkable engineering knowledge of water supply (Viollet, 2000). Only a few Roman writings on this engineering practice were preserved, but archaeology, as in Apamea, offers some precise illustration of their techniques. The surviving written records of Frontinus (Evans, 1994) and Vitruvius (Morgan, 1960) provide some understanding of water supply systems in Roman times, but they reflect pre-scientific views of hydraulic principles. The actual knowledge in fluid mechanics allows, together with the computational capacities of modern computers, a new analysis of the water supply system of the Roman cities, from new archaeological results. In this work, such an analysis is realized about

Apamea, whose political and administrative status could give us an excellent picture of the most advanced Roman technology in late antiquity.

The primary objective of this work is to characterize the flow of water in several elements of the supply system in the north-eastern area of the city. The investigated features were all used in the 6^{th} century A.D. (Period IV c). Global mass and energy balances are used, coupled with local Computational Fluid Dynamic (CFD) simulations. This study provides an hydraulic description of the water supply system of the city, supplementing the field observations about material, construction, chronology, etc. A secondary objective of this work is to tackle some historical open questions, from the results of the hydraulic characterization of the studied system.

Hydraulic System Studied

The excavated hydraulic installations in the north-eastern corner of the city are sketched in Figure 1. Arrows represent the flow of the water in the system during the late Byzantine period (Period IV c). Capital letters indicate the main elements of the system. The ancient aqueduct (A) is blocked at point B and the water was derived into a large cistern in a guard tower. This cistern was built at least in the beginning of the 5^{th} century, and probably in the 3^{rd}. From this cistern, the water was transported by an inner aqueduct (C), roughly oriented North-South. Although this inner aqueduct is covered, the level of water was not reaching its top. Therefore, a free surface flow took place. From point D, the covering blocks are missing. An observation hole is attested in E.

From this inner aqueduct, several derivations are performed. A first one occurs approximately 10 m after the beginning of the aqueduct. It is mainly composed of a canalisation made of the fitting of basic pipes into each other and hence characterized by the repetition of an elementary pattern (Fig. 2). Just after the beginning of the derivation, a room of visit is observed (F). The connection between the aqueduct and the room of visit is dug through the aqueduct wall. It is 34 cm long and has a rectangular section of 19 x 10 cm^2. The first pipe of the canalisation is connected to this room. This derivation carried water into a second cistern. A 90° bend is observed at point G. It is realized by the connection of pipes on a hollow stone.

A second derivation occurs approximately 5 m after the first one. Its destination point is not yet known. It is also mainly composed of a canalisation made of the fitting of basic pipes into each other. The elementary pattern of this canalisation is presented in Figure 2. Just after the beginning of the derivation, a room of visit is observed (H). The connection between the aqueduct and the room of visit is made of two lead pipes crossing the aqueduct wall, each having a rectangular section of 6x4 cm^2. The first pipe of the canalisation is connected to this room. A few m after the beginning of the derivation, a terracotta decanter was excavated (I).

Methodology

The flow rate of water in the inner aqueduct (Q_{aq}) is computed using the Manning equation (Whitaker, 1968):

$$\frac{Q_{\mathrm{aq}}}{\rho bh} = V_{\mathrm{aq}} = \left(\frac{bh}{b+2h}\right)^{2/3} \sqrt{\frac{2g\theta}{29\, n^2}} \qquad (1)$$

where,

h is the water height in the inner aqueduct;

b is the aqueduct width;

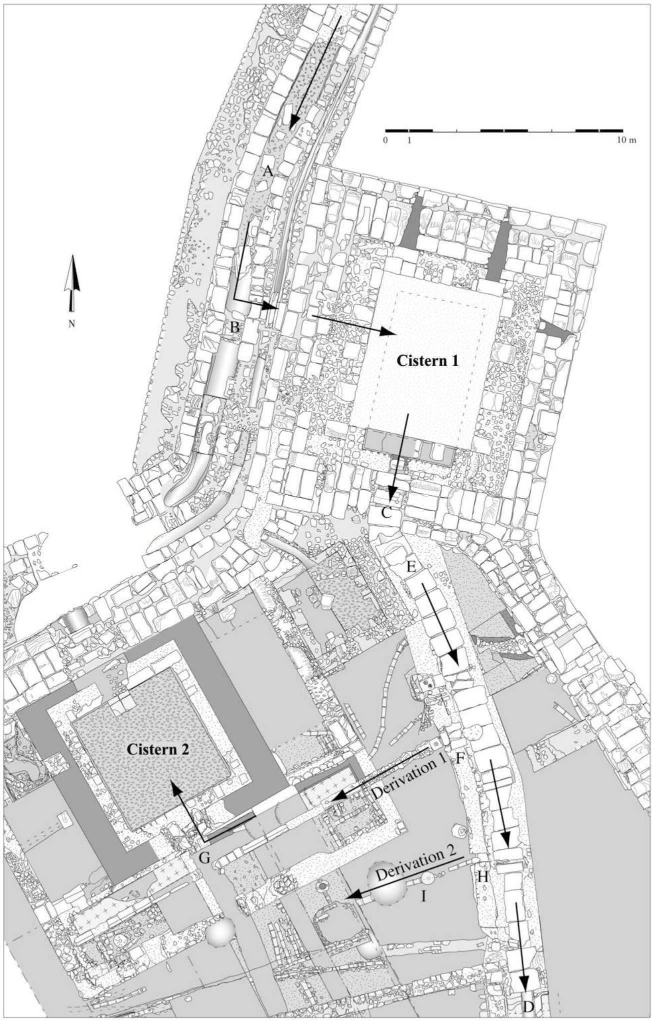

Figure 1 Hydraulic installations in the northeast corner of the city (drawn by Didier Viviers, CA.D. by Nathalie Bloch).

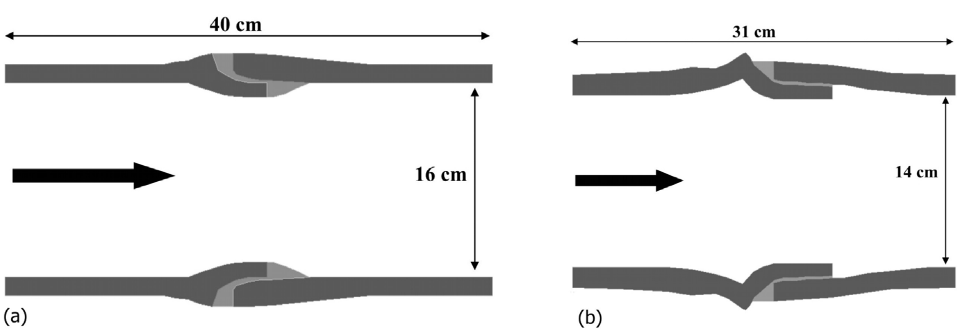

Figure 2 Elementary patterns of the canalisations in the first (a) and the second (b) derivations.

ρ is the volumetric mass of water;
g is the acceleration of the gravity;
θ is the aqueduct slope; and
n is the Manning coefficient, depending on the nature of the aqueduct walls.

b and θ are measured. h is also measured as a calcareous deposit is observed in the aqueduct. Values of n are tabulated (Whitaker, 1968). Therefore, Equation (1) can be used to compute the flow rate in the aqueduct.

The flow rate of water in a derivation, written Q, is computed using the Bernoulli equation. This equation states that the energy of the flow at the beginning of the derivation equals the energy of the flow at the end of the derivation plus the energy lost in the different elements of the derivation (such as the room of visit or the canalisation). When the water leaves a derivation under the form of a jet, the Bernoulli equation for this derivation can be written as follows (Whitaker, 1968):

$$\rho g\left(h+D\right)+\rho\frac{V_{\mathrm{aq}}{}^{2}}{2}=\left(C_{\mathrm{c}}L_{\mathrm{c}}+\sum_{i}C_{i}+\frac{1}{2\rho\Omega_{\mathrm{out}}^{2}}+\frac{1}{4\rho\Omega_{\mathrm{in}}^{2}}\right)Q^{2} \quad (2)$$

where,
L_c is the canalisation length;
Ω_{out} is the area of the outlet of the canalisation;
Ω_{in} is the area of the section of the connection between the aqueduct and the room of visit;
V_{aq} is the velocity of water in the derivation;
D is the height difference between the bottom of the aqueduct near the beginning of the derivation and the outlet of the derivation;
C_c is the energy drop coefficient for one meter of the canalisation.

The different C_i are the energy drop coefficients of the singularities observed in the derivation (room of visit, bend or decanter). C_iQ^2 is the energy loss in a singularity. L_c, D, Ω_{in}, Ω_{out} are measured. V_{aq} and h have been calculated previously. Therefore, if the different energy drop coefficients can be determined, equation (2) can be used to compute the flow rate Q. When the end of a derivation is submerged, the Bernoulli equation for the derivation can be written as follows (Whitaker, 1968):

$$\rho g\left(h+D-H\right)+\rho\frac{V_{\mathrm{aq}}{}^{2}}{2}=\left(C_{\mathrm{c}}L_{\mathrm{c}}+\sum_{i}C_{i}+\frac{1}{2\rho\Omega_{\mathrm{out}}^{2}}+\frac{1}{4\rho\Omega_{\mathrm{in}}^{2}}\right)Q^{2} \quad (3)$$

where H is the height of water above the end of the derivation.

Equation (3) gives a link between H and Q. Therefore, it can be use to predict the time evolution of H. In this work, the energy drop coefficients are calculated using a CFD commercial code: Fluent 6, where the local equations of fluid mechanics can be solved numerically in complex geometries. From the solution of these equations, energy drop coefficients, can be calculated (Versteeg and Malalasekera, 1995).

Numerical Results

Flow rate in the aqueduct

Between the observation hole (E, Fig. 1) and the end of the covered part of the aqueduct (D, Fig. 1), a slope of 2.1 ± 0.3 mm/m is measured. Between the entrance of the aqueduct and a point 2 m beyond the observation hole, a width of 57 ± 2 cm is measured. A calcareous deposit can be observed on the aqueduct walls. A water height of 92 ± 1 cm is obtained. The water level was a few centimetres below the covering blocks. For a calcareous deposit, a

Manning coefficient of 0.014 $m^{1/6}$ can be taken (Whitaker, 1968). Use of these parameters in the Manning equation yields $Q_{aq} = 521 \pm 61$ kg/s. The corresponding mean velocity in the aqueduct is $V_{aq} = 0.97 \pm 0.08$ m/s.

At the beginning of its utilisation, the aqueduct carried a same flow rate, but the roughness of the walls was smaller, as there was no calcareous deposit yet. Indeed, in this case, the water is in contact with a water repellent coating made of mortar, for which a Manning coefficient of 0.01 $m^{1/6}$ can be taken (Whitaker, 1968). Use of the Manning equation yields an initial height of water in the aqueduct of 66 cm.

First derivation

The first derivation is composed of a room of visit, a canalisation and a 90-degree bend. This derivation carries water into a cistern more than 3 m deep and having a floor surface of 24.75 m^2. The entrance in the cistern is located 1.70 m above its bottom.

Equation (2) or (3) can be used to compute the flow rate in the derivation if L_c, h, D, Ω_{in}, Ω_{out}, V_{aq} and the different energy drop coefficients are known. D = 4 cm, $\Omega_{out} = 0.02$ m², L_c = 12 m and $\Omega_{in} = 0.019$ m² have been measured. h = 92 cm have been measured and $V_{aq} = 0.97$ m/s has been calculated previously. CFD simulations allow determining the energy drop coefficients. Results of these simulations are presented in Figure 3. The energy drop coefficient for one meter of the canalisation is calculated assuming the presence of a calcareous deposit on the canalisation walls. It roughness has been measured equal to 350 µm. When the level of water in the cistern is below the end of the canalisation, a flow rate Q=22.6 kg/s is computed using Equation (2).

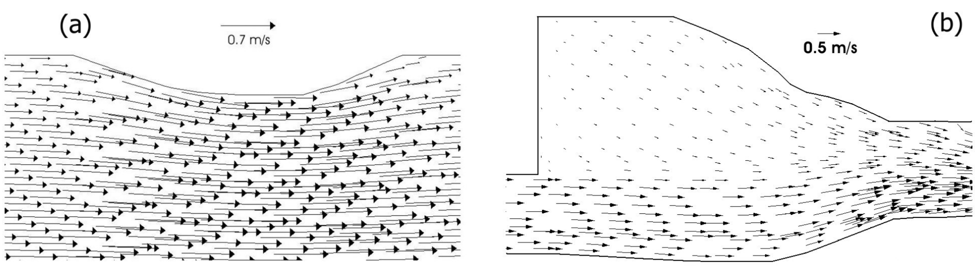

Figure 3 Flow in elements of the first derivation: (a) Flow near the connection between the pipes of the canalisation, Q = 10 kg/s; and (b) Flow in the room of visit, Q = 10 kg/s.

Q_{max} is defined as the flow rate that would be obtained if the derivation could transport the water without any energy loss. Setting all the energy losses to zero in equation (2) yields an equation for Q_{max}. $Q_{max} = 59$ kg/s is found. The efficiency Q/Q_{max} of the derivation is close to 0.4. The total energy loss in the derivation is 8.3 10^3 J/m³. The energy loss in the room of visit is 5.5 10^3 J/m³, the energy loss in the canalisation is 2.2 10^3 J/m³ and the energy loss in the bends is 0.2 10^3 J/m³. As it can be observed, the energy loss in the bend in small compared with other energy losses.

When the level of water in the cistern is above the end of the canalisation, Equation (3) is used to compute a mathematical link between Q and H. When Q = 0, the maximum value of H, written H_{max}, is reached. Setting Q = 0 in equation (3) yields H_{max} = 1 m. The maximum height of water in the cistern is thus 2.7 m. The cistern can be filled with 67 m³ of water. It can be computed that the cistern needs approximately one hour to be filled.

Second derivation

The end of the second derivation has not been found. Based on the topology of the place, it is assumed that the canalisation ends close to the Cardo Maximus (80 m from the aqueduct), and that the water leaves the derivation under the form of a jet. Calculation is similar with that carried out for the first derivation, but the energy loss associated with the decanter is here taken into account in the energy balance. L_c = 80 m is taken. Energy losses associated with possible 90-degree bends are neglected. Results of CFD simulations are presented in Figure 4. When D = 4 m (end of the canalisation on the first floor of a building), Q = 21.2 kg/s is obtained. The efficiency Q/Q_{max} is equal to 0.23. The total energy loss in the derivation is 37.6 10^3 J/m^3. The energy loss in the room of visit is 10.5 10^3 J/m^3 and the energy loss in the canalisation is 20.3 10^3 J/m^3.

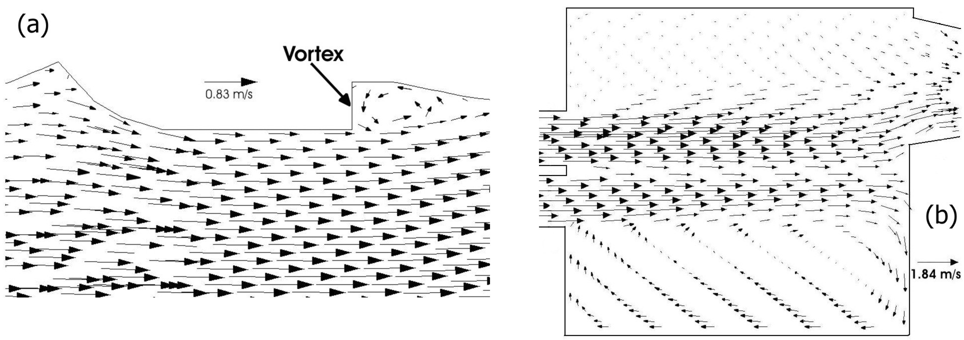

Figure 4 Flow in elements of the second derivation. (a): Flow near the connection between the pipes of the canalisation, Q = 10 kg/s; (b): Flow in the room of visit, Q = 8 kg/s.

Analysis

It has been shown that the aqueduct carried a water flow rate of 0.5 m^3/s or 43.2 10^3 m^3/day. Nowadays, there is an open question about the water consumption in Roman cities. Daily consumptions between 200 and 500 l per capita are reported (Chanson, 2002; Viviers and Vokaer, 2004). According to these values, 43 10^3 m^3/day could fulfilled the needs of a population between 90 and 220 thousands people.

Firstly, the water level in the aqueduct was 66 cm height. As soon as a calcareous deposit was formed, the roughness of the surface increased and hence, the level of water in the aqueduct rose. It finally stabilized at 92 cm, only a few centimetres below the covering blocks. This observation could lead us to think that the Romans had foreseen this elevation of water height at least qualitatively and maybe even quantitatively.

First derivation

This first derivation carries a water flow rate of 23 kg/s towards a cistern that takes approximately one hour to be filled with 66 m^3 of water. Regarding the transport of water, each part of the derivation has good characteristics. The shape given to the mortar, ensuring the fitting of the basic pipes of the canalisation into each other, prevents the apparition of vortices (see Fig. 2, 3 and 4), and hence decreases the energy loss in the canalisations. The energy loss associated with the 90-degree bend is negligible in comparison with energy losses in other parts of the derivation. The engineering technique of this kind of bends had not to be improved. Finally, no vortex is generated in the room of visit. The flow is conducted from the entrance to the exit by a good shaping of the room walls (see Fig. 3). Q/Q_{max} is close to 0.4. Hence, in the total absence of energy loss in the entire derivation (physically impossible as energy is needed to sustain the turbulent flow of the liquid) the cistern would take 24 minutes to be filled instead of 1 hour.

Second derivation

It has been shown that the second derivation is able to carry a large amount of water to and even beyond the Cardo Maximus. Indeed, it has been calculated that if the derivation ended on the first floor of a building close to the Cardo Maximus, the flow rate in the derivation would be approximately 20 kg/s.

Regarding the transport of water, the technical design of this derivation is clearly not as good as the one of the first derivation. This observation is valid for each part of the derivation. The energy loss in the room of visit is here more than twice this energy loss in the first derivation, at a same flow rate. There is no shaping of the room walls, leading the formation of a large vortex that consumes a lot of energy (Fig. 4). At a same flow rate, the energy loss per unit length of the canalisation is here almost twice this energy loss in the first derivation. The vortex generated at the connection between basic pipes is mainly responsible for this difference (Fig. 4). In the first derivation, it is the shape given to the mortar that prevents the apparition of this vortex.

Conclusion

In this paper, the flow in several elements of the water supply system of the city of Apamea is studied. The investigated features were all used in the 6th century A.D. (Period IV c). Global mass and energy balances are used, coupled with local Computational Fluid Dynamic (CFD) simulations, using the commercial code Fluent 6. The studied elements are characterized in terms of water flow rate, energy loss, hydrodynamic regime, etc. This study provides an interesting description of the water supply system of the city, supplementing the field observations about material, construction, chronology, etc.

A secondary objective of this work is to tackle two historical open questions, from the results of the hydraulic characterization of the studied system. First one concerns the number of aqueducts bringing water to the town. The computed flow rate in the aqueduct indicates that this single aqueduct could fulfil the needs of a large population (between 90 and 220 thousand people). This element, joined to the site topography, making more difficult another water adduction which should have been weaker because of the necessity of crossing the wadi or the Ghab valley, seems to confirm the existence of a single aqueduct carrying the water into the city.

Second one concerns the quality of the water supply system operated at the end of the Byzantine period and its ability to carry water beyond the Cardo Maximus. It has been shown that the first derivation, built in the 6th century (Viviers and Vokaer, 2004), is a very good work, reflecting an excellent technical knowledge of water supply, until the end of antiquity. Furthermore, it has been shown that the second derivation is able to carry large amounts of water to and even beyond the Cardo Maximus. This second derivation has an efficiency two time smaller than installations used nowadays.

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Environmental History of Water: Global View of Community Water Supply and Sanitation

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Abstract: Water is life - and life on earth is linked to water. Our existence is dependent on water - or lack of it - in many ways and one could say our whole civilization is built on the use of water. This paper summaries the general outline and some of the main results, which will be published in a book by IWA Publishing with the title: Environmental History of Water: Global View of Community Water Supply and Sanitation.

Keywords History; public health; sanitation; services; water supply.

Introduction

Approximately 50,000 years ago modern man began to inhabit every corner of the world and people were constantly on the move. Occasionally people were troubled by pathogens transmitted by contaminated water, but general aversion for water that tasted revolting, stunk and looked disgusting must have developed quite early during the biological and cultural evolution of mankind. Approximately 10,000 years ago mankind started to practice sedentary agriculture which changed its relationship with water as permanent settlements concentrated near lakes, rivers and wells. Farming, settling down and building of villages and towns meant the start of the problems mankind suffers from this very day - how to get drinkable water for humans and cattle and how to manage the waste we produce.

Water is life - and life on earth is linked to water. Our existence is dependent on water - or the lack of it - in many ways, and one could say that our whole civilization is built on the use of water. This paper summarizes the general outline and some of the main results soon to be published in a book by IWA (Juuti *et al.*, 2006). The authors of individual chapters in the book were requested to view the issues of population growth, health, water consumption, technological choices and governance as appropriate. The book divides into four chronological sections. The first one describes water supply and sanitation services during the first urbanization of ancient civilizations focusing on ancient Greece and Rome. The second section concentrates on the long 19th century (*ca*. 1700-1910 A.D.). The third section deals with urban infrastructure in the 20th century, and the fourth one with the future challenges of water supply and sanitation services.

First Urbanization: Early Systems and Innovations

Modern humans (Homo sapiens) have dwelled on this earth for some 200,000 years, most of that time as a hunter-gatherers, gradually growing in number and inhabiting every corner of the world. Yet, archaeological and written sources concerning water and sanitation can be found only on relatively recent times. Thus, in reconstructing the history of water and sanitation of this hunter-gatherer phase, we have to rely on analogies with later societies. Modern anthropological studies and recorded mythologies of indigenous peoples play an important role in these analogies while observing primates and other more evolved mammals can also give us useful information.

Humankind established permanent settlements about 10,000 years ago, when people adopted an agrarian way of life. This new type of livelihood spread everywhere and the population began to expand faster than ever before. Sedentary agricultural life made it possible to construct villages, cities and eventually states all of which were highly dependent on water. The earliest known permanent settlement, which can be classified as urban, is Jericho from 8,000-7,000 B.C., located near springs and other bodies of water. In Egypt there are traces of wells, and in Mesopotamia of stone rainwater channels, from 3,000 B.C. From the early Bronze Age city of Mohenjo-Daro, located in modern Pakistan, archaeologists have found hundreds of ancient wells, water pipes and toilets. Around 3,000 B.C. the draw well with a counterpoise lift was invented in Mesopotamia and later on introduced by the Greeks and Romans to Central and Western Europe. Since antiquity the best known water supply structures have been the gravitational water pipes or aqueducts built by the Romans. The building of an aqueduct seems to have been a cultural necessity for a respectable town in Roman times. It is justified to argue that the basic reason for building the aqueducts was luxury, the baths, not the acquisition of good drinking water.

The experience of humankind from the very beginning testifies to the importance and safety of groundwater as a water source, particularly springs and wells. The way in which water supply and sanitation was organized was essential for early agricultural societies. If wells and toilets were in good shape, health problems and environmental risks could be avoided. It must be remembered that most people in the world took their drinking water from private or public wells until the last quarter of the 19th century. In the case of cattle farming, watering of livestock accounted for most water use. Wells and latrines are still in use and will certainly remain so in the future.

It has been postulated that the waterborne health risks of hunter-gatherers were small, while pathogens transmitted by contaminated water became a very serious health risk for sedentary agriculturists. Consequently, the first urbanization of Europe during antiquity would not have been possible without transporting or supplying a sufficient amount of good quality water to towns. The realization of the importance of pure water for people is evident already from the myths of ancient cultures. Religious cleanliness and water were important in various ancient cults. Ideas of the salubrity of water were connected to the general "scientific" level of the society. The first known Greek philosophical thinkers and medical writers also recognized the importance of water for the health of people, which was to be a widely held view of ancient Greek and Roman writers.

Classical Greek medicine adopted a sincere confidence in rationality and logic and in the rejection of the supernatural causation of diseases (expressed, e.g., in the so-called Hippocratic writings, mostly written around 400 B.C.). The confidence in rational thinking is clearly expressed in those treatises that deal with the health aspects of water. Cool, tasteless (or tasty), odourless and colourless water was considered the best, while stagnant and marshy water was to be avoided. These ideas remained until the end of antiquity.

Simple settling tanks, sieves, filters and the boiling of water were methods for improving the quality of water already in antiquity. However, available sources do not permit the estimation of the public health effects of these treatment methods. The poor level of waste management, including waste water, was most probably a major danger for public health during antiquity. Consequently, waterborne infections, such as dysentery and various diarrhoeal diseases, must have been one of the main causes of death.

Water supply and sanitation for military needs was a primary concern of the authorities of an imperial power like the Roman Empire needing a strong military machine. The Romans did know how to obtain adequate amounts of drinking water for their garrisons, cities and troops in the field and thus successfully planned their operations according to the availability of water. Army veterans were well accustomed to baths and to an ample water supply during their active service, and they may have been a quite important pressure group for building an aqueduct and bath in a town.

Second Urbanization: The Long 19th Century

After the fall of the Roman Empire, water supply and sewage systems experienced fundamental changes in Europe. Medieval cities, castles and monasteries had their own wells, fountains or cisterns. Usually towns built a few modest latrines for the inhabitants, but these were mostly inadequate for the size of the population. For example, the streets of medieval London or Paris were full of waste. The lack of proper sanitation increased the effects of epidemics in medieval towns. At the same time, for instance in Tokyo, Japan, the situation was relatively much better.

Fundamental changes began to appear: science and knowledge were institutionalized for the first time when the development of modern universities started in the 13th century, and the agricultural world set out to industrialize from the 18th century onwards. Consequently, the growth of world population increased. All this profoundly affected water supply and sanitation.

Along with the industrialization and urbanization of the Western world, enlightened people were fascinated with the idea of progress. Ever since the 18th century, science and reason were considered to be able to lead humankind towards an ever-happier future. This was the period when the first actual water closet was developed. By 1900, the water closet became a generally accepted cultural necessity in the Western world -the same way aqueducts had been in the Roman Empire. The water closet was seen as a victory for public health care without any consideration for where the human excreta went through sewer pipes.

The start of industrialization and the related growth of cities created a situation where public health and environmental problems overwhelmed city governments to a greater degree than before, and novel technology was often seen as the solution. In the 19th century, Great Britain was seen as the forerunner of modern water supply and sanitation systems, but the innovations soon spread to Germany, other parts of Europe, USA and later also elsewhere. In the middle of the 19th century, most Western nations, if not all, started to develop urban water and sanitation services through privately owned companies or private operators. Yet, in most countries the utilities were fairly soon taken over by municipalities. Sanitation in towns around Europe was one of the great achievements of the 19th century. During the century the role of water in the transmission of several important diseases - cholera, dysentery, typhoid fever and diarrhoeas - was realized. The final proof came when the microbes causing these diseases were discovered. Especially cholera served as a justification for the sanitary movement around the world in the 19th century.

Sensory evaluation of water quality was complemented with chemical and microbiological examination. During the 19th century, filtering of the entire water supply of a town was introduced and the systematic chlorination of drinking water started in the early 20th century. The discovery of microbes and the introduction of efficient ways of treating large amounts of water paved the way to an era in which the public health problems caused by polluted water seemed to belong to history.

Third Urbanization: Modern Urban Infrastructure

The 1900s was a period of extensive population growth -the global population about quadrupled while the urban population increased 13-fold. By 2,000 A.D., in almost every country, over half of the population lived in urban areas. The rapidly developing chemical industry enabled pharmaceutical companies to develop a multitude of efficient chemical compounds such as contraceptive pills and antibiotics. The internal combustion engine and the mass production of cars, aeroplanes and other vehicles started to increase travel and mobility. During this century industrial production increased 40-fold and the consumption of energy by a factor of tens. Water and sanitation services had a definite role in this rapid socio-economic change of the entire globe.

In the early 20th century the health problems associated with water pollution seemed to have been resolved in the industrialized countries when chlorination and other water treatment techniques were developed and widely taken into use. Today there is a global shortage of potable water. While microbiological problems related to water are largely a problem of the developing world, new types of biological health hazards transmitted by water are also emerging in the post-modern Western world. Anxiety about chemical and radioactive environmental hazards and their impacts on human health mounted in the 1960s.

In the middle of the 20th century it was considered that the only remaining serious waterborne public health risks were chemical and radioactive contamination of water. However, in the late 20th century the biological hazards transmitted by water emerged again. The overall amount of known biological and chemical health hazards transmitted by water increased manifold during the last half of the 20th century.

In the early 20th century urban water and sanitation services were run by municipalities in most Western countries. However, in the 1980s full privatisation of these services was reintroduced in England and Wales and soon thereafter promotion of transnational private operators began in Latin America. These policies of water service privatisation since the 1980s have completely ignored the lessons of history.

Fourth Urbanization: Future Challenges, does History Matter?

In the historical context, the growth of urban centres has been a continuous and even an escalating trend. Many of these centres are today located in developing economies, while the ensuing problems are concentrated on the poorest people - as always. The most severe constraints include poor living conditions, a lack of democracy, poor hygiene, illiteracy, corruption and a lack of proper water and sanitation services. Especially women and children suffer from these constraints.

When making the big decisions concerning water supply and sewerage, it is also necessary to be ready to make big investments. Although water and wastewater facilities are mainly hidden underground, all city dwellers come daily into contact with the products of water and sewage works: potable water, treated wastewater, cleaner water bodies as well as easier and safer everyday life - or too often their non-existence. Services that are now at a high operational level were not achieved easily and without massive inputs and efforts. This is something to keep in mind when assessing future options and considering required strategies.

In today's world around 10,000 people die every day due to diseases like dysentery, cholera, and various diarrhoeal diseases, caused by a lack of safe water and adequate sanitation. Yet, since most of those who die are children and old people, whose death is considered "natural", or people who are more or less marginalized in their societies (e.g., refugees, the poor) or living outside areas that are important for the global economy, mortality due to these waterborne diseases is too often considered unavoidable.

The level of water supply and sanitation in a society is not necessarily bound with time and place as much as the capability of that society to take responsibility for developing the living environment of its citizens and proper policies. In some cases, the situation was even better earlier than nowadays. Decisions have been made concerning water and sanitation systems - e.g., the universal acceptance of the water closet as a cultural necessity - that through path dependence have limited future options. There have also been situations where the choice of a technology has been regarded as problematic from the first beginning but has been chosen anyway. For instance, lead pipes were considered hazardous for health already in antiquity but continued to be used in house connections until recently.

Water supply and sanitation systems have always required continuous maintenance and adequate rehabilitation. This was already evident with the Roman aqueducts: calcium carbonate incrustation forming within the conduits needed to be removed constantly or it would have stopped the flow of water. The same is true for modern systems: they must be maintained to function properly. In the historical context, we can see both a continuation and a change in the perception of good quality drinking water and waterborne health hazards, which are both highly dependent on the scientific and technological level of a society. The importance of good quality drinking water for urban populations was realized already in antiquity. Yet, the importance of proper sanitation for the health of townspeople was not understood until the 19th century. The building of "modern" urban sewerage systems started in Britain and rapidly spread all over the globe.

The availability of water in large quantities has been considered an essential part of a civilized way of life in different periods: Roman baths needed a lot of water as does the current Western way of life with water closets and showers. Particularly high rates of water use occur when it is not properly charged for. Evidence indicates that as soon as water and wastewater are charged based on real costs, wastage diminishes remarkably. There are numerous development paths that water supply and sanitation can take. From the point of view of the wellbeing of man and the environment, it is essential that water is good and safe - regardless of whether it is from piped systems or point sources like wells. The same applies to sanitation — it is a question of being connected either to the sewer or using proper on-site sanitation solutions. Local conditions, traditions and people have to be in the core of decision making when future solutions are considered. In the long historical perspective, it is evident that regardless of the political system, good local solutions can be found based on local conditions, needs and traditions. Although water - and particularly water services - are largely dependent on local conditions, it is useful to make comparative studies between various regions and cultures, and identify possibly applicable and replicable principles and practices.

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Features of the Urartian Gardens in the Context of the Relationship between Historical Urartian Irrigation Canals

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Abstract: During the development of human civilization, "water" has been a vital element. There has been remarkable effort to use the water for the survival and development of the mankind. These efforts shaped all aspects of life styles and power balance in the regions. The most available regions in the Near East were derived from this labour. By this time, Urartian civilization was built up with aqueducts, dams, reservoirs and irrigation canals and became an important power in that period of time in Mesopotamia. Urartians chose the City of Van as the capital in the eastern part of Turkey, on the border of Iran and developed a hydraulic civilization of their period. Severe natural conditions and kingdom's cultural features formed these hydraulic civilizations abilities and works. Taking guide the Babylon irrigation works and being in that geography resulted Urartians to make similar green areas and gardens in Urartu. These gardens which were set in that time are still forms the green areas in the City of Van. Like historical Urartian irrigation canals, these are the cultural heritage of Turkey and the world, so they should be converse as global values. In this sense, the aim of this paper is to redefine and display the relationship between the irrigation canals and gardens of Urartian, on a case area: Menua (Shamiram/Semiramis) Irrigation Canal and Terraced Gardens. This review paper is based on literatures which are about Urartian period, Urartian aqueducts, nature cults, history of garden and Mesopotamia gardens. According to this literature, it's concluded that, Urartian gardens were similar with the other utilitarian and functional gardens through the human civilization. Beside other functions of these gardens, the water system which the garden depends on, fruit cultivation and use of water helped them to survive or long live. In relationship with Urartian irrigation canals and according to their own properties, these gardens are also part of the cultural heritage. In this sense, it is concluded that Urartian hydraulic heritage and gardens should be conserve and should guide to the modern civilizations and hydraulic technology, today's garden art.

Keywords Urartian irrigation canals; Urartian gardens.

Introduction

The history of human civilization is intertwined with the history of manipulation and using ways of water resources by human. The earliest agricultural communities arose where crops could be grown with dependable rainfall and perennial rivers. Irrigation canals permitted to increase crop production and to have longer growing seasons in dry areas and sewer systems fostered larger population centers.

According to the development of irrigation, gardening has begun as the critical intermediate step between hunting and gathering and agriculture. Passive gathering became active planting, tending and harvesting. As the garden reliably begins to produce a larger portion of the food supply, there is less wondering in pursuit of game, resulting in the settlement of villages around the garden plots. So, gardening is also as old as civilization. According to the natural features of the settlements and cultural features of population, gardens were development in and near human settlements. They are rooted in the desire of citizens to surround themselves with beautiful plants, shade and unique foods. In this sense, the garden was thought of as a medium for serving certain essential purposes. Giving a special distinction and importance to the surroundings of an architectural work and treating as an ideal version of a cultivated plot are some of the important purposes of gardens (Anoymous, 1993). It is possible, with the aid of the surviving gardens and the available descriptions and pictorial records, to list the following features as generally characteristic of gardens of this type: (a) Existence of an individual "water factor", since the system of use, and hence the plan, of the garden depended entirely on its water supply and drainage system; (b) use of trees as standard elements in the design of the spatial structure of the garden; and (c) subordination of the recreational to the utilitarian function (for example, provision of seats in the shade of a vine or fruit-tree, etc.) (Micoulina, 1993).

Through cultivation of plants for food long predates history, the earliest evidence for ornamental gardens is seen in Egypt, Persia and Near East. As the gardens in the Near East, the gardens in Mesopotamia where also Urartu Kingdom established had a religious facet also. These gardens, only set for functional benefits as the ones in early Assyrian Kingdom, differentiate from the gardens which were set for exhibition and pleasure in other traditions. Just as the size may vary, so the purpose of the garden may range widely between what is primarily useful, and what is purely ornamental. At one end of the scale, we find vegetable gardens, orchard gardens, and myriad variations in the small plots of allotment gardens, cultivated for their yield of vegetables, herbs, or soft fruit (Micoulina, 1993).

Turkey was at the crossroads of these ancient civilizations and constitutes one of the world's leading open-air museums with respect to ancient water works, human settlements and functional gardens, some of them being still in operation. The most ancient remains of waterworks in Turkey date back to the II. Millennium B.C. From the first half of the I. Millennium B.C., the Urartu period in Eastern Anatolia, there exist various remains of dams, canals (Türkman and Ösis, 2004). All of these dams, reservoirs and irrigation improved and increased the agricultural production on the region at that time. At that time, Urartians had made agriculture as a main economic source. Although, some of these structures have survived against violent earthquakes from past to today, they need serious conservation. All these structures of the Urartians, the greatest hydraulic civilization of the ancient Near East of that time has to be conserved not to loose the knowledge about their cultural and architectural history. To improve modern water technology and to establish a connection between nature and human, we need to learn more about early civilizations, like Urartians. Urartians was a wealthy civilization with her public works like irrigation and transport projects and infrastructures and stone works as well as mining, agriculture, viniculture and stock-breeding (Anonymous, 2002; Sevin, 2003).

With the combination of the advantage of having water resources in the region, being a hydraulic civilization, through their religious beliefs and relations with nature, Urartian civilization had a remarkable role in today’s landscape of Eastern Anatolia. They were one of the important guides in Mesopotamia and they also learned much from the other civilizations in the region. In the framework, the gardens in Mesopotamia were guided the development of horticulture and gardening in Urartu by the development of irrigation. In this sense, to redefine and display the relationship between the irrigation canals and gardens of Urartian, on the Menua (Shamiram/Semiramis) Irrigation Canal and Terraced Gardens which is the most conserved, which is functional even today (Belli, 1997a).

Study Area and Method

Study area

Between the ninth and sixth centuries B.C., Urartians choose Upper Tigris and Northern and Eastern Side of Euphrates. This is a mountainous area which is about 1500 m height consisting Van, Urmiye, and Gokce lakes. Lake Van is the largest lake in Turkey with an area of 3,713 km². Settling on the coast of Lake Van provided important advantages to Urartians. Capital of Urartian Civilization was located in the City of Van, near Van Lake, which was called Tushpa (Tusba) (Anonymous, 2002). City of Van is in the eastern part of Turkey, on the border of Iran. It is located at an elevation of 1,750 m. Van Region features mountainous terrain with harsh winters. There is a transitional climate between terrestrial and Mediterranean climate in Van. Steppe flora is common in and around the City (Fig.1).

Figure 1 Geographic location of City of Van, study area.

Method

This review paper is based on literatures which are about Urartian period, Urartian aqueducts, nature cults, history of garden, and Mesopotamia gardens. In the literature on the research area, about Urartian dams, reservoirs and aqueducts are archeological data. Literature about the gardens of the area generally depends on the legends and on archeological tablets. So there is not any definite plan about the gardens of that period. According to the information collected from these literature, it's tried to redefine the relationship between architectural works especially aqueducts and Urartian gardens. To display this relationship, the most known and still working Urartian canal, Shamiram Canal and its hanging gardens is the case area of this review.

Findings

Urartian water works

Urartu was one of the important civilizations for the developed infrastructure works especially on this region. They built up the first organized road systems in Eastern Anatolia and also, constructed first harbour on the shores of Van Lake. Besides these, the most important and glaring contribution of Urartians to the civilization of the world and Anatolia is, their irrigation systems. In the first half of the first millennium B.C., Urartian Civilization constructed first irrigation canals, reservoirs and dams. "The Urartians thus represent an important bridge in the development of agricultural irrigation and dam building in Anatolia up to the present day. The Urartian dams on streams and small rivers built nearly three thousand years ago are the forerunners of the modern dams on the Euphrates and Tigris rivers in Eastern Anatolia today" (Figs. 2 and 3) (Belli, 1997a).

Figure 2 Present condition of Urartian irrigation canals (Anonymous, 2004).

Figure 3 Urartian canal that passes through mountains area in Van (Bingöl, 2005).

In Van Plateau and near surrounding, there were about 50-60 irrigation dams and about 33-48 underground irrigation canals which were connected to these dams. In the world, similar to underground irrigation canals which were found in China and Afghanistan, they have seen only in Van in Turkey. These underground irrigation canals had been used also for use and irrigation water although they used for only drinking water in China and Afghanistan (Anonymous, 2005).

Urartian nature cults and gardens

Nature events and natural elements had been very important for Urartians, even idolized. Water resources, caves, monumental trees and reefs had spiritual meanings for them. Fish figures drawn near water resources, cave drawings, life tree figures and reef drawings show the sanctity of these natural elements. Urartians, to whom nature events and natural elements were so important, also gave importance to viniculture and gardening (Belli, 1997a).

When planning a new city, Urartians always had given great attention to set vineyards and fruit gardens beside cities. These gardens had been set up for kings, nobles, king wives, daughters or gods, and name of the gardens had been given according to these owners. In the gardens set for themselves or gods, Urartians had organized sacrifice ceremonies for gods. Therefore, these gardens had also a religious meaning. Especially, fruit and vegetable had been cultivated in these gardens. Scales of the gardens were small and there were pavilions which had been used as gazebo in summer (Belli, 1997a; Sevin, 2003). Until today, two famous irrigation canals have been attested in Eastern Anatolia. One of these is the Menua Canal which has been known for 170 years but has not been extensively studied.

The Menua (Shamıram/Semıramıs) Irrıgatıon Canal

The Menua Irrigation Canal is a marvel of hydraulic engineering. 51 in length, the canal is also a reminder of the legends surrounding the elusive Assyrian queen, Semiramis, Queen of Assyria. The hanging gardens in the form of artificial terraces built by King Menua for his daughter Tariria were intended to rival the hanging gardens of Babylon which were built for Semiramis and became one of the seven wonders of the world (Fig. 4) (Belli 1997b).

Figure 4 Present condition of the Menua (Shamıram/Semıramıs) Irrıgatıon Canal (Belli, 1997b).

Kept in good repair over the 2,800 years since it was built, The Menua Canal carried fresh water from the Gurpınar plain, 50 km south of Van to Van Plain where Tushpa, the capital of Urartu, was situated. Along its entire length, it imports life to the dry soil, watering over 5,000 ha of land. No other irrigation canal in Anatolia or indeed anywhere else in the world has functioned continuously over nearly three millennia. 15 tablets were put on the nearest reefs to the canal and canal walls, made Menua Irrigation Channell, a "tablet monument". Unfortunately, most of the tablets are lost today (Belli 1997a; Sevin 2003).

The altitude of the Menua Channel on the last point in Van Plateu is 1,700 m. The channel had carried water to the Plateau with a slope between 10/10,000 to 3/10,000. The capacity of the channel, carrying 2.5 m³ water average is more than 75 million cubic meters. Carrying water with this slope is also the ideal slope for today's modern engineering calculations. So, State Hydraulic Works Directorate of Van, decided not to change the old way of the Channel made by Urartians. These retain walls are still being used (Belli, 1997a).

Menua Irrigation Channel gives life to the fruit and vegetable gardens on the fertile soil of near surrounding. There are terrace gardens, called Kadem Bastı, formed by lots of soil brought from different places around the Channel. Fruits growing in vineyards and fruit gardens those benefit from the sun light from sunrise to sundown, are the most delicious fruits of Van even today. In Kadem Bastı Region, on the walls of the Channel, below line has been written by King Menua: "*This vineyard is the daughter of Menua, Tariria. Its name is Tariria Vineyard*". Even today, these fruit gardens and vineyards around the Channel are the most beautiful recreational areas on the coast of Lake Van (Belli, 1997a).

Conclusion

As everywhere in the world, water was a driving force for Urartians also. With the aim to reach water resources and using it productive, Urartians developed remarkable hydraulic engineering. Together with nature cults, management style and religion of the Kingdom, this competence helped them to built model irrigation canals for modern hydraulic engineering which are today the cultural heritage of Anatolia and also the world. The dams, reservoirs and irrigation canals built by the Urartian Kings in Eastern Anatolia were used also in medieval and Ottoman Empire period, as today.

Although to the hard conditions of the region, Urartian irrigation canal system provided the development of agriculture and horticulture, especially fruit and vegetable gardens and vineyards. These gardens were set through the geographical, natural and cultural features and also through the Urartian nature cults and religious belief. Mesopotamian gardens especially Hanging Gardens of Babylon, which were formed also by functional features like food, timber and shade, not only by religious beliefs, were the inspiration for the Urartian gardens. According to the literature review about the subject and the area, the characteristics of the relationship between Menua Irrigation Canal and its hanging gardens area are: (a) Menua Irrigation Canal, so the “water” supported to set Menua terraced gardens; (b) beside other functions of this garden and the similar ones in Urartu, fruit cultivating was the main function; and (c) being constructed by the Kingdom for his daughter and having lots of tablets show the kingdoms or nobles role in setting gardens and in the form of Tusba.

In this sense, as the other architectural works, irrigation canals of the Urartians also supported to set functional gardens like any other period in the civilization. Beside other functions of these gardens, the water system which the garden depends on, fruit cultivation and use of water help them to survive or long live. In these sense, Urartian gardens were similar with the other utilitarian and functional gardens through the civilization. In this framework, during a new city planning Urartians gave great importance to set vineyards and fruit gardens nearby the city. These gardens were established by the Kings and other nobles who gave their names, wives’ or daughters’ names.

The irrigation canals and the gardens nearby them used for a long time, till they were mostly destroyed by the wars those took place in the City of Van. Lack of financial support and human resources and hard conditions of the region are the main problems in restoring, conserving and rehabilitating these cultural heritages. The loss of the cultural heritage of any population is a loss to humanity. Lost heritage cannot be rehabilitated or restorated but it is possible to prevent the loss of cultural heritage that is now eroding our stock of experience and ability to respond to adverse conditions. In this sense, that the cultural heritage is an integral element of humanity and that the diversity of such resources is essential for sustaining our ability to cope with the past, present and future, Urartian hydraulic heritage and gardens should be conserved and should guide to the modern civilizations and hydraulic technology, today’s garden art.

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Old Influences in Modern Water Technologies

Pymatuning Earthquake in Pennsylvania and Late Minoan Crisis on Crete, Greece

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Abstract: One of the hypotheses on Late Minoan Crisis on Crete considers water loss in aquifers as a reason that forced late Minoan people to abandon their palaces and eventually leave the island. According to the hypothesis the water loss in aquifers is attributed to the activity of repeated earthquakes at that time. This hypothesis is supported by recent studies of the effects of earthquakes on aquifers in various geological regions. However, one of the most interesting cases, providing insight into geological and social factors refers to the aquifer in Pennsylvania, USA, damaged by the relatively moderate Pymatuning earthquake in 1998. Pymatuning earthquake resulted in devastating effect on approximately 120 households located along the five mile ridge between towns of Greenville and Jamestown. One of the main effects of this earthquake was loss of drinking water from aquifers. The lessons from Pymatuning earthquake and similar events in other geographic regions provide a unique insight into similar situation that could occur 1,600 years B.C. on Crete when multiple earthquakes at that time could damage water supply from aquifers. In this paper the social and geological factors of Pymatuning earthquake are described and generalized in comparison with ancient Crete.

Keywords Crete; earthquakes; Minoan collapse; water supply.

Introduction

The controversy about the collapse of Minoan civilization on Crete is a continuous topic of discussions for the last 100 years and as a result, three hypotheses were developed that linked the collapse with naturally occurring events such as earthquakes, tsunami and aquifer damage (Gorokhovich, 2005). The tsunami hypothesis did not stand the test, however the evidence of multiple destructions caused by earthquakes was found in recent archaeological findings. Multiple repairs on walls of dwellings evidently show that inhabitants of the Late Minoan period were accustomed to earthquakes and this was not necessarily a likely reason for them to abandon palaces.

The hypothesis of aquifer damage due to the seismic events (Gorokhovich, 2005) linked earthquake activity with its probable effect on aquifers that provided vital water supply to Minoans. The study showed multiple examples from various geographic regions when earthquake activity affected aquifers. One of the cases mentioned in the paper refer to the Pymatuning earthquake that occurred in Pennsylvania in 1998. This is the only case comparable to probable scenario on Minoan Crete in terms of geological settings and social context.

During the Pymatuning earthquake more than 120 households in Pennsylvania lost their water supply from wells and were assisted by local and federal authorities. Considering that each household could have 3 people on average, the total number of affected population could reach approximately 400 people. Using gridded population of the world data set developed by the Center for International Earth Science Information Network (CIESIN, 2006), the estimated affected population reaches 1056 people. This is comparable to the number of inhabitants in one or two palaces on ancient Crete more than 3,000 years ago.

Most of Minoan settlements on Crete, also known as "peak sanctuaries", are located on high elevations, either hilltops or hill slopes, similar to the location of the water loss area in Pennsylvania. These similarities make the comparison between two places an interesting case study that could shed more light not only on the cause of Minoan collapse, but also provide an interest in studies of seismic effects on aquifers.

Pymatuning Earthquake and its Effects

Geologic settings

Pymatuning earthquake with a magnitude 5.2 occurred on September 25 and arrival of the P-wave was registered at 3:53 p.m. (Fig. 1) by the College of Wooster seismic station. In Advanced National Seismic System (ANSS) catalogue it is assigned magnitude of 4.5 and depth 5 km (NCEDC, 2006).

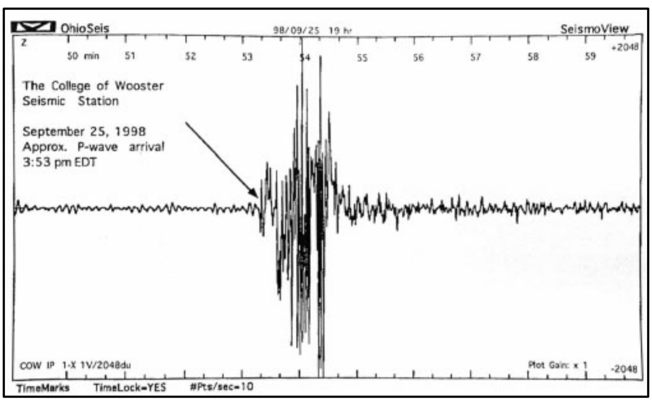

Figure 1 Seismic wave registration from The College of Wooster.

This earthquake was strongest ever recorded in Pennsylvania (Armbruster *et al.*, 1999) and its major effect described in the United States Geologic Survey (USGS) study (Fleeger *et al.*, 1999) was the loss of water supply in household wells located along the ridge between Jamestown and Greenville (Fig. 2). USGS study (Fleeger *et al.*, 1999) contains the following specific information directly related to the seismic effects on groundwater: (a) The ridge area provides recharge for the groundwater table that is located there at much deeper depth than in valleys; ridges can be considered as "hydrologic islands" totally isolated from other ridges and hills (Poth, 1963); the elevation of the ridge is 367.2 m; the maximum relief in elevation from the top of the ridge to the bottom of the valley is about 76.3 m and (b) bedrock is represented by Carboniferous sedimentary rocks (predominantly shales and sandstone), covered by glacial deposits. These rocks lay in sequence shale-sandstone-shale-sandstone with Meadville shale formation (48.8 m thickness) on the top and Cussewago sandstone at the bottom. Meadville shale is dark-gray; it has lenses of siltstone and occasionally beds of limestone (Schiner and Kimmel, 1976). Rock sequences are nearly horizontal.

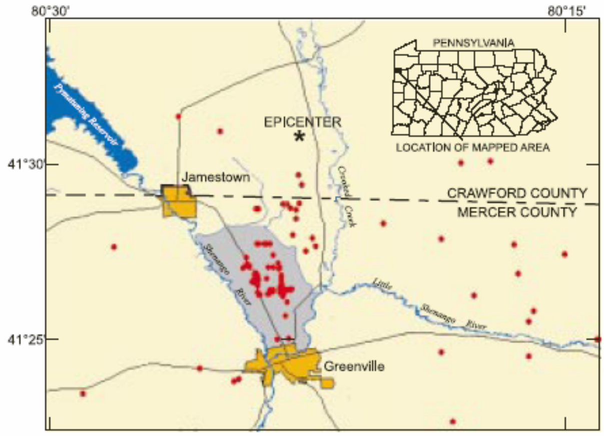

Figure 2 Area between Jamestown and Greenville. Red dots are wells that went dry after the earthquake (Fleeger *et al.*, 1999)

The model of "hydrologic islands", also known as a local system of groundwater flow (Toth, 1963) was expressed in hydrogeology since early 1960s (Norvatov and Popov, 1961). According to Toth (1963), this zone "has its recharge area at a topographic high and its discharge area at a topographic low that are located adjacent to each other". Norvatov and Popov (1961) define this zone as "upper zone of active flow, whose geographical zonality coincides with climatic belts. The lower boundary of this zone coincides with the local base levels of rivers". The idea of "hydrologic islands" was used in USGS study (Fleeger *et al.*, 1999) to explain a potential cause of the water loss in wells along the ridge between Jamestown and Greenville. Figure 3 shows approximate location of the boundary of this feature in relation to the area affected by Pymatuning earthquake. Elevations were derived from the global Shuttle Radar Topographic Mission (SRTM) elevation data (Jarvis *et al.*, 2004).

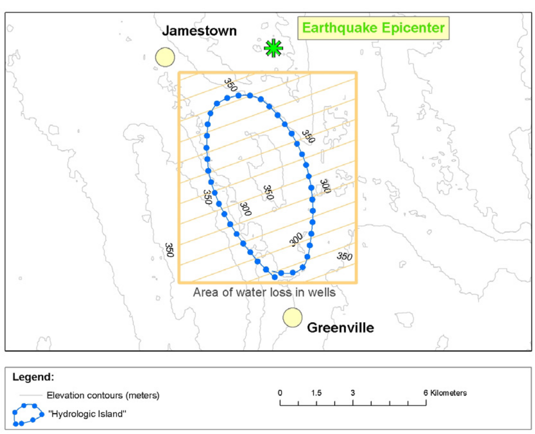

Figure 3 Pymatuning earthquake epicentre, elevations, location of area with water losses and "hydrologic island" boundary.

The boundary of "hydrologic island" follows contours of Meadville shale and valley bottom, making the area of approximately 14-18 km^2. The disturbance of this specific area by seismic shocks could increase permeability of the Meadville shale and "drain" this unconfined aquifer into the valley. This model is supported by the evidence of groundwater flow increase in the valley (Fleeger *et al.*, 1999). Using available geologic evidence and measurements USGS study created a hypothesis that the Pymatuning earthquake created new or widened old fractures that contributed to the increase of hydraulic conductivity and consequent increase of flow in discharge zones of "hydrologic islands". This hypothesis was supported by the results of developed ground-water flow model that showed that pre- and post- hydraulic conductivity changed from 0.122 to 0.695 cm/d.

Hydrologic effects

On September 26, the day after earthquake, residents in vicinity of Jamestown and Greenville towns found that water levels were declining and water colour was changing from clear to brown and dark. These declines were documented in 121 wells (Fleeger *et al.*, 1999). At the same time water levels on the sides of the ridge and in the valley went up by 30.5-1.22 m. Water level went down in practically all wells above elevation 335.5 m, which belongs to the Meadville shale. Water levels have been monitored by the Pennsylvania Geological Survey since the earthquake. As of April, 2006, there has been no sign of recovery to pre-quake water levels. Only seasonal fluctuations have been documented.

Socio-economic effects

Local newspaper "The Herald" (Sharon, PA) covered most of events that happened in community after Pymatuning earthquake. More than 90 homes lost well water after the earthquake, said Jim Thompson of the Mercer County Emergency Management Agency. Most homeowner's insurance policies do not cover well water loss, so residents had to drill new wells at their own expense. "It costs $3,000 to $4,000 to drill a new well, and most families can't afford it…" Newspaper reported that it took more than a month to provide residents with water. Other effects of earthquake included broken walls, windows, ceiling tiles, chimneys, loss of power and one injury (Armbruster *et al.*, 1999).). It took months to drill new wells for community and restore water supply. Mercer County Emergency Management Agency and local municipal and charity organizations were involved in remediation and restoration efforts that included bottled water supply, filling up bath tubs and water tanks.

The community between Jamestown and Greenville does not belong to the wealthy class with average income in 1999 of $34,666 (for example, in Pennsylvania State the median income is $40,106) and almost 12% people below poverty level (US Census Bureau, 2006). Many people support themselves by farming. There is anecdotal evidence that only one household had "earthquake" insurance and the well for this household was drilled for free. The rest of the community had to find their own funding for well drilling. In oral interview, one of the residents mentioned that if he would not have external assistance from the outside he "would leave" (Gorokhovich, 2004).

Correlation between Pennsylvanian and Cretan Geologic Settings

Geomorphologic and hydrologic settings

Most of the palaces (Knossos, Phaistos, etc.) are located on hills or slopes and also known in archaeological studies as “peak sanctuaries”. Elevation of Knossos above sea level is approximately 70 m and Phaistos is 120 m. The relief between valley and the Phaistos palace location is 87 m. For Knossos the relief is approximately 54 m. Figure 4 shows elevation contours developed from SRTM and location of two major Cretan palaces: Phaistos and Knossos. It also shows approximate contours of “hydrologic islands” or localized groundwater recharge zones.

The size of approximated “hydrologic islands” in the vicinity of palaces ranges from 8 to 9 square km. Since more detailed geologic data for Knossos and Phaistos are absent, it is hard to correlate the boundary of “hydrologic islands” with specific deposits. In both areas near Knossos and Phaistos surface deposits are represented by Neogene carbonate rocks (Meulenkamp *et al*., 1979). They were deposited since Miocene and consist of six groups represented by limestone, terrigenous clastic formations, marine marls and clays. There are also some marine terraces and continental deposits related to Pleistocene.

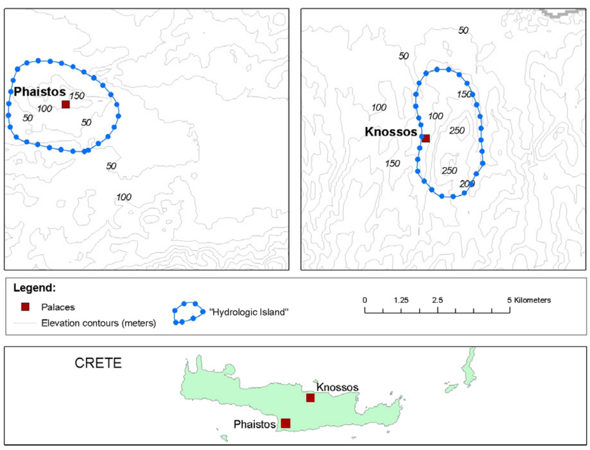

Figure 4 Cretan palaces in relation to elevations (derived from SRTM) and “hydrologic islands”.

Seismic conditions

For the past 100 years in the vicinity of the Pymatuning earthquake epicenter were recorded only four other earthquakes with magnitudes higher than 4.0: in 1964, 1966, 1986, and in 2001. The depth of these earthquakes ranges from 5 to 15 km. Besides hydrogeologic records of Pymatuning earthquake in 1998 and earthquake of 1986 (when according to USGS hydrologists in Ohio hydrologic changes were nearly identical to Pymatuning event) none of other earthquake events contain any documentation about hydrogeologic response. It does not mean that hydrogeologic response was not present because it just could be not recorded or documented.

Earthquake situation on Crete is very different since Crete is located in active subduction zone next to Hellenic arc. Therefore, Crete constantly experiences multiple earthquakes. ANSS catalogue contains 49 records of seismic activity since 1900 exceeding magnitude of

5.0 with highest magnitude of 6.3 in 1972. Figure 5 shows density of earthquakes based on magnitude value. This was calculated using so-called “kernel” method described in (Silverman, 1986). This method is also widely used in crime analysis to define “hot spots” based on number of arrests and specific crimes (McLafferty *et al.*, 2000).

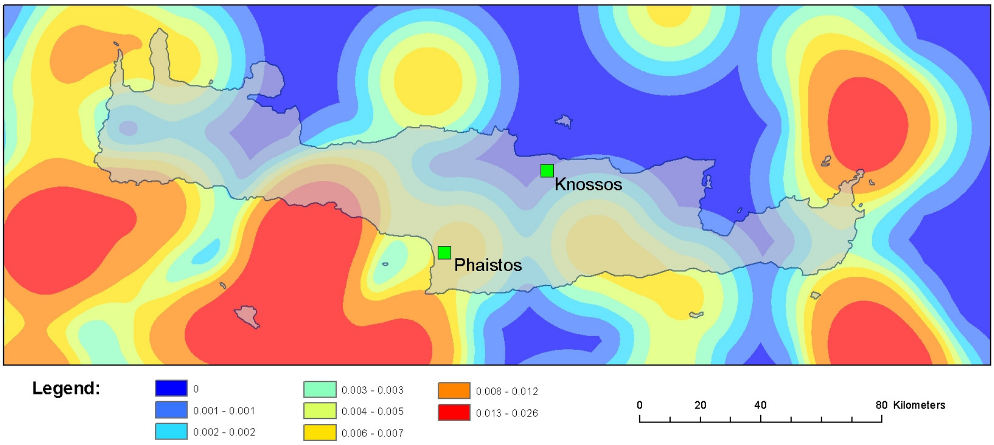

Figure 5 Density of the earthquakes (based on magnitude value and number of epicentres within 30 km radius) with magnitudes greater than 5 for the past 106 years.

Most of the high density earthquake zones are located on the south and east from Crete. This coincides with location of subduction zone on the south (Hellenic trough) and possible strike-slip fault zone on south-east associated with South Cretan trough, Pliny trough and Strabo trough (Huguen *et al.*, 2001). Phaistos palace is much closer to the high density seismic areas with high magnitudes. Knossos is relatively far from them. Average depth of epicentres is 48 km with range from 10 to 87.4 km.

Conclusions

Though both, Phaistos and Knossos locations have similar geomorphologic characteristics, Phaisots has more similarity with “hydrologic island” settings in Pennsylvania than Knossos. However, more detailed analysis is needed near both palaces to identify specific geologic layers and formations. Knossos location on the slope of the hill does not fit specifically the definition of “hydrologic island”, however water supply in Knossos was only partially coming from wells and major part of water supply was coming from Mavrokolybos and Fundana springs located higher on the slope (Angelakis and Koutsoyiannis, 2003). Following “hydrologic islands” model these springs could cease to exist after seismic activity.

Seismic settings are different in Pennsylvania and Crete. If seismic activity influences hydrogeologic conditions, then the higher density of earthquakes and their magnitudes on Crete suggests higher probability of flow changes on Crete due to the earthquake activity. The epicentre of the Pymatuning earthquake was located within 3-5 km from the affected “hydrologic island” and its depth was 5 km. These conditions, coupled with geologic structure resulted in loss of the underground water flow. Considering high frequency of earthquakes on Crete during Bronze Age (Nur and Cline, 2000), there is a possibility that there was an epicentre close enough to palace locationon the hill that disrupted water flow from wells.

Social impacts of disrupted water supply in Pennsylvania included immediate help from local and federal authorities, charities and churches to provide inhabitants of the “hydrologic island” between Jamestown and Greenville with water supply. This included filling bath tubs from fire trucks and supply of bottled water from local supermarkets and stores. In similar case in California in December 22, 2004, San Luis Obispo County residents had to trim their herds due to the loss of water from springs immediately after earthquake (Campbell, 2004). These cases are related to the 21st century with modern technologies, established public policies and disaster management plans. In ancient Crete, 3,600 years ago similar effects would mean the retreat of population and search for new water supply sources.

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Rainfall Changes: Preliminary Assessment of the Sensitivity of Nile River Flows Using a Rainfall-runoff Distributed Modeling System

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Abstract: Egypt is a highly arid country. The Nile is the only river in Egypt and provides 97% of the water requirements. The remaining 3% come from ground water and rainfall. So the seasonal and annual fluctuation of the River Nile natural flow may cause tremendous difficulties for a country like Egypt totally depending on its river. Early information about the river flows was always necessary for short term planning to find out policies for facing shortage and drought conditions. In the absence of long-term storage before the construction of the High Aswan (HAD), the situation was more sensitive and vulnerable to extremely high or low floods. In addition, if climate change results in increased warming, droughts, and evaporation, reduced flow in the Nile would further exacerbate Egypt's problems and the country could face an explosive situation. The objective of this paper is to explore the possible effects of climate change in the Nile basin assuming arbitrary changes in the basin rainfall. The effect of rainfall changes in the basin on runoff were simulated through the rainfall - runoff hydrological model being used in the Ministry of Water Resources and Irrigation (MWRI) in Egypt.

Rainfall Changes Impacts on Egypts' Water Resources

Egypt is defined under various criteria as water stressed country because of its low per capita renewable water resources availability. Over 95% of Egypt's current freshwater originates from the Nile. 'Natural' variability in Nile flows is critical for water supply because the balance between the availability of water and demand for water is very fine. During the decade of low flows in the 1980s, for example, Egypt's water use was secured because of storage in the High Aswan Dam reservoir and the availability of the upstream Sudan's unused allocation. Being the most downstream country on the Nile, Egypt is affected by rainfall changes impacts, not only within its borders, but also within the whole of the basin, which it shares with 9 other countries. Despite being at the low end of the river, Egypt is the largest user of the Nile water at present. Economic developments in upstream countries and adaptation measures are likely to put more pressure on water resources on Egypt.

Rainfall Data and Rainfall Calculation

Although rainfall data is the major input for any rainfall-runoff hydrological model, most of the watersheds in the Nile basin are ungauged or improperly gauged. Even more, most of the available data for the gauged watersheds is often sparse and unreliable. Also, rain gauges records are point measurements, whereas rainfall is highly variable in space. Even in developed regions, such as Europe and US, the number and distribution of gauges provides only an approximation of moisture patterns. For these reasons remotely sensed data from satellites has a valuable effect in enhancing and improving the depiction and representation of rainfall variability.

Since 1989 the rainfall data input to the MWRI model is based on both satellite TRMM radar images of clouds and observed rainfall at ground stations. The weight factors give to the satellite and ground observations are in the order of 0.15 and 0.85, respectively. Thus, the estimates of basin rainfall heavily depend on rain gauge data. When insufficient data on rainfall is available the system falls back on the rainfall normals, available as gridded monthly maps. Before 1989 the satellite images are lacking and data availability only allows for monthly calculations of the rainfall. In order to obtain the most reliable daily rainfall we use as the baseline the rainfall data available in the MWRI for the period 1989 to 2001 (12 years) for the entire basin. These are gridded daily rainfall data that comprise daily rainfall on a grid of approximately 18 km^2. The scenarios were derived simply by changing all the daily rainfall grids with respectively +20%, +10%, -10% and -20%.

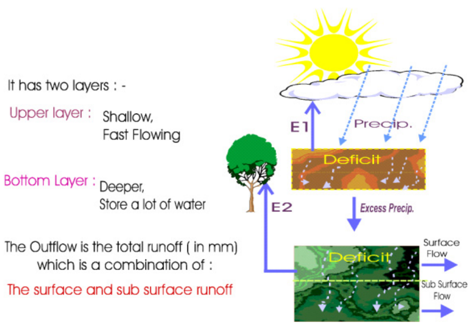
Rainfall - Runoff Hydrological Model

The MWRI rainfall-runoff model is a distributed modeling system divides the basin into grids. It is a grid-based soil moisture account model that calculates the discharge of the Nile and its tributaries on a daily time step. It is based on the quasi-rectangular grid at the METEOSAT satellite projection (average grid cell size is 5.5 x 5.5 km). In brief the MWRI hydrologic model for the Nile system includes a grid-based hydrologic model. For each grid cell (approximately 30 km^2 in size) the transformation from rainfall to runoff is simulated by a water balance model, a hill-slope routing model, and a channel routing model.

The water balance models the rainfall-runoff process in the soil. It has two layers which represent a shallow, fast-flowing upper (surface) soil zone and a slower lower (groundwater) soil zone. The outflow is the total runoff (in mm) which is a combination of the surface and groundwater runoff. The hillslope model serves to rout the runoff from the water balance runoff over land to the channel, effectively producing a time lag and some attenuation for the local runoff within a pixel. The channel routing model routes water from pixel to pixel and cause both a time lag and attenuation of the flow as it moves downstream. Figures 1 and 2 represent the concept of the water balance and hillslope models. The length of a grid cell is approximately 18 km. The model calculates for each grid cell a water balance. The water that is available for runoff is routed to the outlet of the basin along the drainage pattern. The grid-based model covers some 40% of the Nile basin. Not covered are the arid areas of the basin where runoff is insignificant. Also not covered by the grid model are the major lakes, swamps and reservoirs which are modelled separately by lumped parameter models.

Preliminary Assessment of the Sensitivity of Nile Flow to Rainfall Changes

Preliminary to explore the effects of rainfall changes on Nile flow, arbitrary changes in the rainfall over the Nile basin were assumed. A changes of rainfall values were assumed to be -10%, -20%, +10%, and +20%. These changes are comparable with the predictions done with global climate models for the Nile basin. The daily inflows at station Dongola, upstream Lake Nasser, for 12 years for each rainfall scenario, including a scenario that assumed no change, were simulated using the MWRI hydrological model. Figure 3 illustrates the large senstivity of the basin for changes in rainfall. Table 1 shows the effect on the average annual inflow. It is clear that even minor variations in basin precipitation lead to large changes in annual inflows.



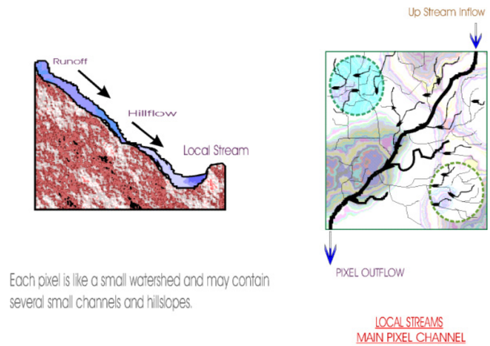


Figure 1 Water balance model. **Figure 2** Hillslope model.

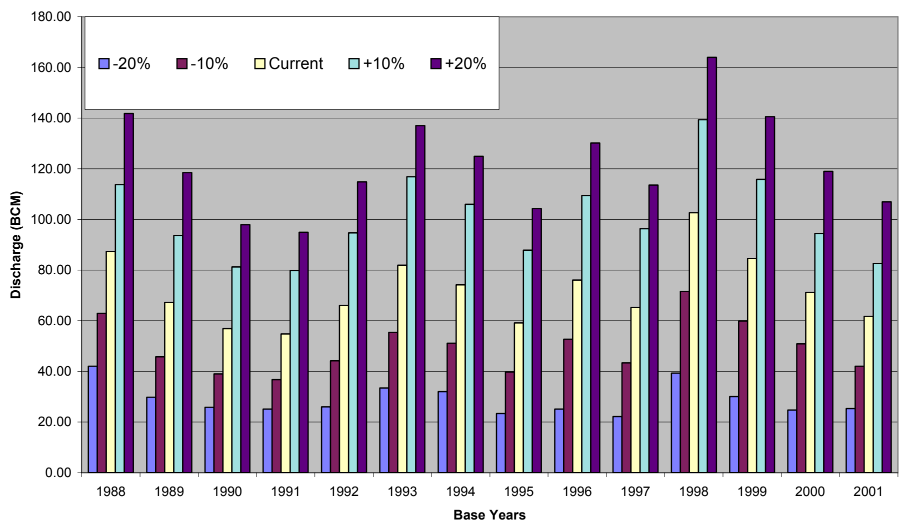


Figure 3 Annual inflow in Lake Nasser resulting from different changes in rainfall.

Table 1 Changes in flood volumes according to different rainfall scenarios.

Rainfall change (%)	-20	-10	0	10	20
Annual inflow (Bm³)	34	58	84	118	143

When concentrating on the effect of changes in rainfall on the runoff during the flood season, the impact of changes in rainfall becomes even more striking. Figure 4 shows the flood volumes during the flood season passing Dongola for the different rainfall scenarios. The average change in the flood volume is shown in the Table 2.

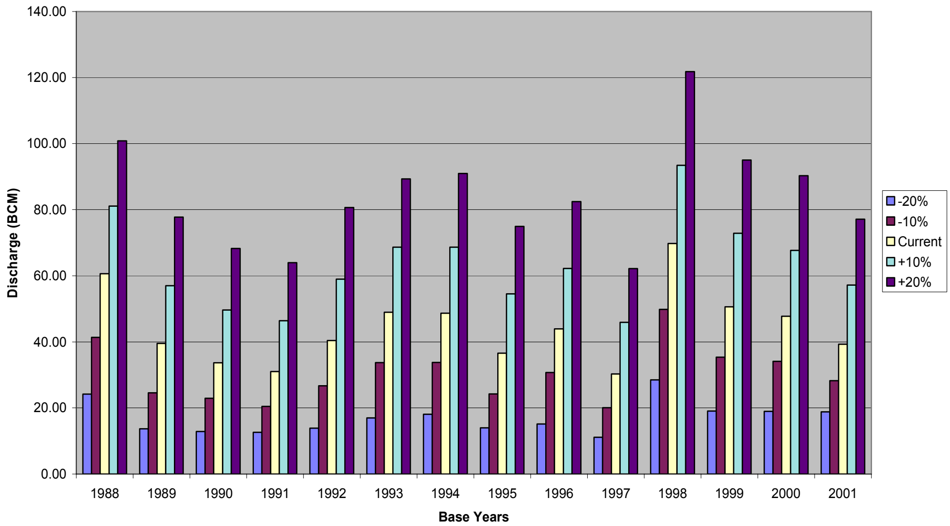


Figure 4 Water arriving at Dongola during the flood season for different changes in basin rainfall.

Table 2 Changes in flood volumes according to different rainfall scenarios.

Rainfall change (%)	-20	-10	0	10	20
Inflow August - October (billion m³)	20	35	52	74	99

Discussion

To illustrate the meaning of the change, the outcomes can be compared with the historical record. During the last 100 years the inflow in Lake Nasser varied between 42 and 120 billion m^3. This means that changes associated with 20% rainfall changes have not occurred in the last 100 years. After all 20% decrease of rainfall would lead to an average inflow of only 20 billion m^3, while an increase of 20% rainfall would lead to an average inflow of 143 billion m^3. The variation in inflow associated with a 10% change in basin precipitation indeed has been observed. However, only 2 years in the record show an annual inflow less than 58 Bm^3 (10% less rainfall) while inflows larger than 118 Bm^3 (10% more rainfall) occurred only three times. The two driest hydrological years were 1984-1985 and 1913-1914 and the two wettest years were 1964-1965 and 1998-1999.

A 10% change in basin rainfall seems small; therefore one would expect that such events should have occurred more often in the past century. Hence, one may expect that these extreme discharges also would have occurred more frequently than currently observed. However, as the Nile basin is very large and the Nile passes several climatic zones on its way from the tropical climate in the south to the arid zone in Egypt a rainfall change of 10% (in the same direction) over the entire basin is not very likely. Variations in rainfall will occur, but the greater rainfall in the one area will be cancelled out by less rainfall in other areas.

The impact on the water supply to Egypt and Sudan can be illustrated by estimating the changes in the shares of both countries. Assuming a decrease in the average natural flow from 84 to 58 would mean that the shares of both countries would decrease to 35 for Egypt and 12 for Sudan. On the other hand assuming an increase in the average natural flow from 84 to 118 would mean that the shares of both countries would increase to approximately 69 for Egypt and 33 for Sudan. These results strongly suggest that that even relatively small changes in the average basin rainfall will lead to huge changes in the inflow in Lake Nasser. In turn the consequences for the water supply for Egypt can hardly be underestimated.

The potential for compensating reduced inflows resulting from rainfall reductions is limited. The first option is to reduce the evaporative losses in Lake Nasser by operating the lake at a lower level. As the annual evaporative losses are in the order of 12-15 billion m^3, even a reduction of the losses to zero (obviously not feasible) is insufficient to compensate for a 10% decrease in annual basin rainfall. There is also no water conservation project in the Nile basin currently thought of that will have comparable effects on the inflow in Lake Nasser as even a 10% change in rainfall. On the other hand a 10% increase in rainfall resulting in an increase of Egypt's share to approximately 69 Bm^3 would mean that the area under agriculture can be increased (e.g., by horizontal expansion) with 1.8 Million feddan.

Conclusions

The paper explored the possible effects of rainfall changes in the Nile basin assuming arbitrary changes in basin rainfall. The effect of rainfall changes in the basin on runoff were simulated using a hydrological model. The result shows the great sensitivity of the inflow of Lake Nasser for any change in basin rainfall. Comparing the changes in annual inflow the results suggest that a 10% increase in basin rainfall will lead to a change of approximately 40% in annual flow. A 10% decrease of rainfall results into a 30% decrease in annual flow. Comparable changes appear during the flood season. The results of the sensitivity study are consistent with the climatic and hydrological observations between 1981 and 1988 (dry) and between 1993 and 2000 (wet). From the record it appeared that the difference in inflow in Lake Nasser between the wet and the dry period was approximately 40%, while the difference in basin rainfall was only 10%.

For the dryer scenarios there potential measures to compensate for the changes are limited. A 10% reduction in rainfall in the entire rainfall cannot be compensated either by changing release strategy of Lake Nasser nor by any single water conservation project currently thought of. For the wetter scenarios the result would be that Egypt has sufficient water for executing horizontal expansion projects. A 10% increase in basin precipitation would mean that the area under agriculture could be extended by approximately 1.8 Million feddan.

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Water for Human Consumption through the History

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Abstract: The evolution of urban water management in ancient Greece begins in Crete during the early Minoan period of the island and takes full control of the Greek territory originally and then to the European continent. A great variety of remarkable developments have been marked in several stages of the Minoan civilization, such as the practices used to supply the cities with clean water even from distant sources. Water for human consumption has had a long and interesting history. It is closely related to the development of human civilizations and thus a great deal of related events occurred in all over the world. All great civilizations had a large chapter written for water transportation, treatment and management of the urban water. In this paper some of the important steps of water history relevant to the water treatment technologies and hygiene of potable water chronologically, since the Minoan era, are presented and discussed.

Keywords Hippocrates sleeve; Minoan era; Phaestos palace; Tylissos house; water hygiene; water filters.

Prolegomena

Historically, drinking water has been cindered the clear water. Considering the scientific knowledge of that era, this simplification was totally justified. Without the tools of chemistry and microbiology, even today, clarity (and probably taste) is the main criterion for classifying water as fit for human consumption. Therefore, the first treatment attempts were aiming at the improvement of the aesthetic conditions of water. An ancient Hindu source presents, probably, the first water standard, dating 4000 years ago. It dictates that the dirty water should be exposed to sun and then a hot cupper bar to be inserted 7 times in it. Then filtration, cooling and storage in clay jar.

The availability of drinking water was always an prerequisite and necessary circumstance throughout the development of human civilization. For thousands of years this factor has been critical for the choice of location for the development of the cities. The first great civilizations were developed close to rivers both for the availability of water suitable for human needs as well as transportation purposes. Initially the water purification was very limited. It is only the last 200 years that water processing has been developed aiming at the improvement of the hygiene and aesthetic conditions.

The scope of this article is not the exhaustive presentation of what is known today about water treatment, related technologies and their uses in water supply since the Minoan era. It presents he main achievements in selected fields of potable water management chronologically extend from early Minoan to the present. Emphasis is given to the periods of great achievements.

Period before 500 B.C.

Archaeological and other evidence indicate that during the Middle Bronze Age a "cultural explosion", unparalleled in the history of other ancient civilizations, occurred on the island of Crete. A striking indication of this is manifested, *inter alia*, in the advanced urban water management techniques practised in Crete at that time. One of the salient characteristics of the Minoan civilization (*ca*. 3,300-1,200 B.C.) was the treatment devises used for water supply in palaces, cities, and villages from the beginning of the Bronze Age. Two examples of water management findings are the Tylissos houses and the Phaestos Palace.

Tylissos houses

In the Tylissos houses the water was transported through the an aqueduct to the three Minoan houses from the Agios Mama Spring to a distance of about 3km. Terraccota infiltration devices were discovered in the place of the Agios Mamas, where is located the spring, from where water was transported to the Tylissos village (Fig. 1). These devices were filled with charcoal, thus playing the role of activated carbon treatment processes of removing both organic and inorganic constituents. In addition to that devices, a terracotta pipe of 42m length, similar of those used in Knossos was discovered in the northwestern site of House B. Other remains of the aqueduct are shown in Figures 2. A small cistern of stone was used for removal of suspended solids of water before its storage to the main cistern (Fig. 1a). This cylindrical-chapped cistern (Fig. 2b) was located in the northern site of the House C and was considered as a party of the aqueduct (Hatzidakis, 1934).

Figure 1 Terraccota infiltration device discovered in the spring of Agios Mamas, Tylissos (Photo courtesy of M. Nikiforakis, 2006).

Phaestos palace

In palace of Phaestos as in other cities and villages in Minoan Crete the water supply system was dependent directly on precipitation: here, the rainwater was collected from the roofs and yards of buildings in cisterns. In Phaestos the water supply system was dependent directly on surface runoff; there, rainfall water was collected in spatial cisterns from the roofs and yards of buildings. Special care was taken to hygienic of collecting water by (Angelakis and Spyridakis, 1996): (a) cleaning the surfaces used for collecting the runoff water (Fig. 3a) and

(b) filtering in coarse sandy filters the water before it flew into the cisterns in order to maintain the purity of water (Fig. 3b). It was estimated that about 8 Mm^3 of rainwater were collected in an average year. That water was mainly used for washing clothes and for other cleaning tasks.

(a)

(b)

Figure 2 Small cistern of stone (a) used for removal of suspended solids of water before its storage to the main cylindrical-chapped cistern (b) used for water supply of the house.

(a)

(b)

Figure 3 Open yard (a) and special cistern (b) with sandy filter in the Phaestos palace.

Period 500 B.C. - 1000 A.D.

Since the prehistoric era the availability of water source was the primary criterion for the selection of small site settlements. All other criteria such as the natural protection of the site, the good soil and the ease of approach, were considered as secondary.

Gradually, as the small settlements grew to cities, during the archaic and classic period, the sources of fresh water within the boundaries of the city were not sufficient for the needs of the larger population. So they had to be enhanced with water quantities brought from sources outside the boundaries of the city. These sources had to be as close as possible in order to make the transportation of water easy and safe. The Mycenaean cities had constructed under the walls tunnels that provided safe underground passages to water sources, in order to secure adequate supply of water during seizures. The same period important water projects are realized such as the draining of Lake Kopaes and the dam near Myticas in W. Greece.

During the historic years, after 8th century B.C., the settlements and cities obtain drinking water from springs, wells, rivers and precipitating water collected from roofs to reservoirs. The use of remote sources required water transportation. The Hellenes (Greeks is a name imposed later by the Romans) used mostly the clay pipes. Since every City-State had limited ruling domain the water sources had to be as close as possible to the walls so the protection of the water system could be effective. The most impressive remote water transportation system was constructed in the island of Samos by the Tyrant Polycrates who constructed a 1000m underground tunnel through the mountain based on the design of the famous engineer Eupalenos. The particular tunnel is an engineering marvel, since the construction started simultaneously from the two opposite ends and at the meeting point the deviation of the two axis was just 1.8 meters. Later the King of Pergamos, Eumenes the 2nd (197-159 B.C.) constructed the first complete Hellenic water transportation and storage system based on branching pipes.

Despite the fact that during the classic era Hellenes had both the financial and technical capacity (the technology of arch construction was known since Mycenaean years) for large scale constructions, they did not build long, above ground, open water transportation systems for a number of reasons. First of all are political reasons. The organization of relatively small City-States resulted in frequent conflict. Open and long water transportation systems were vulnerable. Underground pipe systems are not visible and not easy to reach and inflict damage. City-States are relatively small. They did not need huge amounts of water, therefore, relatively small clay pipes of manageable size for that level of technology, would suffice. Closed pipe systems are also known to offer the best protection against natural pollution. Hippocrates probably influenced the choice towards closed systems. He had identified the significance of good water quality for good health. He indicated that it is preferable to use water from a good source than attempting to treat water from an inferior source. Moreover, he is credited with the development of the “Hippocrates sleeve” made of clothe and used to filter rain water.

The small diameter closed water transportation systems had two particular problems, besides the usual structural and leakage problems. Calcium carbonate deposits in the pipes used. The predominance of limestone formations in the Balkan Peninsula as well in many places across Europe, result in high concentrations of calcium carbonate in surface and underground water as well as relatively alkaline pH values. These conditions cause high rate of calcium salts depositions on the surface of pipes, which in practice can not be removed. So, the pipes gradually had the diameter reduced and the amount of water flow considerably diminished. This problem has been noticed in many excavations of ancient water pipes. Lead was also used as a sealing medium in clay pipes of larger diameters as well as to form pipes of small diameters. As far as we know, ancient civilizations ignored the epidemiology of lead, but the problems arising from lead use would be the same as they are today. For the construction of lead pipes were set up specialized workshops. Their remains have been uncovered in a number of excavations.

As the cities and states grew bigger and more confident, shifted their technology to longer and bigger water transportation systems, namely the open aqueducts. The Carthage water transportation system was 132 km long above ground. The first Roman aqueduct supported on consecutive arches, known as Aqua Marcia, was constructed in 144 B.C. by Marcius Rex.

It was 90 km long and the last 9 km was supported on arches. When the Romans concluded the occupation of the Hellenic states, after the era of emperor August, a great deal of long aqueducts was constructed in the Hellenic region as well as all over Europe. However, the vulnerability of these open systems never ceased to be a problem. In 537 A.D. the aqueduct of Rome was destroyed by the Goths and was used as a weak point to enter the city.

Figure 4 Remain sections of the aqueduct of Patras in western Greece.

The extensive use of open aqueducts was aided be the technology of brick which and the strong bonding mixture called *pozzolana* which made the constructions of these type inexpensive and fast to execute. The distribution of water inside the cities was made trough pipes, clay and lead for smaller diameters, brickwork sealed with specialized hydraulic plaster for larger diameters. These distribution systems were operating under pressure which allowed the construction of recreational jet fountains. It is known that the water system in ancient Pergamos, 45 km long, reached inside the city the pressure of 20 atm.

Figure 5 Lead water pipe of the roman period.

Figure 6 Ceramic water pipes from an excavation in Aigio in western Greece.

Despite the availability of public water supply, individual houses maintained their own water sources. Where there was available underground water, a well was constructed. The internal surface of the wall was covered with built stones or clay rings, which at regular interval had holes to facilitate the access to the bottom of the well for maintenance. They also utilized the rain water which was collected from the roofs of the houses and stored in built tanks, usually underground. This water was mostly used for cleaning the house if running water was available for human consumption.

During the Classic and mostly during the Roman period, water was extensively used for human personal hygiene. Baths were both private and public. Public baths were more than places for hygiene. They were places for social conduct and recreation. The "complete" Roman bath included a first cold bath called *frigidarium*, followed by a stage of mild warm bath called *tepidariuma* and finished with a hot stage called *caldarium*. The space was heated by hot air passing in clay pipes inside the walls and in the empty space under the false floor.

During 8th century A.D. the Arab alchemist Gever distilled water to render it free from evil spirits and 11th century A.D. the Persian physician Avicenna advised travelers to boil the water or at least filter it through a cloth.

Figure 7 Cylindrical terracotta rings, for coating the walls of a Roman well.

Figure 8 Tank to catch rain water in the atrium of a roman house in Patras, west Greece.

Figure 9 Hypocaust columns of a roman bath.

Figure 10 An early Christian bath in Patras, Western Greece.

Period 1000 A.D. to Today

As in every other field of art and science middle age has to present no progress on the area of water treatment.

17th century

The British philosopher and scientist Francis Bacon who managed to transform nature probing to scientific conclusions devoted considerable effort in studying water purification techniques. In 1627 he published experimental results on percolation, filtration, distillation and coagulation. In 1680 Dutch naturalist Antony van Leeuwenhoek discovers the microscope and in 1984 gives a first account of bacteria observed in water which he named as “animacules”. These findings were dismissed by the scientific community as unimportant curiosities. It would take another 200 years in order to be understood the importance of the van Leeuwenhoek’s findings for the public health. In 1685 the Italian Lu Antonio Porzio designed the first multi-pass filter containing a straining section and two sand filtration passes.

18th century

France is taking the lead. In 1703 the scientist Phillippe La Hire presented a home filter suitable for treating rain water consisting of a sand filter and a storage tank. He also noticed that the water coming from underground aquifers is rarely polluted. In 1746 Joseph Amy received the first patent for a water filter that in 1750 he put on the market. The filter was made of sponge, wool and sand. However, it is the British architect James Peacock that he manages to claim a patent for a sand filter with backwashing.

19th century

In 1804, Paisley, Scotland, became the site of the first filter facility to deliver water to an entire town. In 1806, a large water treatment plant opened in Paris, using the River Seine as a source. Water was settled for 12 hours prior to filtration then run through sponge prefilters that were renewed every hour. The main filters consisted of coarse river sand, clean sand, pounded charcoal, and clean Fountainebleau sand. The filters were renewed every six hours. A simple form of aeration was also part of the process, and pumps were driven by horses working in three shifts (steam power was too expensive). This plant operated for 50 years. In 1807 in Glasgow, Scotland, filtered water was piped directly to customers.

The first slow sand filtration plant in the USA was built in 1832 in Richmond. In 1833, the plant had 295 water subscribers. The next USA plant to open was in Elizabeth, N.J., in 1855. Slow sand filters were introduced in Massachusetts in the mid-1870s. Sand filters and other treatments were primarily designed to improve the aesthetic quality of water. By the end of the century the rapid sand technology has been practiced. At that time it becomes evident that in addition to the suspended solids removal, extensive bacteria removal is achieved. Also, at the same time the first attempts to use chlorine and ozone for water disinfection has been made.

20th century

In 1906 ozone is used for the first time for disinfection in Nice (France) and becomes very popular in Europe. In USA, chlorine is mostly used for disinfection due to the complexity and the cost of the ozone equipment. The Europeans were particularly negative against chlorine due to its use in the chemical warfare durin 1st world war. In 1908 sodium hypochloride is used in Jersey (USA) for disinfection and in 1917 chloramines are used first time for disinfection in Ottawa (Canada) and Denver (USA). The first serious efforts on water desalination technology were made during World War II for the supply of units which encountered difficulties in securing drinking water.

Epilogue

Relationships based on exchange are known between the Minoans and continental Greece, Egypt, and the Levant. There is no doubt that some hydraulic practices and water management has been transferred from Mesopotamia and Syria to Crete by that time since such several works concerning the management of water have been already applied in these areas. However, the Minoans applied this skill and developed it, especially in urban hydraulics, in the palaces, cities and villages, up to a degree, which had never been reached before (Angelakis and Koutsoyiannis, 2003). Thus, the first indication for development practices relevant to the treatment of urban water and hygienic of water supply lies in Minoan civilization. At that time the first aqueduct were constructed to transport clean water to the urban areas. Also, the first sedimentation tanks and the first sand filters appear to be developed at that period. It seems likely that these technologies have been transferred to the Mycenaeans in continental Greece (Angelakis and Spyridakis, 1996).

Later, during the Hellenistic and Roman periods, significant developments were done by water engineers, in the construction and operation of aqueducts, cisterns, sedimentation tanks, water filters and disinfection technologies. Greeks and Romans capitalized on this knowledge and made great advances in potable water management (Petropoulos, 2006). The unfortunate middle Ages period of stagnation is followed by the revival of letters and technology. Slow in the beginning, faster and faster as time was passing, progress in drinking water transportation, treatment and management was made. The fast progress has created huge problems and the ease of communication has made the problems global. As usually the problems are emerging from politics in the broad sense. Looking to the future we wander: What is going to grow faster, the problems or the technology than can solve them?

Acknowledgement

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The Po River Delta Evolution and the Hydraulic Works

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Abstract: The Po Delta, in the Adriatic sea (Italy), is the extreme manifestation of the complex morphological events, which in the arc of about one million years have from the beginning filled the vast area enclosed by the Alps and the Apennines with sediments, thus constructing the Po valley, about 34,000 km², that extends into the Adriatic sea, giving rise to a projection of the delta. This paper shows, utilizing maps and geomorphological reconstructions, the interference between the natural and the man induced evolution of the Po river delta. Particular consideration is devoted to the importance of the hydraulic works during the last 400 years.

Keywords Deltas; environment; Environmental Impact Assessment Studies; geomorphology; Po river.

Introduction

The Po Delta, in the Adriatic sea, is the extreme manifestation of the complex morphological events, which in the arc of about one million years have from the beginning filled the vast area enclosed by the Alps and the Apennines with sediments, thus constructing the Po valley, about 34,000 km², that extends into the Adriatic sea, giving rise to a projection of the delta. The formation process of the deltaic system dates back to about 2,000 years.

Today the Po Delta is formed of 5 principal outlets and 14 secondary tributaries. The surface is 73,000 ha, of which 60,000 are reclaimed land and the remainder are brackish lagoons, with dams or open foreshores and emerging sandy banks. The continous riverborne sediments have progressively heaped up the expansion into the sea of the deltaic system. Notwithstanding the reduced quantity with respect to the past, the solid contribution is conspicuous today both in coarse material (sand) and in fine material (silt and clays) (Nelson, 1972). It is nearly impossible to follow step by step the various phases of the Po Delta growth process due to both the numerous modifications of the various fluvial branches, many of whose traces have been lost today, and to the fragmentary information which has been handed down to us. It is practicable to trace the fundamental stages through the study of the variations of those shorelines obtained from both topography and remote surveying and interpret them in the light of historical sources.

Materials and Methods

In 1967, Ciabatti individualized seven beach ridges of sand dunes from the pre-Etruscan period up to about 1600 corresponding to shorelines in different times, on which ten cuspate deltas of various arms of the Po lie (Fig. 1). The deltas after 1600 are lobate; thus, the entire Po River Delta zone has been characterized by two phases of deposition (cuspate and lobate deltas) with different growth rates.

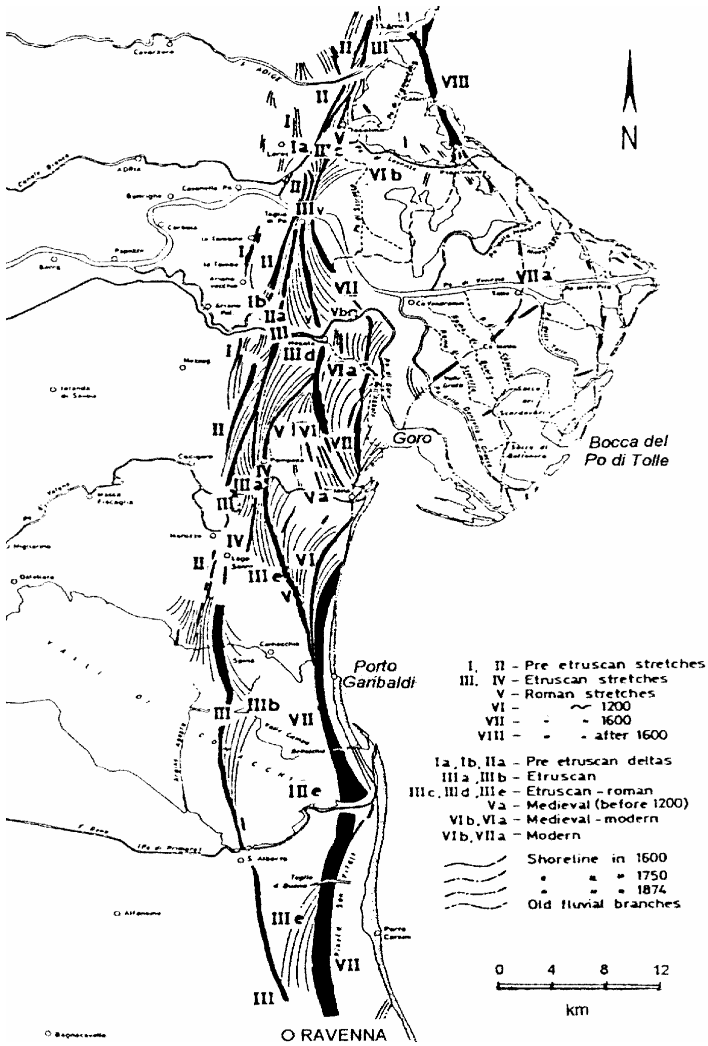

Figure 1 Old and present beach ridges along the line Ravenna-Chioggia (southern Venice Lagoon) crossing the Po River Delta (Ciabatti, 1967).

Through a very long, chronological sequence of maps from 1600 up to the present day, the morphological evolution of the Po River expansion into the sea and the seafloor can be followed. A continuous and conspicuous development seaward of the coastline had occurred for three centuries; a lower rate of prograding is observable starting at the beginning of 1900. This low steadily increased due to the diminished sediment yield (partly due to man's intervention) is evident in the 1953 survey. In the entire delta, and mostly in the southern coastal section, a regressive process became dominant, clearly showing an inversion in the trend (Ciabatti *et al.*, 1984; Cessari *et al.*, 1998).

By 1500 the southern Venetian laggon was on the verge of being filled-in, jeopardizing port activity. To avoid this, the Venetian Republic in 1599 began the construction of the 7 km long canal, *Taglio di Porto Viro*, to divert the Po to the South. This hydraulic work, completed in 1604, accomplished its aim and thereafter the Po Delta began to take on its present configuration with an accretion velocity toward the soyth much greater than the previous one (Marabini, 1985a). It is worth reading through the historical chronicles preceding 1600 and concerning the evolution of the Po River to evidence how some natural and man-induced events changed the hydrographic features of the Delta area in the coastal zone.

In 1135 (or more probably around 1150), an important avulsion event, the *breaching of Ficarolo*, occured near Ferrara on the left bank of the Po river. There is no news if it occured naturally or due to human intervention. It is for sure that in those years the river floods seriously threatened the surrounding territories. The breach at the riverbank at Ficarolo could have been caused by the force of the river flood or by the intervention made by man to avoid worse disasters elsewhere. Anyway, as a result the watercourse was divided into two branches and the main riverbed laden in sediment yield moved northward.

Results and Discussion

The comparison among the shorelines points out the main advancing from 1600 up to 1750 and 1820 evidencing the lower rate of increase after this period and before interference of human activity. Comparing the width of the strip, in which the cuspate deltas develop, with the remaining distance to the sea, we immediately have an idea of how different the rate of growth was before and after 1600. In fact, the mean velocity increase from the Etruscan period (about 6th century B.C.) up to 1600 is estimated about 450 m/century. For the last 350 years instead, considering the 25 km, which separate the 1600 shoreline from the present one, it is about 7 km/century (Ciabatti, 1967; Marabini, 1985b). The different rate of advancement in the different periods can be explained considering climatic changes, the main factor before the role of human intervention.

Worth observing is the correspondence between the major development of the Po delta system and the cold/wet weather conditions; significant examples are the Ficarolo breach (12th century) that occured during the negative climatic period following the warm/dry medieval climatic one, and the large advancing of the Po delta building from 1600 up to 1820 occured during the “Little Ice Age” (Marabini and Veggiani, 1990; Marabini and Veggiani, 1991; Marabini *et al.*, 1993; Marabini, 1994). A particular case is the description of the evolution in the second half of the 20th century when the tremendous effects of anthropogenic subsidence minimized the climatic ones (Carbognin *et al.*, 1984a; Carbognin *et al.*, 1984b, Carbognin and Marabini, 1989). Generally speaking, even if the influence of man’s intervention (rash removal of riverbed materials, destruction of sand dunes, subsidence by extractions of fluids, etc.) on coastal zones during the 20th century is of primary importance, the role of climatic cycles is not negligible (Marabini, 1997).

Conclusions

In synthesis, the following conclusions can be drawn: (a) The natural tendency of the river has always been to develop its northern branches, while the southern branches have always tended to be less important; (b) after the construction of the *Taglio di Porto Viro*, canal the accretion of the Delta was southward and the velocity of increase became 20 times greater than the average one of the ancient period; and (c) the present shape of the delta is more the result of human intervention than natural evolution.

This paper shows, utilizing maps and geomorphological reconstructions, the interference between the natural and the man induced evolution of the Po river delta. Particular consideration is devoted to the importance of the hydraulic works during the last 400 years.

Acknowledgements

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Historical Development of Water Supply in Iraklio City, Greece

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Abstract: The history of water supply and wastewater engineering in the city of Iraklio goes back more than 4,500 years. From the Early Minoan period II (*ca*. 2900- 2300 B.C.) settlement at Knossos, these issues were considered to be of great importance and hence they were developed. With the emergence of the Minoan "palaces" in the Middle Minoan Ib (*ca*. 20th B.C.) a variety of techniques concerning water and wastewater management were applied. Mycenaean Greeks that "invaded" the island during the Late Minoan II period (*ca*. 1450 B.C.) adopted the sophisticated techniques first applied by the Minoans. As the island was a crossroad of people a number of different techniques of water and wastewater management were practiced. Crete was occupied by different cultures and civilizations that contributed with different solutions and several features in the area around Iraklio. People living in the Roman, the Arabic, the Byzantine, the Venetians and the Ottoman period gave their own perspective in the problems related to water and wastewater. A review of all these techniques is presented in this paper.

Keywords Crete; Iraklio; Minoan civilization; wastewater history; water supply.

Introduction

Guiseppe Gerola had studied the hydraulics technology during the years that Crete was under the Venetians. In his important work *Monumenti Veneti nell'isola di Creta* published in the early 20th century he mentions that "three civilizations left their remains on their approaches to solve the drinking water problem in Crete: the Romans, the Venetians and the Turks". However, a long time before these civilizations, the people living in Bronze Age in Crete were aware of how to deal with problems involving water and wastewater management (Koutsoyiannis *et al.,* 2006). Excavations of the early 20th century revealed settlements and "palaces" of a civilization that flourished mainly in the first half of the 2nd millennium B.C. (Middle Minoan Ib- Late Minoan Ia-b). The civilization, considered to be the first in Europe, was named Minoan after the legendary King Minos mentioned in the ancient Greek Mythology. Minoans practiced applications on water hydraulics engineering that can be considered as advanced and sophisticated (Angelakis and Koutsoyiannis, 2003). They had developed techniques in the water supply such as aqueducts, cisterns, and wells, while they also managed wastewaters with the construction of sewerage systems. Moreover, they used water for recreational uses and purgatory reasons in the toilet, as was found in several buildings.

The scope of this article is to present a number of characteristic examples in selected fields of water supply of Iraklio city extend from early Minoan to the Ottoman periods. Emphasis is given to the periods of great achievements

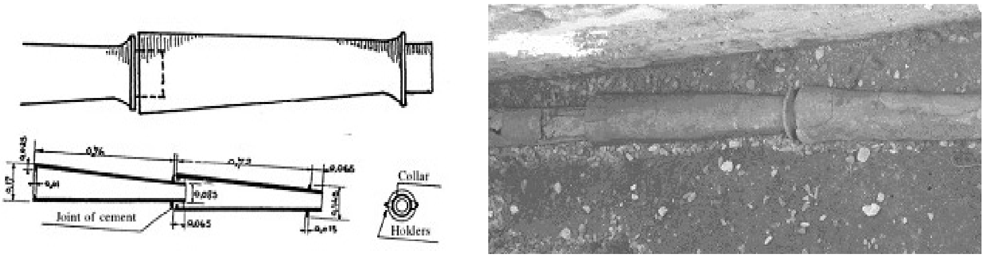
The Minoans

The evolution of urban water management in ancient Greece began in Crete during the Early Bronze Age (*ca*. 3500- 2000 B.C.). A great variety of remarkable developments have been marked in several stages of the Minoan civilization, a civilization that flourished during the Bronze Age in Crete. These included various scientific fields of water resources such as wells and ground-water hydrology, aqueducts, cisterns, water distribution and domestic water supply, construction and use of fountains, and even recreational uses of water. One of the salient characteristics of the Minoan civilization was the architectural and hydraulic function of its water supply systems in the “palaces” and other settlements. It must be suggested, therefore, that a specific group of technicians-“engineers” living in Bronze Age Crete were aware, long ago, of some basic principles of what we call today water and environmental sciences (Koutsoyiannis *et al*., 2006).

Minoan hydraulic engineers were apparently concerned with the solution of some water engineering problems and were able to provide cities and “palaces” with complete water supply systems. On the basis of their accomplishments it can be assumed that they were, in a sense, aware of the basic hydrostatic law, known today as the principle of communicating vessels. It is manifested in the water supply of the Knossos “palace” through pipes and conduits fed by springs; this is supported by the discovery of the Minoan conduit heading towards the Knossos “palace” from Mavrokolybos which suggests a descending and subsequently ascending channel (Evans, 1921-1935; Hutchinson, 1950). However, it appears that Minoans had only a vague understanding of the relationship between flow and friction.

Arthur Evans (1921-1935) mentioned that the Minoans knew the use of siphon and they also used communicating vessel principle in order to transfer water from the nearby river Maurokolympos into the “palace”. Remains of an aqueduct were found next to the river. Other water sources were probably developed later on, such as the springs of *Paradeisi* and *Karydaki* to satisfy the increased water demand. In the “palace” we can see nowadays the remains of internal installation of sewerage and drainage systems. They were so perfect that they still operate after 5,000 years. The water of the springs and wells was transferred into aqueducts with opened channels and opened or closed ceramic pipes. The closed pipes were perfectly fitted to each other and specifically designed to avoid clogging phenomena inside them. They were engineered with a small diameter inlet and bigger diameter outlet so that the pressure made up could not allow any solids inside the pipe. Those ceramic pipes can still be seen in the “palace” (Fig. 1).

The Minoans also invented techniques for the treatment of drinking water as well as its distribution inside the “palace”. They could also reduce the flowrate at the end of each pipe with the use of ceramic vessels so that the water could flow smoothly inside the rooms of the “palace”. The stormwater flew beneath the stairs of the “palace” and it was used for cleaning purposes. It is very important that by that time water was also used for visual pleasure and entertainment. Inside the “palace” several fountains and squirts are found. Iosif Hatzidakis mentioned that remains of an aqueduct of the same age were found in *Tylisso*s, meaning that apart from the “palace” the water engineering developed by the Minoans was applied also in other Minoan cities. Minoan engineers were also pioneers in the development of toilet technologies. The first known flashing toilet was installed in the “palaces” at Knossos.



(a) (b)

Figure 1 Minoan water supply pipes (terracotta pipe sections): (a) Overview and real dimensions (Buffet and Evrard, 1950) and (b) today's view.

Arabic Period (824- 961 A.D.)

When the Arabs conquered the island of Crete in 824 A.D., they named the city of Iraklio 'Handax' and they constructed city walls as well as a huge ditch all around it. The Arabs remained in Crete for 137 years mostly involved in piracy of the Aegean Sea. The first Arabic citizens suffered from water shortage. At that period water was coming to Iraklio from surface springs through aqueducts. There is indication that the water of *Funtana* spring was used at that time for water supply of Knossos (Spanakis, 1981), and further development of the *Funtana* aqueduct was done during the Egyptian period (*ca*. 1830- 1840 A.D.). However, the majority of the water used was coming from wells and rainfalls collected into small aqueducts. Big amounts of water coming from wells were of high salinity, dew to the wells position nearby the sea. The water was only suitable for the purposes of cooking and cleaning.

The Years of Byzantine (961- 1204 A.D.)

From 961 A.D. to 1204 A.D., Crete was part of the Byzantine Empire. 'Handax' was the headquarter of the Duke of Crete. During this period the technologies applied for water supply of the city were more or less the same to those applied in the Arabic period. In many cases, rainwater collected from the roofs of the houses and other opened areas in cisterns and wells was a basic practice. High salinity water was still used from the wells. Every house had a well and the richer people had their own drinking water tank. The water supply in the city of Iraklio during the Arabic and the Byzantine years can be considered to be primitive relatively with the history of the area. The Minoans managed to have integrated water and wastewater solutions thousands years before.

The Venetians (1204-1669 A.D.)

The island was conquered from the Crusaders running their 4th Crusade in the beginning of the 13th century. Later, the Venetians bought the island of Crete from them and made their most important dominion in the Eastern Mediterranean. Crete contributed like no other in the progression of the Venetian kingdom. The Venetian Lords were used to the excessive water consumption for baths and home uses. At the beginning they used the existing water aqueducts. The Duke of Crete with a document of 1403 A.D. commands the maintenance of the water tank of the Duke's "palace" mentioning: *'...because the water is a high necessity for the palace and the family of the Duke of Crete*'. The Duke's "palace" used also 3 nearby wells.

Later on, Francesco Morozini, general forecaster those days, commanded the maintenance of all existing water tanks in the city. The city still suffered of water shortage. In 1629, Fr. Morozini stated that the biggest disadvantage of the city was the water shortage (Spanakis, 1981). The richer inhabitants had to transfer water from a distances of 8-10 km using for this purpose people and animals. The poor people had to give their children for buying some contaminated water from the river of *Katsaba*s. As far as this issue is concerned it was also mentioned by many travellers of the island during the Venetian days. Buodelmonti, who visited the city in 1415, mentioned that young people used to take water from the wells nearby the river of *Katsabas* and to sell it in the city roads (Spanakis, 1981).

From the 16th century the Ottoman threat begun to be very clear. Special care was taken by that time for the water supply of the city, as well as in case of a city siege. Attention was focused on the existing wells and water storage tanks. The Venetian senate commanded the government of Crete to immediately build three very big water tanks with high water capacity, to be filled with rainwater or water from the river *Katsaba*s, and to be locked with a key as well as to be guard at all times. All in 1474 these are described in a letter sent from the Venetian senate to the Cretan governor. The richer people owing water tanks were forced to maintain them and fill them with the water during the foreseen siege, as described in the same letter. In 1591 a special well expert was sent to the city from the Venetian senate. In 1602 Filippo Pasqualigo cleaned thoroughly three of the city's wells so they could be used on. In 1620 the same action was ordered by Marc'Antonio Venier, and about 520 wells were cleaned.

Finally, just before the city fell to the Ottomans, in 1639, Isepo Civran mentions that out ot the 1270 wells and 273 water storage tanks in the city, 40 and 17 of them were destroyed, respectively. The last 133 of those tanks were built during the last decade 1629-1639, indicative of the necessity during the siege for conservation of water. Fr. Morozini mentioned that there more than 140 tanks in the old part of the city. For the period 1612-1614 he was named the Duke of the city, and was the first Venetian to give much attention to the water supply issues. He leaded the construction of a 15.64 km line which the water was transferred from three surface springs in the area of *Karydaki* into the city centre. The construction was huge and thousands of workers participated. Three major water bridges (*Karidaki*, *Fortetsa*, and *Lazaretou*) were constructed as well as many canals inside the city walls, and the water flew underneath monasteries and through the fortress of *Fortezza*. ended up in the city centre and was running out from the mouths of four marmoreal lions. All this construction was then called *Morozini's aqueduct*. The water bridge at the area of *Karydaki* is shown in Figure 2.

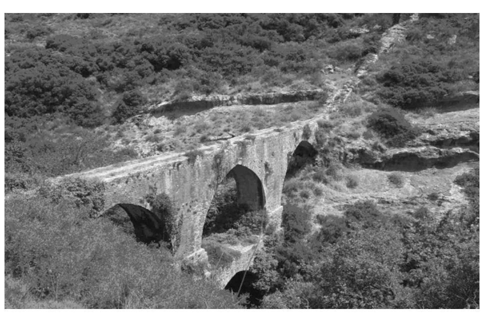


Figure 2 Water bridge at Karidaki.

The Ottoman Period (1669- 1898 A.D.)

For Ottomans, water was connected with their religion. In front of every *Tzami* it had to be a water tap so they could be washed before praying five times a day. They maintained and used the *Morozini's aqueduct*. Excessive water was needed for the *hammam*, the hot water baths that was very popular those days. Generally, people in that particular period did not pay any attention to increase the quantity of the water brought into the city. The maintained and kept all the constructions that they found in the city from the Venetians.

The Egyptian Period (1830-1840 A.D.)

During the Egyptian period a new water source was added with the Italian name *Funtana.* The *Funtana* is a typical karstic spring at a distance of about 5-6 km from the "palace" at Knossos and an elevation of about 220 m. *Funtana* appears to have been used for domestic water supply purposes throughout the history of the city of Iraklio. That spring was probably used for water supply of Knossos during the Roman period (Spanakis, 1981). At that time the tunnel at *Scalani* was constructed of 1 x 2 m² cross section and 1150 m in length. Accordingly to Spanakis (1981), the *Funtana* aqueduct was reconstructed, the *Scalani* tunnel was cleaned up, and the water bridge at *Agia Irini* was constructed later on (*ca*. 1839). Remains of that aqueduct are shown in Figure 3. The water of *Funtana* spring is still in use. The quality of its potable water is still considered to be one of the best in the city. Some of its qualitative characteristics are given in Table 1.

Table 1 Qualitative characteristics of water of *Funtana* spring.

Parameter	Units	Values			
		1991	1994	2001	2006
pH		7.4	7.5	7.6	7.6
EC	dS/m	0,65	0,68	0,70	0,75
Hardness ($CaCO_3$)	^oD	16.8	17.5	19.0	17- 20
Cl^-	mg/L	50	53	60	;
NO_3	Mg/L	9	13	15	16-18

(a) (b)

Figure 3 Remains of *Funtana* aqueducts¨(a) at *Scalani* and (b) at *Agia Irini*.

Discussion and Conclusion

In Minoan Crete, fundamental technologies regarding water supply (such as aqueducts, tunnels, wells, cisterns, and distribution systems) were very well developed up to a degree, which had never been reached before (Viollet, 2003). The advanced water supply systems in various Minoans "palaces" and settlements is remarkable; no such advanced systems have been known before the Minoan era, whilst there is strong evidence that this technology was developed by Minoans. Similar terracotta pipes of those used for water distribution in Knossos, were found in some other Minoan settlements, such as Tilissos, Gournia, Gortys, Malia and thereafter in Hellenistic and Roman settlements. The Minoan water supply systems were transferred to the mainland Greece and the Aegean islands in Mycenaean times (Koutsoyiannis and Angelakis, 2003). Later the technology was spread all over Greece and it can be assumed that it passed the borders and transferred in Europe and all over the eastern world. On the other hand, water supply of Iraklio city throughout the centuries, appears to be depended on surface springs and transferred by aqueducts. These was the basic technology applied up to the beginning of the last century. Thereafter, the water supply of Iraklio city depended on groundwater of the Kastelli, Malia, Tylissos, Agios Myronas, and Krousona aquifers.

When reviewing the technological achievements of water supply in Iraklio, an important question raised is whether any of these achievements are reflected in modern technologies or were they forgotten due to the passage of time and the regression of technology in the dark ages and had to be re-invented in modern times. The answer to this question is complex. Some of the engineering principles were lost probably during the Byzantine Empire and had to be reinvented. These are clear examples of the discontinuity in the history of technology.

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The Ethnoarchaeology and Proto-industrial Archaeology of Water on the Islands of the Aegean: Water Power in Samothrace, Greece

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Abstract: The ethnoarchaeological study of watermills and olive oil mills in Samothrace aimed at analyzing the systemic relationship between water management and the associated material remains and examining the related technology. The latter is linked (a) to the nuclear settlement pattern observed on the island till the end of the 19th cent. and connected with the pre-industrial watermills, and (b) to its subsequent dispersion in the villages of the south-central part of the island, when the proto-industrial olive oil mills made their appearance there, as a result of the dynamics that developed between the agrarian settlements and land use in the olive zone. The watermills of Samothrace are of the “Eastern” or “Greek” type with a horizontal water wheel. The Samothracian watermill is a usually one storey building with a single rectangular or slightly trapeziform room, 38-77 m² in area. The olive oil mills are generally oblong buildings with a linear-extended layout of the rooms and a total area 70-584 m². In general the water powered olive oil mills of Samothrace depended on the vertically mounted water wheel-*rodhána* until about 1925 and subsequently on turbines until the end of the ’60s.

Keywords Ethnoarchaeology; olive oil mills; proto-industrial archaeology; Samothrace; water management; watermills.

Introduction: Theoretical Considerations

The theoretical and methodological considerations of “New Archaeology” (Binford, 1962) chiefly in the decade of the ‘70s, had as a result the systematization of the relationship between archaeology and ethnography. Although the field of research in the scientific branch that has become known as *ethnoarchaeology* is a continuous process of debate (David and Kramer, 2001:6), ethnoarchaeology may be considered as a combination of the archaeological and ethnographic approaches, which comprises a systematic study on the one hand of a part of the material culture of a contemporary society, and on the other of the manner in which the material elements of this culture are incorporated into the archaeological record (Renfrew and Bahn, 1991: 166). The collection of primary ethnographic data, with special reference to the relationship between material culture and human behavior in the present or the immediate past (Schiffer, 1976: 8; Murray and Runnels, 1984: 1; Trigger, 1989: 371), aims at providing support for archaeological interpretation

(Hodder, 1982: 28) in a "middle range" model[1]. Ethnoarchaeological research in Greece has a special connexion with "Laographia", as N. Politis in 1884 called the discipline that has its subject the Greek people and culture[2], which, however has until recently remained closely linked to the ideological orientation of the different periods of modern Greek history and, in one view[3], has "stagnated", while the relatively recent dialogue between archaeology and folklore in Western Europe has the aim of enriching archaeological practice and reasoning[4].

Field Research

The purpose of the ethnoarchaeological study on watermills and olive oil mills that was carried out by the ΙΘ΄ Ephorate of Prehistoric and Classical Antiquities in the mid 80s (1985-8), as part of a diachronic[5] archaeological survey[6] of the western part of the island, was twofold: an analysis of the systemic relationship between water management and the associated material remains, and secondly a study of the related technology. The latter in Samothrace is linked to the nuclear settlement pattern and its subsequent dispersion in the villages of the south-central part of the island marking, in our view, first the transition from the pre-industrial - watermills - to the proto-industrial - olive oil mills - era[7], and secondly the dynamics that developed between the agrarian settlements and land use[8] in the olive zone.

The progressive shift in Greek society from the agrarian to the industrial, from the traditional to the modern, a shift in economy, society and ideology[9], is generally placed in the decade of the '50s, a decade characterized in Samothrace by the start of the migratory wave[10] towards mainland Greece and Western Europe and the following gradual desertion of the traditional character of the countryside on the island. In Samothrace this change took place, has perhaps still been taking place until recently, with slow steps, a tardiness that was due to the rigid social and economic structures on the island, which broke out with great difficulty from its isolation. The disruption of the pre-industrial technical systems is generally placed in the decade of the '60s[11], and the time shortly afterwards, at the beginning of the '70s, we may consider as the end of pre-industrial waterpower[12]. The end of man's direct relationship with his environment in the pre-industrial society of Samothrace, when time consisted of a slow cyclical repetition[13], the Braudelian[14] *longue* durée[15], was very recent in the period of our field work; it was this that enabled us some two decades later to unearth many, perhaps most, of the material remains of the waterpower in the landscape of the island and to meet with many of its, already very old, leading figures.

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1 Jameson et al. 1994, 11· Ευστρατίου 2002, 19.
2 Κυριακίδου-Νέστορος 1978, 15· Λουκάτος 1985, 21.
3 Παπαδόπουλος 2003, 166.
4 Gazin-Schwartz – Holtorf 1999.
5 Cf. Renfrew – Wagstaff 1982.
6 For the problems of the early '80s cf. Keller – Rupp 1983, 17-44 and especially Cherry 1983.
7 See Μάτσας 1999· cf. van Andel – Runnels 1987· Whitelaw 1991.
8 Cf. Jacobsen 1985, 99.
9 Κυριακίδου-Νέστορος 1979, 41.
10 Faugères – Kolodny 1972, 101.
11 Παπαδόπουλος 2003, 427.
12 Cf. Παπαδόπουλος 2003, 436 for the area of Epirus in NW Greece and Σορδίνας 1981, 115 for Corfu.
13 Παπαδόπουλος 2003, 204.
14 Braudel 1966.
15 Cf. Hexter 1972, 505.

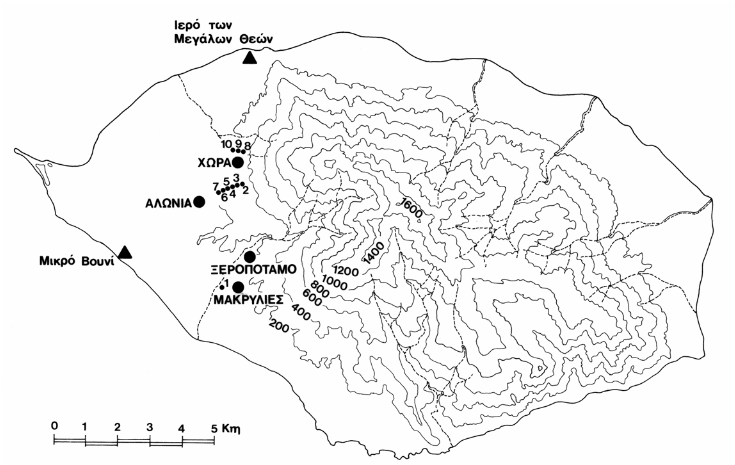
The Rural Landscape of Samothrace

As a result of the interaction of man with the environment, the landscape is defined by the area of usable land on the island combined with the intensity of its exploitation. The relationship between the natural environment and the cultural models of the past and the present enters into all forms of the management of local resources, and especially into this study of water resources[16]. The most striking feature of the rural landscape of Samothrace is the degree of its strict territorial specialization, and at first sight this is surprising in such a little developed economy and in a land so parceled out into individual properties. This specialization appears to have been the result of a natural necessity, from which the traditional model of exploitation was unable to find a way out. It is not known how old this specialization is, nor how much it follows the ancient model[17]. The concentration of wheat cultivation in the western part of the island is especially indicative and characteristic of the practices of a traditional economic autarкy[18] and is associated with *Chóra*, as the unique nuclear ekistic centre in pre-industrial Samothrace. The watermills are concentrated on the outskirts of this village.

Water Management

The central mountainous mass with its great height and steep slopes is the principal morphological feature of Samothrace[19]. Snow covers the highest parts during most of the year and feeds the sides with water that ends up in the sea, since the steep slopes prevent its retention. Thus the *Sáos*, as the island mountain range is called, forms a rather “leaky” reservoir of water, with only a small capacity, which in midsummer supplies only a few springs. Of a large number of streams that flow during the winter months, only five have water during the summer. Until the end of the ’80s, when drilling began, the western part of Samothrace was fed exclusively by water from springs that were used for the needs of the settlements and irrigation, as well as for powering the machinery of the watermills centered there[20]. The springs are at the foot of the imposing crevices that surround the central mountain mass, at the point of contact between the older impermeable and the more recent, generally permeable terrain[21]. This peculiarity results in the very fast runoff of the water below the springs and explains the location of the watermill installations (Fig. 1), which functioned all year round, while the olive oil mills usually worked from November to January-February[22], a period when even the rivulets have water. However, Samothrace has abundant supplies of water by standards of Aegean islands, where, although the Mediterranean tower wind mill dominated, also watermills were favoured when even a small quantity of water existed.[23]

[16] Cf. Harper 1976, 40.
[17] Cf. Snodgrass 1987, 93· van Andel – Runnels 1987, 4.
[18] Faugères – Kolodny 1972, 84.
[19] Μάτσας – Μπακιρτζής 2001, 16.
[20] Although the wind dynamics in Samothrace favors also the wind-energy, there were only watermills (cf. Τσενόγλου – Νομικός 1989, 97 and Νομικός 1991, 199).
[21] Cf. van Andel and Runnels 1987, 16.
[22] Μάτσας 1999, 127 n. 37.
[23] Cf. e.g. the watermills on the mountainous and well-watered Cycladic island of Andros. In general, apart from the watermills, very few other water-driven installations operated in the Aegean including the olive oil mills of Lesvos and Samothrace.



Water Mills

The watermills of Samothrace (Fig. 1)[24] are of the “Eastern” or “Greek” type[25] with a horizontal water wheel (*fterotí*), which is mounted on the lower end of an axle. The axle passes through the lower grindstone (*katópetra*) and is attached to the upper grindstone (*panópetra*), which it revolves, while the lower grindstone remains stationary. The watermills are almost all in *Chóra*, in two separate groups: the first on the eastern and the second on the southern edge of the village. The second group was the more numerous, in which 12 mills are reported, while the first comprised only 4.

The Samothracian watermill is a usually one storey building with a single rectangular or slightly trapeziform room, measuring on average 5.30 x 9.50 m, with an area varying between 38 and 77 m². The machinery of the mill is close to one of the two narrow sides of the building and set on two levels. The usual height of the lower one, which housed the horizontal water wheel (*fterotí*) and it is known in the local dialect as the *kontoloúki,* is 0.80 m, and is characterized by an arched opening for the water to escape in the wall of the facade of the watermill. The water wheels of the Samothracian watermills that we saw were of metal, had a diameter of 1.40-1.50 m and were made on the island. The water wheel, which was originally of wood with paddles of cedar wood, was mounted on the *tampáni* or *tampanóxylo*, a horizontal oak board secured to the ground with stones. To the centre of the *tampanóxylo* was fixed the *foliá* (gudgeon), one of two bronze *velónia*, in which the upper *velóni* (pin) revolved. The wooden *róka*, which formed the axle of the water wheel, fitted into the upper *velóni*. In the centre of its upper part the *róka* has a vertical mortise from side to side, into which, an iron plate is wedged and fixed by a clamp. This plate terminates in two horizontal projections at its lower end and in a dowel shaped like an inverted T at the upper end, the *chelidhóna*. The horizontal arm of this dowel goes into a socket of corresponding shape and size in the lower surface of the upper millstone. To the end of the *tampanóxylo* originally the wooden and later the metal *stavrós* was fixed, which formed a mechanism for raising the upper millstone when it was necessary to produce a coarse flour. To complete the description of the lower level of the machinery, of the *water wheel* chamber,

[24] Μάτσας 2006.
[25] Cf. Νομικός 1991, 191.

we should also mention the wooden *stamatíra*, which deflected the flow of water that rushed out of the *axái*.

On the upper level, in the miller's work place, which had a height of 1.25 – 3.20 m, the machinery of the watermill, starting at the top, included the *kofinídha*, a wooden quadrilateral hexahedron ca. 0.65 m high with an opening ca. 0.60 x 0.60 m, into which went the grain. Four vertical wooden supports[26] arranged in a rectangular shape in plan[27] and joined to each other by horizontal crossbeams, kept the *kofinídha* in place. From the horizontal crossbeams hung the outer end of a rhomb-shaped plank leveled lengthwise; in its centre were openings into which were wedged the *vardhária*, two pieces of wood, like "little hammers", that struck the upper millstone. The inner end of the wooden rhomb, towards the *kofinídha*, fitted into the *koukí*, which was held in the *karávi*. As the stone revolved, the *vardhária* struck the top of it and moved the *koukí*, and as it went up and down the grain passed from the *karávi* to the millstones. A rope was fastened to the *kofinídha*, at one end of which two old horseshoes or a bell were attached: when the grain was used up, the horseshoes or bell were loosed and dropped onto the millstone, making a noise that warned the miller feed more grain into the mill.

The millstones, which have a diameter of 0.60 – 1.00 m, came chiefly from Phókies in Asia Minor and to a lesser extent from Milos. The former, being harder, were considered better and they arrived at Samothrace in pieces. The *varádha*, the water tower which had always to be kept full and at whose upper mouth the *anegós*, the water chute, ended, was originally made of wood, but was later built of stone; it had the shape of an elongated cone or pyramid inside, and outside it was rectangular in section with a stepped façade. The stone-built *varádhes* that were studied constituted the most carefully constructed and impressive part of the watermill installation. The diameter of the circular or oval mouth of the water tower varied between 0.95 and 1.65, while its height ranged from 6.18 to 19.20 m, and the angle of its inclination from 49 to 59 degrees. A metal grill to collect the leaves and twigs and prevent their entering the *varádha* was placed in the last section of the *anegós* before the mouth of the former. The lower part of the *varádha*, where it narrowed, was called the *kouléthra*, and to it was fitted the wooden *zournás*. Into the *zournás* the wooden *axái* also was tied, with a hole that had different sized diameters according to the volume of the water.

The watermills milled barley, wheat, *migádi*[28] and maize, as well as beans and figs. The daily output (in a period of 24 hours) was usually 200-250 kg of flour and the *dikaíoma* (miller's fee), known as the *axár*[29], was 10%. Nearly all the mills were partnerships and shared between them several portions, which were divided out on a monthly basis.

Olive Oil Mills

The island's largest olive plantation covers many thousands of "stremmata"[30] on the sunny slopes of the foothills of the south-central ridges of Mt *Sáos*, a considerable distance from

[26] The front, which form with the upper horizontal beam the shape of the Greek letter Π, are ca 1,70 and the back ca 0,90 m in height.
[27] In the front and back sides they are ca 0,90., while in the lateral sides ca 0,80 m apart.
[28] Mixture of equal quantities of wheat and barley.
[29] Derived from the latin exăgĭum. Cf.. Lewis 1879,672: exăgĭum, ii, n. [ex-ago; cf. examen, II.], *a weighing*, *weight*; *a balance* (late Lat.), Theod. Et Val. Nov. 25; Inscr. Orell. 3166; cf. εξάγιον pensatio εξαγιάζω examino, Gloss. Philox. Glare 1982, 630: **2a** The exaction, calling in (of taxes, debts, etc). **b** the enforcement (of labour). Liddel et al. 1940, 580 and Glare – Thompson 1996, 119: εξαγιάζω (Fr. Lat. *exagium*.), *assay*, *Gloss*.:-Pass., of measures, *to be fixed*, Hero *Stereom*. 2.54.3; εξάγιον, το (Lat. *exagium*.), *assaying*, *testing*, ποιε□σθαί τινος Gp. 2.32. tit. **II**. *part payment*, *POxy*. 3955 (AD 611).
[30] A "stremma" equals 1000 m².

Chóra. However, the petrological, topographical and soil conditions play an equally important role. Today in Samothrace there are ca 9,000 stremmata of olive plantations and ca 170,000 olive trees.

The olive oil mills are found chiefly in the region of the olive plantations, with the exception of one olive oil mill in *Chóra*, which clearly represents the period before the diaspora of the population outside this nucleated village. Of the remaining olive oil mills, seven are in the southern and one in the northeastern part of the island. All except one, which was rotated by animals, utilized the abundant water power of the island[31] for their operation.

The olive oil mills are generally oblong buildings with a linear-extended layout of the rooms and a total area varying between 70 and 584 m². They consist of the principal oil mill with the stone or stones[32], the press[33], the jars for storing the oil, the repositories for the olives that were brought by the growers and awaited their turn, in spaces that were exclusively for the storage of the olives, the oil, the olive pits and in the house where the owner or employees lived. Two olive oil mills also had a flour mill, and in one case there was also a *kafeneío* (=coffee bar) which, as well as wine, ouzo and coffee, during the time when the "works" were in operation also offered food to the customers and employees.

The employees who worked in the olive oil mills of Samothrace fluctuated between one and six or seven persons, who had specialized jobs in the "works", such as recording receiver, engineer and binder. The daily payment was equal to 2.5 – 4.5 kg of olive oil for the master or the mechanic and 1.5 – 2.5 kg for the workers, from the *dikaíoma,* which was 10-13%. The daily output of the olive oil mills varied from 600 to 1000 kg of olive oil, corresponding to 60 to 100 tons/yr. The information at our disposal show that in the olive oil mills in the southern part of the island there was no essential difference in size of production between the water-, diesel- and electricity- powered operations. The edible oil produced had an acid content of 1-5 degrees, and the olive stones were sold in Chalkídha, Mytilíni and Thásos. The profits to the owners of the olive oil mills were particularly high. As an example it is said that the costs of an olive oil mill in Samothrace were covered by the sale of the olive stones alone.

The earliest use of water power to operate an olive oil mill in Samothrace, based on the surviving material remains, was in1896 and took place in *Lákkoma*, in the south-central part of the island. Water from the stream was channelled through the *anegós*, which reached close to the mill, and from there through a wooden conduit it ran onto the *rodhána*[34], the vertically mounted water wheel, which gave the millstones their movement. Shortly afterwards, in

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[31] N. B. ΦΑΡΔΥΣ, "Σαμοθρακικά (Μέρος πρώτο, Τοπογραφία-Φυσική Γεωγραφία)" in Παπαγεωργίου 1982, 217.

[32] The stones, with a diameter of 1,00-1,20 and a thickness of 0,35-0,38 m, were local (in two cases stones from Poros are reported) and came from the knoll of *Toúrli*, near *Chóra*.

[33] The hand-operated presses initially were wooden and later of metal. However, hydraulic and mechanically operated presses were used alongside hand-operated. Apart from the wooden hand-operated presses, they, as a rule, were manufactured in Piraeus, and mainly at the Vasileiádhis machine works. The latter was one of the two first machine works (the other is of the Greek Steamship Company in Syros) established (ca 1860). In machinery drawings by the Vasileiádis machine works found in Samothrace, this company appears as "Greek Machine Works & Limited Liability Stock Company" in 1906, "Greek Machine Works & Shipyard & Stock Company" in 1907, and "Limited Liability Stock Company" in 1912.

[34] In Samothrace the vertically mounted overshot and backshot water wheel –*rodhána* – of the olive oil mills is rotated by falling water striking the paddles –*doulápia*-, as it became evident from the two *rodhánas* preserved in the period of our fieldwork on the island. The oveshot wheel does not require rapid water flow and gains advantage from gravity: the force of the flowing water is partially transferred to the wheel and its weight (see. Russo 1986, 153) also imparts additional energy. Overshot water wheels used the olive oil mills of Megísti Lávra (Μαμαλούκος 1996), Vatopédi (Κουφόπουλος – Μυριανθεύς 1996), and Simonópetra Monasteries (Nomikos 1991, 88-112) on Mount Athos.

1901, the olive oil mill in *Chóra* was also operated by a *rodhána*, which however soon ceased to function, perhaps before 1910, because in 1901 the owner built another mill[35], this time at the olive plantation in the southeast of the island. The Vasileiádhis machine works in Piraeus undertook in 1912 the installation of a water powered olive oil and flour mill at the expense of the owner of the two last olive oil "factories", who this time moved to the western part of the island's southern olive plantation. The new oil mill operated with this machinery, which used a vertically mounted water wheel, until 1925 when, according to the owner's son, a 40-50 horsepower turbine from England was installed.

In general the water powered olive oil mills of Samothrace depended on the vertically mounted water wheel – *rodhána* until about 1925 and subsequently on turbines until the end of the '60s. However, in two instances the installation of a turbine in the village of *Lákkoma*, was unsuccessful. One of them is considered the largest investment in terms of infrastructure: here in 1925 was built the most substantial example of proto-industrial architecture in Samothrace with important influences from the architecture of Lesvos[36] and Asia Minor, while the stone-built with lime mortar *anegós* that was constructed was some 700 m in length. The turbine also did not work satisfactorily in another olive oil mill that was constructed in 1912[37]. On the contrary, the *rodhána* technology used to power the millstones and the press survived at *Lákkoma* until the beginning of the '70s. This *rodhána* (Figs. 11, 13), which had a metal frame with a wooden drum and *doulápia*, had a width of 0.60-0.80 and a diameter of 8 m. Projecting from the corresponding radials of the circular drum were 56 boards forming the first constituent element of the *doulápia*. The second element was the wooden vanes that formed angles in the order of 115 grades with the boards. An olive oil mill in the northeast part of the island also had a *rodhána*, which survived in pieces until 1987 (Figs. 14, 15). It was of oak and made in this shape at the beginning of the '60s by the last owners of the olive oil mill. It was 3.90 in diameter and 0.55 m wide. The roughly 32 wooden vanes are fixed directly to the drum. The angles they formed with the assumed corresponding radials of the circle of the *rodhána* were in the order of 127-131 grades. The framework of the *rodhána* was formed by two pairs of parallel sticks of square section whose centres intersected at right angles. The *rodhána* turned the mill stone[38], while the press was hand-operated.

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[35] The diameter of the not survived *rodhána*, was calculated at 7.00 and its width at 0,60-0,80 m.

[36] Cf. Σηφουνάκης et al. 1986, 23 fig. 21, 49 fig. 54, 140 fig. 211, 142 fig. 213-4, 163 fig. 240.

[37] Evidently, the turbines did not work satisfactorily, because the level of the water supply from the *anegós* above the turbine had not adequate height. Cf. Μαυρουδή et al. 1998.

[38] Cf. Sordinas 1971, 8.

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A Database of Ancient Greek Harbours

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Abstract: The "Limenoscope" database was organized and is being updated in the framework of the Project "Harbours of Ancient Greece" undertaken by the Laboratory of Harbour Works, School of Civil Engineering, NTUA. The whole effort represents an example of the NTUA contribution to the promotion of the country's cultural heritage and the dissemination of the relevant information with a view to helping research on that particular cognitive field. The financial support received from private maritime engineering firms attests to the credit given to this contribution. The aim of the Project has been the realisation of a database, where one can search for concise information relevant to the historical role, the topography, the morphology, the harbour works and installations of ancient harbours in the Mediterranean and the Black Sea. The Database started off with the registration of examples of harbours located in the Aegean Sea and Cyprus, dating from Archaic to Byzantine times. Special emphasis is laid on the bibliographical update of the data forms of the harbour sites, as well as the related references in ancient literature. The Database enables the locating of these sites on a general map whereas photographs, plans etc. are also cited. In this contribution the principles of the database structure are briefly presented as well as an example among the harbours registered therein.

Keywords Ancient harbours; Greek harbours; harbour technologies; sea trade.

Introduction

The database "Limenoscope" was developed and is being updated within the Research Project "Harbours of Ancient Greece" undertaken by the School of Civil Engineering of the National Technical University of Athens (NTUA). The inspiration of the project belongs to two professors of the NTUA Dr Th. Tassios and Dr C. Memos. In due course the project was also supported by a variety of institutions including the Ephorate of Underwater Antiquities and the Institute for the Study of Ancient Technology.

This article, in continuation of previous similar articles presented in the 3rd National Conference of Harbour Works (Tassios, 2003; Ziros *et al.*, 2003), outlines the aims of the project and the structure of the database, giving a brief summary of the harbours that have already been incorporated, along with a brief description of the indexing process. Finally an example drawn from the base is presented with a tour of the Phalasarna inner harbour in western Crete. The database is available on the web at: www.limenoscope.ntua.gr and its homepage can be seen in Figure 1.

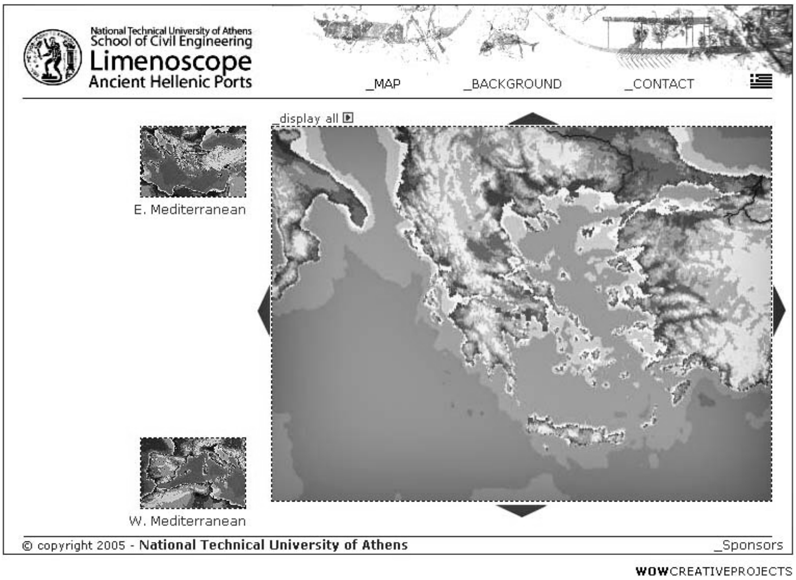


Figure 1 The FrontPage of the website.

Scope of the Project

Harbours are unique constructions built on the interface between land and sea which, by nature, is an unstable and ever-changing environment given the tectonic movements, sediment transports and sea-level changes that affect the coasts over the centuries. Ancient harbours played a unique role in commerce and cultural exchange since they were the sole gates of exported and imported goods in bulky consignments. The ancient road system was fairly primitive, since the construction and maintenance of such a network implied both large resources and a powerful central government. For this reason maritime was the preferred and economically sound mode of transport used in antiquity. The exchange of goods also enhanced the communication of news, ideas, knowledge, and consequently cultural and political inter-influence.

In almost all ancient Greek cities or states, and, beyond Greece, in the various cultures and political entities of the Eastern Mediterranean, every aspiration for political and economic strength had as a prerequisite the domination of the sea either in an commercial or military sense. This can be seen since the Minoan domination of the Aegean well into the Athenian Classical period. A central role in these maritime cultures was played by the harbours that were developed so that ships of all types could be protected, serviced, repaired or built.

Harbours were a crucial part of the infrastructure of the ancient city and affected not only the short-term development of the economy or the military expansion of the cities, but in the history and continuation of the "polis" as an economic and political entity. It is justifiable to presume, therefore, that harbour works were carefully designed and constructed to best serve the needs of the city over a long period of time, whilst also being able to withstand the attacks of nature and man over this time span. However this approach was not inherited by some of today's designers whose harbour projects not only lack a sensible approach to the needs of the area but burden, also, both the environment and the economy through excessive costs.

For the above reasons the discussed database can serve both as a catalogue of ancient harbours and as a reference point for those interested in the relevant inception and technical aspects or for those who today design similar installations. The research project “Ancient Greek Harbours” was designed to cover this need by providing an internet accessible database whereby the historic, technical, and operational data of ancient Greek harbours would be available.

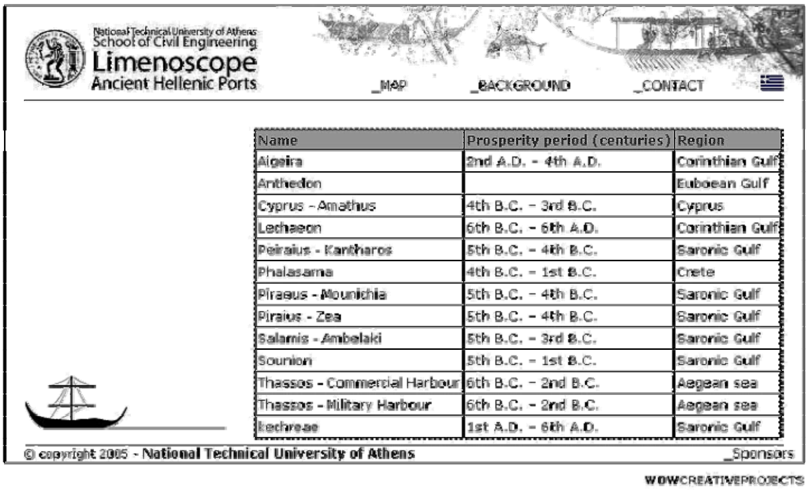
The geographical coverage is originally the Aegean Sea with a view that it will be extended in the near future to cover harbours in the entire Mediterranean basin and the Black Sea. It is hoped that ancient harbours in those areas will be included whether or not there have been archaeological studies for these. Indeed, efforts are being undertaken so that the first harbours to be introduced in the database encompass those that have undergone full archaeological investigation (i.e., Amathus in Cyprus), those undergone certain stage of survey and investigation (Pireaus harbours), and finally those that have simply been recorded (Salamis).

The Database

For the implementation of the harbour database, material concerning ancient sites was collected from ancient texts, modern research reports, photographs, maps, etc. It must be noted at this point that research concerning the harbour sites of antiquity in Greece, and the rest of the Mediterranean basin, has not been as enthusiastic as would had been expected, especially when the number of sites studied is compared to the number of ancient harbours. As for marine archaeology, harbour installations have been largely ignored in favour of shipwrecks which offer a variety of artefacts undisturbed by time or man, in addition to being easier for a variety of technical reasons as compared to ancient harbours. Thankfully, this trend seems to have changed over the last few years with the influx of new archaeologists, whose interest in harbour sites reflects the importance of this area of research.

Following the initial compilation of material for the database, and after many discussions concerning the scope of the new web-site, the cataloguing process was formulated. The basic principle adopted was to follow a concise and standardised method describing each entry, placing emphasis on compiling extended bibliography so that, along with the general information to be given for each harbour, the user have a comprehensive reading list at his/her disposal. Subsequently, the technical aspects of the web-site were streamlined, along with the development of software “Diavlos” which feeds the site with new data. The database allows the user to search and select any number of harbour sites that have been registered from a general map, and to view photographs and location maps. With the information written in both Greek and English, and through internet, the database aims at being accessible to the widest possible range of public. Translation of the material from Greek to English is already under way.

The database contains, up to now, information concerning sites from Greece and Cyprus, covering a time span from the Prehistoric to the Byzantine period. The following harbours are included: Kantharos, Zea, and Mounichia of Piraeus, the naval base of Sounion, the harbour of Ambelaki on Salamis island, the naval and commercial harbours of Thassos, the harbour of Anthedon on the Euboean Gulf, the harbours of Aigeira and Lechaeon on the Corinthian Gulf, the harbour of Kenchreai on the Saronic Gulf, the harbour of Phalasarna in western Crete, and the harbour of Amathous in Cyprus (Fig. 2).



Name	Prosperity period (centuries)	Region
Aigeira	2nd A.D. - 4th A.D.	Corinthian Gulf
Anthedon		Euboean Gulf
Cyprus - Amathus	4th B.C. - 3rd B.C.	Cyprus
Lechaeon	6th B.C. - 6th A.D.	Corinthian Gulf
Peiraius - Kantharos	5th B.C. - 4th B.C.	Saronic Gulf
Phalasarna	4th B.C. - 1st B.C.	Crete
Piraeus - Mounichia	5th B.C. - 4th B.C.	Saronic Gulf
Piraius - Zea	5th B.C. - 4th B.C.	Saronic Gulf
Salamis - Ambelaki	5th B.C. - 3rd B.C.	Saronic Gulf
Sounion	5th B.C. - 1st B.C.	Saronic Gulf
Thassos - Commercial Harbour	6th B.C. - 2nd B.C.	Aegean sea
Thassos - Military Harbour	6th B.C. - 2nd B.C.	Aegean sea
Kechreae	1st A.D. - 6th A.D.	Saronic Gulf

Figure 2 The table with the harbours of the database.

The Data Forms- The Harbour of Phalasarna as an Example

The data forms list information in the manner shown below. It is possible that some spaces are left blank due to lack of relevant information. The aim, however, is to constantly supply the forms with as much relevant information as possible. In the following the harbour of Phalasarna has been used as an example with the filled-in information placed in italics next to each heading. A general layout of the area can be seen in Figure 3.

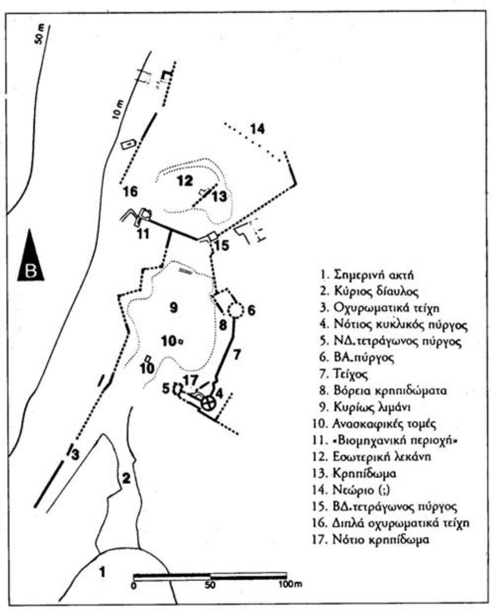


Figure 3 General Plan of the harbour area of Phalasarna (Hadjidaki, 1993: 590).

General features

Historical and archaeological evidence pertaining to the surrounding area of the harbour. The ancient city of Phalasarna is located in the middle of the west coast of Crete, by the tip of the Gramvousa cape. Pottery from the surrounding area proves that the city was already inhabited in the Middle Minoan period, while its development is depicted by the Archaic and Classical tombs discovered in the nearby area. The city was at its peak between the middle of the 4th century B.C. and the middle of the 1st century B.C. During this period a “limen kleistos” (walled harbour) was constructed, coins were issued and naval trade and warfare was developed, exploiting the city’s strategic position in-between the Aegean-Egypt and Western-Eastern Mediterranean sea crossroads. The Romans destroyed the city in 67 B.C., most probably because of its turning to piracy. Relics of houses, temples and quarries have been located around the harbour area. Today the port is found inland due to tectonic action in the Crete region. Excavation is taking place by the Ephorate of Underwater Antiquities.

Main features

(a) Region: Selection from a table: Aegean Sea, Ionian Sea, Saronic Gulf, Euboean Gulf, Pagasetic Gulf, Corinthian Gulf, Ambracian Gulf, Peloponese, Crete, Cyprus: Crete.
(b) Use: Selection from a table: Commercial, Military, Commercial-Military, Anchorage, Loading Pier, Naval Base, Not Defined: Commercial-Military.
(c) Prosperity period (centuries): Mention of the relevant centuries: 4th - 1st c. B.C.
(d) Existence of contemporary port: Yes/No question. In case of “Yes” synoptically mention the relation with the ancient harbour: No. The harbour is inland today.
(e) Surviving structures: Yes/No question. In case of “Yes” synoptically mention the surviving features of the harbour: Yes, two basins, remains of defending walls and towers, a quay with mooring stones and two channels.

General description

Description of the harbour installations and the relevant structures such as ship-sheds, stoae, stores, defense structures, sanctuaries-temples, lighthouses, etc. The harbour of Phalasarna was established in an existing basin, which was dredged and reshaped. Access to the open sea was achieved by building a channel from the port to the sea that was also functioning as a drainage work. This channel was most probably walled and sealed by a chain, in order to create the “limen kleistos”, as mentioned in Skylax (47). A second channel, which intersected the first one, discharged further north and was built probably for preventing siltation in the port. The main basin, 75x100m wide, was enclosed by walls and protected with at least four fortification towers. In the inner side of the walls quays equipped with mooring stones were built. A stone stepladder was also discovered. In the middle of 2nd century B.C. a second port basin was created northern than the first one. Its entrance was built from the remainders of a fortification tower. A small canal (50x50cm.) allowed water circulation. The existing walls-quays were used for mooring.

Technical features

(a) Construction period (centuries): Chronology in centuries and mention any other dating feature: 4th c. B.C. The harbour was constructed around 335 B.C. By the middle of 2nd ca. B.C. the second basin was formed.

(b) Harbour configuration: Selection from a table: Natural Harbour, Artificial Harbour, Outer Harbour, Inner Harbour: Artificial Harbour, Inner Harbour.
(c) Harbour size: The estimated size during use 7,500m².
(d) Land development: Reference to the size of the zone around the harbour, used for its operation: Not known.
(e) Critical wind sector: Selection from a table: N, NE, SE, S, SW W NW, S.
(f) Harbour entrance: Reference to the direction and the type of the harbour's entrance: The entrance to the harbour was made via an artificial channel, 100m long, which was formed through the marsh and the rocky beach, at the south of the basin.
(g) Sea level rise: Reference to the change of sea level from the period of construction: No data.
(h) Sedimentation: Yes/No question: Yes.
(i) Outer harbour structures: Selection from a table: Breakwaters, Moles: -.
(j) Inner harbour structures: Selection from a table: Basins, Quays, Wharves, Piers, Canals: Basins, Quays, Canals.
(k) Land facilities: Selection from a table: Ship-sheds, Store Buildings, Stoes, Shops, Temples, Lighthouses, Defence Structures: Temples-Sanctuaries, Defence Structures.
(l) Building system: Selection from a table: Natural Stone, Carved Stone, Crashed Material: Carved Stone.
(m) Neotectonic history: Selection from a table: Lift, Sink: Lift.
(n) Horizontal displacement of coastline: Selection from a table: Erosion, Siltation: Siltation.

Function and operations

Phalasarna bay seems to be active since the Middle Minoan period as a naval station, in the form of a natural protected basin communicating with the open sea. Around the middle of the 4^{th} century B.C. works took place in the basin and the entrance, so the city of Phalasarna acquired a modern enclosed harbour that brought about its peak, being an important naval trading and warfare center. Sea level rose in the harbour about 20cm until the 2nd century B.C. and its functionality was thus affected, forcing builders to intervene and elevate the surrounding structures. After the 2^{nd} century B.C. the port was used as a pirate hideout, which drew the Romans' attention and led to its destruction. Boulders found in the channel prove that the entrance was deliberately blocked, while stone bullets located in the basin are evidence of hostilities. Total annihilation occurred during the 4^{th} century A.D., probably in 365 A.D., when the whole area rose by about 6.6 m due to a severe earthquake that caused also a tsunami. The city and the port were buried irreversibly by tectonic action.

Sources

The main sources are:
(a) References in the ancient literature: Reference to ancient written sources: A total of 6 references is given (see website)
(b) Relevant research: Selection from a table: Archaeological, Geological, Seismical: Archaeological, Geological, Seismical
(c) Findings in museums: Yes/No question. If "Yes" what and in which museum: No
(d) References: The broader possible list of bibliography: A total of 17 references is given (see website).

Pictures and plans

A page of relevant pictures and plans given in bibliography with a reference to every certain source. There is also the possibility of showing the location of the harbour on a map of Mediterranean. Due to space limitation only two sample pictures are given (Figs. 3 and 4).

Acknowledgments

The funding of the project by NTUA as well as by the consulting firms DENCO, TRITON, MARNET is gratefully acknowledged. Ath. Ziros and Chr. Contaxi have also contributed to this project. The web-site was developed by S. Kozanis who along with A. Christophidis, both of NTUA, provide technical support. Graphics design by WowCreative Projects.

Figure 4 Part of quay with binding holes and mooring stones (Hadjidaki and Stefanakis, 2004: 115).

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The Water in the Royal Monastery of Santa Maria de Poblet, Tarragona, Spain

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Abstract: The history and water-related features in the Poblet Cistercian Monastery, located in Tarragona province, Spain are described. The study is undertaken with the main purpose of obtaining data for the establishment of an integrated water management system inside the walls of the abbey, which is suffering water scarcity due to increasing demands and the prevalent semiarid conditions.

Keywords Poblet Cistercian Monastery; rainwater; water management; water reclamation.

Introduction

120 km southwest of Barcelona lays an old Cistercian monastery, Santa Maria de Poblet, located in a semiarid area, where the water is a scarce good during hot summers. Romans and Arabs, which used to live in the area, left down material evidence of water infrastructures, some of them still in use. Water does have still a main role in the whole area. Water demands are increasing due to the growing number of visitors, the development of the surrounding towns and the reintroduction of vineyards. Those demands need to be carefully managed. For this reason, the monastery and the University of Barcelona have reached an agreement to study the waters inside the walls, and the historical remnants of the water distribution systems, with the purpose of seeing the possibilities of using waters arriving from outside, rainwater and reclaimed wastewater. The main aims are to implement an integrated management system for the monastery waters and to study the history of old water infrastructures still existing inside the walled enclosure.

The History

Santa Maria de Poblet Cistercian Monastery was founded in 1151, when Ramon Berenguer IV donated lands to Cistercian monks coming from the French Fontfroide Abbey, located near Narbonne. The monks settled down besides a river with a lot of poplars (*Populus alba*) named "populetum" in that time; the Latin name was the basis for the present Poblet denomination. The monks lived according to the Benedictine rule ("Ora et labora") and built a chapel, farms and a dormitory. Following the customs of every Cistercian monastery, a fountain was flowing inside the cloister, in front of the refectory. In this way, the monks washed their hands before the only daily meal. Along the centuries, Poblet was heavily

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favoured by the Counts of Barcelona, at the same time kings of Aragon, and was called Royal because some kings, who donated land, towns and money to the monastery, were buried inside the church.

Together with the monasteries of Montserrat (Benedictines), Vallbona de les Monges and Santes Creus (Cistercians), Poblet became a reference for the religious life of the country. The monastery favoured the development of agriculture and forestry in the surrounding villages and its other possessions, which arrived even near Valencia, 200 km southwards. Woodlands, vineyards, and other cultures thrived under the aegis of the monks. In 1836, the Spanish Government issued a Decree (amortización de Mendizábal) requisitioning all the properties of the Church, which afterwards were privatized. There were bad times for the precincts, but in 1940, the monks returned and the Spanish and Catalan governments backed heavily the monastery, reconstructing several of the buildings and the walls. At present, although some parts are still under works, the medieval buildings have a magnificent aspect. In 1988, Poblet was declared part of the World Human Heritage by the UNESCO. Currently is the biggest inhabited monastery in Europe. Nowadays, the precincts (Fig. 1) occupy 17.3 ha; 60% for agricultural purposes and the rest are buildings and areas open for tourism or for private use of the monks.

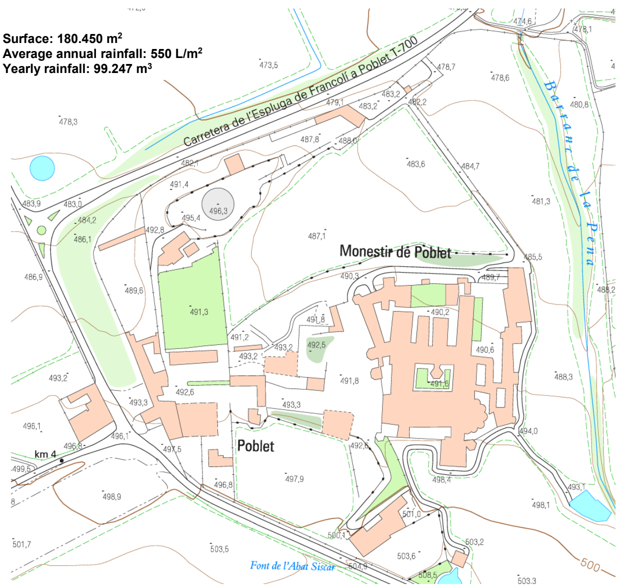

Figure 1 The Royal Monastery of Poblet, Tarragona province, Catalonia, Spain.

Hydrogeology

The monastery lies in the vicinity of the Prades mountains, part of the Catalonia Prelitoral range. The surrounding area, known as Bosc de Poblet (Poblet Forest) is protected under a legal figure named Natural Place with National Interest (Paratge Natural d'Interès Nacional) where the Palaeozoic and Triassic terrains are predominant with granite zones; and in the valleys and the monastery plain the Oligocene and Quaternary areas are majority. The Francolí river valley is clearly limiting the area in the Northern boundary. This river gains the majority of its water in the area (more than 3,000 ha) of the Poblet Forest and Titllar, a natural reserve, where water infiltrates in the karst and creates the underground flow surfacing in the cave called Font Major (greatest fountain) in the neighbouring of l'Espluga de Francolí village. The Francolí River starts in this cave.

The natural reserve reaches its higher altitude in the Tossal de la Baltassana peak (1,220 m), while in the monastery the height is around 500 m. From the geological point of view, there are two main units. The first one corresponds to the oldest formations; starting with the Siluric ampelitic shales, followed by Carboniferous sandy grey shales and a big granitic block and finishing with the Triassic conglomerates, clays and decomposed sands. There are also huge calcareous strata where the most important aquifer of the area is located. The second unit is formed by modern materials; marl and clay form the Eocene and Oligocene, and Quaternary alluvial sediments.

Both units are clearly separated by the fault located on the northern part of the system. The fault, with a vertical dip, made appear the older materials, distorting at the same time the most modern ones. Due to the tectonic movements and the huge amount of energy available, areas with a contact metamorphism were formed where several materials could have been mineralised. The granitic block is well represented in the Titllar and Castellfollit gullies, with diverse textures and high variations in the quartz, feldspar and mica contents. Nearly, porphyryc and fine grained textures are found. As it is appreciated in the Figure 2, describing the geology of the area, the granitic block is the great barrier which separates the aquifers located in the mountain (La Pena zone) from the ones in the sedimentary sector (Abbey zone).

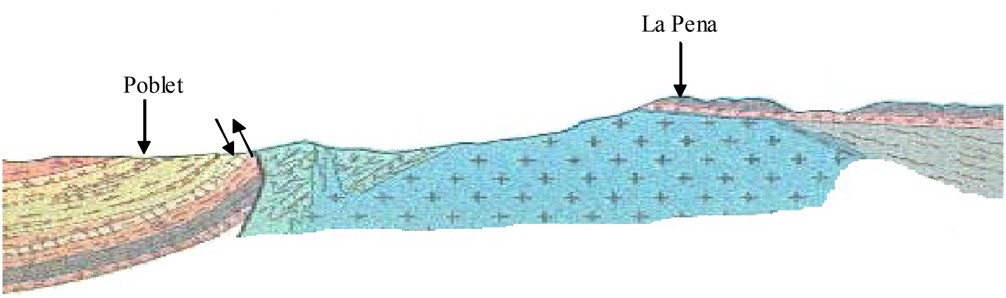

Figure 2 Geological cross section of the Poblet area.

Inside this zone there is another discontinuity layer separating the higher from the lower aquifers: the Triassic red conglomerates and decomposed sands which are absolutely impervious. Three main zones can be perfectly established from the hydrogeological point of view: (a) The higher mountain, where the Mesozoic limestone lies, with the most important aquifer of the area; (b) the lower mountain, where aquifers with permeability due to fissures or karst can be found; alternating limestone and shale levels; and (c) the valley, where the aquifers can be free or confined, with natural discharge and predominating clay and marl matrix. The water resources of the area depend on all the mentioned aquifers and the runoff, which must be carefully exploited and preserved. The average rainfall is around 550 mm/yr, with a Mediterranean regime, alternating humid and dry periods, which affect the extractions from small shallow aquifers.

The Water History in Relation with the Monastery

Water is strongly needed, especially during the hot summers in the area, so a special relationship regarding agricultural practices was established between the monastery and the surrounding villages: l'Espluga de Francolí, Montblanc and Vimbodí (at present, the monastery belongs to the municipal area of the last one). Groundwater was, and still is, the main water resource and several wells were used to feed water conduits towards the villages and the monastery.

The monks constructed their water infrastructures on top of the roman and Arabic water ones, but the bigger works were undertaken from the 16th century on, when two abbots, Porta and Guimerà, decided to improve water supply and even reuse. Irrigation channels, pools for water storage, channels for rainwater recovery, a tower for gaining head pressure in order to supply the higher buildings were built. Aqueducts and other structures show stones with the seal of the abbot.

Among the infrastructures the most important one is the Mill pool (bassa del molí, Fig. 3) with 1,140 m^3 and a special shape. The pool supplied water to the grain mill and also to the monastery buildings through the water tower. The water reached the tower by means of a dovetail stone pipe with pieces of 50x50 cm and an internal free diameter of 20 cm. From this tower water reached the buildings through an aqueduct. All these structures wear the seal of Porta abbot and were designed with a military and severe aspect, corresponding to the nature of the order.

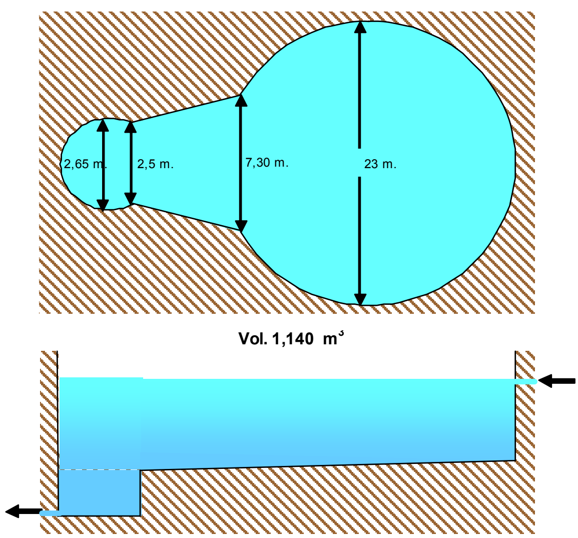

Figure 3 The main pool (Mill pool) in the Poblet Monastery.

Guimerà abbot leaded more ornamented works, although practical at the same time, offering more elaborated pieces from the aesthetic point of view. Water coming from the fountains was directed towards a pool in the second precinct of the abbey, which communicated with the vegetable garden, and was used for irrigation. Documents (1578, 1594 and 1750) located in the municipality of Vimbodí describe the ordinations of the abbots with a marked rural character. Those ordinations were law like, and the offenders could be prosecuted and sent to the monastery jail. Health procedures were enforced; such as the one which did not allow sick animals to drink in the public watering places. During the rainy season, water was pounding in the clayey places soil, and then the passage of animals was not allowed at least during three days after the rain episode.

Towards the end of 17th century the population realized that water from special wells could cure some diseases and later on the result was a thermal spa (Villa Engracia, built in the 19th century) and the baths of l'Espluga de Francolí. Nowadays, an iron well (Font del

Ferro) is still flowing. By the end of the 18th century new water infrastructures were built, carrying water from the Nerola well to the abbey (2.5 km long). After the return of the monks in the 20th century, and because the well remained inside the possessions of the Riudabella castle, the water distribution changed and the monastery is using that water 5 days per week.

The Present Situation in Relation with Water

Several features, important for later calculations and study of the possibilities of water uses, are described below:

(a) The legal influence of the monastery is today limited to the area located inside the walls.
(b) 37 monks dwell in the precincts. There are also guest quarters, with a maximum capacity for 80 people. 150,000 visitors per year are received, with peaks of 1,200 people during the weekends and summertime.
(c) The library is being reorganized and several historical legacies are being transferred to the monastery. This is why the presence of scientific visitors is slowly increasing every year.
(d) There is no livestock. Part of the agricultural land within the walls is rented to a private firm for growing vineyards. The monks have an orchard, where they grow vegetables, tomatoes, onions and beans.
(e) The built surface is 21,164 m^2. The impervious surface not built (yards, paved roads, etc.) is 41,969 m^2. Gardens and cultivated areas occupy 88,667 m^2.
(f) The mean rainfall is 550 mm/yr; with peaks of 675 mm/yr and historical minimums of 429 mm/yr.

Among the visible infrastructures in relation with water, we can describe:

(a) A water tower, used for gaining pressure for later distribution inside the buildings.
(b) A rambla (small watercourse) is crossing the precinct, but only wears water after the rain episodes, up to a week. Nevertheless, a small aquifer, not directly exploited, is associated to this stream.
(c) There are no classical wells but several springs, with not so much flow.
(d) There are some visible water conduits, but it is not clear how the water is being distributed in the area limited by the walls.
(e) The water can be diverted to several ponds, located in different places inside the precinct which have a capacity around 3,000 m^3 and occupying nearly 1,500 m^2.
(f) An old ice well built in 1748, is located in the vicinity of the main buildings.

The already known scheme of water distribution is depicted in the Figure 4. The tap water is obtained from the Tarantí well and Nerola fountain, and a treatment of decantation and chlorination is provided. Actually, wastewater is treated by an existing plant, which is undersized and does not perform correctly. A plan is made by the Water Agency (Agència Catalana de l’Aigua) to transport wastewater to a neighbouring (5 km) wastewater treatment plant serving the municipality of l’Espluga de Francolí. There is a strong desire to implement an extensive wastewater treatment plant within the precincts, which will allow the reclamation and reuse of the water. Then, the conduit will be used as a by-pass in case of failures or excess rainwater.

Water Offer and Water Demand

The water being used for the monastery comes from several wells which are inside the precincts and from a gallery, 1 km far away, in the geological fault, which gives 100 m³/d.

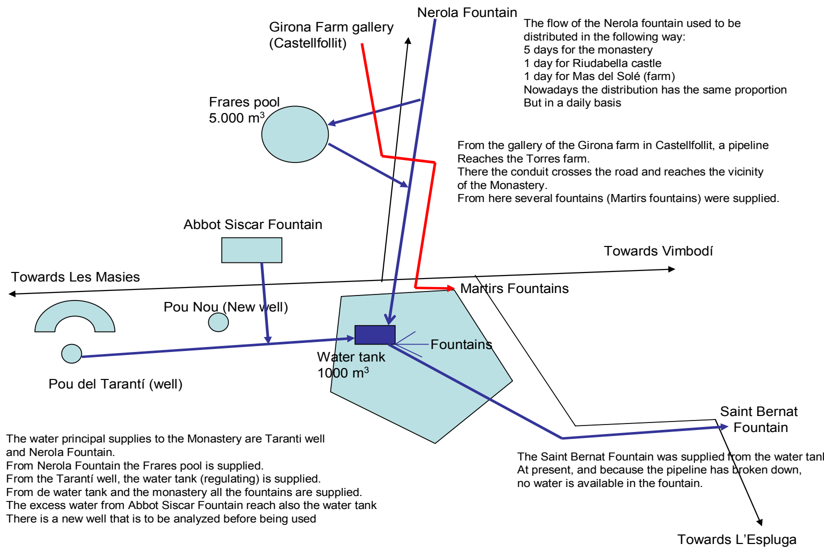

Figure 4 Water supply to the Poblet Monastery.

Since the amount of water reaching the place scarcely covers the needs, there are recurrent droughts in the area, and the demand of water is supposed to increase in the near future; the Abbey has decided to study the possibility to increase supply without further depending on external sources.

Today, the tap water demand is estimated to be 150 m³/d. When the guest quarters become fully operative, the demand will slowly increase, reaching an estimated peak of 200 m³/d. The vineyards are not irrigated, but the vegetable garden is supplied with 20 m³/d as average. Water is also used for cleaning purposes and toilets for visitors. Analyzing the known conduits and the distribution of the space inside the monastery, several possibilities arise to gain equilibrium between offer and demand:

(a) fully determining the amount of water entering the precincts and its distribution will allow a better planning of the uses,

(b) determining the impervious surfaces and the covered surfaces will allow to determine if rainwater can be collected and stored for further use, and

(c) implementing a wastewater reuse scheme could facilitate extra resources.

Some initial studies have been undertaken, dealing with impervious surface availability, rainwater management structures, old water infrastructures, and recent water infrastructures.

Conclusions

There are evidences that not all the water infrastructure in the Poblet Monastery is known, especially in relation with the runoff management and reclamation. For wastewater reclamation and reuse in the abbey precinct, the implementation of a wastewater treatment plant is compulsory and further studies are needed. The known and unknown water management inside the walls of the monastery will be fully studied and a planning procedure will be undertaken in order to lead future water works.

Acknowledgements

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The Ancient Lake Albano Tunnel: Origins and Considerations Regarding the Hydraulic Regulation Achieved

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Abstract: A brief description of the geomorphological, historical, and archaeological aspects of the Colli Albani area, where the volcanic lakes of Albano and Nemi are situated, is followed by an examination on the problem of the policies of lake Albano regulation, by means of an ancient tunnel dating at least to the 5th century B.C. In particular, it is investigated how, in the presence of even severe atmospheric phenomena, it was possible to control fluctuations in the level of the lake on the banks of which there were large settlements. Mathematical model simulations indicate the effectiveness of the ancient tunnel in achieving these objectives.

Keywords Ancient tunnel; Colli Albani; lake Albano; level regulation; volcanic lakes.

Overview of the Area Considered

Geology and its relation to volcanic activity

The Colli Albani coincide geographically with the Lazio Volcano, a volcanic structure located about 30 km southwest of Rome that was active between 700,000 and about 20,000 years ago. However, recent research (Funiciello *et al.*, 2002) seems to date the final activity of the volcano to much more recent times (about 5,000 years ago).

Most of the volcanic activity took place between 530,000 and 360,000 years ago. During this period a first central edifice was produced, known as the Tuscolano-Artemisio edifice, which collapsed at the end of this period, forming the existing caldera of the same name some 10 km in diameter. The final phases of the Colli Albani volcanic complex are of a hydormagmatic nature that is, caused by the magma coming into contact with the water table. This activity produced a series of eccentric craters located in the western sector of the volcanic complex, namely the Albano, Giuturna, Nemi and Ariccia craters. The craters that now contain the lakes of Albano and Nemi are situated along the south-western edge of the Tuscolano-Artemisia caldera, which were thus lowered in this area. The end of the hydromagmatic activity may be dated to around 20,000 years ago. The Colli Albani have however continued to be a site of slight but continual seismicity which occurs at different intervals (Amato, 1999).

Actual geological phenomena and legend mingle closely in the case of Lake Albano

It must be noted that the digging of the Albano tunnel is related to a sudden inexplicable rise in the lake level believed to have occurred in 399-398 B.C., during the war between Rome and the Etruscan city of Veio. Several ancient authors (Valerius Maximus, bk. 1, Ch.6;

Plutarch, Life of Camillus; Cicero, Divinatione bks. 1 and 2 and Dionysus,bk. XII; Titus Livy, Ab Urbe condita, Bk.V Ch.15) tell us that during the siege of Veio, the Etruscan outpost near the city of Rome, the lake water level suddenly rose and that, in order to obtain the favour of the gods as well as to bring the water back to its original level, the project was rapidly carried out. However, also justifications of a scientific nature have been proposed for this prodigious phenomenon.

In particular, Funiciello *et al.* (2002) postulate that, after the Albano peperino was laid down about 23,000 years ago (hitherto regarded as the last volcanic episode in the Colli Albani), further eruptions occurred in the Albano crater, accompanied by various catastrophic events involving the violent ejection of mud flows (lahars) from the lower part of the crater edge in question. The rise in the water level in the lake is thus believed to have been caused by the release of large quantities of carbon dioxide and hot fluids from the lake bottom on the occasion of seismic events capable of activating the profound hydrothermal system underlying the Albano crater. The lake surface, already at a level several tens of meters higher than that regulated by the existing tunnel, is thus believed to have been further raised until it overflowed on several occasions from the lower part of the crater facing present-day Ciampino. According to this theory the lake tunnel could be viewed as a defense against the hydrogeological hazard represented by the possible violent overflow of water from the crater.

It should be pointed out that similar phenomena occurred in the 1980s in the African crater lakes of Monoun and Nyos (Sigurdsson *et al.*, 1987); in the latter cases, a large-scale release of CO_2 caused the sudden death of a thousand or so persons together with that of an unspecified number of animals. Also in periods prior to the digging of the tunnel Lake Albano was liable to considerable drops in level; underwater archaeological research has indeed pointed to the existence of two now submerged levels (Bersani and Castellani, 2005) at -11/12 m from the tunnel entrance level, where the remains of a palafitte village from the middle Bronze Age once stood and at -5/6 m where evidence of another level, probably dating to the Iron Age, has been found. Lowering of the lake level below the tunnel mouth has been recorded also in recent historical times, in 1683 (Eschinardi, 1750) and in 1834 (Giorni, 1842). Since 2004, the Colli Albani have been classified as the tenth largest active Italian volcano on the basis in any case of the recent age of the latest volcanic and present seismicity.

Morphology and characteristic data of the lake and the hydrographic basin

The Albano crater (Funiciello *et al.*, 2002) represents a polygenetic phreatomagmatic centre comprising coalescent craters arranged in the form of a ellipse with a maximum diameter of 3.5 km, running in a northwest - southeast direction. In the crater the surfacing aquifer forms Lake Albano or Lake Castel Gandolfo, which with its depth of about 175 m (measured from the tunnel entrance level at 293 m a.s.l.) represents the deepest crater lake in Italy. The lake has a surface area at 293 m a.s.l. of about 6 km², while the hydrographic basin of Lake Albano totals 10.66 km² (Servizio Idrografico e Mareografico Nazionale, 1999). The great depth of the lake water means that it is fed by springs below the upper surface of the water originating from several aquifers located at different heights in the surrounding land that are hydraulically separate. In the lake and on its banks many underwater and surface points where carbon dioxide is released have been found. The lake water is stratified as a function of the density. The temperature ranges from about 8° - 9° between the bottom and a depth of 90 m, then gradually increasing from -90 m up to the surface depending on the climatic and seasonal conditions.

The Ancient Tunnel and Water Use

Characteristics of the Lake Albano tunnel

These two lakes, which the ancient Romans called the Eyes of Jupiter, had ancient tunnels that in their age, method of construction and purpose for which they were built, may justly be considered twin works. The two tunnels regulate the water of Lake Nemi at a height of 316 m a.s.l. and the Lake Albano water at 293 m a.s.l. This suggests that the two aquifers feeding the two lakes, which are only 2.5 km apart, are hydraulically separate. Figure 1 illustrates the two Albano lakes together with the plan view of the ancient tunnels. Disregarding the legend (paragraph 1.1), believed by some to be at the origin of the decision to build the Lake Albano tunnel described in the present note, those who conceived of it attained a two-fold objective: to control and regulate lake level and, at the same time, to obtain a permanent source of water to irrigate the fields lying below the lake in the direction of the sea.

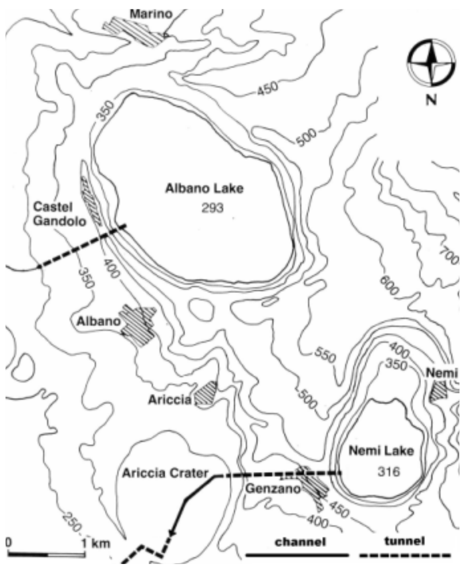

Figure 1 Albano and Nemi lakes (Castellani, 1999).

The Lake Albano tunnel is 1450 m long with a gradient of about 2 m (293 m a.s.l. at the mouth and 291 m a.s.l. at the outlet). The original size of the tunnel was one meter wide by two and a half meters high. The lakeside entrance to the tunnel displays a series of interesting structures which, among other things, were illustrated by Piranesi in a well-known series of prints in 1762. An analysis of the tunnel allowed the design and operating techniques used to be ascertained. The direction and height of the tunnel were probably determined using the straightline '*coltellatio*' technique involving the use of a *groma* and surveyor's stakes. This technique is based on the use of a sight and the leveling of a series of vertical stakes aligned on the outside which bypassed the crest and joined the entrance and exit of the future tunnel. Using this technique it was therefore possible to define the axis of a tunnel, the sum of the horizontal distances measured corresponding to the length of the tunnel, while the sum of the vertical distances equal to zero levels the excavation axis.

Inside the tunnel there are two vertical shafts with a rectangular section respectively 80 m (depth 3 m) and a 400 m (34 m deep) from the downstream outlet. The latter shaft is perfectly flush with the tunnel walls, which seems to indicate that it was excavated, at least partly, starting from inside the tunnel. The two shafts near the outlet (Castellani, 1999) had the function, the first after a short section (and short excavation) of marking in the subsoil as a first approximation the direction of the tunnel, and the second, appreciably more distant, of establishing more accurately the final direction owing to its greater measurement 'base'.

The excavations was thus probably started blind from the two opposite extremities, directly with the conduit for the downstream outlet, while upstream (owing to the problem of the presence of the water) they began with a shaft (still visible in the vicinity of the lakeside entrance) which, starting from a higher level than the lake water, descended to the established level. Once the two excavation fronts met (Castellani and Dragoni, 1991) the rock diaphragm between the shaft closest to the lake and the lake itself was demolished and the monumental entrance was constructed. The present entrance is a Silla era restoration. The meeting of the two tunnel sections excavated from opposite directions probably took place about 740 m from the inlet. Figure 2 shows the cross section and plan view of the Lake Albano tunnel. The Figure does not include the shaft in the vicinity of the upstream inlet as the latter is incorporated in the monumental entrance; moreover, as evidence on the ground shows, the lake level was certainly several metres above the inlet height when it was constructed.

The use of lake water over time

The favourable climate, the abundance of water and the morphological configuration of the Colli Albani favoured the settlement and occupation of human groups from prehistoric times (Ghini, 1999). In Imperial Roman times numerous villas dotted the area, especially around the two lakes of Albano and Nemi. The emperors Augustus, Domitian, Claudius and Caligola were frequent visitors to the sumptuous villas of which some archaeological evidence still remains.

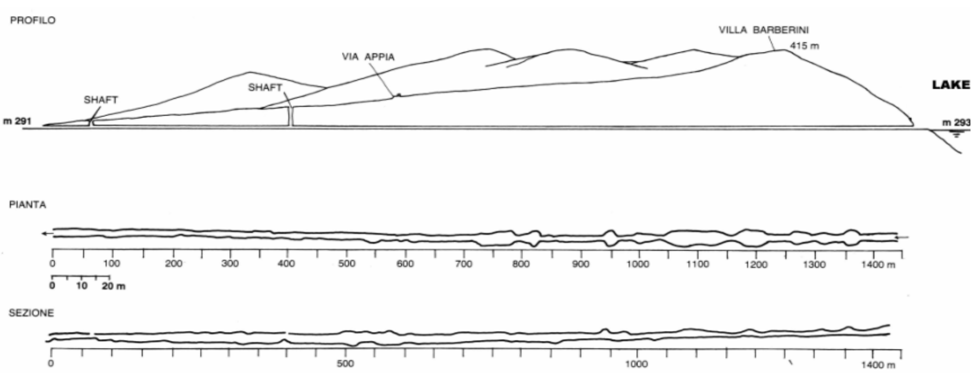

Figure 2 Albano's ancient tunnel (Castellani, 1999).

The construction of the Lake Albano tunnel made it possible to irrigate the downstream land. Also the fact that the lake water level could be regulated by about 2 m, made available a considerable reserve of water, amounting to over 10 million m³. Starting from Roman times, the withdrawal from springs on the inner crater of the lake provided drinking water to the surrounding urban settlements through aqueducts. The tunnel outlet in situated in the area of Mole di Castel Gandolfo, where in ancient times the "*rivus albanus*" rose and where, in the year 1730, Pope Benedict XIII Orsini (or Pope Clement XII Corsini) built a series of large tanks and canals. It is interesting to note that this water was first used for washing clothes, then used to drive mill wheels and lastly to irrigate the fields. Nowadays, the water is used mainly for tourist purposes, that is swimming and canoeing, especially in summer. It should be noted that Lake Albano hosted the canoeing races at the 1960 Rome Olympics. Lastly, the lake represents a natural reserve of water to be used by firefighting aircraft especially during the summer period.

Lake Water Regulation Criteria and Simulation Model

Lake level perturbation factors

The Lake Albano (or Castel Gandolfo) water level indicated on the official maps (Istituto Geografico Militare) is 293 m a.s.l., which corresponds to the altitude of the tunnel inlet. This level was fixed by using manually operated sluice gates which maintain the water level 2 meters above the floor of the tunnel inlet. This height provided a free zone that in Roman times could be used to absorb any sudden rise in the lake level caused by prolonged heavy rain, but above all (see section 2.2), ensured an important water reserve for periods of drought.

Since the early 1990s, because of the increasingly lower water level, the tunnel no longer drains the lake water and the downstream outlet has been walled up for hygienic reasons. The present-day water level is some 4 meters lower than in 1960, at the time of the Rome Olympics. The reasons for the current lower level are to be sought essentially in the excessive withdrawals of groundwater (Capelli *et al.*, 2000) both in the Colli Albani area and in the industrial zone of Pomezia towards the Tyrrhenian coast. For the purpose of the following analysis, reference is made to several successive days of rainfall; in particular the isohyers reconstructed from the hydrological annals of the year 1965 published by the *Ufficio Idrografico - Compartimento di Roma* for the Tiber flooding of 3 September 1965, indicate a rainfall of 300 mm in the Colli Albani area over the 3 day period from 1-3 September.

Hydraulic regulation objectives

At this point a question may be asked: what hypotheses may be advanced concerning the Lake Albano water regulation with special reference to the original intentions of its builders? Corresponding to the entrance to the tunnel on the side still accessible nowadays, the walls display vertical cuts that are difficult to date but in any case reveal traces of grooves made to insert and slide sluice gates or slabs. The entrance system to the tunnel also comprises a double grille with perforated stone slabs followed by a vertical comb grille (again made of stone), both of which may be recognized from the residual structures (Fig. 3). As may be seen in the nearby Lake Nemi (Drusiani, 2003), it consists of a sophisticated system for regulating the flow and not merely a simple overflow canal. Moreover, Dionysius of Alicarnasso (*Antiquitates romanae*, I, 66) acknowledged that the populations occupying the area before the Romans had considerable skill in regulating water level by means of sluice gates.

The presence of a “potential hydraulic head” on the upstream sluice gates was a necessary condition to guarantee whenever necessary a timely and controlled runoff of the lake water in order to stabilize the lake water level after heavy rainfall, as well as to allow a rational use of the water (irrigation, driving mill wheels, etc.) at the mouth of the tunnel by means of an adequately controlled drawdown. These functioning methods are seen to be even more obvious if the lake level is investigated using a numerical simulation model in the case of heavy rainfall.

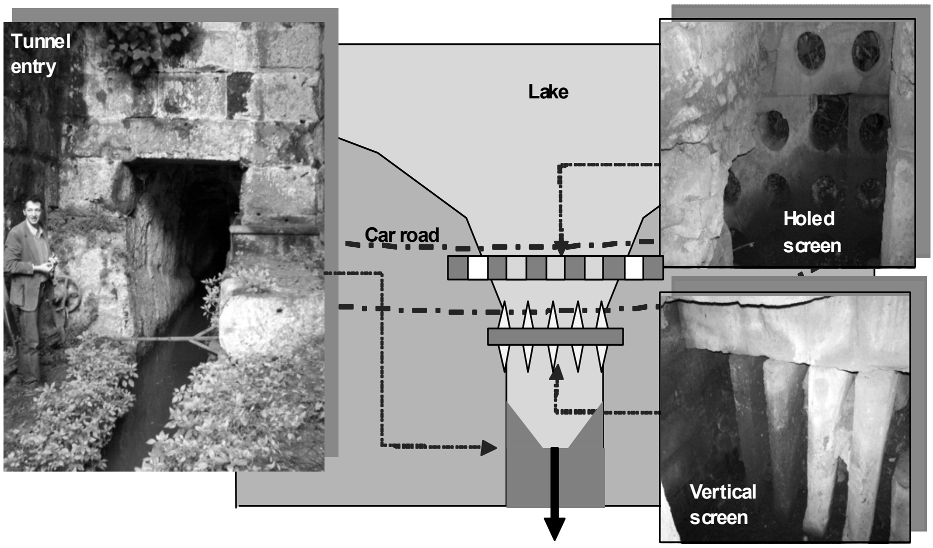

Figure 3 Entry of the tunnel and auxiliary structures.

The simulations performed

As a rainfall event for the purpose of simulation reference was made to that of September 1965. The depth of rainfall reached (300 mm in three days) cannot be considered exceptional if it is accepted that the period in which the tunnel was built was characterized by a climatic situation with moderate fluctuations, compared with today, of cool and mild weather. On the basis of the characteristics of the basin in question, the runoff travel time was estimated at about one hour (Kirpich's formula), while the shared of water retained by the soil was estimated as 50% of the total rainfall; the area of the hydrographic basin and the lake itself were assumed to be 10.66 and 6.00 km², respectively. Figure 4 shows a three-dimensional profile of the volcanic basin and relative basin diagram (level as a function of the volume) obtained from existing altimetric and bathymetric charts. Under constant climatic conditions the trend over time of the rise in lake water level versus the level at time 0 was simulated in the three cases: (a) Absence of tunnel and therefore absence of any outflow (in the short term this means that the rain falling in the lake catchment increases the volume of the lake itself); (b) existence of tunnel with the function of simple overflow device (the lake water level at time 0 coincides with the tunnel base); and (c) existence of tunnel equipped with regulatory sluice gate (lake water level at time 0 coincides with the liquid head on the initially lowered sluice).

The height of the water level over the initial level for the various hypotheses considered is shown in Figure 5; as expected the level is higher when the tunnel acts as a simple overflow device (Case 2) and obviously in its absence (Case 1). The choice of functioning conditions referring to the initial head at the sluice gates (envisaged in the simulation carried out 1 meter above the tunnel entrance floor) and the mean roughness coefficient of the entire tunnel are such as to maintain the velocity within 1.2 m³/s (corresponding to a maximum flow rate of 2.2 m³/s). Even if maintained for prolonged periods should not give rise to significant erosion of the tunnel and consequent landslips; in any case, maximum flow rates of the order to 2 m³/s have been found at the real level (Ucelli 1940; Penta, 1999) on the similar Lake Nemi tunnel.

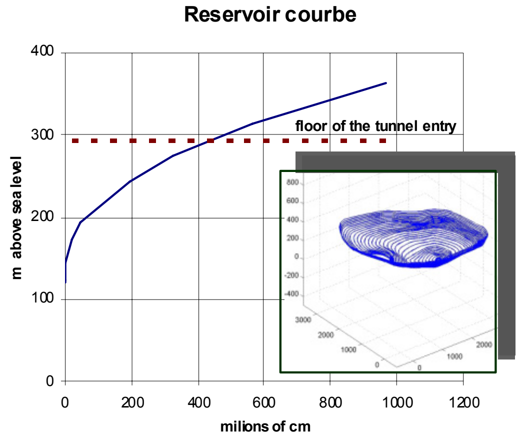

Figure 4 Volume of water function of level and 3D model.

The outflowing flow rate is shown in figure 6; the same figure illustrates the flow rate (on a 1:10 scale) reaching the lake after the rainfall considered. This shows that the presence of sluice gate regulation allows significant quantities of water to be discharged at the first signs of the effect of the rainfall, thus allowing, in the case of particularly heavy falls like the one considered, limiting the maximum water level height and in any case considerably reducing its duration.

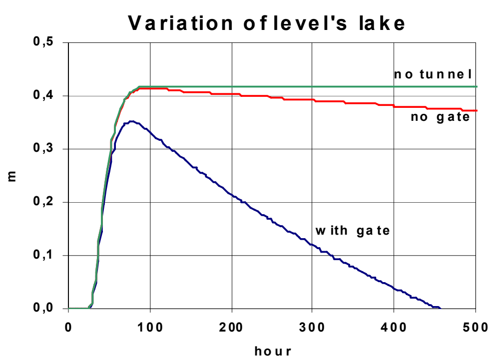

Figure 5 Simulation of level's lake.

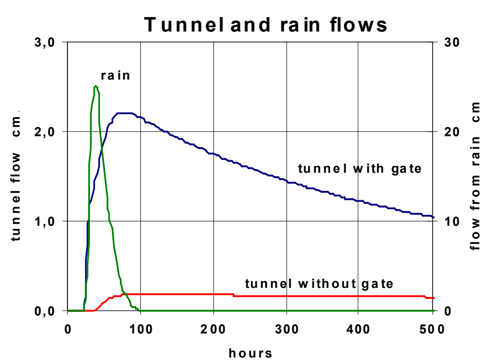

Figure 6 Simulation of tunnel's water flow.

The mathematical model of the system including the various elements (rainfall graph, basin curve, tunnel, etc.) was implemented using Matlab language; as far as the hydraulic behaviour of the tunnel is concerned, Manning's formulae were used assuming a roughness coefficient of 0.035 and postulating a free flow (no hydraulic jump) at the outlet. With reference to the short duration of the phenomenon considered (only a few days) no account was taken of the contributions/outflows due to natural evaporation, the aquifer and the springs.

Conclusion

The numeric simulation of the behavior of the ancient tunnel of the Albano lake's allows us to comprise and to appreciate the functionality and the effectiveness of this hydraulic work in the regulation of the level in particular on the short period in consequence of heavy storm.

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Archaeology and Landscape Settings of the Ancient Water Supply Systems in Jerusalem

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Abstract: The aim of this paper is to review the technical issues and water landscaping of ancient water supply systems in Jerusalem during the Chalcolithic period (4500-3200 B.C.) until the present time. Archaeological evidences and landscape settings were applied utilizing all available and accessible literature relevant to ancient water resources management in Jerusalem. People of the Bronze epoch, of early iron period, Middle Ages etc. went, but the role of water played an important role and currently still having great value in a Mediterranean semi-arid climate. Irrigation agriculture was practiced for many centuries in this region, hence sustainable water supply facilities were erected including well developed aqueduct, water harvesting pools and irrigation channels for water storage and landscaping purposes. To cope with seismic, soil subsidence and water leakage, ancient water engineers and architects applied innovative construction methods for the erection of water pools, channels and aqueduct systems. Ancient water supply systems in Jerusalem are valuable civilization treasures and crucial urban environmental facilities and their protection is consistent with sustainable development principles. Effective environmental assessment as a decision-making process for sustainable development can be applied to preserve threatened ancient water facilities caused by major development proposals and urban infrastructure projects in Jerusalem.

Keywords Ancient water systems; archaeology; Jerusalem; landscape sitting; sustainability.

Introduction

Jerusalem city had a long occupation history started from the Chalcolithic period (3200-4500 B.C.) until the present time. Therefore it is considered as a perfect place that gives the archaeologists and water engineers the opportunity to study the ancient water systems of Jerusalem. Mostly all archaeological and historical studies tried to answer the chronological questions related to biblical fictions, while on the other hand there is little focus on the landscape setting of the ancient water systems in Jerusalem. Hopefully, the landscape setting of the ancient water systems in Jerusalem might have an efficient role in the near future to understand the technical design, construction and functional aspects of ancient water systems. However, the behaviour of the ordinary societies lived along side of ancient water systems of Jerusalem through the courses of the time is not well explored. Angelakis and Koutsoyiannis (2003) reported that ancient Greek livelihood improvements and significant cultural developments were based on innovative technologies to collect, store, and transport water, as well as legislation and institutions to effectively manage the available water resources.

A thorough understanding of ancient water systems in Jerusalem calls for categorization and should be based on the landscape setting, water resources and their technical function. The aim of this article is to make a review on the various ancient water systems in Jerusalem including underground water system, the water harvesting pools and the aqueduct systems. Archaeological evidences and landscape settings were applied utilizing all available and accessible literature relevant to ancient water resources management in Jerusalem.

Water Resources Management during the Bronze and Iron Ages

Many archaeological excavations and surveys made in Jerusalem area in 1867 by Warren, Parker 1909-1911, Kenyon 1967, Shiloh 1978-84 revealed that the underground water system as the first water supply technology in Jerusalem (Kenyon 1974). Recent excavations carried out by Reich's and Eli Shukron's during 1995 contributed to discover the details of the system structure. Within the area of settlement of Jerusalem at Tell Abu Ed-Duhur during Bronze and Iron Ages, there were two springs; Umm Al Daraj and Bir Ayyub springs. Both of them are located topographically at the bottom of Wadi Sitti Miriam (Wadi is a small seasonal stream), which is located east of the present Jerusalem wall (Fig. 1). According to Kenyon (1974), the spring's location especially Umm Al Daraj determined the landscape setting of the urban settlement of the Jerusalem city during the middle Bronze Age (2000-1500 B.C.).

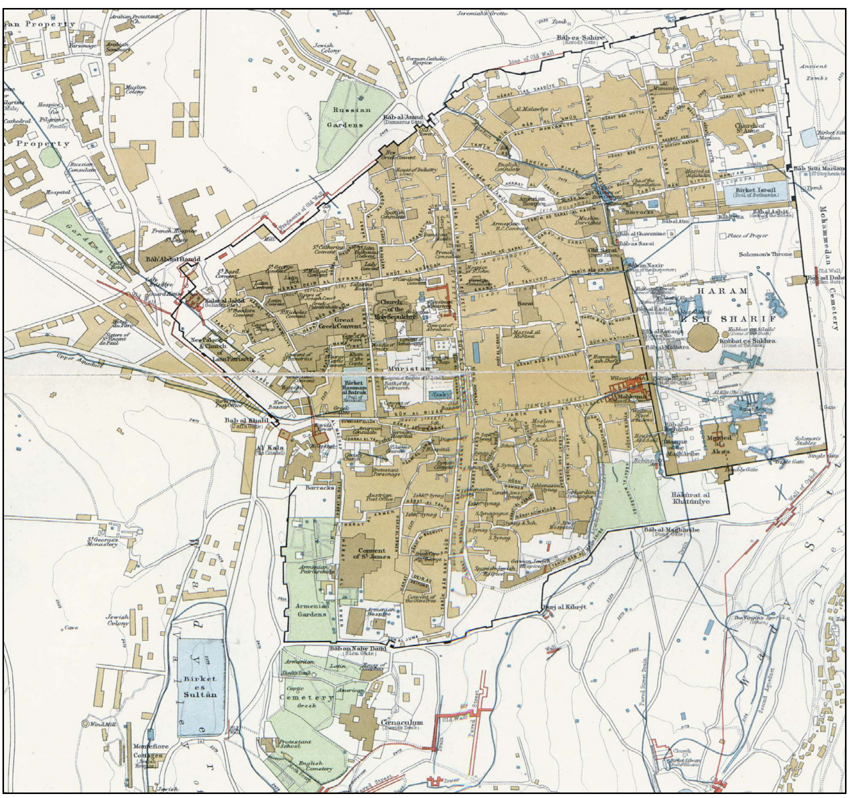

Figure 1 Map of Jerusalem city with main geographical features.

Ain Um Al Daraj (Figs. 2 and 3) consists of a natural cave, where the entrance of the cave is made of rock steps maybe constructed sometime in middle Bronze Age, hence the local people of Silwan village gave it the Arabic name “Ain Um Al Daraj”, which means the spring of (with) mother steps (Wilkinson, 1974). Archaeologically, this spring was used by people before arise the Middle Bronze city, to irrigate the agricultural fields systems which are located in the Wadi. The archaeological evidence from the excavations made by Kenyon (1974) in the Wadi shows there is shreds of pottery and structures dating to the Early Bronze Age (3200-2000 B.C.). In addition to that, the morphological evidence in the Wadi indicates that the original Wadi surface is about 0.1 m below the current Wadi surface. This was explained by Reih and Shukron (2000) due to agricultural activities conducted along the Wadi course during that era.

The archaeological evidences for different excavations in the area of the settlement of Jerusalem at Tell Abu Ed-Duhur (Kenyon 1974) show arise of the first fortification wall of Jerusalem city during the Middle Bronze Age. This reflects the re-urbanization process in Palestine during the Middle Bronze Age, which occurred after the collapse of the urban centers at end of early Bronze Age (Fig. 3). Technically, according to the researchers the construction of the underground water system in Middle Bronze Age in Jerusalem is to find a technical solution to link the water resources from Um Al Daraj cave with Middle Bronze Age of city wall. Basically the under ground system consists of ten structures as shown in Figure 3. These include warren shaft, access tunnel, vaulted chamber, stepped tunnel, horizontal tunnel, vertical, tunnel linking to spring, Um Al Daraj cave, side cave, trial shaft, Hezekiah’s tunnel (Shoham, 2000). Many interpretations were made by archaeologists to give reasons for the construction of the underground water system; mostly, all the scholars have been adopting security reasons. Therefore, people can protect water resources by the construction of the underground system at unrest conditions (Shoham, 2000; Reih and Shukron, 2000).

Figure 2 Structural view of Ain Um Al Daraj spring (holy land photos).

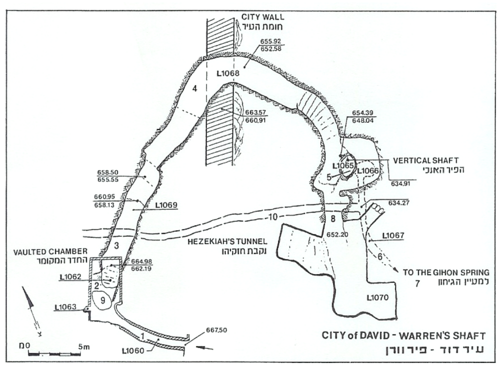

Figure 3 Under ground water structures during the Middle Bronze Age (Shoham, 2000).

At Iron Age (1200-538 B.C.) many water installations were constructed in Wadi Sitti Miriam (Mary) especially in the vicinity of the underground water system. The function of water installations in Wadi Sitti Miriam was most likely to convey the water through irrigation systems into the southern part of the Wadi in order to irrigate the agricultural fields. Figure 4 shows the important irrigation systems developed during the Iron Age including Silam’s Channel (Qanat Silwan) and Silwan Tunnel (Hezekaih’s tunnel). Qanat Silwan is located about three meters above the Um Al Daraj spring. The archaeological evidence at Um Al Daraj spring shows a higher damming wall that was used in the past to (hydraulic) raise the water from Um Al Daraj spring into the channel. The length of Qanat Silwan is about 400 m and conveyed water through Wadi Sitti Miriam into the Birket Al-Hamra (Al-Hamra pool), the total area of the pool is 2562 m² (Abells and Arbit, 1994).

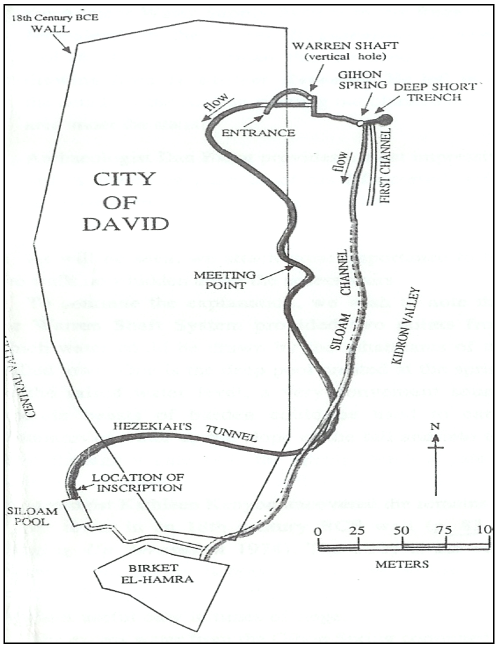

Figure 4 Qanat Silwan and Silwan tunnel as irrigation systems (Abells and Arbit, 1994).

Silwan Tunnel, along side of Qanat Silwan in Wadi Sitti Miriam, was constructed over a total length of about 513 m during the late Iron Age. The tunnel, hawed by workers in natural crakes, was expanded to carry water from Um Al Daraj spring until the Birket Silam, than into the Birket Al-Hamra in Wadi Sitti Miriam (Abells and Arbit, 1994).

Water Harvesting Pools for Domestic and Agricultural Purposes

The harvesting pools in Jerusalem during different times are considered as one of the major water technologies applied to collect water runoff. Actually, some of them pools are natural topographical ponds, while others are originally man-made cutting stones areas, created in different times for stone mining used for construction purposes in Jerusalem city.

In terms of the landscape setting of water harvesting pools in Jerusalem, few pools are located now inside the current city wall, as Birket Hammam Setti Miriam, Birket Israel, and Birket Hammam Al Batrak. These pools are included later within the city wall after construction for various uses. Few harvesting pools are located now far from the present city wall, exactly at west-north of the city side, such as Birket Husseini and Birket Mamilla (Fig. 5). Topographically, the landscape settings of the harvesting pools in and out city wall are mostly related with the fact to the slope of landscape of the pools that were contributed to bring the water runoff into the pools. According to Wilkinson (1974), few pools were connected together by a channel. For example discovering a channel segment connecting Birket Mamilla with Birkect Hammam Al Batrak, this connection transported water from the high pool (Birkect Mamilla) into the lower one (Birket Hammam Al Batrak).

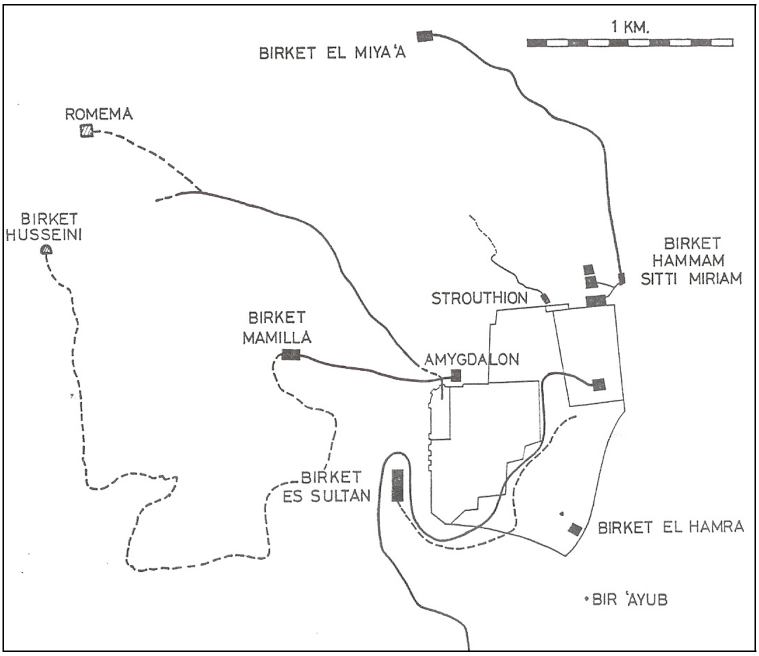

Figure 5 Water harvesting pools in and out Jerusalem city wall (Wilkinson, 1975).

The underground water system and the harvesting pools system were the main ancient water systems in Jerusalem city until the construction of aqueducts at the early Roman period. Actually, the use of the underground water system and associated parts was not completely for domestic purposes, but some of the system parts as the springs and channels were used in agricultural activities in Wadi Sitti Miriam. Meanwhile, some the harvesting pools were working alone, while others were incorporated with aqueducts water system.

Jerusalem Aqueduct System during the Roman Era until the British Mandate

The construction of the aqueduct water system in the Roman period was a consequence of the impact of urban grind Jerusalem. Upon occupation, the Romans changed Jerusalem location form Tell Abu ed-Duhur (Middle Bronze and Iron Ages) and the *Roman Jerusalem* was re-sited at a new location relatively in the same location of the current *Old Jerusalem.* This change in city location was associated with the establishment of water aqueduct systems to transport freshwater from springs located in Jerusalem south until the British Mandated.

Due to these changes, the ancient water system of Jerusalem during the Roman period included aqueducts over long distances in addition to springs, pools, and tunnels. The various elements of this water system worked together under one unified water aqueducts system to provide Jerusalem with domestic water. One main reason behind adopting this water transport mean is that the springs are located at Jerusalem south, exactly in between the village of Artas and the Hebron region. Within this region, there were many freshwater springs with a shallow water table characterized by strong water discharges. In addition to that, these springs have approximately the same elevation of ancient Jerusalem city, thus allowed conveying the water by natural gravity through aqueducts from Hebron-Artas region into Jerusalem city during the different historical periods (Fig. 6).

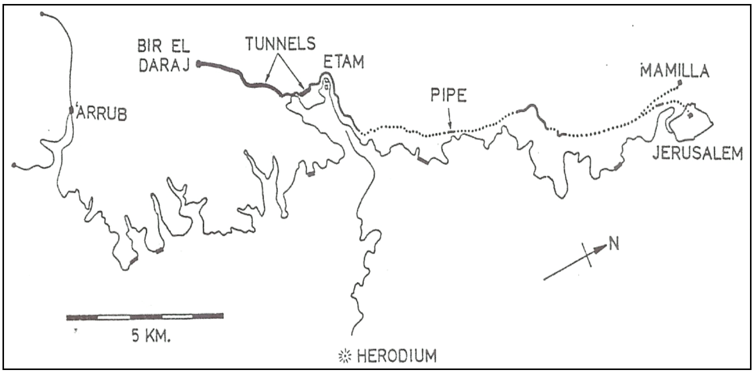

Figure 6 Al-Arroub and lower aqueducts between Hebron-Artas region and Jerusalem city (Wilkinson, 1975)

Freshwater springs and aqueducts in Wadi Al-Arroub region

In Wadi Al-Arrub region, there are many springs as Kuweiziba spring, Qanat Al-Arayis spring, Ed Dilba spring, and Al-Arrub spring, where all are connected by a channel to bring the water into Al-Arrub pool. The latter is located at about 8 km south of Artas village with a surface area of about 4,080 m² and securing a storage capacity of around 200,000 m³. All of the stored water in Al-Arrub pool was usually transferred through Al-Arrub aqueduct. This aqueduct is running from Al-Arrub pool until the middle pool in Artas valley. The total length of Al-Arrub aqueduct is about 44.2 km, the depth of aqueduct ranges between 0.70 and 0.90 m and has a width of 0.50 m (Mazar, 1976; Abells and Arbi, 1994). The long distance of Al-Arrub aqueduct is synchronized with the topographical contours of landscape region in order to transport the water through the aqueduct by gravity into middle pool of Artas valley. Along the distance of Al-Arrub aqueduct, there are many water installations, the most important of them are the three tunnels used to cross the valleys or to avoid the sudden rise of the topography located in the aqueduct path.

Review of Arabic historical records (see Arabic references) revealed that Al-Arrub aqueduct had been restored many times; the most important one was done by Qansawa Al Yahyawi in the year 1483 A.D. This information indicates that Al-Arrub aqueduct may not be in use before this restoration process, but surely it was reused during the late Mamluk period (1483-1517 A.D.) and the Ottoman (1517-1917 A.D.) era. At the early British Mandate (after 1918), the function of Al- Arrub aqueduct was stopped and a new iron pipe was installed from of Wadi Al-Arrub springs into the new urban areas located to the south of historical Jerusalem. During the Roman period, the Wadi Al-Biyar aqueduct was constructed at south of Artas (Fig. 6), where Wadi Al-Biyar spring was the main spring which fed this aqueduct. The aqueduct consisted of four parts; the first part is a tunnel, its length about 3 km, its internal height about 1.5 m, and its internal width is about 0.80 m. Within this tunnel there are about 80 vertical shafts of variable heights (5-23 m) from ground surface down into the tunnel.

The second part of the Wadi Al-Biyar aqueduct is an open channel; its length about 700 m. The third element of Al-Biyar aqueduct is a tunnel; its length about 700 m, and it has 10 vertical shafts. Finally, the fourth part is an open channel (1 km long) that forms the final link between the Al-Biyer aqueduct and upper pool in Artas valley. Al-Biyar aqueduct was functional from the date of its construction in the Roman Period until the British Mandate. The reason behind the aqueduct long-term use might be the adequate design and construction, as a closed tunnel to avoid aqueduct blockage through sediment and waste. As shown in Figure 6, the upper Artas valley consists of the upper, middle and lower pools, in addition to several springs such Salih, Faruja, Burak, and Attan springs, forming the heart of Jerusalem aqueduct system. Table 1 lists the technically dimensions of Artas valley pool system. Probably, the Romans have constructed this pools system for water balancing rather than water storage. They transported water from the pools in south by Al-Arrub and Wadi Al-Biyer aqueducts and functioned as booster pools for domestic water further to Jerusalem through two aqueducts; the upper and lower aqueducts.

Table 1 Technical aspects of Artas valley pools system.

Name	Length (m)	Width (m)	Depth (m)	Storage Capacity (m^3)
Upper pool	119	72	9-11	85,000
Middle pool	135	50-70	10-12	90,000
Lower pool	179	46-61	8-16	113,000

Salih spring, located west to upper pool, has the function to feed water to the upper pool through a 120 m long tunnel. The upper and middle pools are connected together by an under ground water tunnel. Until the pre-Mamluk Period (1250 -1517 A.D.) both pools have fed the lower aqueduct, while the upper pool supplied the upper aqueduct with water. According to Hawari *et al.* (2000), under the control of Qaytaby (1468-1495), the lower pool was constructed to increase the water storage capacity in the upper Artas valley, thus increasing the total amount of domestic water transported by the lower aqueduct to Jerusalem. Archaeologically, the surface archaeological evidence in upper Artas valley reveals two archaeological sites located near the pools, Khirbet ‘Alya, and Khirbet Al-Khaukh (Fig. 7). These have probably a satellite function in the region to protect the pools and aqueducts during the Roman period and onward. The satellite function hypothesis is evident more during the Ottoman period.

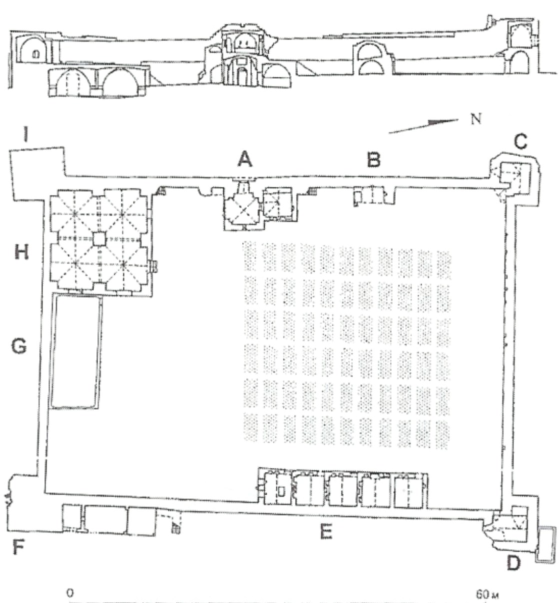

Figure 7 Al-Burak castle in the upper Artas valley (Hawari *et al.*, 2000).

During the rune of Othman II (1618-1622 A.D.), Al-Burak castle (Arabic Qala`t Al-Burak) was built to promote the Ottoman rule as to centralized control over the Artas valley to protect the pools and the lower aqueduct. Located to north-west of the upper pool, Al-Burak castle exists until present time, having a rectangular structure with a length of 70 m and about 45 m in width (Hawari *et al.*, 2000). During the late Ottoman period, local villagers in the area replaced the Ottoman rule and took over the Artas pools protection, where as the castle sustained its function until the early British Mandated.

Upper and lower aqueducts as ancient water supply systems for Jerusalem

As mention above, all the water storage in the pools of the upper Artas valley was conveyed further to Jerusalem by two aqueducts, the upper and lower aqueducts. The upper aqueduct, erected with wheel stone of 13 km in length, was connected with upper pool, and reached into the Citadel of the Jerusalem city (see Fig. 6). The height of the upper aqueduct ranged between 0.90 and 1 m with an internal diameter of 0.33 m central hole. The wheel stones fitted together formed a stone pipe over a total length of about 3 km; however Mazar (1976) reported that only 300 m were preserved in the ground until now (Fig. 8). At Byzantine era, the upper aqueduct was not functional, which assumes that the lower aqueduct was the only main water supply system for Jerusalem until the British Mandated.

Figure 8 The upper aqueduct with wheel stones (RIWAQ, 2002).

Chronologically, the lower aqueduct was constructed at early Roman period, and supplied with water from the upper and middle pool, also from Ain Atan spring, which is located to south east of the middle pool. As the lower pool was added in the Mamluk Period, the lower aqueduct was reconnected with the lower pool. The archaeological evidence shows that some parts of lower aqueduct were dug in the rock, or built by stones to create a channel, while other aqueduct sections were covered by slab stones either to prevent water evaporation or to preserve the water quality against soil intrusion and waste materials.

Starting from Artas Valley until the south wall of Jerusalem city, the total length of the lower aqueduct is about 21 km with variable width (0.40-0.50 m) and a height of about 0.60 m. Abells and Arbit (1994) presented an approximate path of the lower aqueduct showing the tunnels with vertical shafts (Fig. 9). The lower aqueduct entails also two tunnels, the first is located at Bethlehem north (length: 360 m), the second is located in Jabal Al-Mukabbir region in Jerusalem south. The latter has a length of about 423 m and within which three vertical shafts are built. Actually, the aim of tunnels construction at that time was probably to avoid the topography level increment in the course way of the lower aqueduct.

During the various ancient eras, the lower aqueduct supplied many pools in Jerusalem with water; some of pools were located outside the city wall, while others were inside the wall of the city (Fig. 10). Located outside, west-north of the city wall, Birket Es Sultan was the most important pool (length: 595 m; width: 245-275 m, and depth: 35-42 m). According to Wilkinson (1975), there were seven pools located within the wall of the city, the most important of which was located in Al Haram Ash-Sharif.

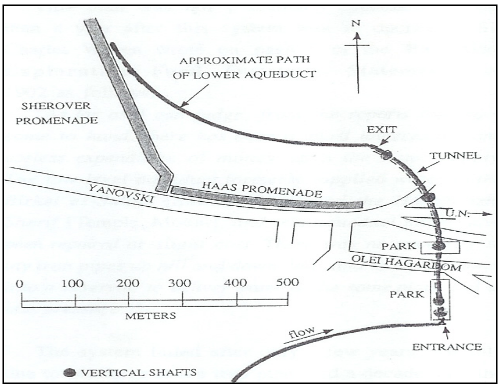

Figure 9 Lower aqueduct showing tunnels with vertical shafts (Abells and Arbit, 1994).

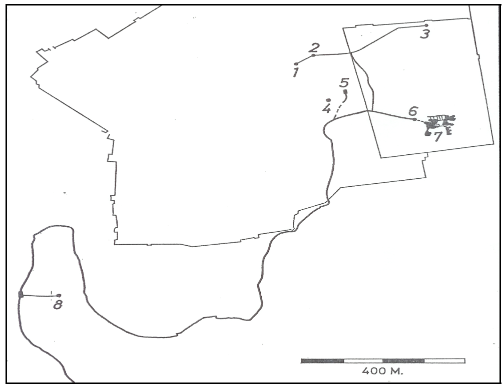

Figure 10 Location of pools inside and outside Jerusalem wall (Wilkinson, 1975).

Actually, the lower aqueduct was the main water supply system of Jerusalem during early Roman period until the mandated period (1918-1948); so there was a lot of a restoration process made in the past by administrative management of the water at Jerusalem, to maintain the water running in the lower aqueduct. Historically, the documents show that Thaher Bibarus (1267 A.D.), King Mohammad Ibn Qalawun (1327 A.D.) in the Mamluk Period.

Ottoman Era Aqueduct Systems

At early Ottoman epoch, the Sulaiman Al Qanuni (1541-1568 A.D) made many restorations activities including cleaning processes within the lower aqueduct. The causes of malfunctions in the lower aqueduct were occasionally due to the accumulations of waste materials in the aqueduct, which caused complete aqueduct blockage. In addition to that, at late Ottoman epoch (1786 A.D.), water resources managers made civil works changes on the aqueduct system. They replaced the open channel sections in the lower aqueduct by pottery pipes. The pottery water pipes installation during the Ottoman era represented stat-of-art technology aimed at efficient use of available scarce water resources. Compared to open aqueduct sections, closed piping systems reduced water evaporation during hot summer, minimized pollution caused by animals accessed open water course for drinking and prevented farmers irrigate their agricultural fields located along open aqueduct sections.

However, lack of practical knowledge in operation and maintenance, clogging of pottery pipes with time formed a real operational problem and a technological challenge for municipal water supply engineers. They realized that sediment transport from the water pools and accumulation of sediment and formation of biofilm structures enhanced by the rough internal surface of pottery pipes minimized flow rate. To solve the pottery pipe clocking of the lower aqueduct, the water supply engineer's of late Ottoman epoch (1898 A.D.) installed an iron pipe (Fig. 11) between Bethlehem and Jerusalem. The installation of the iron pipe during the late Ottoman period in the lower aqueduct was considered as the first application of western know-how in water supply technologies in Palestine.

Figure 11 Installed iron water pipe during the Othman epoch (RIWAQ, 2002).

British Mandate Era

During the British Mandate period, the government applied modern water technology through digging vertical wells in Jerusalem region, and installed water mains to supply the new urban area located at the south of the historical city of Jerusalem. The lower aqueduct was still in function at the Mandate period to supply few parts of the old city. However, gravitational conveyance of drinking water from Artas pools into old Jerusalem was replaced by installing poster stations to transport drinking water through the pipe of the lower aqueduct. The lower aqueduct was last in operation until the war 1948, since then it was divided and managed by Jordanian and Israeli authorities.

Major Threats and Future Outlook

There are various threats to the sustainability of ancient water systems in Jerusalem such as lack of an up-to-date statutory outline plan, absence of a comprehensive urban master plan, combined with the socio-economic problems. Although the level of threat to ancient water supply systems has generally decreased recently, ancient water facilities are still at risk from major unsustainable development because of they lack solid protection in the past and current planning systems. National planning policy guidance refers to the nature conservation and amenity value of ancient water systems that may lie outside non-designated sites, but offers no further guidance on how to assess projects that affect ancient water facilities. Local development plans may, however, contain policies referring to the conservation and value of ancient water and sanitation infrastructures. Hence, sustainability is particularly relevant to Jerusalem, where national and international responsibilities must be coordinated to protect the ancient water and sanitation systems and to preserve the heritage values that are carved into its landscape, while maintaining respect for the different needs and beliefs of its various population communities.

Conclusions

The archaeologists and water engineers from the Bronze era until the British mandate were able to achieve the principles of integrated water resources management in the context of public health hygiene and efficient use of available water resources in Jerusalem. Ancient aqueduct systems, water pools and channels were well engineered designed, implemented and operated in a way similar current urban water systems developed in the 19th century A.D. However, all ancient water supply systems in Jerusalem are a topic hard to cover in one paper of limited space. Review and critical analysis of available literature revealed that Jerusalem ancient water systems are very complicated as they served most likely multi-functional uses along different historical periods. Hence, further studies should concentrate not only on the ancient water supply systems but also to explore the sanitary and stormwater management to understand the so-economic structures of ancient societies lived in Jerusalem area. Also, the ancient water systems of Jerusalem should be classified as world heritage resource. For their protection and technical and financial support should be secured by local, regional and international communities. As a tool for sustainable development, effective environmental assessment can be applied to protect ancient water facilities of national heritage value caused by major development proposals and urban infrastructure projects in Jerusalem.

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Effect of Water Quality on the Microbial Quality of Food Crops

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Abstract: There is growing awareness that high quality irrigation water is an important factor in the production of safe fruits and vegetables. This study was conducted to assess the influence of the quality of irrigation water on the microbial quality of food crops. The ability of microorganisms to penetrate and migrate through the plant tissue was also evaluated. Soil samples and food crop samples were analyzed for the prevalence of total coliform and fecal coliform bacteria. Juice harvested from oranges irrigated with low quality effluents was found to be free of total coliform. However, carrot samples from the market and from a field irrigated with tertiary effluent contained up to 100 MPN/g coliform bacteria in the inner tissues. Low concentrations of coliform bacteria were detected on the leaves of parsley irrigated with fresh water and leaves of carrots irrigated with tertiary effluent. Up to 1500 MPN/g coliform bacteria were detected on leaves of grass irrigated with low quality effluent. The results of this study suggest that root crops and leaves of vegetables eaten raw are more vulnerable to microbial contamination than fruits. Juice from oranges irrigated with low quality effluents was found to be free of microbial contamination. Therefore, where low quality effluents are available, with suitable planning, it is possible to produce food crops with low risks to public health.

Keywords Food crops; fruits irrigation; microbial contamination; reuse; wastewater.

Introduction

Potable water shortages in arid regions force authorities to search for alternative water sources for various activities especially for agriculture. Wastewater reuse in agriculture and aquaculture has been practiced for centuries by ancient civilizations in China and Egypt. Nowadays, farmers in various parts of the world are utilizing the benefits from applying low quality effluents for crop irrigation. For example, in India raw wastewater use for irrigation for over 15 years resulted in improving the soil structure (Mathan, 1994). In Israel, where wastewater reuse has been practiced for 3 decades, it is possible to adjust the effluent quality (treatment level) to the irrigated crop (Halprin, 1999). Although several advantages can be accomplished by wastewater reuse, there are major public health risks associated with this practice, including exposure to infectious microorganisms and heavy metals.

Pathogenic organisms identified as capable of causing illness when present in water or on food crops include such microorganisms as viruses, bacteria, protozoan parasites and blue green algae. More than 140 different types of viruses are known to infect human intestinal tract, from which they are subsequently excreted in feces. Viruses that infect the intestines are referred to as enteric viruses. The enteric virus group consists of the following major groups: (a) Enteroviruses, which are the first viruses to be isolated from sewage and include polioviruses, coxsackie viruses, and the echoviruses; (b) Hepatitis A and E viruses, which are spread by fecally contaminated water and food. In addition to waterborne outbreaks, HAV is associated also with foodborne outbreaks, especially shellfish (Nasser, 1994); (c) Enteric Adenoviruses 41 and 42, which are known to be the most thermal resistant viruses.

The existence of enteric bacterial pathogens in irrigation water has been known for more than a hundred years. Bacterial foodborne outbreaks tend to occur when the crops are irrigated with contaminated effluents. The major bacteria of concern are Salmonella, Shigella, Campylobacter, Yersina, Escherichia and Vibrio. Opportunistic bacterial pathogens include heterotrophic Gram-negative bacteria, such as Pseudomonas, Aeromonas, Klebsiella, Flavobacterium, Enterobacter, Citrobacter ect. The prevalence of *Cryptosporidium* infection is largely attributed to its life cycle, where the organism produces environmentally stable oocysts that are released into the environment in the feces of infected individuals. *Giardia* cysts, *Cryptosporidium* oocysts are very stable in the environment, especially at low temperatures and may survive for many weeks. Concentrations of chlorine commonly used in drinking water treatment (1-2 mg/L) are not enough to kill the organism. Consequently, filtration is the primary technique used to protect water supply from contamination by this organisms. Because the infectious dose of *Cryptosporidium* is relatively low -132 oocysts in healthy person (Dupont *et al.*, 1995)- and oocysts are highly resistant to commonly used water disinfectants, alternative disinfection methods are required to reduce the public health hazard posed by *Cryptosporidium* parasites.

The standards for unrestricted wastewater reuse for crop irrigation set in 1999 in Israel, are based on high rate filtration and chlorination. The standard is based on effluent microbial quality of less than 20 cfu/ 100 ml fecal coliform and a turbidity of less than 5 NTU. This standard is considered as a compromise between the highly stringent California standard ($\leq$2.2 cfu/100ml fecal coliform) for wastewater reuse and the WHO guideline of $\leq$1000 cfu/100ml fecal coliform. Previous studies have shown that protozoan parasites, *Cryptosporidium* and *Giardia*, and enteric viruses are more resistant to the chlorine concentrations used for water and effluent disinfection than the microbial indicator fecal coliform (Carpenter *et al.*, 1999).

The survival potential of pathogenic microorganisms in wastewater in soil and on crop surfaces enhances their dissemination. Furthermore, survival is highly subject to the particular characteristics of the microorganisms themselves (Yates and Gerba, 1985; Nasser *et al.* 2002). Little or no data currently exists concerning emerging pathogens (i.e., adenovirus, rotavirus, calicivirus), their fate and transport under various environmental conditions. Hepatitis A virus, poliovirus and Echovirus 1 were detected in soil columns matrix after 4 month application of secondary effluent at 5 and 25°C (Nasser *et al.*, 1989). Greater virus concentration was detected in soil incubated at 5°C. These results indicate that conditions fevering persistence may result in microbial contamination of soil and food crops. Temperature is the most important factor that influences virus inactivation (Yates and Yates, 1991; Nasser and Oman, 1999). Inactivation rates increase with temperature and temperature can therefore be a useful predictor of viral die-off in the environment. Moisture content and loss of moisture are also related to microbial survival (Hurst, 2001).

Evidence for the association between the application of contaminated irrigation water and the dissemination of pathogenic microorganisms was found by detecting *E.coli* O167:H7 on lettuce leaves or by the observation of increased disease occurrence in areas where wastewater is used for crop irrigation. Investigations on lettuce contamination with *E.coli* O167:H7 have shown that bacteria can be actively transferred to lettuce plants (Solomon *et al.*, 2002). E. coli were detected in the lettuce tissues including parts which are not reached by washing water. These studies emphasize the importance of water quality used for irrigating crops eaten without cooking. *L. monocytogenes* was detected in 9% of lettuce samples in the UK and in Spain. *L. monocytogenes* was also detected on potatoes and radishes in the USA. It has been reported that up to 10^4 cfu/g Aeromonas were detected on fresh fruits and vegetables. Fresh eaten vegetables were reported as sources of salmonella in Egypt. Moreover, salads were found to be contaminated with Shigella and Staphylococcus. Limiting the consumption of certain crops in Chile has resulted in a significant decrease in the cases of hepatitis, cholera, and other enteric diseases. Post harvest washing of crops may reduce the microbial load on the surface; however, microorganisms inside the plant tissues may survive the treatment. This study was conducted to determine the effect of the microbial quality of the irrigating water on the microbial quality of the crops. Especially, to determine the microbial contamination level on the surfaces of the food crops and in their tissues.

Materials and Methods

Crop and soil samples were collected in sterile plastic bags. Samples were transported within an hour to the laboratory. Leaf samples were immersed in distilled water and shaken for 10 min. Soil samples were suspended 1:5 Vol/Vol in distilled water and then allowed to settle for 10 min and then transferred to tryptose broth. Samples were incubated for 48 h at 37°C. A sample was considered positive when gas and turbidity developed. Orange juice was prepared by sterilizing the surface of the orange with 70% ethanol and then slicing it into two halves and collecting the juice in a sterile beaker. Samples of 1 ml were transferred to tryptose broth and incubated for 48 h at 37°C. Carrot juice was prepared either with or without pealing and exposure to 100 mg/L chlorine solution for 10 min. Juice was produced out of carrots by a homogenizer. Samples of 1 ml were transferred to tryptose broth and incubated for 48 h at 37°C. To make sure that the surface was sterile, carrots were washed with 100 ml sterile distilled water and the water was tested for the presence of total coliform. *E. coli* strain K13 was maintained in the laboratory by passage on mFC selective agar and cultivated to a high concentration in nutrient broth (APHA, 1999). *E. coli* strain K13 and endogenous fecal coliform in crop samples were enumerated on mFC. *E.coli* strain K13 was also used for cultivation and enumeration of coliphages of wastewater effluents (Nasser *et al.*, 2003). Total coliform in samples washed from surfaces of crops and homogenized crop samples were enumerated by the MPN method in tryptose broth and confirmed in brilliant green (APHA, 1999).

Results

Secondary treatment of wastewater is planned to reduce the organic load, whereas the removal of microorganisms is inefficient. Although reuse of treated wastewater effluents in agriculture can be beneficial for the conservation of potable water sources, inadequately treated effluents can disseminate pathogenic microorganisms. Pathogenic protozoan parasites, such as *Cryptosporidium* and *Giardia* and other pathogenic microorganisms, have been found to be prevalent at high concentrations in secondary effluents (Table 1). Table 1 presents the average concentration of pathogenic microorganisms present in secondary effluent treated by activated sludge. *Giardia* cysts and *Cryptosporidium* oocysts were found to be present in all analyzed samples at an average concentration of 401 cysts/10L and 40 oocysts/10L, respectively. These results indicate that reuse of secondary effluents for irrigation may introduce public health risks to the consumers and farm workers.

To determine the effect of the microbial load of irrigation water on the microbial quality of crops, samples of crops from various sources were analyzed. Irrigation with low quality effluents may result in the increase of the concentration of pathogenic microorganisms on crop surfaces and in the soil. The concentration of total coliform detected in soil and grass surfaces irrigated with low quality effluent was by three orders of magnitude greater than that detected in soil and parsley leaves surfaces irrigated with potable water (Fig. 1). These results indicate that enteric microorganisms may accumulate on leaves surfaces of vegetables irrigated with low quality effluents, and result in enteric disease when consumed raw. Furthermore, the concentration of total coliform on the leaves and in the soil was in correlation with the concentration of enteric microorganisms in the irrigation water. The grass irrigated with low quality effluent is utilized for landscaping and gardening.

Table 1 Prevalence of Indicator and pathogenic microorganisms in secondary effluent.

Giardia Cysts/10L	Crypto Oocysts/10L	Coliphages pfu/100ml	F. coliform cfu/100ml	Turbidity (NTU)
401	40	290	550,000	3.7
1200-2	100-8	600-150	630,000-340,000	4.3-3.3

The concentration of total coliform in soil, surfaces of leaves and carrot surfaces irrigated with tertiary effluent was influenced by the time elapsed between irrigation and sampling. On certain sampling dates the concentration of total coliform was high while on others it was below the detection level. The average concentration of total coliform was 524 cfu/10g soil, 15.8 cfu/10g leaves and 65 cfu/10g carrots. The results indicate that the effluent quality influences the microbial load on the carrot surfaces. There was no difference observed between the concentrations of total coliform in carrot juice samples from fields irrigated with tertiary effluent or carrot samples obtained from the market (data not shown). Moreover, juice samples from pealed and disinfected carrots were found positive for total coliform and 2 out of 4 samples were found positive for fecal coliform (Table 2). These results indicate that enteric microorganisms can penetrate into the inner tissues of the carrot and can be protected in the root tissues from disinfectants. Furthermore, the results suggest that root crops are vulnerable to microbial contamination from irrigation effluents. Therefore, considering the fact that microorganisms can penetrate root tissues and be protected from disinfectants, root crops eaten raw should be produced with high quality waters.

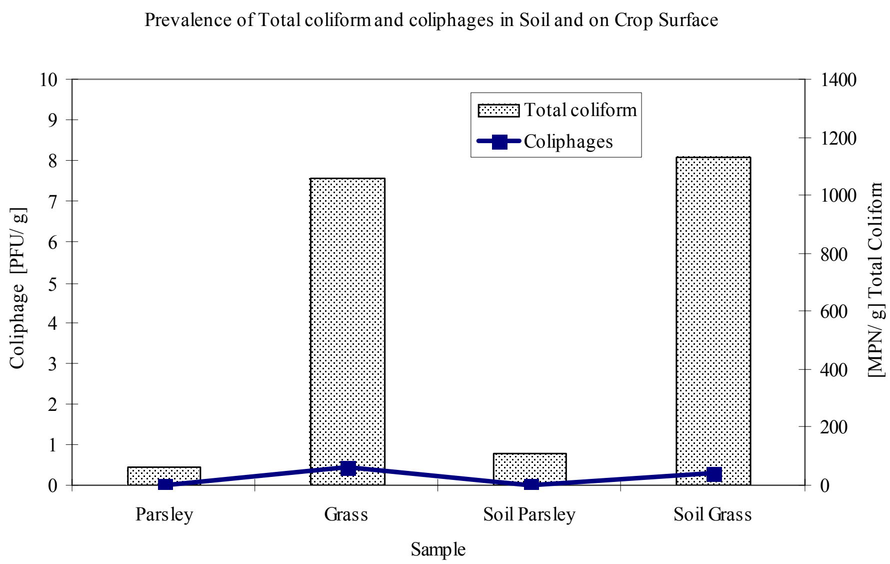

Figure 1 The concentration of total coliform and coliphages on leaf surface of grass and parsley irrigated with low quality effluent and potable waters, respectively.

Table 2 Concentration of indicator bacteria in carrot juice from carrots pealed and not pealed before disinfection.

	Not Pealed			Pealed			Date
F.coliform	Cl_2 (ppm)	Total Coliform $\left({CFU}/{10gr}\right)$	Date	F.coliform	Total Coliform $\left({CFU}/{10gr}\right)$	Cl_2 (ppm)	
--	00	>960	20/07.	--	48	100	28/07
--	00	>960	27/07	--	356	300	28/07
--	300	>960	28/07	++	>960	300	31/07
ND	ND	ND	ND[1]	++	>960	100	31/07
		>960			>581		Average

[1]not done

Very low concentrations (mostly below the detection limit) of total and fecal coliform were detected on orange surfaces irrigated by dripping with low quality effluents. It is important to emphasize that all orange juice samples were found negative for total coliform (Table 3). The results indicate that although the irrigation effluent is of low quality, the enteric microorganisms do not migrate to the orange fruit through the tree transport system. Furthermore, in Israel the irrigation season is during the summer months and the oranges are harvested during the winter months, allowing a three months lag without irrigation. This enables operators to correctly plan for irrigating with low quality effluents with minimal risk for the dissemination of pathogenic microorganisms by food crops. Operators should take into consideration to what extent these pathogens can survive under environmental conditions and being transferred to surface and groundwater.

Table 3 Prevalence of Total coliform and fecal coliform on the surface of organges and in organge juice.

Sample Type			Sample source	Date
Juice	Washing water			
Total Coliform (MPN/100ml)	Fecal Coliform (cfu/100ml)	Total Coliform (cfu/100ml)		
			Market	
0	<1	0	1	
0	<1	0	2	16/11/05
0	TNTC	1.2*104	3	
0	5.1	73	1	
0	1	0	2	05/11/29
0	<1	0	3	
			Field	
0	0	0	1	
0	2.5	1	2	
0	0	0	3	05/12/8
0	0	1	4	
0	1	0	5	
0	<1	>100	1	
0	<1	0	2	05/12/12
0	<1	TNTC	3	
0	<1	0	4	

Discussion

Where other sources of water are scarce, wastewater is often a contested resource. In addition to being a valuable resource, wastewater can be the source of nutrients and nutrient recycling has been the objective of wastewater recycling for centuries. Wastewater and night soil application in agriculture in China is a traditional practice to fertilize and replenish depleted soil nutrients (Wang, 1997). The report of the first royal commission on sewage disposal in England in 1865 stated that "the right way to dispose of town sewage is to apply it continuously to the land and it is by such a application that the pollution of rivers can be avoided" (Shuval *et al.*, 1986). Consequently, sewage farms were established in major cities in the UK. Irrigation with wastewater became popular in other parts of Europe during the 1800s and early 1900s. In Paris, by 1904, discharge of wastewater to the Seine River stopped and all the wastewater was applied to the sewage farms. In Berlin, the first sewage farm was established in 1876 and the utilization of wastewater for irrigation increased to a total area of 17,000 ha by 1910. The main portion of the land was managed by the city authorities and the rest was managed by private farmers who produced vegetable crops for the local market. In addition cattle were grazed on grassland irrigated with wastewater (Shuval *et al.*, 1986).

Wastewater contains numerous types of pathogenic microorganism's endemic within the community. Many of these pathogens can survive for prolonged periods when discharged onto land. Application of low quality effluents may cause the dissemination of pathogenic microorganisms. This study was conducted to evaluate the effect of water quality on the microbial quality of food crops. Studies have shown that Salmonellosis, shigellosis, Norwalk virus, and hepatitis A virus were associated with lettuce, scallions, parsley, strawberries, melon, and celery (Beuchat, 2002). The enteric pathogens are of great concern on fresh fruits and vegetables, because of their potential to grow and their very low infectious dose. *Salmonella*, *E. coli O157:H7* and *Listeria monocytogenes* were detected in animal feces and irrigation water. These microorganisms can contaminate lettuce plants and migrate throughout the plant (Solomon *et al.*, 2002; Wachtel *et al.*, 2002). Furthermore, evidence has been presented concerning the association of salmonella with stems and leaves of tomato plants (Guo *et al.*, 2002). Therefore, to limit the introduction of pathogenic microorganisms through irrigation, the source and quality of the irrigation water should be well known. The results of this study are in agreement with previously presented data concerning the potential for the penetration of microorganisms into the roots stems and leaves. The results suggest that microorganisms are capable of penetrating to the root tissues of the carrot, therefore root crops consumed raw should be irrigated with high quality waters.

The microbial quality of fruits and juice not in direct contact with soil, although irrigated with low quality effluent, have been found to be of high quality and orange juice has been found to be free of microbial contamination. These results indicate that some food crops are less vulnerable than others to microbial contamination from the irrigation water which makes it possible to utilize low quality effluents for their production. Wastewater can be safely used in agriculture if adequate control measures are consistently practiced and workers and consumers adopted basic precautions and hygienic practices. This fact is of outmost importance for countries suffering from water shortages that can not apply sophisticated technology for wastewater treatment.

Conclusions

The following conclusions can be drawn from this study: (a) Irrigation water quality determines the microbial quality of leaf and root crops; (b) root crops consumed raw are vulnerable to microbial contamination, because microorganisms may penetrate the root tissue, therefore, they should be irrigated with high quality waters; and (c) Irrigation of trees with low quality effluents did not result in microbial contamination of citrus fruits, therefore well designed irrigation is beneficial for fruit production.

Acknowledgements

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Sizing UV Reactors for Poor Quality Wastewater

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Abstract: This paper discusses the issues involved in sizing ultraviolet (UV) disinfection systems for poor water qualities, such as those found in poor quality water or wet weather flows. Discussions of UV reactor dynamics and the merits of bioassay validation are provided. The discussions provide the basis for the research presented here, which encompasses the modeling and design of UV reactors for poor quality water applications such as primary wastewater and combined sewer overflow (CSO) water, validation of the models, concepts and reactors; and the development of statistical models to determine UV dose levels required for achieving microbial limits. Some practical aspects of applying UV technology in this way will also be examined

Keywords Bioassay; combined sewer overflow; ultraviolet; ultraviolet dose.

Introduction

Ultraviolet (UV) disinfection has proven to be an effective technology for the disinfection of both water and wastewater. To date, the majority of UV disinfection has been applied in secondary and tertiary wastewater, as well as drinking water and ultrapure industrial process applications. UV technologies are becoming better recognized as potent tools in the arsenal for protection of public health and the environment against pathogens and chemical contaminants in our water.

For the past 14 years Trojan has conducted laboratory and pilot scale research to gauge the suitability of applying UV disinfection for poor quality water such as primary wastewater and combined sewer overflow (CSO) water. This paper will summarize a number of the findings from the research and address key issues associated with sizing UV reactors for poor quality water. Increasingly, pressures are being placed on wastewater facilities to limit or treat storm flow discharges to sensitive receiving waters. Options for storing large volumes of storm water for later treatment during low flow periods are expensive and sometimes space constraints render this option impossible. UV disinfection offers an alternative treatment method for such projects.

The Impact of Water Quality on UV Reactor Design, Sizing and Performance

UV reactor fundamentals

The effectiveness of a disinfectant to inactivate an organism is typically correlated to the dose of the disinfectant. The UV analogy to chlorine dose, defined as concentration multiplied by exposure time, is UV dose, defined as the UV light intensity times exposure time.

Ideal UV reactor behaviour is characterized by a uniform dose distribution. In a batch reactor, such as a collimated beam apparatus, close to ideal reactor behaviour can be achieved if the fluid within the reactor is thoroughly mixed. Ideal flow-through reactors are modeled with the assumption of plug flow. The ideal, or average, dose (D_{avg}) delivered by a plug flow reactor is calculated by multiplying the average UV intensity (I_{avg}) within the volume of the reactor by the average residence time (t_{avg}),

$$D_{avg} = I_{avg} \times t_{avg}$$

The average intensity can be determined by integrating the UV intensity (I) distribution within the volume of the reactor and dividing by the reactor volume (V),

$$I_{avg} = \frac{1}{V}\iiint I \, dV$$

The average residence time is given simply by dividing the reactor volume (V) by the flow rate (Q), $t_{avg} = V/Q$. While the ideal reactor model appears simple, models for the spatial distribution of UV intensity (I) can be quite complex. Figure 1(a) (Petri and Olson (2001)) plots the bioassay determined dose versus average (ideal) dose for a UV reactor system under varying flow rates, UVTs and lamp power settings. Poor correlation exists between the model and actual data, and using ideal dose calculations to size UV reactor systems is, therefore, inappropriate, for several reasons: (a) the spatial distribution of UV intensity is very difficult to model, (b) the absolute UV lamp output is difficult to quantify, and (c) hydraulic effects are not accounted for. The following paragraphs will briefly discuss these three points.

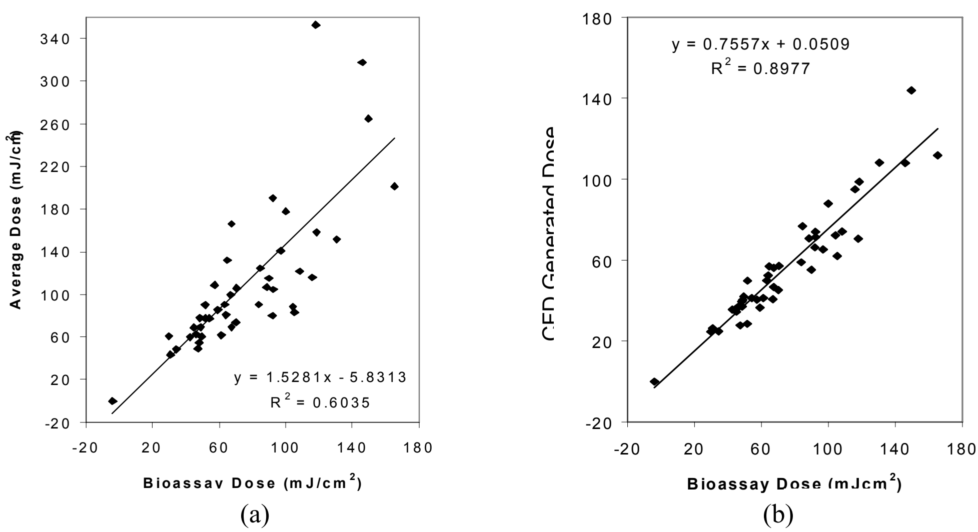

Figure 1 Bioassay dose vs. (a) average dose, (b) CFD.

A number of models have been used to predict the spatial UV intensity within reactors. The most commonly used are the point source summation model and the radial model. Simple application of these models does not account for reflection and refraction within the sleeve / water interface. Furthermore, lamp output can vary along its length. Modeling done at Trojan suggests that errors in spatial intensity distribution can lead to differences in reactor performance predictions by greater than 30%. Lamp measurement can be grouped into two basic methodologies: near-field and far-field. Near-field measurements are done with the output detector placed close to the lamp. Far-field measurements are done with the detector placed at a greater distance from the lamp. Ideal measurements would be accomplished by placing the detector so far away from the lamp that the lamp could be treated as a point source, however, due to geometric limitations, this is not practical. Errors associated with both near-field and far-field measurement include: angular response of detector, detector irradiance calibration and drift, impact of temperature on lamp output, and the effect of the assumed lamp output distribution. The measurement errors can contribute 50% or more in the calculation error of ideal dose calculations.

In a real flow-through reactor, no two microbe, or particle, trajectories are the same and thus each microbe flowing through the reactor will receive a unique dose. For reactors that have a free surface over its radiation zone (i.e. open channel reactors), careful attention needs to be given to managing the water layer. Recently, UV lamp manufacturers have produced significantly more powerful UV lamps. While increasing lamp output can lead to a reduction in system size, the result is a greater amount of water is required to be treated on a per-lamp basis. Greater flow per lamp will increase headloss with the potential result of standing wave formation. Improper management of the water layer above the lamps can lead to significant short-circuiting. Several authors have pointed out that hydraulic profiles, as well as, intensity gradients, within UV reactors give rise to a distribution of delivered doses as opposed to a fixed value (Qualls *et al.* (1989), Scheible (1985), Chiu *et al.* (1997)). Figure 2 depicts a dose histogram of a real UV reactor achieved by Computational Fluid Dynamics (CFD) modeling. Increasing radial mixing will decrease the breadth of the dose distribution. Clearly, as mixing approaches complete mixing, the dose distribution will approach a single dose frequency, simulating the ideal reactor. Errors associated with improper quantification of dose distribution can be 30% or greater. The key to modeling real UV reactor performance is in the ability to accurately quantify the dose distribution for the reactor at each UV transmittance (UVT), flow rate and lamp power condition.

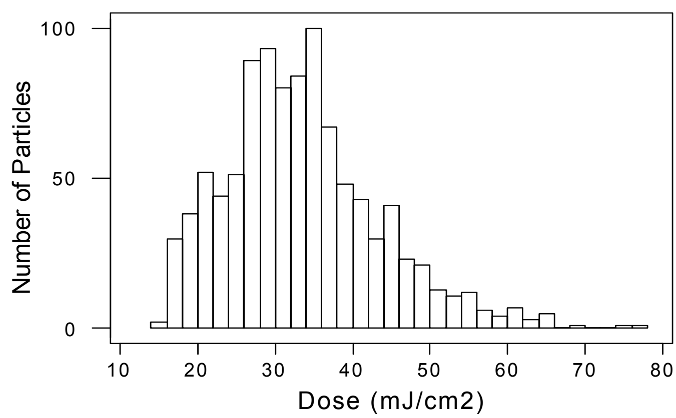

Figure 2 CFD generated histogram of dose delivered to microbes in a UV reactor.

The dose distribution could be approximated mathematically by the formula (Wright and Lawryshyn 2000):

$$f(x \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\pi} x \sigma} e^{-\frac{(\log(x)-\mu)^2}{2\sigma^2}}$$

where μ and σ are constants used to fit a given distribution.

Impact of UV transmittance

Because of the important impact of hydraulics on reactor performance, both reactor design and sizing must account for non-ideal hydraulic behaviour. In real UV reactor design, UVT is the key parameter for determining the optimal UV light path length, or water layer. The water layer is typically defined as the distance between two lamps, center to center, minus the diameter of the quartz sleeve. For a given UVT, increasing the water layer increases the amount of UV energy that is absorbed by the water. However, an increased water layer will have larger "dark" (low UV intensity) zones. As well, a larger water layer will have less ideal hydraulic behaviour for the simple reason that the mixing layer is greater. The less the ideal mixing and the larger the dark zones, the greater the potential exists for low dose paths and short-circuiting. Conversely, decreasing the water layer will improve ideal *hydraulic* reactor behaviour, but because the water layer is smaller, less UV energy will be absorbed by the fluid. Balancing the hydraulic and absorption efficiencies through proper choice of water layer is the key to reactor design optimization for a given UVT.

Impact of particles

As noted above, UVT plays an important role in reactor performance. Effectively, for a given reactor and flow rate, UVT determines the limit of the amount of dose the reactor can deliver. Particles, on the other hand, impact the inactivation kinetics of particle associated microbes. In a sense, particles determine how much UV dose is required to achieve a certain level of inactivation. Physically, particles may consist of organic and inorganic material as well as microbes. Microbes that are associated with particles and are internal to the particle will be partially or wholly shielded from the UV light and will be less likely inactivated. The microbial inactivation kinetics are often modeled as second order. Figure 3 plots typical fecal coliform inactivation kinetics for primary, secondary and tertiary wastewater. As can be seen, primary wastewater, which contains significantly greater particle counts and particle sizes experiences "tailing" of the microbial kinetics after approximately 2.5 logs inactivation of the free microbes compared to the secondary and tertiary wastewater. Typically, the tailing portion of the curve tends to flatten to a curve with a slope of zero after a certain higher dose value. Any increase in UV dose results in no increased microbial inactivation. It should be noted, that second order kinetic modeling cannot capture this phenomenon.

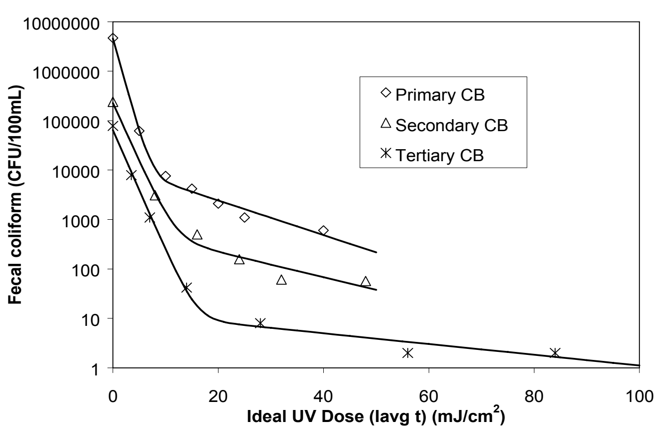

Figure 3 Wastewater UV dose-response kinetics as determined using a collimated beam apparatus.

Impact of quartz sleeve fouling

While the rate of fouling is site dependant, all quartz sleeves, that enclose the lamps, will foul. Various chemical characteristics of the effluent result in sleeve fouling. Organic and inorganic deposits absorb UV light and decrease the UV light penetration into the effluent. Fouling decreases the UV dose resulting in reduced disinfection performance. Online and / or periodic offline cleaning is required. System designs should account for fouling by incorporating an appropriate fouling factor.

Method of System Design and Performance Validation

To achieve optimal UV reactor performance in low quality water, Trojan has utilized numerical modeling to optimize reactor design, bioassay testing to validate reactor performance and collimated beam studies to determine the appropriate UV dose levels required for meeting disinfection criteria. The following sub-sections will briefly summarize the methods used.

UV reactor modeling

A computational disinfection model that accounts for hydraulics, UV optics and disinfection kinetics has been developed at Trojan (Buffle *et al.*, 2000). The technique is based on using Computational Fluid Dynamics (CFD) to predict the trajectories of particles as they flow through the reactor. Integration of the modeled UV intensity within the reactor with simulated particle residence time results in a simulated dose delivered to each particle trajectory. By compiling numerous particle doses into one dose distribution curve, the overall performance of the reactor, or "Delivered Dose", can be predicted. Figure 4 plots a simulated UV irradiance map within a generic reactor geometry. Figure 5 shows a single microbial path through a portion of the generic reactor. In this particular study, the numerical models were used to understand the impact of water layer, effectively lamp spacing, on reactor performance for varying UVT. Three, four and five inch lamps spacings were modeled. As well, different static mixing technologies were modeled in an effort to increase reactor performance and decrease the associated reactor headloss that typically accompanies reactor designs with tight lamp spacing.

UV reactor validation: the bioassay method

The key to effective UV reactor sizing is to match the target inactivation level for the target pathogen or microbe with a reactor that can deliver the required inactivation level. As mentioned above, average dose calculations for reactor sizing are wholly inadequate and should be avoided. While numerical models have been shown to predict reactor performance quite well, each model requires validation to the given reactor geometry. The bioassay protocol is the standard approach provided by all current regulatory guidance, and is currently the globally accepted approach for validation of the dose delivery performance of a UV disinfection reactor. The bioassay protocol is divided into three parts (Fig. 6): firstly the development of a UV dose-response curve with an ideal laboratory reactor for a culture of challenge organism; secondly the passing of the challenge microbes from the same culture through the reactor being validated while it operates under specified conditions of flow rate, lamp power level and water quality; and thirdly, a comparison of the inactivation of the culture following passage through the reactor with the laboratory dose-response curve to determine which dose delivered by the ideal reactor gives the same microbe inactivation.

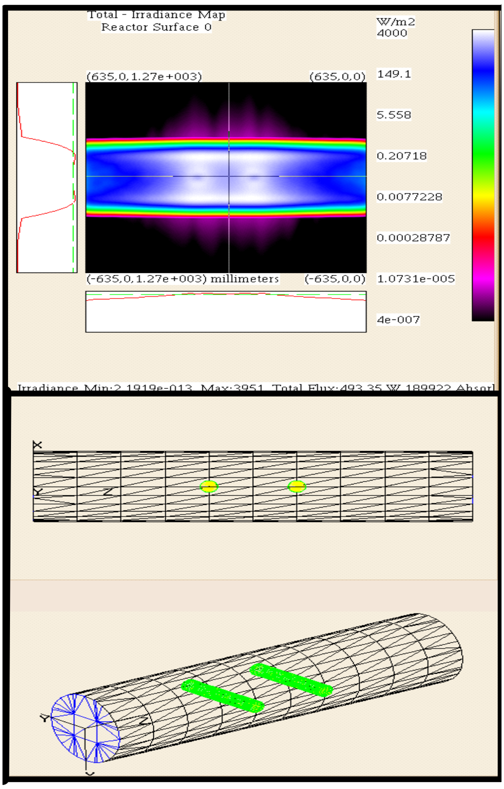

Figure 4 UV irradiation map of a two lamps annular reactor.

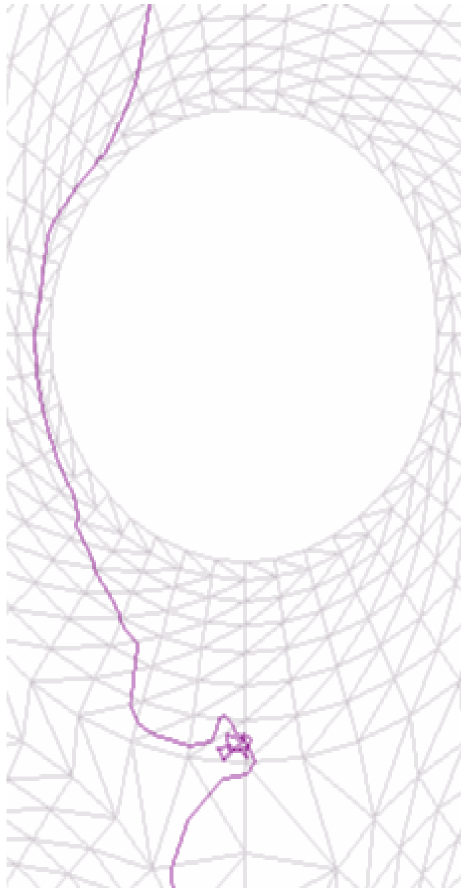

Figure 5 Microbe path in a flow around a lamp.

For those conditions of operation, the reactor is thereby validated to deliver the Bioassay Equivalent Dose read from the dose-response curve. Typically, a bioassay validated UV reactor curve is plotted as flow per lamp on the x-axis and dose on the y-axis for a given UVT. As discussed by Wright and Lawryshyn (2000), it is important that the challenge organism has similar inactivation kinetics to that of the target pathogen.

Collimated beam study

Trojan Technologies Inc. has collected over 18,000 collimated beam inactivation data points over a period of approximately 15 years. Each data point pertains to a given microbial inactivation level for a collimated beam applied UV dose. Associated with each data point is information regarding the type of treatment process that was used for the given water sample, UV transmittance (UVT) of the water, microbe type, total suspended solids (TSS), particle size distribution, as well as other parameters. Applying statistical analysis, it is possible to determine the dose required to achieve a certain level of inactivation with a specified confidence, and hence the feasibility of disinfecting low quality wastewater.

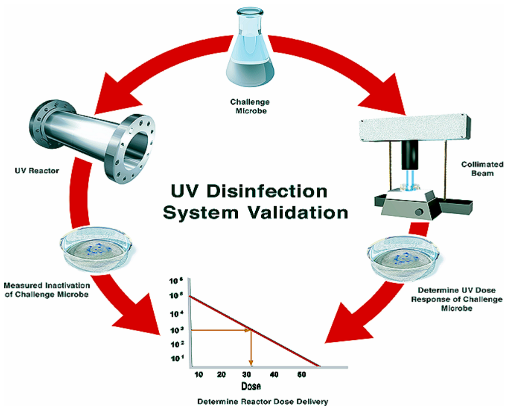

Figure 6 Graphical depiction of the bioassay protocol.

Results

UV reactor modeling

In Figure 7, the inactivation performance of the 4 and 5-inch reactors relative to the 3-inch reactor performance is shown as a function of UVT. With the same energy consumption, the 5-inch reactor only achieved 40% log inactivation of the 3-inch reactor at UVT lower than 45%. The 5-inch reactor achieved only 60% of the 3-inch reactor's performance at a transmittance of 60%. Hence, it can be concluded that a 5-inch reactor is only 40-60% efficient when compared to a 3-inch spacing reactor at equivalent flow rate and lamp power. As expected, however, increasing UVT will lead to better performance with the greater water layer. While not done in this study, it is expected that at 75% UVT, the 4-inch reactor would outperform the 3-inch one. For a complete discussion of the effect of lamp spacing on UV reactor performance, see Chiu and Buffle (2001). Different mixing technologies were tested using the numerical models. The models showed a 10% to 30% improvement in reactor performance at UVT values below 40%. Figure 8 plots numerically generated pathlines associated with static mixers attached on the upstream ends of UV lamps.

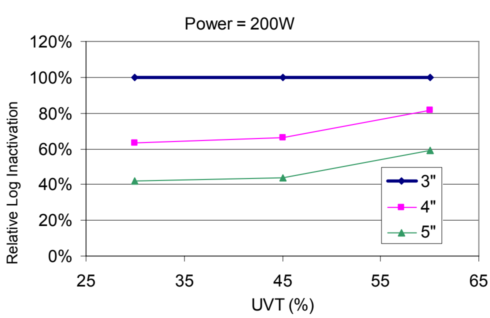

Figure 7 Model inactivation performance of the 4 and 5-inch lamp spacing reactor relative to the 3-inch reactor as a function of UVT.

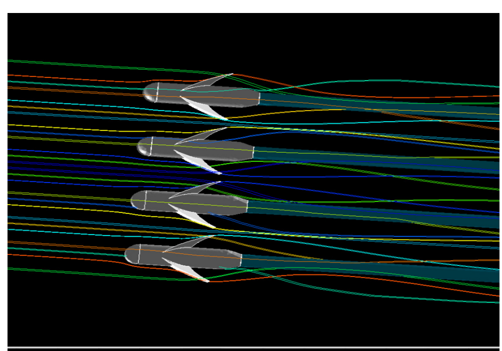

Figure 8 Modeling the effect of static mixers.

UV reactor validation: the bioassay method

In Figure 9, comparisons of bioassay results and model predictions are shown for 45% and 60% UVT. The levels of microbial inactivation of the three systems are displayed as relative values to the performance of the 3-inch lamp spacing reactor. The bioassay (pilot) data clearly substantiates the modeled trend of improved reactor performance with decreased water layer at low UVT. Furthermore, it can be seen that in all cases, the models agreed quite well with the pilot data. It should be emphasized that UV reactor dynamics is a highly non-linear problem, and only through sophisticated modeling can strong correlation be achieved. An ideal model would predict the opposite of the actual phenomena – namely at 45%, it would predict that the 5-inch reactor would outperform the 3-inch reactor by roughly 5%.

As mentioned above, while reducing the water layer improves reactor performance for low UVT water, water layer reduction increases headloss. Bioassay validation of the mixing technology compared the reactor performance of a reactor with a tight water layer, with that of a reactor with a water layer two times greater with a mixer. The following Table summarizes the impact on reactor performance and headloss. As can be seen, the performance of the two reactors was identical; however the headloss with the mixing technology and increased water layer was significantly reduced.

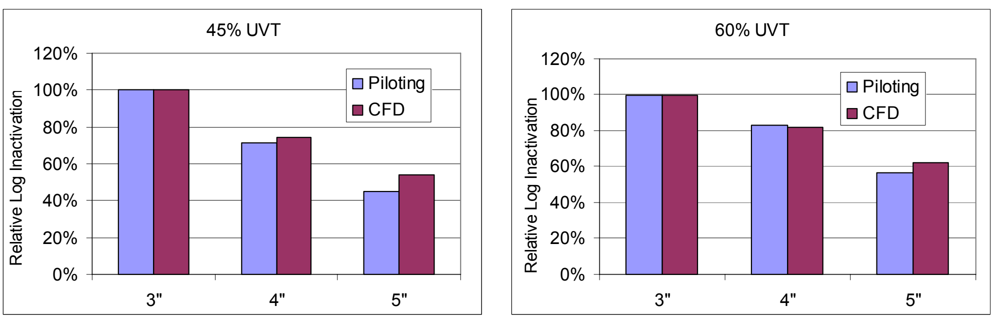

Figure 9 Comparisons of bioassays and numerical results at 45% and 60% UVT. Data have been normalized to the performance of the 3-inch lamp spacing reactor.

Table 1 Effect on disinfection performance and headloss of mixing technology.

	Small Water Layer – No Mixer	Large Water Layer – With Mixing Technology
Reactor Power Setting Required to Achieve Disinfection Limit of 18,000 Enterococci cfu/100 mL – 99%ile for Primary Wastewater at 25% UVT	80%	80%
Headloss (inches of water) at 700 gpm	17.0	9.5

Collimated beam study

Figure 10 plots the dose response for fecal coliform bacteria for secondary, primary and CSO wastewater effluent. Table 2 provides the statistics on the data used for this analysis. Figure 11 plots the 50th, 90th and 99th percentiles of the data presented in Figure 10. To achieve the 200 fecal coliform cfu/100 mL geometric mean limits, approximately 5.5 times higher dose is required for CSO compared to secondary wastewater.

Table 2 Secondary and CSO sample statistics.

	Secondary	Primary	CSO
No of samples	67	94	64
TSS range	10 - 20	22 - 180	46 - 451
UVT range	34 - 81	15 - 58	2.8 - 49

It should be emphasized that comparisons need to be made along the horizontal (Fig. 12). The impact of increasing percentiles is also significant. For the secondary application, approximately 2.3 times greater dose is required to meet the 90th percentile compared to the geometric mean value. No attempt has been made in this presentation to develop the time-dependence of CSO water quality during a storm event and to determine the design dose required (e.g., first flush versus steady-state) or to determine the storm event average impact if the UV dose is allowed to vary with the water quality during the event. All of these impacts can be extracted from the database and related to historic or site specific storm event water quality and flow characteristics.

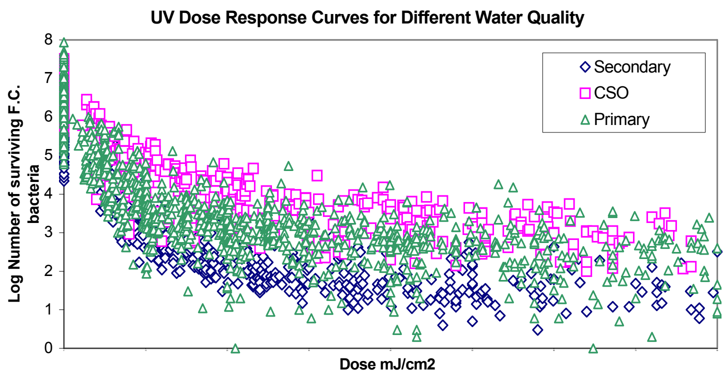

Figure 10 Collimated beam dose response curves for primary and secondary effluent and combined sewer overflow (CSO).

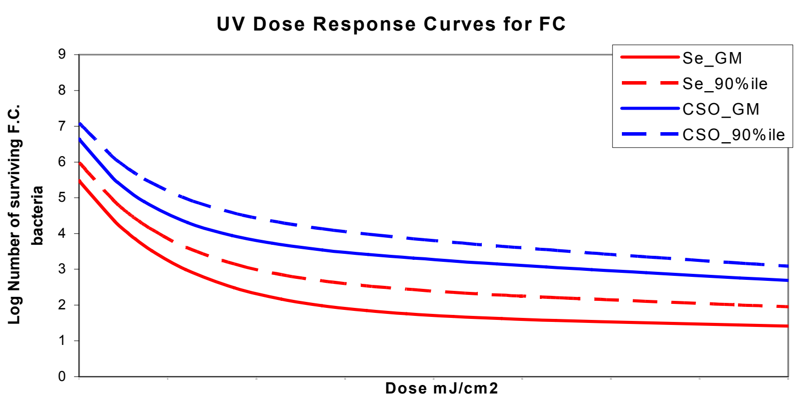

Figure 11 Fecal coliform kinetic response for secondary and CSO wastewater effluent.

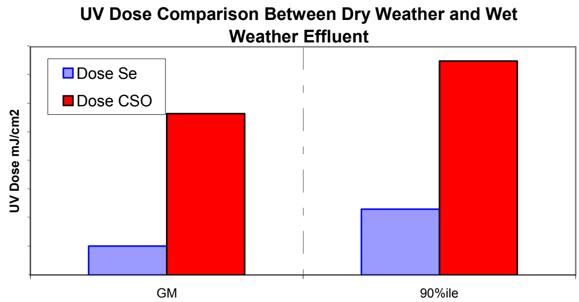

Figure 12 Dose to achieve 200 FC/100ml limit comparison between secondary and CSO wastewater effluent.

Conclusions

Applying UV for poor water quality is feasible. The most important factors to consider are: (a) UV reactor design for low transmittance water, (b) reactor and model validation, and (c) thorough understanding of the microbial inactivation kinetics. Optimal reactor design will reduce up front capital costs and ongoing operating and maintenance costs. Validated models and a thorough understanding of microbial inactivation kinetics will help ensure that reactor sizing is done correctly for the application at hand.

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Short Papers

The Water Channel Delivery System in Ancient Region of Darab, Iran

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Abstract: Water delivery through channels was an important part of water utilization in ancient Iran (Persia). The main purpose of this study is to describe an ancient water delivery system in Darab region, an important agricultural and historical place in Fars Province. The water resources and delivery system of Kheir Abad plain, located in the southeastern part of present day Darab city, was investigated in the field. The main water uses in this region were for irrigation, human consumption, and energy source for water mills. This plain had two water resources, both of which were delivered through water channels, build overland or dogged in the land surface. Mountainside contours played an important role in construction and direction of the channels from the water source to the plain area. The channels were also protected from floodwaters through small bridges, either over the channels or under the channels.

Keywords Persia; Sassanid dynasty; water technology.

Introduction

Water scarcity is one of the typical climatic characteristics in the ancient country of Iran, also known as Pars or Persia in history. Close to 90% of the country is classified as arid and hyper-arid. Therefore, water has always been an extremely valuable and holly commodity among the ancient Persians, as they believed in Anahita, Goddess of water.

The ancient Fars Province is located in southern part of Iran, and is the birthplace of two great empires of Iran, the Achaemenids (550-330 B.C.) and Sassanid (224-653 A.D.) dynasties. Agriculture has always played an important role in this region, as in other parts of Iran. This region is also classified as arid. The surface fresh water resources are scarce in Fars, similar to the rest of the country. Therefore, efficient utilization of the limited water resources was an important priority since the early establishment of human settlements in this region. The water resources of Fars Province consist of surface and underground resources. The old historians have categorized these resources as Qanats, Springs and Rivers (Shirazi, 1983; Rastegar Fasaei, 1988; 1995). The ancient Persians used dams to bring up the level of the rivers to land surface for irrigating their agricultural lands. But surface water resources, both in terms of quantity and quality, were not as reliable as the underground resources. The underground resources were extracted and utilized through a series of interconnected wells known as qanats. In this way they used to bring the underground waters from far away mountainous regions to plains, where the agricultural lands and settlements were located.

The main uses of water were irrigation of agricultural lands, human consumption, and energy for water mills, an important agro-industrial sector since thousands of years ago. However, due to introduction of modern technology and fossil fuel and electricity, this industry has changed dramatically from its traditional way. The water technologies in this region, which is representative of many arid parts of the country, were developed in three main categories: (a) water extraction from underground aquifers, (b) development of water delivery systems through channels, and (c) storage of water. The focus of this presentation is on water delivery system. Therefore, the main purpose of this study is to describe an ancient water delivery system that was still in use less than a century ago, in the ancient region of Darab, an important agricultural and historical place in Fars Province.

Methods and Materials

As was mentioned before, Fars Province is the birthplace of two great empires of the ancient world, Achaemenids and Sassanids. In the geographical land division of the Sassanid Empire, Darab was the center of one of the five main regions in Fars (Rastegar Fasaei, 1995). This area, which still is one of the biggest agricultural regions of Fars, is the birthplace of Sassanid dynasty. Since many ancient water delivery systems exist in this area, this region was chosen as the location to evaluate the surface channel water delivery systems of ancient times, which goes as far back as the Sassanid Dynasty.

In southeast of present time Darab city, it is located the great Kheir Abad plain. Cultivation of cereal crops in this plane dates back as far as two thousand years ago. The irrigation water supply and delivery system to this vast plain, which do not have any surface rivers, were examined during this study. The main water resources outlets, water mills, and channels for water delivery were located in topographic maps of the area. Also, all of these locations were visited and examined in the field. The channel ways were followed in the field as well, and the methods of protecting them from sedimentation and floodwaters were evaluated. The height from sea level of important points along the channel ways was also measured, using a GPS instrument.

Discussions

The engineering ingenuity of the people in Sassanid era was evident from the field observations and investigations of the historical remains. The water extraction (through qanats), water mill, and delivery systems (through various types of channels) were still in use till the last few decades ago, since they were originally built around two thousand years ago. Local rulers and dynasties after Sassanid mainly rebuilt or repaired this extensive system. This efficient water delivery and utilization system was one of the main reasons for the prosperity and power of this empire.

The field investigations revealed that the Kheir Abad water requirements were supplied by two sources, which will be described separately. One was the qanat (inter-connected chain of wells) in Barfkooh Mountain (meaning Snow Mountain). This mountain is located in northeast of present Darab city, and northeast of Kheir Abad plain. The evidences suggest that this qanat may have been in use even before the Sassanid Dynasty. That is because, along the water channel to Kheir Abad plain, there is a very old water mill and a temple that were built in the same era. The water mill worked using the water from the Barfkooh mountain qanat. The water from the outlet of the water mill was diverted toward the plain for irrigation purposes. The temple, which is now called Masjid Sangi (Stone Mosque), is a classical example of temples for worshiping Anahita, Goddess of water, who was one of the main gods of Zoroastrians. The temple and water mill were built, or better to say carved in the stony mountains, with less than 100 m distance from each other, by architects of that era.

The water from outlet of Barfkooh qanat was guided toward the Kheir Abad plain by channels that were built on the land surface and appropriate contours along the mountainsides and hills. The dimensions of the channels were about 50 cm in diameter and 35 cm deep. The construction materials were mainly stones and Sarooj. Sarooj, which was used extensively in the ancient times as cementing agent, is a mixture of lime, gravel, ash and water. Since the introduction of cement, Sarooj is no longer in use. The length of the channel way from the Barfkooh qanat outlet (1,332 m a.s.l.) to the Kheir Abad water mill (1,133 m a.s.l.) and the plain is about 7 km. The architects of that era efficiently used the land slopes and contours in the side of stony mountains to overcome the low valleys and deliver the water safely to the designated plain. If they didn't use the mountain contours and wanted to deliver the water straight to the plain, they had to build several high and long bridges to overcome the low valleys and slope problems. But this was not economical and was very difficult to maintain and protect from natural and unnatural disasters. Instead they used the mountain contours at the height of 1,166 m a.s.l. to deliver the water with just the right slope and speed to the top of the water mill (1,133 m a.s.l.). From there, channel was divided in to two channel ways. One was towards the water mill and the other one toward the next plain (Zein Abad plain).

The second water source for Kheir Abad plain comes from the qanats of Roodbal region, located in northeastern mountains of Darab city. This qanat chain was established in 1881 A.D., by the local governor of the area. The main purpose was to deliver more water to that plain and cultivate more lands. The water from the Roodbal qanat outlet was also delivered to the Kheir Abad plain by channels, which were finally connecting to the overland channels from Barfkooh Mountain. The Roodbal channel was digged in the ground rather than build over the surface. The main reason was the appropriate land slope from Roodbal to where the channels were joined.

Field observations and historical remains also revealed the technologies used to protect the clean fresh waters of the qanats from muddy floodwaters. In several locations along the way, small bridges were made to cross the channel over the seasonal riverbeds and flood ways. Also in several other locations wide waterways were built over the water channels to direct the floodwater through them, and prevent the destruction of fresh water channels by floodwater.

The ancient water delivery system to Kheir Abad plain in ancient Darab region was described. The advanced water technology and engineering knowledge of architects of Sassanid era and even before them, is evident in all the fields, such as extraction of underground waters; construction and digging of channels for water delivery; efficient utilization of water as energy source for water mills, human consumption and irrigation; and protection from flood waters. Many parts of these systems are still in good shape after many centuries, telling the new generations about the beliefs and ingenuity of their forefathers.

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Dams of the Ancient City of Istakhr

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Abstract: Istakhr, from 500 B.C. to A.D. 1000 was a large metropolitan city of the ancient world. From the Achaemenid era to the early Islamic centuries, Istakhr was either the capital of the Persian Empire or the center of Istakhr province, a part of which is now called Fars Province. A major reason for the growth of Istakhr and its sustaining for 1,500 years, besides other considerations, was the presence of Sivand River (Pulvar River in history). To use water for domestic and irrigation purposes, many storage and diversion dams were constructed on the 150 km long Sivand River. Other hydraulic structures, such as water mills, tunnels, canals, aqueducts, bridges, and water control systems, were also built around this river. Most of the diversion dams and the hydraulic structures are of stone masonry work with sarooj mortar. The stonework is coursed on the face and uncoursed inside the structure. Stones are of high quality broken limestone and brought from nearby quarries. In this paper, we introduce some of the remainders of the diversion dams that still are surviving on the Sivand River for more than 2,500 years.

Keywords Ancient dams; Istakhr; Sarooj; Sivand River.

Introduction

Istakhr city

The large mound of the Achaemenian city of Istakhr lies six kilometers northeast of Persepolis and north of the plain of Marvdasht. The actual domain of Istakhr was much wider than its present mound. In fact, Istakhr was the name of several interrelated districts of a long metropolitan city throughout its 1500-year history from Achaemenids era to the early Islamic centuries (Fig. 1). Different parts of the city were located in four different fertile plains. Namely, from south to north, Marvdasht, Khafrak, Kamin and Pasargadae. The Achaemenid royal tombs of Naqsh-i Rustam and Persepolis palaces are located in Marvdasht plain and the fascinating tomb of Cyrus the Great and the ruins of the Toll-i Takht citadel is situated in the plain of Pasargadae. Many other monuments from Sassanid dynasty are identified in these plains.

After the invasion of Arabs to Persia in the 7th century and the fall of Sassanid dynasty, Istakhr suffered extensive damage and lost its importance. Many people of Istakhr were killed or migrated to other places and the city started to disintegrate until finally only a name was left from it in history and geography books. Nevertheless, the ruins of many palaces, buildings, tombs, temples, roads and the relics of several hydraulic structures are remained that points to the extension and the glory of one of the greatest city of the ancient world. The hydraulic structures are mostly diversion dams, water mills, canals, tunnels, water control structures, and bridges.

Sivand River

The strategic features of the land of Istakhr was perhaps the first factor for the Achaemenians to consider and select Pasargadae as their first capital. The plain of Pasargadae was far enough from borders of the Empire and more difficult for enemies to reach it. It was also surrounded by mountains that made the defense of the city easier. The fertile plains of Pasargadae, Kamin, Khafrak and Marvdasht and the pleasant climate of the region were of course other factors for the growth of the capital. However, the presence of Sivand River (Pulvar River or Parvab River in history) that flows from north to south through these four plains was a major advantage for the development and sustaining of the city of Istakhr (Fig. 2). Water from Sivand River was used for irrigation and domestic purposes. Many diversion and storage dams were constructed on the river. Water was flowing throughout the city and gardens in canals and ditches.

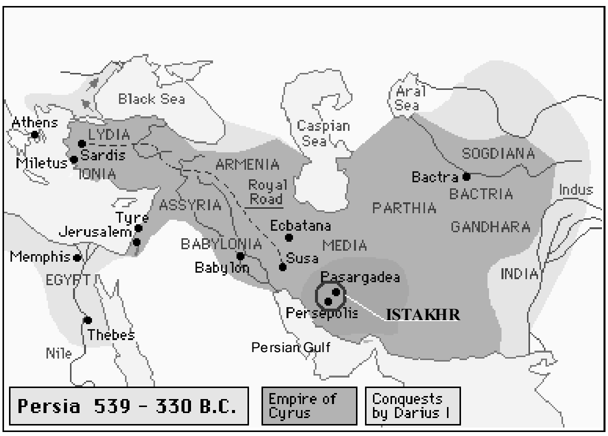

Figure 1 Istakhr, Pasargadae, Persepolis and the Persian Empire.

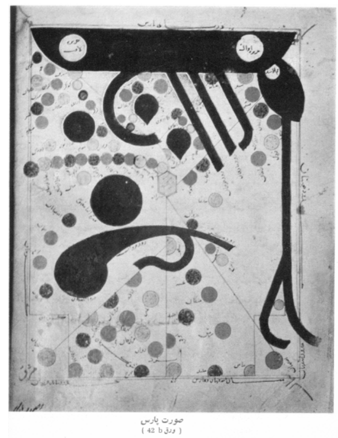

Figure 2 Map of Pars Province and the city of Istakhr (drawn 1000 years ago).

Diversion Dams of Istakhr

Field investigation

During a one-week field survey, several remainders of dams and other related hydraulic structures were detected. The time for survey was chose in such a way that the river has its minimum water flowing, that is, in October. For each structure the geographical coordinates were recorded, at least one picture was taken and the type of material used in construction of the dam was identified. In the following sections we concisely discuss the characteristics of each structure. However, before that, we have to open an introduction to the materials that have been used in almost all of these dams body.

Materials Properties

Sarooj. Sarooj is a Persian term for a mortar that may be called Iranian Cement. The word sarooj is derived from the middle Persian word “Charook” that means something compounded of four different materials. According to the old Iranian masons, these four compounds are lime, ash, water and cattail flower. The flower of cattail is added to sarooj mortar only if sarooj is supposed to be applied on the surface of walls for plastering. It acts as a reinforcement for distributing the shrinkage of the plaster and prevent it from cracking. There are of course other types of sarooj for special jobs. Like the one with egg white added to lime for sealing cracks. When for the first time Portland cement appeared in Iran as a new construction material, people called it "sarooj-e farangi" meaning "European sarooj". Sarooj has been widely used as mortar in almost all of the ancient hydraulic structures of Iran to bind bricks or pieces of stones together. Sarooj has been also used to plaster the surface of walls. There are different types of sarooj.

Air-setting sarooj. For ordinary buildings, sarooj is made from a mixture of quick lime, ash and water. This stiff paste is mixed and compacted vigorously for 12 hours and then applied to the work.

Hydraulic-setting sarooj. For hydraulic structures, burnt clay is also added to make a hydraulic sarooj. Burnt clay powder mixed with ash is derived from the so-called nanak (bread shape). To make nanak, water is added to manure and clay to make a paste. Using this paste, disks of nanak 4 cm thick and 30 cm in diameter are made. After drying the nanaks under the sun, they are set on each other to make a hollow truncated cone with dry manure in between. Finally, the whole cone is covered and filled with dry manure, leaves and bushes and set fire to it. After 12 hours burning, the furnace is let to cool. At last all the produced materials are pulverized to get nanak powder.

The Remainders of the Dams and Bridges of Istakhr

Starting from the jointing point of Sivand and Kor River and going upstream, we located the remainders of the dams as follows.

Dam No 1

This is Madabad Dam with its spillway at the middle of the dam. The spillway is gated with eight sliding gates. The spillway downstream surface is of the so-called ogee shape ending in a widening stilling basin. Two separate water mills are incorporated inside the two left and right non-overflow parts of the dam. Madabad Dam was rehabilitated many times during its long life. The last time rehabilitated was 100 years ago. Up to 30 years ago, the dam was functioning properly. From that time, the irrigation water for the plain of Marvdasht was supplied from the one billion-cubic meter reservoir of Dariush the Great Dam. Consequently, Madabad dam was left idle with no protection or repair. Madabod Dam is a gravity stone masonry dam constructed with broken limestone and sarooj mortar. The ceilings of the water mills are arched with bricks and gypsum mortar and covered with stone and sarooj mortar (Figs. 3 and 4).

Dam No 2

Nothing is remained of this dam except a part of the stone masonry body inside the right bank of the river, and probably the foundation that is under water and not visible.

Dam No 3

The lower part of this dam is still surviving. This dam is a good sample to be investigated for detailed information regarding the foundation and stilling basin of such typical dams (Fig. 5).

Figure 3 Madabad Diversion Dam on the Sivand River (downstream face).

Figure 4 Madabad Diversion Dam on the Sivand River (upstream face).

Dam No 4

From this oblique dam, only the foundation is remained. The designer of this dam decided to choose the dam axis not at right angle to the direction of water flow in order to have a longer spillway crest and a thinner water layer on the spillway during flood seasons. The upstream face of the dam is plastered with sarooj mortar to prevent water from seeping through the dam (Fig. 6).

Figure 5 A typical stone masonry diversion dam of the city of Istakhr.

Figure 6 An oblique diversion dam with sarooj plaster on the upstream face.

Dam No 5

Before excavation, we are not sure whether this is the remainder of a dam or a bridge or both.

Takht-i Tavoos hydraulic structure

This is the remainder of a control gate and a bridge on it. Other parts of this structure that have been made of wood, iron and bricks are completely destroyed. Only stone parts of the structure are remained. This structure has been a part of a water supply system for conveying water from Sivand River to Persepolis palaces and probably to some parts of Marvdasht Plain (Fig. 7).

Conveyance channel

This is a channel dug in the rock to convey water to Persepolis. It starts from the aforementioned Takht-i Tavoos gate structure and after 6 km, reaches Persepolis (Fig. 8).

Figure 7 The remainder of Takht-i Tavoos control gate.

Figure 8 The remainder of conveyance canal to Persepolis.

The Arches of the Aqueduct of Kavala, Greece

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Abstract: The landmark of Kavala city is a wonderful potable supply system and an aqueduct constructed by Grand Suleiman in 16th century to transfer water from the hills to the old town of Kavala. It is a stone construction with sixty big and small arches and a ditch on its top for water transferring. This paper provides some historical and technical information for this construction, illustrated by designs, drawings and photographic representations.

Keywords Aqueduct; arches; drinking water supply; water carriage.

Kavala, a Historic City

Kavala is a municipality located in the Northern Greece with 54,162 permanent residents (2001 census). The geographical position of the city and especially its port has always been an important commercial point, and this is the reason why Goths, Huns, Normans and Bulgarians have attacked it. The ancient city was known as Neapoli and as Christoupolis from the 5th century. In 1185 it was burned down by the Normans. It was a part of the Byzantine Empire until the Ottomans conquered it in 1387, when it was given the name that has today, until the end of 19th century when it was finally freed. During mid 19th century started the tobacco trade and the city's reputation reached far beyond its borders (see also Prefecture of Kavala, 2006). The city's landmark is the Arches that used to transfer water from the hills to the old town of Kavala (Figure 1).

Figure 1 Remains of the city of Kavala and the arches as preserved today.

The Arches History

One of the works whose implementation coincides with the Turkish occupation in Kavala, is "The Arches", and the aqueduct that supplied the town with potable water from the surrounding mountains and particularly the mountain "Symbolo". Taken into consideration that Kavala is built on a rocky peninsula has always faced the problem of the necessary water resources transfer. Based on historic evidence, these infrastructure works started in 1530 changing the area face and giving life to the developing town. It was considered as a colossal work in the time of its construction and brought the valuable water to the houses of Panagia and in the Fortress where the town was located then (Figure 2). Water came from mountains in the north of Kavala and it reached Karagatsia with natural flow. Human intervention started from this point to bring water to the old city of Kavala. Proof of the achieved water adequacy was the construction of many water public taps in the town squares (Lasaridis, 1969; Papakosmas, 2006).

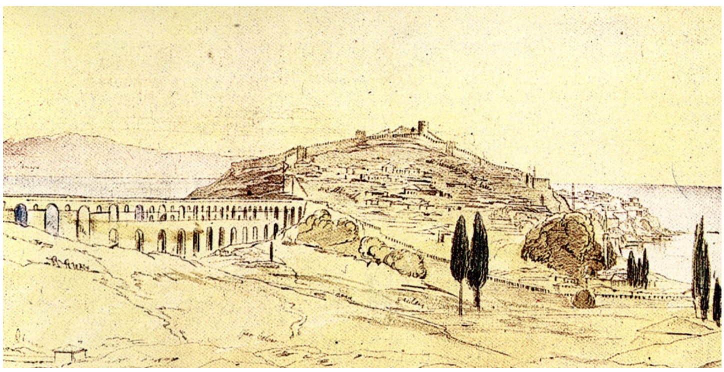

Figure 2 The arches as depicted in a drawing of Edward Lear (26-09-1856). In the background is depicted the fortress of the old town (H.L.A.K., 2006).

Technical Information

The construction consists of 60 arches of four different sizes with a double and sometimes a triple array of successive arches as shown in Figure 3. At the top of that, there is a double wall that secures protection and inside it, water used to supply the town with a natural flow. Before this, water provision was satisfied through many private wells inside the town (Papakosmas, 2006).

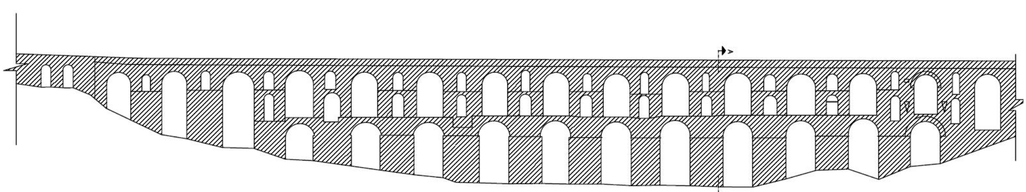

Figure 3 West view of the arches.

The total length of the double arched structure is more than 280 m long and its highest point is 25 m. Its central part is extended in a double arch-array which, after a certain point becomes single to end up as a compact structure in its endings. The monument consists of 18 piers and arch openings (Figure 4). Eleven of them have double arches and seven single ones. On top of the third array, there is a ditch 50 cm deep and 30 cm wide. It is coated with a reddish hydraulic plaster and is also covered by slate.

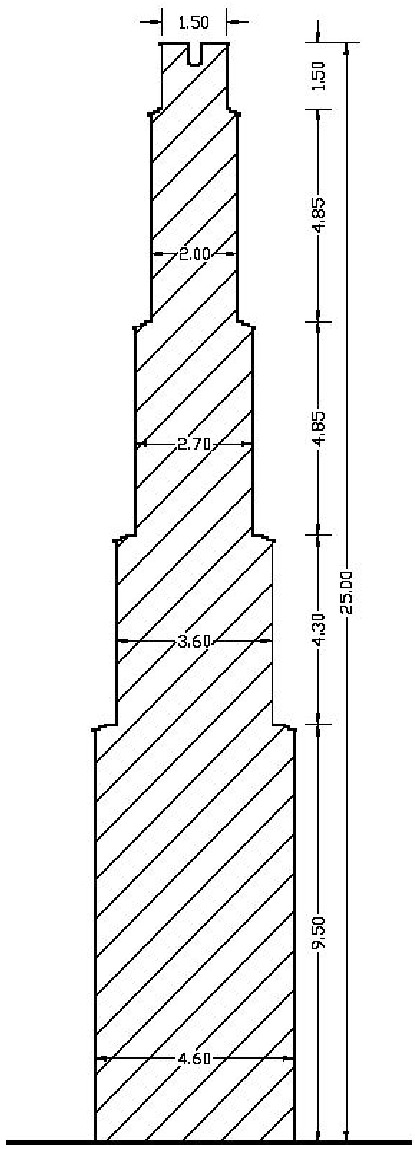

Figure 4 Schematic cross-section (at A-A length of Figure 3).

The arches bridge the lowered ground part, that interferes between the peninsula rock and the opposite hills (up to the altitude of 75 m). Thus they facilitate the smooth water flow in the ditch constructed on top of them (see Figure 5). Water, following the old route, went through Deve Tsesme, today's Byzantiou St., and reached the opposite rocky peninsula. From there it was distributed in specific points of the town, such as the public springs - taps, with tubs from old roman sarcophagus, placed near the town entrances and beside the large mosque, or it reached even the Turkish-bath, the big tank of the acropolis and the smaller cisterns beside the other mosques- one of subsequent times still exists beside the mosque of Kadi Achmet efenti (Stefanidou, 1991).

Figure 5 Close views of the arches and the water supply ditch, as they are preserved today.

Building Materials and Preservation

The monument is structured with stones of granite. This local type of stone is compact at its quarrying stage, but is also susceptible to fracture by weather conditions and human or naturally caused pollution. Two types of stonework making are observed. The older is less systematic with stones of various shapes and the newer, which is located in the south part. Half-processed stones are used there with particular characteristic in the configuration of the edges of the piers and an intention to create the impression of an equal structured system. The edifice is supported by an extended system of wood ties, which today has been decomposed to a large degree.

The monument has a large variety of arched openings. They could be grouped in those topped with a half cyclical foil and those topped with a kinked foil which appears in the foils of the upper arch array. Some of them also bear a plinth wall, while others have exclusively stonework. The arch faces are in most cases plain without any decorations. Only in the south part do we meet a different building technique. The arch face, there, is configured through the interchange of single stones and brick pairs. The face is finished with a plaster zone, which bears interchanging reddish and white squares. A peculiarity is the presence of a brick zone in three consecutive piers south of America Red Cross St, which appeared during some restoration works.

There is a white plaster at some places. It is not safe to tell with confidence that the whole monument was covered with plaster in its initial structure form, or it is a matter of later attempts of restoration. After all the plaster does not have the same synthesis everywhere. The connecting mortar is made up of slaked lime and pebbly sand, with deviations in the ingredients size. The monuments have been depicted through time by paintings and photos, as shown in Figures 6 and 7.

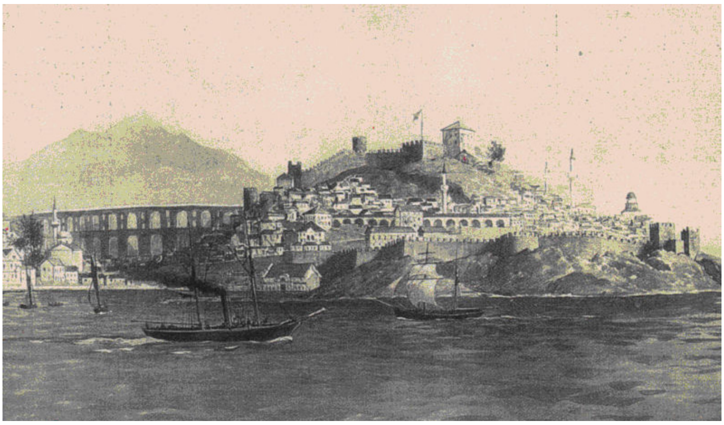

Figure 6 Panorama of Kavala, last quarter of the 19^{th} century (H.L.A.K., 2006).

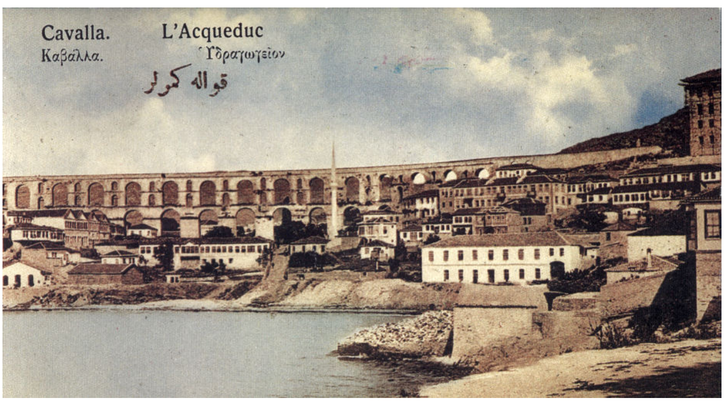

Figure 7 East view in a picture card of 1910 (H.L.A.K., 2006).

Acknowledgements

Thanks are due to Mr Argiris Mpakirtzis, architect from the 12^{th} Department of Byzantine Antiquities, for providing information concerning this paper.

Conclusion

The arches of Kavala have been a unique construction for water carriage with architectural respect and functional superiority. Lessons should be learned from such creations from modern engineers.

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Sedimentation Tanks through the Ages

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Abstract: It is generally thought that sedimentation tanks are a fairly new technology in wastewater treatment dating from the middle of the 19th century. However, archaeological excavations have revealed sedimentation tanks that were being used from ancient civilizations like the Minoan or more recent ones such as the Roman for the settling of solids and impurities in wastewaters, streamwaters, and stormwaters.

Keywords Minoan; Roman; sedimentation tanks; wastewater.

Introduction

Primary treatment of wastewater is usually carried out through primary sedimentation, which refers to the quiescent detention of wastewater in a specially designed settling tank to remove settleable and floating solids. “Settling tanks,” “sedimentation basins,” and “clarifiers” are considered equivalent terms and can be used interchangeably. There are three main functions of sedimentation tanks: (a) Remove solids (sludge) from liquid by sedimentation, (b) remove solids (scum, grease, and floating debris) from liquid by flotation, and (c) thicken solids for removal and subsequent processing.

The primary treated effluent can undergo further treatment (secondary or biological) or it can be used, under specific circumstances, for a variety of purposes such as irrigation. Today there are two main types of sedimentation tanks: circular or rectangular, whilst the square and stacked types are less common (Water Environment Federation, 1996).

It is generally believed that sedimentation tanks are a fairly new technology in wastewater treatment dating from the middle of the 19th century. However, there are significant indications that sedimentation tanks, or at least some forms of them, had been employed from the ancient times and can be dated as far back as the Roman times or even earlier, in 1700 B.C. during the Minoan Civilization and were used for a variety of purposes such as settling of impurities in spring water or even wastewater and stormwater treatment and reuse.

Evolution of Sedimentation Tanks through the Ages

Ancient world (2500 B.C. – 1390 B.C.)

The need for waste and wastewater management strategies begun rising only after the nomadic tribes were starting to settle down and forming communities that would occupy a certain territory instead of moving from one place to another. Cities of the Indus Valley from 2500 B.C had houses with bathrooms with water flushing toilets and well-designed drainage systems (Kahn, 2000).

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The Minoan Civilization on the Island of Crete between 1700 – 1500 B.C. had a highly developed waste management system. They had very advanced plumbing and designed places to dispose of organic wastes. Knossos, which was the capital city, had baths that were filled and emptied using terra-cotta pipes. They had flushing toilets, with wooden seats and an overhead reservoir. Excavations revealed four large separate drainage systems that emptied into large sewers built of stone. The stormwater sewerage system found in the outer stairway of the northwest wing of Knossos Palace was one of the most advanced techniques practiced in Minoan Crete (Evans, 1964, Angelakis *et al.*, 2004). On the one side of the stairway there is a small open sewer that follows the parabolic flow path (Figure 1) instead of the line of the stairs in order to avoid any erosion and nuisance to the people using the stairs as the stormwater flows downwards (Angelakis *et al.*, 2004). The further arrangements of these channels were little tanks, like small sedimentation tanks, placed at proper intervals to allow it to settle to the bottom and freeing the stormwater from impurities so that it could be used for washing or other purposes.

Figure 1 Palace of Knossos: Stairway with a parabolic flowpath on the side leading to a small settling tank.

One of the most advanced Minoan sanitary and storm sewer systems was discovered in Hagia Triada (Angelakis *et al.*, 2004) 60 km southwest of Knossos palace. Researchers that visited the excavated sites and inspected the sewer system could witness that all the sewers were still functioning perfectly, after 4000 years of their construction. The sewers were leading to large (1.5 x 2 m^2) stone-built sedimentation tanks (Fig. 2) that were used for the settling of the wastewater and the removal of gross solids and floating debris.

Figure 2 Sedimentation tank discovered in Hagia Triada.

Another remarkable case of sedimentation tank in Late Minoan period (1425-1320 B.C.) was found in Minoan Tylissos, 14 km west of the palace of Knossos. A network of clay pipes was excavated by Joseph Chatzidakis in 1902-1913 that carried the water of the spring of Agios Mamas, which even today is the water source of the village. The clay pipes led to a sedimentation tank (Fig. 3) that slowed the flow of the spring water and allowed any large particles and impurities to settle.

Figure 3 Sedimentation tank found in Tylissos.

Roman times

Ancient Rome had eleven major aqueducts, built between 312 B.C. (*Aqua Appia*) 226 A.D. (*Aqua Alexandrina*), which were the first real artificial rivers that provided water for entire cities. Aqueducts were channels bored through the rock from the water intake in the hills almost to the distribution cistern in Rome (www.informa.it/aquaduct). The depth of the channel below ground varied so as to maintain a constant and shallow gradient through the length of the aqueduct. Along each channel, at particular points there were sedimentation tanks where the flow of the water slowed down and impurities were deposited. According to Hodge (2002), settling tanks were also found along the main stretches of the aqueduct, though they occurred more often near the beginning (Fig. 4), to clear the water on leaving the springs, or near the terminal *castellum* and the urban network.

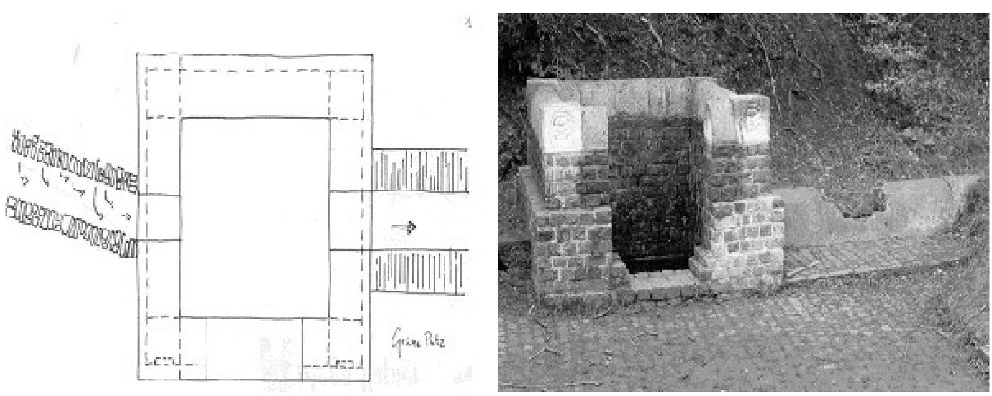

Figure 4 Layout and photo of Grüne Pütz, the start of the aqueduct at Cologne, Germany.

On the aqueduct at Siga, in Algeria, there was a series of at least twenty small basins, which varied in shapes; some were oval and some others round with 1 m^3 capacity. The normal form however was a barrel – or a cross-vaulted chamber or set of chambers – through which the water made its way (Hodge, 2002). In any case the importance of the settling may be gauged from the pebbles found in the settling tank of the Anio Novus at the Villa Bertone, shortly before its entry into Rome where the pebbles are a size of a pea and completely round.

During the Roman times Gortyn was the capital of Crete. Gortyn had initially one major aqueduct which was put out of use following repeated catastrophes and subsequent rebuilding, until a new water-supply system with three built aqueducts leading to the city was established in the 6th century A.D. Recent studies have provided us with a picture of the system of water supply in the city dating to the Late Roman and Early Byzantine periods. The basin that is shown in Figure 5 is thought to be the ruins of a settling tank that was built during the course of the water that flowed from the aqueduct to the city.

Figure 5 Remains of a settling tank found in Gortyn.

Middle Ages and Renaissance

Around 500 A.D. during the middle ages, the practice of separating drinking water and human wastes was abandoned and human wastes could easily migrate from pits into wells. As Kahn (2000) states, "the taps were being turned off all over Europe and they would be turned on again nearly a thousand years later: Sanitation technology entered its dark ages". As the Middle Ages were passing, certain changes started taking place and during the Renaissance more concern was given to health and water issues. It was during the Renaissance when the cesspool was developed. Cesspool was not a typical septic tank but it was employed for the same purpose and it can be described as a simple pit, which allowed solid to settle and the liquid to seep directly into the soil. However, the solids were not as efficiently decomposed as in regular septic tank and more frequent cleaning was necessary (Burks and Minnis, 1994).

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Traditional Water Techniques: Cultural Heritage for a Sustainable Future

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Abstract: Ancient practices of water harvesting, catchment and distribution had guaranteed for years water supplying to the countries and the towns all over the Mediterranean area. An articulated variety of water systems, such as foggaras, qanats, khattaras - drainage tunnels, shadufs - wells with a balance bar, filter cisterns, terracing, drainages, stone barrows, harvesting soils and diversion dikes, shaped through time the Mediterranean landscape, thus acting on its functionality and on its beauty as well. Nowadays, the risk of water shortage, desertification and degradation of soils depending on global warming climate heating, the increase of urbanization and the agricultural industrialization is high. As consequence of this, the reuse of the traditional water systems is on one hand a fundamental contribution to the water resource management based on the local sustainability and on the other hand the recovery of aesthetical values of the monuments which are a further resource for people. The case studies the project focuses on are the leading examples for methodologies which could be applicable to existing global scenarios.

Keywords Sustainability; traditional; water catchment technologies; water harvesting.

Introduction and Content

The Project is coordinated by Maria Luisa Vitobello (ETJN GEIE, ejtn@ieni.cnr.it). The scientific management is under the direction of Fekri A. Hassan (CULTNAT, Egypt/UCL,UK) and Pietro Laureano (IPOGEA, Italy). Partnership includes: CULTNAT-National Center For Documentation Of Cultural And Natural Heritage, Egypt; IPOGEA, Italy; NAGREF-National Agricultural Research Foundation, Greece; PNT-Petra National Trust, Jordan; Sarl Societe Sud Timmi, Algeria; SIDATA-Information & Communication, Systems Ltd., Palestine; Université Moulay Ismail De Meknes, Morocco; USTO-Université des Sciences et de la Technologie D'Oran -Mohamed Boudiaf, Algeria; VIA MARIS, Palestine. The project officially started on July 1, 2004. The kick-off meeting was held in Brussels, Belgium on July 9, 2004. Four following meetings were held in Adrar (February 2005), Algeria, Valencia (July 2005), Spain, Brussels, Belgium. (March 2006) and Amman (July 2006), Jordan.

The project aims to contribute to the development of a bank of information on traditional and indigenous technologies and to focus attention on the rich and diverse water saving, water irrigation and wastewater-related heritage in the Mediterranean region. It also aims to provide a model of how archaeological data integrated with historical information and traditional knowledge could create a new sense of awareness of the role of water and wastewater in society and nature, and to integrate a long-term understanding of water management with efforts to develop sustainable development strategies. At a time when water scarcity and poor management of the environment threaten human lives and the integrity of ecosystems, the SHADUF project is a very important step toward a better future. Contributions from this project after 18 months have already revealed the potential not only for the means by which people can live in harmony with their environment, but also how traditional water technologies and managerial skills can improve the living conditions in arid areas. The specific objectives of SHADUF project are as follows:

(a) The preparation of a database of all case studies with entries related to archaeological, historical, technical, hydrological, ecological and socioeconomic parameters.
(b) Characterization of the archaeological and historical monumental value, character and cultural significance of water heritage sites.
(c) Proposals for a strategy for restoration.
(d) Evaluation of the sustainability of current water management activities.
(e) Recommendations for the valorisation of water heritage, increasing public awareness, and promoting cultural and eco-tourism.
(f) Case studies from different countries have been selected to highlight the range of the spectrum of water harvesting systems in the Mediterranean region.
(g) Drainage, tanks, terracing systems in selected area in Italy.
(h) Shaduf and Seguia irrigation in Saoura and Gourara (Sahara region) in Algeria.
(i) Khattaras (foggaras) in Morocco.
(j) Ancient Nabatean harvesting and delivery systems in Petra in Jordan.
(k) Underground tunnels and aqueducts in Jerusalem & historical uses and modifications, Palestine.
(l) Flood water harvesting in the Faiyum Oasis (Fig. 1), Egypt.
(m) Drainage and wastewater management in Greece.
(n) Rainwater harvesting techniques in Syria.

Figure 1 Siwa Oasis, Egypt.

The project will document in a computer data base of site plans, photos, and textual information the traditional techniques. Ancient dams, cisterns, channels and flush flood control measures will be carefully recorded. This is an important study since water harvesting is now considered an appropriate and sustainable water management strategy in all arid lands, where water scarcity and water conflicts are severe.

European Dimension

The project engages three European Institutions, ETJN GEIE, IPOGEA and NAGREF who are engaged both in the demonstration of the project and the project scientific management as well as responsibility for work in Italy, Greece, and Syria. Professor Fekri Hassan, University College London, is also involved in the scientific management of the project.

Innovation and Originality

The project has already made numerous innovative approaches and original discoveries in the domain of traditional water management. It has initiated the development of the first comprehensive data base structure of water harvesting systems. The data base will provide the basis for a bank of information using icons for a user friendly approach for the Public and for Educational purposes. The project has already brought into recognition ancient water works that have been long ignored such as the oldest high Dam in the world in Wadi Garawi, Egypt, as well as the oldest national waterworks in the Faiyum Oasis, Egypt. In Morocco, the SHADUF project is pioneering the use of GIS-based modeling of Khattara water management systems on a regional scale. In Algeria, the SHADUF project is pioneering a model of public participation in the rehabilitation of Shaduf around Talmine (Adrar, Algeria). Another team carried out a detailed investigation of the declining use of the Shaduf along the Western Sahara erg in the Saoura region, in the area between Karzaz and Beni Abbes, and around Talmine, Adrar, Algeria (Fig. 2).

Figure 2 Shaduf, Talminen, Algeria.

The results reveal that the SHADUF is still of significant symbolic value and that it continues to be used in specific situation as a back- up system. In Jordan, the Nabatean water harvesting system has been mapped providing an outstanding panorama of a complex and diverse water management techniques in an urban context. In Greece, water management technologies have been identified and dated. Construction of dams, excavation of wells and cisterns, reuse of rainwater are found to date back to *ca.* 2,500 B.C. Gravity drains and pipes and long distance aqueducts date to 2,000 B.C. Domestic water management dates back to 1500 BC. Pipes and siphons were used as early as 1,000 B.C. In Italy, survey has been carried out over the area of Matera, a troglodyte town whose urban layout is necessary for rainwater catchment and management. Research has demonstrated that this accurate ability of resources water management had origins dating back to prehistory. The vestiges of the Neolithic villages in Matera are surrounded by deep ditches which had been intended as defensive structures. The photogrammetric survey has proved their water use and their function as water drainage systems and water harvesting devices.

Impacts

The project is already having a significant impact in different arenas; it has attracted the attention of EUWI, The EU water commission, and its results have been included in the World Water Day, Mexico. Several contributions have appeared in professional journals. In addition, articles in newspapers and magazines are providing the general public with a fresh outlook on traditional water management systems. The project uses as a communication tool among partners its own website and offers an electronic portal to support information and international dissemination to the public at present in English: at project completion contents will be offered in French and Arabic as well. The Portal website is: www.shaduf-eu.org.

Conclusion

SHADUF Project, in progress at present, ending by June 2007, proposes an adaptive reuse of monuments/sites and an integrated approach to conservation. Water scarcity is, in fact, a potential source of conflict, poverty, and environmental degradation. The project aims to provide an innovative approach to dealing with this problem in a variety of ways. This innovative perspective reflects the philosophy of UNESCO International Hydrological Program (IHP) which had established programs on “Water and Civilization” and “Water and Society” to provide a means by which social and cultural aspects of water management in the past and in different societies could contribute to turn potential conflicts to cooperation.

The methods may even be extended and applied to other areas. Archaeological data here will serve a basis for contributing to the current scientific experimentation with water harvesting. The proposed study will explore the means by which they can become a centre for learning about water, thus contributing to the efforts undertaken by UNESCO to enhance public awareness of water issues. The study will also explore sound mechanisms for community development projects associated with the ancient water harvesting system of the city.

Local MPC communities, social groups, community solidarity entities related to water management will be involved in re-use of the researched techniques. Local MPC agencies will be enabled to originate local cultural tourism (Petra, Sahara, etc.) through tour packages to visit ancient water management sites all over the Mediterranean: tourists will be hosted at local communities. This is an innovative approach that promotes an economic return and brings added value that will justify the efforts in re-using and revitalizing these ancient water management technologies.

Acknowledgements

The extended abstract was prepared based on contributions by Prof. Fekri Hassan, C ULTNAT, Egypt/University College London, UK. Authorship of this document refers to project coordinator’s capacity.

Combination of GIS, Geostatistic and Remote Sensing Methods for the Evaluation of Groundwater Potentiality of Ziz Basin at Tafilalet, Morocco

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Abstract: The aim of this study repose on the computation of digital, spatial and time related data encompassing all relevant information related to the management of groundwater resources in Ziz-basin (Tafilalet/Morocco). This approach leads to the elaboration of five basic spatial documents in Raster and vector format. As meta-information, we have computed maps dealing with the quality of estimation. This spatial methodology required some deterministic and probabilistic approaches and the recourse to different statistical methods (multiple regression, principal components analysis). The combination of Geographical Information Systems (GIS), Geostatistic and the Remote Sensing (RS) represents an original contribution. This information system provides engineers and managers with analytical tools and decision-making assistance in term of planning.

Keywords GIS; Groundwater; Ziz-basin.

Introduction

Due to its orographic position and its geographic location, the South-Eastern of Morocco suffers both from the weakness of rainfall contributions and from the severity of dry Saharan influences. Indeed, the atlantic and mediterranean air masses, which convey precipitation that have already lost their importance while crossing the atlasic-rifain barrier before arriving in expansion in this back country, which is generally a steppe area. They undergo new forced ascent only on some high and suitably exposed and aligned massifs. The decrease of rainfall quantity from the North southward and from west eastward is so stressed by the configuration of the relief imposed by the Rif - Middle Atlas - High Atlas barrier.

This situation is furthermore complicated by the seasonal and inter annual climatic irregularity. Several dry years can alternate with few relatively wet years. This climatic variability in intensity and frequency make dry periods succeed wet ones which influence, more or less directly the availability of water resources. During the last decades, the periods of strong drought have become strikingly more frequent. Therefore, the behaviour of groundwater, the regime of certain sources, and the river runoff are subject to important variability.

Except in periods of flood, the main part of the current available water is provided by the runoff and the underflow of the main rivers and their tributaries, which are fed by sources.

Most of these water resources are resurgences of water tables overflow. Actually, feeder and communication between these subterranean reservoirs are unknown in most cases. The traditional economy of these regions is generally based on agro-pastoral activities which are extensive in rural areas and intensive in oasian environment. The traditional agro-pastoral activities were strictly bound by water availability. Dry farming (*bour*) is often unpredictable. The irrigated cultures exploited stream water and sources gushing on slopes at the piedmont of permeable reliefs. Subterranean water was exploited for irrigation by means of digging *khettara*s (subterranean channels draining perched water tables) and of wells using *oughrour* or s*haduf*.

Besides, the Hassan Addakhil dam was completed in 1971 on Oued Ziz, upstream of Errachidia, but without the creation of a new irrigated perimeter. Nevertheless, the old palm groves of Tafilalet located downstream benefit from it by regular releases of water, thus protecting cultures against devastating floods and feeding underflows which constitute the main exploited water table.

During the 1980s, the ancestral technique of construction of small dams on valleys increased with establishment of a government program. These small traditional seasonal reservoirs known under various names proliferated under the name of " *Barrages collinaires*" ("Hill dams"). They are sometimes really small low cost dams which provide some water for livestock and breeders, and even for irrigation. They also play a role in keeping back sediments, reducing thus silting up of great dams situated downstream; they also keep feeding local water tables. Besides, they engender microclimates around their small lakes which stretch according to rainfall.

In Tafilalet, another meaningful case is represented by the Todgha-Ferkla basin, where the available water is essentially conveyed by a little deep alluvial water table. The regime of piezometric level fluctuations is function of contributions of rivers and overflowing sources to runoff and underflow, besides rainfall and pumping intensity. The measurements of fluctuation and the observed facts are sometimes alarming, not only at the quantitative level, but also on the qualitative level because of presence of sectors with high risk of salinity.

Methodology

The methodology followed include: (a) Digital database; (b) image analysis of Spot data; (c) image analysis of ERS SAR sensors; (d) extraction of backscattering coefficient from SAR images and relations with ground parameters and analysis of temporal evolution; (e) experimental ground campaign in Moroccan case study test-site campaign in order to follow the used methodology and better understand the typology of data needed by the hydrological models; and (f) simulation of hydrological model.

Results

To find out the most realistic groundwater potentiality map of studied area, the relevant layers which include slope, lineament, drainage, hydrogeological parameters and precipitation were integrated in ArcInfo grid environment (Fig. 1 to 7). Criteria for Geographical Information Systems (GIS) analysis have been defined on the basis of groundwater conditions and appropriate weightage has been assigned to each layer information according to relative contribution towards the desired output. The simulation of a rain event is ensured by means of an interactive menu from which the user chooses initially the construction of the input files to the model in an automatic manner from database managed under ArcView GIS files, and to run the model. The visualization of the results is ensured through ArcView GIS. The map of groundwater potential zone generated through this model was verified with the yield data to ascertain the validity of the developed model. The verification showed that groundwater potential zones demarcated through the model are in agreement with the hydrogeological wells data. Since in the present approach was built with logical conditions and reasoning, this approach can be successfully used elsewhere with appropriate modifications. Thus, above study has clearly demonstrated the capabilities of GIS, Geostatistic and Remote sensing technique in demarcation of different groundwater potential zones.

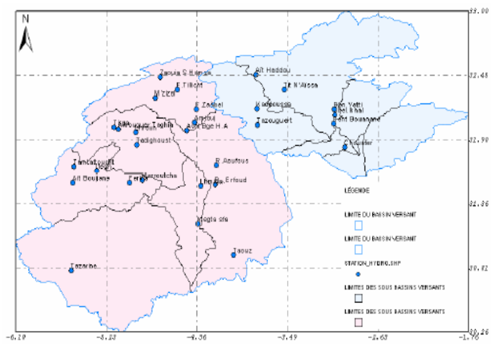

Figure 1 Map of hydrological monitoring network in Ziz Basin.

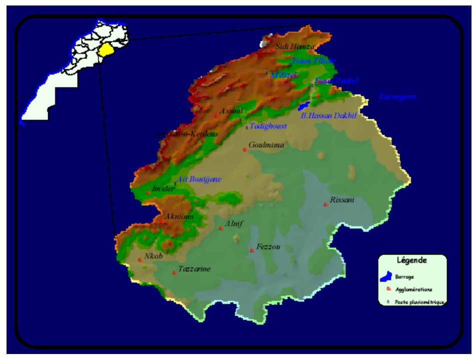

Figure 2 Field digital model and digital modelisation.

Remote sensing offers potential means to monitor much large areas than ground survey and aid in targeting key ground observations. Furthermore environmental management problems are all concerned with spatially distributed phenomena. Benefits of the functions of GIS include visualization, decision making, organize combine and analyze data as well as to make predictions and to derive new data from existing data in order to provide answers.

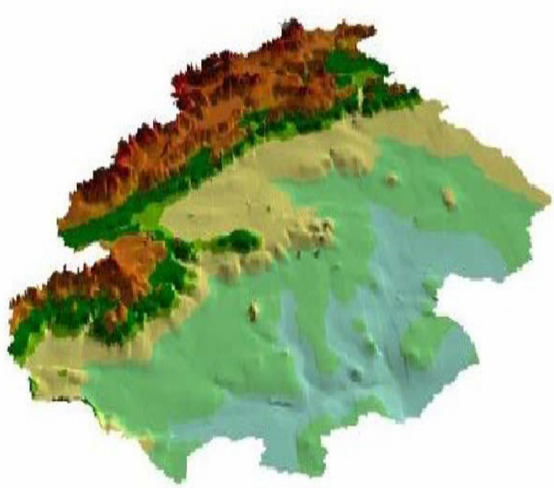

Figure 3 Generation of physical characteristics of Ziz Basin in digital model.

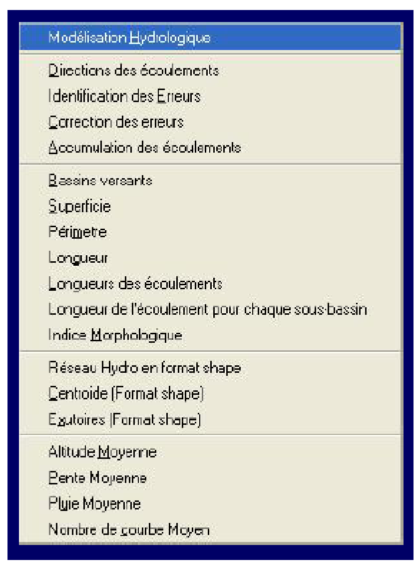

Figure 4 ArcView GIS charateristics used as GIS interface in hydrological modelisation.

Conclusion

The combination of GIS, Geostatistic and the Remote Sensing (RS) represents an original contribution. This information system provides engineers and managers with analytical tools and decision-making assistance in term of planning. Since in the present approach was built with logical conditions and reasoning, this approach can be successfully used elsewhere with appropriate modifications. Thus, above study has clearly demonstrated the capabilities of GIS, Geostatistic and Remote sensing technique in demarcation of different groundwater potential zones.

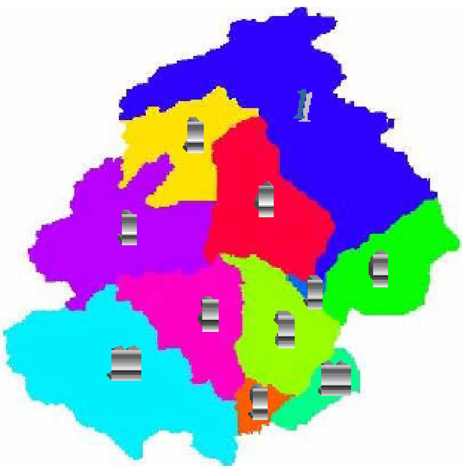

Figure 5 Ziz sub-Basins in Raster format.

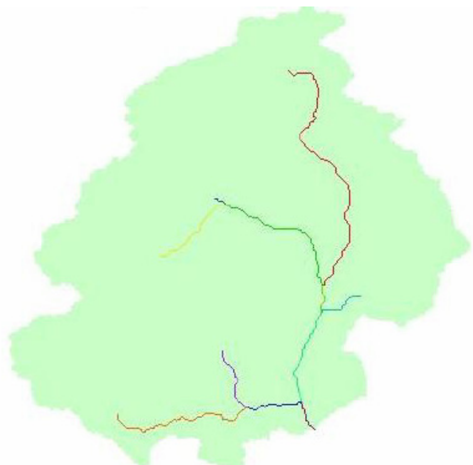

Figure 6 Hydrographic map in Raster format.

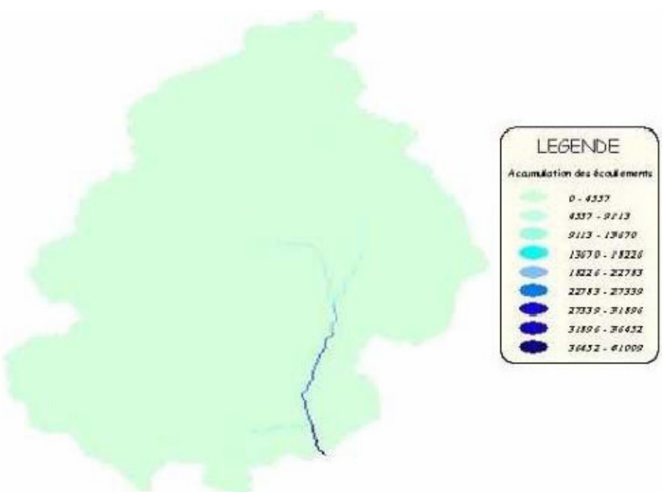

Figure 7 Digital model of accumulated-flow in Ziz basin.

Renovation of Khettaras in Tafilalet, Morocco

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Abstract: This paper describes the research and action under taken by a Moroccan research consortium that conducted a wide study of Khettaras in the region of Tafilalet (South-East of Moroco) recognised by UNESCO as Biosphere Reserve in 2000. Within the framework of the Foggara and Shaduf projects (INCO-MED/ CE) on traditional water management, some of the most important Khettaras sites were re-visited in 2003, 2004 and 2005. The research project described in this paper looks at the use and values of a potentially sustainable Khettara system in a changing modern environment.

Keywords Khettara; Renovation; Tafilalet; Ziz basin.

Introduction

In Tafilalet, many ancient Khettara irrigation systems have been abandoned due to falling water tables as a result of drought and the increased use of modern electric and diesel-pumped wells. In this stydy, we documented geographical, socio-economic, and hydrological characteristics and interviewed local experts and officials from various institutions. We found a total of 570 khettaras of which 304 were still in active use. Others were dry or drizzling and almost abandoned.

History of Khettara

An impressive 300 km network of khettara was excavated in the Tafilalet basin beginning in the late 14th century (Figuer 1). Some of these tap into the aquifer at the base of mountains along the western margin of the oasis (Figure 2). Others exploit the shallow water tables adjacent to major stream channels which pass through the basin. Eighty of these chains provided perennial water for 28 qsour (villages; sing. qsar) in the northern part of the oasis. The qsour and khettara simultaneously developed following the breakup of Sijilmassa (Lightfoot and Miller, 1996). Qsour in the central and southern oasis-where the water table was and is much deeper-continued to rely on the same sources of water (wells and surface canals) for irrigation and drinking water that sustained Sijilmassa.

It is possible that khettara first came to Morocco from the Middle East following the Islamic revolution; the pattern of diffusion closely follows the historic dispersal of Islam. However, it is not certain if this technology was introduced by Muslims first to Morocco and later to Islamic Spain, or whether it first swept into Islamic Spain from North Africa, and then diffused back into Morocco. It appears that qanat technology had earlier diffused to

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Roman Spain from the Near East where the Romans, presumably borrowing Persian technology, had built and used qanats in Jordan and Syria, so there could have been an Iberian precedent to Morocco's filtration gallery systems.

Figure 1 Khettaras systems in the Tafilalet (Morocco) / www.waterhistory.org

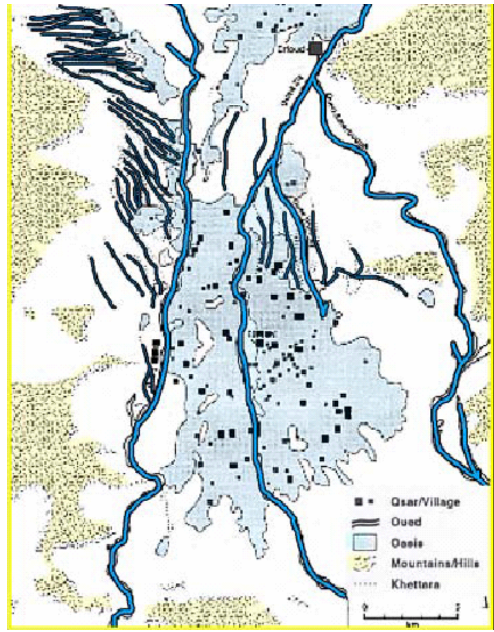

Figure 2 Oasis of Tafilalet - Ziz basin / www.libro.uca.edu

The Moroccan hearth for khettara was the Haouz Plain around Marrakech, where khettara were being built by the early 12th century, followed by the Sous Valley of southern Morocco (Joffe, 1992). Although the technology was surely known in Sijilmassa by at least this time (if not earlier), khettara did not appear in the Tafilalet until late in the 14th century, shortly after the fall of Sijilmassa (Lightfoot and Miller, 1996). Fourteen medieval accounts of substantive interest - dating from the 9th-14th centuries - describe Sijilmassa and its environs, yet make no mention of khettara in this area, and most Tafilalet khettara irrigated agricultural fields which lay outside of the original Sijilmassa-era fields. Tafilalet khettara are closely associated with post-Sijilmassa qsour, which were only built after the fall of the city as its inhabitants divided along family/clan lines and dispersed across the oasis (Lightfoot and Miller, 1996). It is possible that the adoption of this new water technology even facilitated the disintegration of Sijilmassa or, at least, made the devolution from central city to dispersed villages both thinkable and achievable for the northern Tafilalet. Khettara technology accords well with the layout of scattered qsour, each with its ruling lineages and mechanisms for organizing labor at a more localized level (Lightfoot and Miller, 1996). Many of the khettara are flamed after the qsour which built and used them. Many more are named after Alouite kings who ruled the Tafilalet after the fall of Sijilmassa. Therefore, networks of dispersed villages with associated khettara appear to have emerged in the Tafilalet in the late 14th through the 16th centuries; a few of the Sifa district (northwest Tafilalet) khettara being originally constructed as late as the 1730s (Margat, 1961).

Khettara continued to provide the only reliable irrigation water for north Tafilalet qsour until the early 1970s, when new technologies and government policies forced changes in traditional water management. Insufficient water (from the dam) and non-sustainable methods of groundwater use (overuse of diesel pumps) have, since the early 1970s, resulted in a dramatic lowering of the water table underlying the oasis. These modern water technologies, because they are proffered and subsidized by the government, continue to replace the few remaining khettara, which are abandoned as the water table drops.

Renovation of Khettara

Traditionally, Khettaras should be cleaned on a regular basis to prevent silting, collapsing and disfunctioning. It helps in keeping the Khettara flowing even in dry seasons. But as soon as Khettaras are giving less water, young people loose interest and start looking for revenues in off-farm work. The urban environment is financially much more attractive than traditional Khettara farming. This group of youngsters literally abandons Khettaras. With the abandonment of Khettaras the indigenous knowledge and community co-operation critical for Khettaras upkeep also disappears and more Khettaras collapse or dry up. A vicious circle is complete. As a result a valuable cultural heritage is vanishing. Not only are Khettaras relics of a prosperous past, but alsosustainable and environmentally friendly systems of extracting groundwater.

Constraints of geography have allowed only 28 of the 132 qsour of the Tafilalet to construct and utilize khettara. For these qsour khettara became essential to their survival. Qsour and khettara have functioned symbiotically. With one exception, all qsour with khettara are in the north of the Tafilalet, where the water table has always been most shallow, and khettara mother wells did not have to be sunk into the basin alluvium more than a few meters. Khettara are employed either as primary irrigation sources or at least to supplement the water from mechanized wells and government canals. Qsour which used to operate khettara have abandoned theirs only because "the water has gone dry". Usually this means that water no longer flows through the khettara because the water table has dropped, but it may also mean that an earthquake or flood has damaged the subterranean conduit, or the tunnel has collapsed, or side walls have blown out into a neighboring tunnel as the result of dynamite (occasionally) used during cleaning operations.

The competition between traditional and modern water systems is both environmental and cultural. Environmentally, diesel-pumped wells and government canals have led to the abandonment of a sustainable technology in favor of systems which are capable of providing greater quantities of water but are not sustainable. Culturally, the adoption of newer technologies has led to the abandonment of traditional technologies like khettara, altering the land use patterns which evolved through the historic reliance of villages on khettara. There has been some loss of local control over water resources, because much of the water villages need comes only from the Errachidia reservoir and drinking water pipes, both regulated by the government. Khettara are qsour operated and collectively maintained, and intricate relationships have evolved to manage them and distribute their benefits according to each shareholder's inputs of land, labor, tools, and money. Diesel-pumped wells are often privately owned and, as a result, the traditional ties that bind village society are breaking down. Non-farm sources of income continue to draw young men away from villages and out of the oasis, disrupting the social organization of khettara systems. Furthermore, the traditional source of wealth in the oasis, trade in dates, has been irreparably altered. Only 60% of the palm trees in the Tafilalet still produce a date crop today. The others no longer produce dates or have died as a result of periodic date blight and/or sustained desiccation.

There were originally 80 khettara in a 300 km network providing water for 28 qsour in the northern Tafilalet. Today there are only 19 khettara in a 90 km network watering 12 qsour (possibly as many as 36 khettara for 16 qsour, if all of the galleries between Sifa district and Jorf in the northwest Tafilalet, active in 1970, were still active; a few of these still flow, but some are now dry, and the status of each of these 17 khettara between Sifa and Jorf is not known). All 80 khettara originally irrigated about 3000 ha of the Tafilalet oasis. This is about 14% of the potentially arable land in the Tafilalet, and about 20% of the roughly 14,000 ha actually farmed at any time.

The last of the khettara will dry up in the near future, as the water table becomes so deep that "following the water" by extending the depth of mother wells would necessitate the excavation of new horizontal shafts; in essence, excavating new khettara from source to terminus, parallel to the old galleries but at greater depth. This would prove prohibitively labor-intensive and expensive.

Conclusion

In Tafilalet, we have seen that combining ancient qanats and modern drip irrigation systems for fruit trees might prolong the life of some Khettaras and encourage younger generations to commit to their upkeep. Another option to think of is to encourage eco-tourism based around Khettaras to provide alternative income for the farmers. The water of Tafilalet Khettaras is used mainly for irrigation since the date they were dug. The division of the water is based on a local system of rights and regulations. Successful renovation of Khettaras in Tafilalet is technically possible but thorough social and hydrological assessment is required in advance of renovation.

The project followed an integrated holistic approach led by the priorities and needs of the community. The anthropological action research was supported by other disciplines such as hydrogeology, agronomy and Modelisation. An interdisciplinary team of scientists of both social and bio-physical disciplines thus collected data on various topics. In general the data collection can be divided into a social focus and a technical focus.

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Airs, Waters, and Places in the Work of Xenophon of Athens

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Abstract: In the *Cyropaedia* (I,VI,6), one of the major work composed by Xenophon of Athens, Cambyses explains how the body of the residents of a place demonstrates the environmental health or the unhealthiness of an area. By its style and its content, this reminds us of the treatise *On Airs, Waters and Places* attributed to Hippocrates. This paper describes the relationship between health, the biotope (including water, climate and topography), and food (including water), as presented by Xenophon. The way this author perceives the links between the biotope and health, or the physical shape of the inhabitants, has a major impact on his perception of foreigners. Like Hippocrates and Herodotus, Xenophon correlates physical and moral characteristics with certain geographical situations, and he classifies the world's regions according to their habitability. Xenophon departs from his predecessors in two detailed site descriptions, where he describes an ecosystem and discerns the concept of biotope. This notion is even reflected in his descriptions of Persian Paradises: Game parks dedicated to Anahita, the Persian goddess of water. Water played an essential role in Xenophon's estate at Scillus.

Keywords Environment; paradise; water; Xenophon.

Loan or Common Place?

This paper looks at the concept of natural environment as depicted in the work of Xenophon of Athens, an author who lived between 431 and 355 B.C. In the *Cyropaedia*, a romanced biography of Cyrus the Elder who was king of Persia between 550 and 530 B.C., King Cambyses explains how the body of its inhabitants shows the wholesomeness or the unwholesomeness of the place where they live:

> *If you are getting ready to stay long in one place, first you must not neglect the healthy condition of your camp, and if you give your mind to the matter you can hardly fail to find it. Men, we know, are forever discussing what places are healthy and what are not, and their own complexions and the state of their own bodies is the clearest evidence. But you will not content yourself with choosing a site, you will remember the care you take yourself for your own health* (Cyropaedia I,VI,16-17).

The passage is reminiscent, by its general content of *On Airs, Water and Places*, a treatise attributed to Hippocrates. This work presents a theory in which the physical environment determines the health of the inhabitants of a region. Since it has already been studied by a number of authors, as our bibliography shows, we will not consider that treatise in detail, but it might be useful to draw its broad lines. The treatise is composed in two parts of equal length: in the first part the author develops a general theory of the influence of the environment on humans, and in the second part he presents some concrete examples taken from Europe and Asia. The date of composition is uncertain. Hippocrates himself might be the author, but the texts of the Hippocratic corpus are actually the creation of many authors who lived between 450 and 350 B.C. On the other hand, the expression used by Xenophon, "Men, we know, are forever discussing what places are healthy and what are not", might indicate that the association between health and the wholesomeness of a place was a notion that was commonly employed. The presence of this utterance in Xenophon might indicate one of two things: either the author of the *Cyropaedia* knew the Hippocratic treatise, or the general content of the treatise was known by the educated public. Now, it has been shown that the Hippocratic treatise demonstrates a real knowledge of two essential geographic concepts: the climate and the environment (Staszak, 1995: 13-14). This observation gets its importance from the fact that these two notions are absent from later authors like Aristotle, even in his *Meteorologica* (Staszak, 1995: 13).

Xenophon is neither a physician nor a geographer, and even if he knew these theories, he doesn't expound on them in his writing. Therefore, their presence can only be detected by reading between the lines, since Xenophon is writing with totally different goals in mind. The theme of the influence of the environment on health is obviously present, but using a commonplace does not presuppose any real knowledge linked with that particular expression. One can repeat that "all is relative" without possessing any knowledge of the theory of general relativity. There is a real possibility that Xenophon knew the Hippocratic corpus. He was among the few Athenians who had a library[1], and he states in the *Memorabilia* that: "there are many texts written by physicians"[2]. We know that he was interested in medicine, and we find allusions to hygiene and health in many of his works[3].

The Centre of the World

Apart from his interest in medicine, Xenophon's concern for geography is less noticeable. In addition to the passage already cited, another one refers to the influence of the geographic setting on quality of life. In this excerpt, Xenophon classifies some regions according to their habitability:

> *From that moment, his empire was limited on the east by the Red Sea (the Indian Ocean), on the north by the Pontos Euxinos (the Black Sea), where the sun sets by Cyprus and Egypt, on the south by Ethiopia. The extremes of these regions are uninhabitable either because of heat, or because of the cold, or because of too much water or because of too little of it. Cyrus himself made his residence in the centre of these countries* (Cyropaedia VIII,6,21-22).

This distribution of habitable lands in the center of a world whose boundaries are uninhabitable because of climatic conditions bears a strong resemblance to paragraph XII of *On Airs, Waters, and Places*. Again, this idea could be a commonplace. The belief that heat increases constantly towards the south and that cold increases in the north is widespread in

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1 Delebecque (1957: 308 and 241); Pomeroy (1994: 215).

2 IV,2,10: πολλά γαρ και ιατρών εστί συγγράματα.

3 For example, in the *Oeconomicus*, Ischomachus discusses the care of the body and the importance of exercise, both for him and his wife (XI,11-18; X,9-13); adding that Cyrus the Elder would not eat unless he did strenuous exercise beforehand (IV,24, and in the *Cyropaedia* VIII,1,38). In the *Cyropaedia* (I,2,16 and VIII,8,11), Xenophon describe how the Persians eliminate liquid bodily waste by exercising. He also talks about the dangers of heavy wine drinking for health (I,3,10 and VIII,8,11). A passage from the *Memorabilia* (IV,2,31) establishes that the causes of disease resides in drinks, food and occupations (επιτηδεύματα). Finally, Xenophon records that Cyrus established a free health care system (*Cyropaedia* VIII,2,24).

Antiquity, notably in Herodotus[4] and Anaximander[5]. In our case, the theory that some places are more wholesome than others is applied by the aging Cyrus when he chooses his residence. The Greek word that I translate by ‘residence’ (η δίαιτα) has a strong medical connotation. This word describes a way of life that is wholesome[6]. Therefore, Xenophon justifies Cyrus’s decision to live in the middle of his empire for sanitary, rather than political, reasons.

This preamble allows us to draw three conclusions: Xenophon knew some of the theories related to environmental determinism; he knew some of the writings published by physicians; and he was interested in health and healthy practices. These three points are important when one considers the fact that Xenophon had traveled a lot and that he had visited some far away places unknown to the average Greek. His own experience allowed him to make a number of observations related to the effects of climate, water and physical setting on the inhabitants of a place. The *Anabasis* relates the long expedition in Asia Minor undertaken by Xenophon and a group of about ten thousand Greek mercenaries. This incursion in Asia and the safe return of most of the men made a vivid impression on Athenians. Xenophon’s narrative nourished Greek propaganda and was used to validate panhellenism, a doctrine put forward by the orator Isocrates[7]. This idea is partly rooted in the theory of environmental determinism as it is presented in *On Airs, Waters, and Places*. According to supporters of panhellenism, inhabitants of a land are a reflection of their environment. Consequently, the areas offering the best combination of climate and physical environment will engender the best individuals, and, since these individuals are naturally superior, they will naturally dominate the entire inhabited world.

Rivers and the Environment

The word ‘environment’ can be defined as “the surroundings within which man, animals and plants live” (Witherick, 1995: 80), and with which they “are constantly exchanging matter and energy” (George, 1993: 295). Xenophon alludes to that concept when he refers to places that are healthy or unhealthy. The word translated ‘place’, χωριόν, has a connotation wide enough to include this meaning (properly speaking, this substantive refers to any area or any geometrically define space), without being limited to it. Even a quick survey shows that most landscape descriptions in Xenophon are circumstantial and adapted to the need of the moment, which is itself dictated by the narrative. This is especially true in the case of rivers, as it has been shown (Basley, 1995: 84-85), since most rivers are presented only as obstacles to cross and have little interest on their own. Consider the following example:

> *Thus Cyrus, with the troops which I have named, set out from Sardis, and marched on and on through Lydia three stages, a distance of two-and-twenty parasangs, to the river Meander. That river is two hundred feet broad, and was spanned by a bridge consisting of seven boats* (Anabasis I, 2, 5).

Real geographical descriptions are rare, but not totally absent, especially in the Anabasis (I,II,22; I,V,1-2). Even when the author describes animals and their environment, the description remains on an anecdotal level. His primary aim is to reflect the exotic nature of the place he is visiting.

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[4] Cf. Hartog (1980: 33).
[5] Cf. *Memorabilia* I,1,11-14.
[6] Cf. *Memorabilia* III,14,7; I,3,3: *Cyropaedia* I,3,2.
[7] Isocrates had the *Anabasis* in mind when he said that the Greeks who went on the expedition against the Great King “came back more safely than ambassadors who went to him as friends” (*Panegyricus* 149). Cf. Laforse (2000).

In Search for a Living Space

Xenophon begins his treatise entitled *The Ways and Means* (I,1-3) by explaining how Attica can live in an autarchy. In order to show that the country is capable of creating an income, Xenophon describes the nature of Attica (την φύσιν της Αττικής). By the word "physis", Xenophon refers to the geographical and geological nature, and he provides an inventory of its natural and physical features. His demonstration is articulated around economic and political considerations. He begins by noticing that the climate (or rather the seasons: τάς ώρας) is temperate. He adds that the crops are a proof of this, since plants that could not survive elsewhere live in Athens. After this, he explains that the mineral resources are plentiful. Finally, he discusses the geographical position of Athens in relation to the rest of the world:

> *Indeed it would be scarcely irrational to maintain that the city of Athens lies at the centre of Hellas, and even of the habitable world. So true is it, that the farther we remove from Athens the greater the extreme of heat or cold to be encountered; and if one desires to traverse the confines of Hellas from end to end, he will find that, whether he voyages by sea or by land, he is describing a circle, the centre of which is Athens* (Ways and Means I, 6-7).

This description is reminiscent of the Hippocratic treaty and the passage from the *Cyropaedia* (VIII,6,21-22) mentioned earlier. No information on the health of the Athenians is inferred from Attica's privileged situation. At the most we can conclude that Attica is more comfortable than the rest of the inhabited world - the *oikoumene*. This inhabited world actually represents the whole of the inhabitable world, since as one leaves the centre the heat or the cold become intolerable. By a symmetrical effect, the climate of Athens becomes the point of equilibrium between these two extremes. With this claim, Xenophon answers aesthetic considerations, since a rational world is symmetrical for him. Finally, all the winds serve Athens by helping in the importing and exporting of goods. Nevertheless his whole description is geographic, even if some key elements, like the inhabitants and their way of life, are missing. In omitting these elements, the passage does not imply that the climate of Attica produces healthier inhabitants. It is just that the author is mostly preoccupied by geopolitics. His description of the environment aims at evaluating the economic and strategic potential of Attica. Xenophon sometimes has the eye of a colonist who assesses an area according to its potential as a place of residence. This is shown clearly in one of his most complete descriptions:

> *The place which goes by the name of Calpe Haven is in Asiatic Thrace, the name given to a region extending from the mouth of the Euxine all the way to Heraclea, which lies on the right hand as you sail into the Euxine .... Now the haven of Calpe lies exactly midway, halving the voyage between Byzantium and Heraclea. It is a long promontory running out into the sea; the seaward portion being a rocky precipice, at no point less than twenty fathoms high; but on the landward side there is a neck about four plethra wide; and the space inside the neck is capable of accommodating ten thousand inhabitants, and there is a haven immediately under the crag with a beach facing the west. Then there is a copious spring of fresh water flowing on the very border of the sea commanded by the stronghold. Again, there is plenty of wood of various sorts; but most plentiful of all, fine shipbuilding timber down to the very edge of the sea. The upland stretches into the heart of the country for twenty furlongs at least. It is good loamy soil, free from stones. For a still greater distance the seaboard is thickly grown with large timber trees of every description. The surrounding country is beautiful and spacious, containing numerous well-populated villages. The soil produces barley and wheat, and pulse of all sorts, millet and sesame,*

figs in ample supply, with numerous vines producing sweet wines, and indeed everything else except olive trees (Anabasis, VI, 4,1-6).

This time, the awareness of geography is certain. The place is first located at the scale of the continent: Calpe is on Asiatic Thrace. The focus then moves to the regional position of Calpe, between two Greek cities: Byzantium and Heraclea. The place is economically promising. The isthmus possesses a military and strategic value, its narrowness making it defendable by the population that it shelters. A large spring and fertile ground provide a stable supply. This spring is situated on a beach facing west, a position that would have worried a reader of *On Airs, Waters, and Places,* since a spring facing west is supposedly less suitable for consumption[8]. Now, the description of Calpe Haven is primarily a text of propaganda designed to convince the Greeks that it is a good place to establish a colony (Delebecque, 1957: 100-104). Nevertheless, this text shows that Xenophon can evaluate the ability of an environment to sustain life.

The Nourishing Earth

The main problem at Calpe Haven concerns water and food supply. Xenophon, who knew very well the logistical problems than an army might encounter, also knew about the side effects of a diet that is too generous (*Anabasis* V,4,32), or scarce (*Anabasis* IV,5,7-9), as well as the dangerous effect of local food in some regions (first the Greeks eat dates that give them terrible headaches in *Anabasis* II,3,16, and later some eat maddening honey in *Anabasis* IV,8,20)[9]. These are examples of environmental hazards, but to find an example where Xenophon demonstrates a real awareness of the impact of the environment on living organisms, we must turn our attention to an artificial environment described many times in Xenophon's work:

"Children, how we were playing like fools when we were hunting game in the Paradise! It seems that it was like hunting animals that were tied up. First we were in a very small area and then the beasts were miserable and scabby, one was limping and the other mutilated. But on the contrary, the beasts from the mountains and the plains how they seem beautiful tall and fatty" (Cyropaedia I,4,11).

Xenophon is describing how animals living in a Persian 'Paradise' are physically inferior to animals found in the wild. Even if they are imperfect as living environments, these Paradises left a strong impression on Xenophon when he travelled through Asia Minor. Xenophon liked this type of garden so much that he introduced it to Greece under its Hellenized Persian name, ο παράδεισος: an adaptation of the Ancient Persian word meaning 'surrounded by walls'[10]. He described some of these Paradises in the *Anabasis* (I,2,7; I,4,10; II,4,14;16), the *Cyropaedia* (I,3,14; I,4,5; I,4,11; VIII,1,38; VIII,6,12), the *Oeconomicus* (IV,13; IV,20-25), and the *Hellenica* (IV,1,15-16)[11].

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8 *On Airs, Waters, and Places* V,1. Direct allusions to meteorology are rare in Xenophon. In the *Cynegeticus* (V,3) he refers to winds that eliminate the smell of animals, or the effect of the moon on their tracks (V,4).

9 *Cf.* L'Allier (2001: 110); *cf.* Dioscorides *Materia Medica*, II,82.

10 *Cf.* Kent (1950: 191 and 195). The Old Persian *paradayadam* 'pleasant retreat' stands for *paridaidam* (Avestic *pairidaeza*) 'circled by walls'; the word is composed of *pairiy* 'around' (*cf.* Greek περί and Sanskrit *pári*) and *daeza* 'wall' (*cf.* Greek τείχος and Sanskrit *dehí*). *Cf.* also Chantraine (1968) under παράδεισος and Moynihan (1979: 1): "Cyrus called his garden a pairidaeza, which is a simple combination of *pairi* (around) and *daeza* (wall)"; *cf.* S. E. Hirsh (1985: 152, note 11).

11 P. Grimal (1969) asserts that that type of land use was not known in Greece before Xenophon and it is through his writings that the concept was popularised in Greece proper; see also Moynihan (1979).

We can imagine roughly the Paradises that Xenophon saw: they were basically parks or gardens, designed according to a regular plan[12], fenced[13], and crossed by alleys of trees and trails where horses could run without endangering their riders[14]. The game that lived in these parks was captured in the wild and then released inside the Paradises for the hunt[15]. Always close to a river, the Paradises were suited both to relaxation and exercise. I have shown elsewhere that, in addition to introducing the word in Greece, Xenophon tried to reproduce that type of landscaping on his own estate of Skillus, near Olympia[16]. He describes this estate in an important passage of the *Anabasis* (V,3,7-12):

> *....7. Taking (that money) Xenophon bought for the goddess a plot of ground at a point indicated to him by the god. 8. It happened that the river Selinus was flowing through the plot, just as at Ephesus the river Selinus flows past the temple of Artemis. In both rivers, fish and mussels are to be found; but on the estate at Skillus there is also hunting of all sorts of wild beasts... 10.....And boars, gazelles and stags were captured partly from the sacred land itself, partly from the Pholoe. 11.....And within the sacred land there is a meadow and wood-covered hills suited for the breeding of pigs, goats, cattle and horses... 12. Around the temple itself, a sacred grove17 of cultivated trees was planted, yielding fruits in their season. The temple looks like the temple at Ephesus as much as the small may look like the big, and the wooden statue looks like the one at Ephesus as much as cypress wood may look like gold.*

The thoroughness of his description is motivated by the fact that this is an artificial landscape, unseen before in Greece. Moreover, if one reads the description carefully, one finds an almost complete ecosystem: a river, some open and wooded land, and a mountain, all designed to allow wild and domestic animals to live freely. The absence of a fence allows for the necessary space that was lacking in Persian Paradises[18].

The Goddess of Paradise

The Persian gardens were, for the adepts of Mazdeism, sanctuaries dedicated to the Goddess Anaïta (or Anaïtis)[19]. In the *Avesta*, Anaïta, a goddess of the sacred waters and sap, received from Ahuramazda the responsibility of guarding the creation, and ensuring the fecundity of the cattle and all living beings[20]. She helped women to give birth and bestowed on all females timely milk. Originally she was a Babylonian goddess[21] corresponding to the goddess Inanna of the Sumerians. The association between Anaïtis and the Persian Paradises is shown by the trilingual text of a dedication offered to Anaïta and the gods Ahuramazda and Mithra for the inauguration of a palace located in a Paradise near Susa[22]. The Ephesian

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[12] According to Pomeroy (1994: 252) the quincuncial pattern of the paradises represents the ideal of order that Xenophon wants to see in his house.

[13] The walls were used to delimit and to accentuate the geometric shapes of the park. When there were wild animals in the park, the walls were essential. Remains from the VII[th] century C.E. of a fenced park of large dimensions (122 ha) can be seen at Qasr-i-Shirim, Zagros (Moynihan, 1979: 36).

[14] In the *Cyropaedia* (I,4,7-8), the experienced hunters that are with Cyrus pretend that the chase in a natural habitat is more dangerous than the chase in a Paradise.

[15] *Cyropaedia* I,3,14.

[16] L'Allier (1998). This article offers a more complete treatment of the nature of the sanctuary and the goddess Artemis-Anahïtis.

[17] Λειμών. Motte (1973: 6).

[18] L'Allier (1998: 5-6).

[19] Moynihan (1979, 19). Same in Hirsh (1985: 13).

[20] Nyaish 4.1-4.2. *Cf.* Maneckji (1965).

[21] *Cf.* Benveniste (1929: 38-39).

[22] *Cf.* Kent (1950: 154-155), inscription A^2Sd. Artaxerxes II ruled from 404 to 358, he was the opponent of the Ten Thousand.

Artemis is depicted in sculpture and coinage as a Mistress of animals, bearing among her attributes the deer, the lion and marine animals[23]. She symbolises on the one hand fecundity, as shown by the ritual breast-plate that her statue is wearing[24], but she also dominates the animal world[25].

The Twin Rivers

We saw that rivers had little practical interest, but we will see that they can have a strong ideological value. The construction of Xenophon's park followed a very precise plan[26]. He reminds us that a river flows through his land and that it is called the Selinus, just like the Selinus of Ephesus. We have already mentioned the importance of water in the religion of Ahuramazda, and the fact that the two rivers share the same name is noteworthy. The two places are indeed quite similar. Both rivers end on a low coastline with mountains in the background. The river is actually the connecting link between the two sites and the estate of Skillus could mimic the sanctuary of Ephesus precisely because of the exact correspondence between the two rivers and their symbolic nature. Once that first parallel had been established, Xenophon could complete it with a temple and a statue[27].

The importance of the river is emphasized by the fact that the passage where Xenophon writes about the estate of Skillus is one of the very few occasions where he mentions the presence of live fish (the other cases are precisely linked to a religious context or to a Paradise). It is also the only instance where he mentions the presence of mussels[28]. Moreover, water, fishes, and aquatic birds are important to the followers of the goddess Anaïtis[29]. The choice of the exact location or, as Xenophon says, the "point indicated to him by the god" was determined by the presence of water and the similarities between the two rivers. Not only does this illustrate the importance of water in the worship of the Ephesian Artemis, but it shows that water was essential and not merely desirable.

Conclusion

Geography and especially the description of bodies of water had only a secondary place in the work of Xenophon; when rivers are present, they are used to answer practical needs or described as obstacles as in the *Anabasis*. The author provides a more complete description of an environment only when he is directly involved, first when he describes the Haven of

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[23] *Cf.* Fleischer (1973).

[24] The statues of the Ephesian Artemis bear a number of bumps on the abdomen that were taken as breasts. Those protuberances were obviously part of a breast-plate that the statue was wearing (*cf.* Picard, 1922). The protuberances were afterward thought to be ostrich eggs offered to the goddess (*cf.* Picard, 1962). A more recent interpretation sees a ritual breast-plate covered with bull testicles whose power of procreation was offered in sacrifice (Seiterle, 1979).

[25] The oldest representations of Artemis show her flanked by two animals (either birds, deer, or lions) in a submissive position, *cf.* Le Lasseur (1919: 176-185).

[26] Cf. L'Allier (1998). For the location of Skillus, *cf.* Delebecque (1955).

[27] The description of Xenophon's estate is in book V,3 of the *Anabasis*. Azoulay (2004: 198-201) showed that the position of this description within the *Anabasis* can be explained by Xenophon's desire to tell the reader how the estate had been paid with the war booty left in Ephesus, and not with money that he earned as a mercenary. This being said, I disagree with Azoulay when he implies that nothing can be learned about the estate itself (199: 139).

[28] Fishes are mentioned in the *Anabasis* I,4,9, where they are domesticated sacred animals, and in the *Hellenica* IV,1,16, in the paradise of Pharnabazus; a final reference occurs is in the *Cyropaedia* VIII,2,6, where fishes are to be eaten.

[29] *C.f.* Boyce (1982: 202) and Moynihan (1979 : 35). Fishes, water and mussels are also linked to Artemis; Picard (1922: 378-379) sees a link with the Great-Mother of Asia.

Calpe and then when he describes his own estate. These two cases are the only ones where he pays attention to the beneficial presence of water, the first as a spring of potable water and in the second as a river having onomastic (the two Selinus), geographical (same landscape), ecological (in both rivers, fish and mussels are to be found), and religious (one river flows by the temple of Ephesus, the other by Xenophon's temple) parallels with the river of Ephesus. In the last case, for religious and pratical reasons, water plays a determinant role in the choice of the location of his estate at Scillus.

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Sanitation Systems Practiced in the Ancient Sri Lankan Society

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Abstract: Sri Lanka has a 2,500 years old written history. Evidences are available to believe that the ancient Sri Lankans had been using sanitary disposal technologies to get rid of human excreta and urine in a reasonably safe manner according to the technology available at that time. The author has visited some of these sites and physically verified the kind of technology employed at those places. The study showed that urine separation was in practice during the period from 4th century B.C. up to about 11th century. It appears to be that this practice had been given up since 12th century. The report includes 15 photographs to evidence this. However, no evidence could be found to confirm that the urine collected had been used as a fertilizer or as any other resource other than using as an ingredient for some local medical treatment.

Objective of the Study

The Sri Lankan cultural history is 2500 years old. Many historical evidences are still physically available in many parts of the country to prove this. It is interesting to note that there are evidences available believe that the ancient Sri Lankans have been using sanitary disposal technologies to get rid of human excreta and urine. Archaeological excavations have revealed that some kind of toilets were in existence for upper class society including large Buddhist temples where hundreds to thousands of monks lived together. It was expected to visit some of these sites physically by the researcher and verify what kind of technology had been employed at those places with a view of adopting the learning points for the benefit of the modern society.

Background

The written history of Sri Lanka dates from the arrival of Prince Vijaya and his group from North India (West Bengal) in the sixth century B.C. although there are evidences available that the country had been inhabited since 150,0000 years back. It appears that the arrival of Vijaya had a graete influence on the life of the native Yaksha and Naga clans who had already been reasonably civilized by the time Vijaya arrived. However, Vijaya's arrival made a considerable change in the Sri Lankan cultural history. The first king of Sri Lanka, the King Vijaya started his kingdom at Panduwasnuwara in North Western Province of Sri Lanka in the 6th century B.C., which was moved to Anuradhapura in the North Central Province later. The capital was again moved to Polonnaruwa for more safety against South Indian invasions during the 11th century.

Buddhism was brought to Sri Lanka in the 3rd century when the Kingdom had been established at Anuradhapura. This event had a great influence in shaping the whole history of the country in many aspects. As a result of this influence many big cities have been systematically developed in various parts of the Island. Special attention had been given to establish proper water supply, sanitation systems together with other developments such as water resources development, road networks with a view to support a healthy nation. Health was considered to be the most valuable wealth of the human under the teaching of Buddhism.

There are very interesting archeological evidences to show that there have been very efficient systems of sanitation existing especially for the Palaces of nobles, Buddhist temples where large number of monks lived and in Universities where large number of students were educated on residential basis.

Methodology

Four major kingdoms were visited during the study to collect information. Major places visited were: Anuradhapura (4th Century B.C.), Polonnaruwa (11th Century), Panduwasnuwara (12th Century).

Findings

No evidence of using toilets could be found within King Vijaya's period. In contrast there are many archeological remains still existing to show that very good sanitation practices have been in operation during the Anuradhapira era. The remains of several toilet complexes in ancient Buddhist monasteries show the Engineering capabilities of the designers. Some of the examples are depicted below: A small hole with an approximate diameter of 20 mm has been provided at the bottom of the collection pan. Step stones have been provided to facilitate the squatting position for the user. The small size of the hole prevents misuse.

Figure 1 A urinal stone at Anuradhapura.

Figure 2 An ancient squatting pan out of Rock.

The feces collected in the basin are flushed through the side hole. The wide grove around the step stones shows that they used water for cleaning. The facility has been provided in front of the user to keep the water pot for anal cleaning. It is interesting to note that a separate bathing unit has been constructed adjoining the toilet compartment. The rich stone carvings show the wealthy of the user. This is a very valuable piece of art and is considered as the most beautiful urinal stone existing. The rich carvings show the importance of the user. The urine collected from the urinal stone has been diverted in to a series of terracotta pots directing them in to the deep soil. Urine flows through the each pot filled with charcoal through a small hole provided in the bottom. It is believed that this technology has reduced the smell.

Figure 3 A squatting pan.

Figures 4 and 5 A toilet in a Noble Palace.

Figure 6 A urinal stone at an isolated temple.

Figure 7 A urinal used by the Great King Dutugemunu.

The flow arrangement is different than other commonly used urinal stones. This has a side outlet unlike the other urinal stones with a hole in the bottom. The deeper portion of the pit has been lined with brick and terracotta rings have been placed at the upper part of the pit where loose soil exists. The terracotta rings also seals off the seepage to the upper soil layer. This type of collection pits were seen only at Pollonnaruwa and not during Anuradhapura era.

Figure 8 Urine disposal method during Anuradhapura era.

Figure 9 A urinal in a hospital in Polonnaruwa.

Figure 10 A urine collection pit.

Figure 11 The toilet at the palace of the Parakrmabahu, Panduwasnuwara-12th Century.

Parakramabahu was a regional ruler at Panduwasnuwara in the 12th century. This is a complete attached toilet with a squatting pan, washing place, out let drain and a circular pit covered with stone. The full unit has been constructed as part of the inner palace. Plastered brick construction has replaced the former stone carved squatting pans by this time. There are no more evidence avialble for separate urinal systems.

Figure 12 Collection pit of the toilet.

Figure 13 Combined toilet and washing room.

The pit has been constructed adjoining the outer wall of the toilet. Thick walls might have prevented smell. Terracotta rings have been installed for the deeper portion of the pit. This unit has been constructed at a Buddhist temple in Panduwasnuwara. The construction is out of brick covered with lime plaster. A stand has been provided in the middle of the room either to sit or to keep the washbasin. Three toilets had been constructed in series with three separate collection pits. The construction is totally out of burnt bricks plastered with lime paste.

Figure 14 Squatting pan and the pit covered with stone slabs.

Figure 15 A toilet complex at a Buddhist University in Panduwasnuwara.

Conclusions

It is to be seen that up to the 12th Century, urine has been separately disposed without allowing mixing with faeces. Special attention had been given by the builders misuse of urinal pan by providing a very to prevent small discharge hole. There are no evidence available that the urine collected separately had been used for any productive activity or in agriculture. However, further study through a literature survey is recommended to confirm this. Water appears to be the main cleaning mode after defecation all the time. The practice of using a separate facility for urination was been given up from the 12th century onwards.

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