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Urban wastewater and stormwater technologies in ancient Greece

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Abstract

The status of urban sewerage and stormwater drainage systems in ancient Greece is reviewed, based on the results of archaeological studies of the 20th century. Emphasis is given to the construction, operation, and management of sewerage and stormwater drainage systems during the Minoan period (2nd millennium B.C.). The achievements of this period in dealing with the hygienic and the functional requirements of palaces and cities, were so advanced that they can only be compared to modern urban water systems, developed in Europe and North America in the second half of the 19th century A.D. The advanced Minoan technologies were exported to all parts of Greece in later periods of the Greek civilization, i.e. in Mycenaean, Archaic, Classical, and Hellenistic periods.

Keywords: Ancient Greece; Athens; Bathrooms; Bronze age; Cycladic civilization; Flush toilet; Knossos; Minoan civilization; Mycenaean civilization; Sanitary structures; Sewer systems; Stormwater management; Urban drainage; Sewage management

1. Introduction

> One day, after a heavy downpour of rain, I was interested to find that all the drains [of the Villa Hagia Triada of Minoan Crete] acted perfectly, and I saw the water flow from the sewers through which a man could walk upright. I doubt if there is any other instance of a drainage system acting after ca. 4000 years (Mosso, 1907).

We frequently hear people speak of "modern sanitation" as if it were something rather recently developed, and there appears to be a prevalent idea that municipal sewerage is a very modern thing that began some time about the middle of the last [19th] century. Perhaps these ideas do something to bolster up a somewhat wobbly pride in modern civilization […], but when examined in the light of history these ideas are seen to be far from new or even recent. Indeed, in the light of history it is a matter of astonishment, if not chagrin, that man in this respect has progressed so very little, if at all, in some 4000 years. […] All in all, the archaeological researchers on this [Minoan] site yield a picture of a people who had progressed far along the path of comfortable and hygienic living, with a considerable degree of beauty and luxury in the surroundings. And this had been accomplished some four thousand years ago (Gray, 1940).

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Archaeological studies from the beginning of the 20th century have established clearly that the critical foundations for many modern technological achievements in water resources were established in ancient Greece. Ancient Greek approaches, remarkably advanced, encompass various fields of water resources such as groundwater exploitation, water transportation, even from long distances, water supply, stormwater and wastewater sewer systems, construction and use of fountains, baths and other sanitary and purgatory facilities, flood protection, drainage, and irrigation of agricultural lands and even recreational uses of water (Angelakis and Koutsoyiannis, 2003). Interestingly, some of the most significant achievements of hydraulic technology can be traced not to Classical Greece, which is mainly characterized by mental and artistic achievements like poetry, philosophy, science, politics, and sculpture, but to the earlier Minoan and Mycenaean civilizations that flourished in the 2nd millennium BC.

Unlike preceding civilizations such as those in Mesopotamia and Egypt, which were based on the exploitation of water of the large rivers (i.e., the Tigres, Euphrates and Nile), the Greek civilization has been characterized by limited, and often inadequate natural water resources. Although the rainfall regime, and consequently the water availability, varies significantly throughout Greece, the most advanced cultural developments occurred in semiarid areas with the lowest rainfall and, thus, the most limited water resources.

From several studies on climate variations in the Mediterranean region during the Holocene period, it is known that a number of different climatic periods have occurred during the past 5000 years (e.g. cold period, ca. 4500–3000; cold and humid period, ca. 3000–2200; and a warm period, ca. 2200–1400 B.C.) (Issar, 1995; Angelakis and Spyridakis, 1996b). Despite varying climatic conditions during the past 5000 years, it may be conjectured that the abundance of water resources was never the case in the Greek cites of significant cultural development including: Knossos in Crete, the Cyclades islands, and Athens on the mainland. Under these climatic and hydrological conditions, the early Greeks had to develop innovative technological means to capture, store, and convey water even from long distances, as well as legislation and institutions to manage water more effectively (Angelakis and Koutsoyiannis, 2003). Naturally, the main technical and hydraulic operations associated with water resources development, were followed by the development of sewer and drainage systems, including urinals and toilets, bathrooms with tubs, laundry slabs and basins, and disposal sites for the effluent. Such operations have been practised in varying forms since ca. 3000 B.C. (Angelakis and Spyridakis, 1996a).

In this paper, wastewater and urban drainage systems developed in ancient Greece are reviewed, based on the results of recent archaeological studies. Emphasis is given to the achievements of the Minoan period in the construction, operation, and management of such systems. Developed to support the hygienic and the functional requirements of palaces and cities, these systems were so advanced that they can only be compared to modern systems, developed in Europe and North America in the second half of the 19th century A.D. Developments during the Minoan civilization are considered in the following three sections, followed by a brief description of systems implemented in later periods of the Greek civilization, i.e. in Mycenaean, Archaic, Classical and Hellenistic.

2. A brief history of the Minoan civilization

Based on archaeological and other evidence, a cultural explosion unparalleled in the history of other ancient civilizations occurred in various parts of ancient Greece starting about ca. 3000 B.C. (Cahill, 2003). A striking example of this awakening is manifested, inter alia, in the advanced water resources techniques practised in Greece at that time. One of the most interesting contributions of the Minoan civilization, which developed on the island of Crete, was the remarkable architectural and hydraulic infrastructure for the management of water, stormwater and wastewater sewerage in palaces and cities. There are also indications that wastewater was used for agricultural irrigation at that time. It must be concluded, therefore, that Minoan water engineers were aware, long ago, of some basic principles that are used today in water and environmental studies.

As early as the Neolithic age, Crete was inhabited by a scattered population living partly in caves some distance from the coast but also concentrated at Knossos, in one of the largest settlements of that period in the eastern Mediterranean. Although little is known of the origins of these early settlers, the associations suggested by pottery and other artefacts, point to Anatolia, and possibly Egypt, rather than the Greek mainland. The population of Crete increased significantly at the beginning of the Bronze Age, i.e. shortly after 3000 B.C. with the arrival of' new settlers, perhaps from Asia Minor. Moreover, based on linguistic and toponymic affinities, it appears that a considerable element in the Cretan population may have been related to the Luwians who, in the Middle and Late Bronze Ages, were established in Asia Minor, south-west of the Hittites (Angelakis and Spyridakis, 1996a).

Cultural advancements can be observed throughout the third and second millennia B.C., but great progress was made in Crete, especially in the Middle Bronze Age (ca. 2100–1600 B.C.) when the population in its central and southern regions increased, towns were developed,

the first palaces were built, and Crete achieved a prosperous and uniform culture. By the end of this period, both manufacturing and the arts flourished and the islanders engaged in extensive trade with Egypt, the Aegean Archipelago, and the Near East. In the early phases of the Late Bronze Age (ca. 1600–1400 B.C.), Crete appears to have prospered even more, as evidenced by the larger houses and more luxurious palaces of this period (History of the Greek Nation, 1970). At this time, the flourishing arts, improvements in metal-work along with the construction of better-equipped palaces, and an excellent road system, reveal a wealthy, highly cultured, well-organized society and government in Crete. Subsequently, the importance and power of the island decreased following the destruction of the Minoan palaces ca. 1400 B.C. (Angelakis and Spyridakis, 1996a).

3. Domestic sanitary structures

It is evident that in Minoan civilization extensive systems and elaborate structures for water supply, irrigation and drainage were planned, designed and built to supply the growing population centers and irrigated agriculture with water (Angelakis and Koutsoyiannis, 2003; Angelakis and Spyridakis, 1996a). Thus, in several Minoan Palaces discovered by archaeologists in the 20th century, one of the most important elements was the provision and distribution of water by means of sophisticated hydraulic systems. It seems that bathrooms and sewers were not necessary, merely convenient, and most palaces did not have them. Although the function of Minoan rooms is difficult to define with certainty, Evans, the famous archaeologist who discovered the Knossos Palace, identified three rooms at the Knossos as bathrooms.

One of the most interesting rooms in the ground-floor in the residential quarter of the Knossos Palace was identified as a toilet with a wooden seat and a small flushing conduit is shown in Fig. 1. Remains of a clay tube were found just outside the door of the room. Apparently, water was poured through a hole in the floor immediately outside the lavatory door; an under-floor channel linked the hole with the vertical clay pipe under the toilet seat (Castleden, 1993). The toilet could thus be flushed even during a rainless summer, either by an attendant outside the lavatory or by the user. The toilet illustrated in Fig. 1 is probably the earliest flush toilet in history.

The toilet is similar in function to that of the so called Queen's Hall and the toilets found in the Phaistos and Mallia palaces and in some of the houses as well. Fortunately, one of the houses near the Palace at Mallia, known as Da, contains a toilet seat in nearly perfect condition, since it was made not of wood, like the seat of the Palace of Minos in Knossos but of solid stone. This stone seat is 68.6 cm long by 45.7 cm wide front to back and its surface is 35–38 cm above the floor. It is built directly against an outside wall through which a large sewer passes. Like the Knossos find, the structure was evidently intended to be used as a seat rather than a stand; thus, it resembles the "Egyptian" toilet more closely than the so-called "Turkish" type found in the Palaces at Mari and Alalakh in Syria (Graham, 1987). A similar toilet has been discovered in the west side of the so called "Queen's Apartment" at Phaistos. It was connected to a closed sewer, part of which still exists.

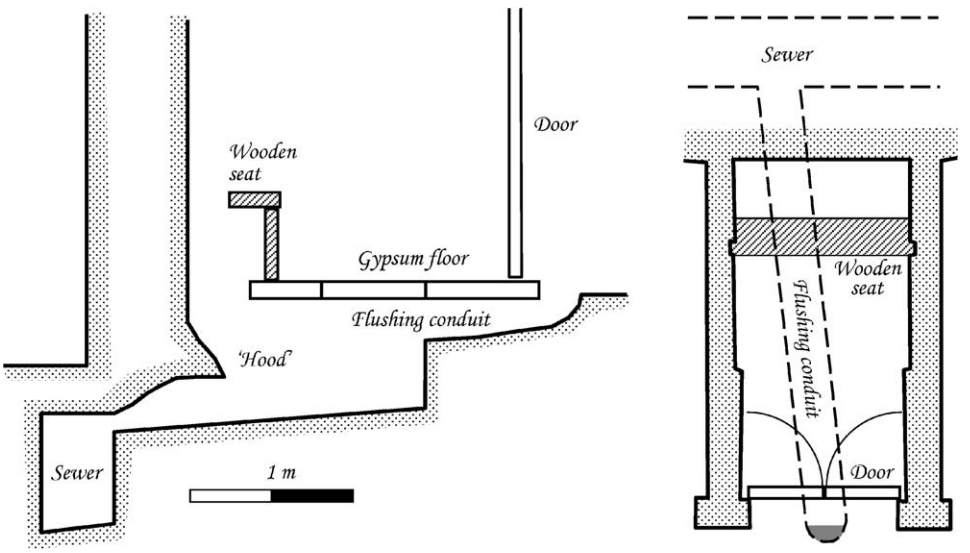

Fig. 1. Section and plan of ground-floor toilet in the residential quarter of Palace of Minos (adapted from Graham (1987)).

Another toilet sewer was discovered in House C at Tylissos (Angelakis and Spyridakis, 1996b).

At certain times of the year the sewers in the Palace of Minos may have been flushed out adequately by the rain that fell into the light-wells, however, it appears that water was poured into the toilets to flush them. In fact, Evans noted the existence of sufficient space for placing a large pitcher at one end of the seat at Knossos and so concluded with evident delight (Evans, 1964)

> As an anticipation of scientific methods of sanitation, the system of which we have here the record, has been attained by few nations even at the present day.

Similar bathrooms have been reported in other Minoan sites. Platon (1990) has provided us with some preliminary statistical data on Minoan cisterns, bathrooms and other sanitary and purgatory facilities. She concluded that, in terms of chronology, most of them should be placed in the Middle Minoan period; in regards to location, 16 are found next to domestic rooms, seven near holy altars and two in palace entrances. In only two instances various facilities for baths were found, seven were filled up with earth and two had been rebuilt and converted into bathrooms. Also, in 14 of these sites various holy objects were found, while in 9, cement coats were indicated. Finally, frescoes related mainly to various holy subjects, were found only in two purgatory cisterns located in the south house of the Knossos Palace and in one cistern-bathroom at the north-eastern part of the Zakros Palace. The absence of bath facilities in some purgatory cisterns and their existence in other places, should not be considered coincidental. Graham (1987) and Platon (1974) have reported that purgatory cisterns were used for the cleansing of both body and soul. Note also that most Minoan baths were connected to independent septic systems in the outside, a practice indicative of the advanced water resources management and environmental techniques of that period (Panagiotakis, 1987).

The clay tubs in the Minoan bathrooms must have been filled and emptied by hand rather than directly connected to the sewers. However, on the "Caravanserai", a rest house on the inland route just south of palace, a footbath for the weary travellers was supplied by a direct pipe, and the overflow discharged by another conduit; a branch of the water channel also served a drinking trough (Angelakis and Spyridakis, 1996a).

4. Municipal sewerage and drainage systems

The sewerage and drainage facilities at Knossos, Zakros and Phaistos, and Hagia Triadha are considered briefly to provide an introduction to and to illustrate the level of development in the Minoan civilization.

4.1. The sewerage and drainage system of Knossos

In the entire structure of the Minoan palace nothing is more remarkable than the elaborate sewerage system that runs throughout its domestic quarter and adjoining halls. Evans (1964) and MacDonald and Driessen (1988), described the course of these sewers and drew plans of what they considered to have been their original form. A stone-by-stone description of the sewerage system with reference to the architecture above has been reported (MacDonald and Driessen, 1988). A description of the Knossos sewerage system has been reported in (Angelakis and Spyridakis, 1996b). The total extent of the sewerage system, including outlets and tributaries, exceeds one hundred and fifty meters.

Surface water from a part of the Central Court of the Palace of Minos was handled by a very large capacity underground channel built of stone and lined with cement. The channel, located beneath the passage leading from the north entrance, received several flows from various quarters. The most fully explored part of the palace sewerage system is the portion which runs beneath the floors of the residential quarter. This underground channel formed a great loop with its high point located under the light-well, next to the grand staircase, and emptied via a combined channel down the slope to the east of the palace (Evans, 1964). In the area of the Hall of the Double-Axes and the Queen's Hall with its associated chambers, wastewater from no less than five light-wells were discharged to the channel; which also served a toilet on the lowest floor, and was connected with three vertical shafts. The latter, evidently, received stormwater from the roof and were probably connected with toilets on the upper floors. The sewer was built of stone blocks lined with cement and measured about 79×38 cm per section. The sewers were large enough to permit a person to enter for cleaning or maintenance; in fact, access ports (i.e., manholes) were provided for that purpose. Air-shafts at intervals also helped to ventilate sewers (Graham, 1987).

Certainly, the plumbing arrangements and especially the sewers in the Minoan cities were carefully planned. Covered by stone, slab-built sewerage systems are evident in many cities to carry away sewage including stormwaters. In the remains at Knossos Palace, there remains clear evidence of how rain-water was drained from the roof by way of light-wells and used to flush out sewage from three bathrooms in the East wing (Angelakis and Spyridakis, 1996b). Stormwater from the flat roofs of the Palace at Knossos was carried off by vertical pipes; one of these, located in the eastern wing, emptied into a stone sewerhead from which a stone channel discharged it (Evans, 1964).

4.2. Sewerage and drainage systems of Zakros and Phaistos

In addition to Knossos and other Minoan cities, Zakros provides us with well-preserved remains of sophisticated networks in which descending shafts and well-constructed stone sewers and drains, large enough to permit the passage of a person (Platon, 1974). Yet, there is evidence that the entire system was not effective in times of intense or extended storms. However, due to the privileged location of the site in a natural slope, the final disposal of wastewater and stormwater at sea was easily attained. Platon (1974) finds three basic types of conduits in the sewerage system of Zakros: (a) a clay-conduit, (b) a conduit built up with stones, and (c) a narrow type of conduit constructed with stones but open at the top. Very similar practice were applied in the palace of Phaistos. Small sections of the Zakros and Phaistos sewerage and drainage systems as they appear today is shown in Fig. 2.

4.3. Sewerage and drainage system of Hagia Triadha

One of the most advanced Minoan sanitary and storm sewer systems was discovered in Hagia Triadha (close to the south coast of Crete). The Italian writer Angelo Mosso who visited the villa of Hagia Triadha in the beginning of the 20th century and inspected the storm sewer system (Fig. 3) noticed that all the sewers of the villa functioned perfectly and was amazed to see stormwater come out of sewers, 4000 years after their construction (Mosso, 1907). Gray (1940) who relates this story and quotes Mosso (see the quotation in the beginning of the paper) adds the following statement

> Perhaps we also may be permitted to doubt whether our modern sewerage systems will still be functioning after even one thousand years.

5. Outlets and disposal and reuse sites

The end section of the main part of the sewerage system of the Knossos Palace is shown in Fig. 4. The outlet of the Phaistos Palace system appears to be similar. Evans (1964) and MacDonald and Driessen (1988) considered that the main part of the system had been planned and constructed originally in Middle Minoan time. The main disposal sites at the Knossos and Zakros Palaces were directed to the Kairatos river and to the sea, respectively. However, there are indications that in the Palace of Phaistos and in the villa of Hagia Triadha cisterns were also used as disposal sites of surface water, along with appropriate landforms.

As reported earlier, the Minoan civilization most probably experienced several periods of severe water shortage due to climatic conditions. To maximize the utilization of the limited water resources, it was necessary to use and reuse water. Certain human activities such as bathing produce water which today is called "gray water". Bath or cooking water might be

Fig. 3. Parts of the sanitary and storm sewerage systems in Hagia Triadha.

Fig. 2. Section of sanitary and storm sewerage system at Zakros (left) and Phaistos (right) Palaces.

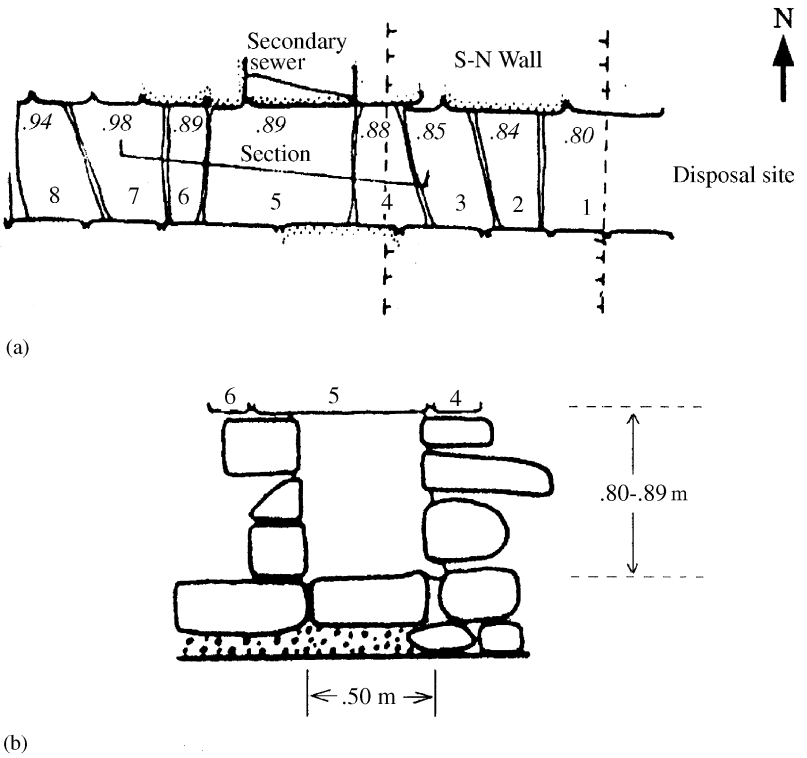

Fig. 4. The end part of sewerage system in Knossos: (a) overview and (b) section (from Angelakis and Spyridakis, 1996b).

given to animals, used to wash floors, or used to irrigate house plants, since only soap was used (Crouch, 1996).

Non-potable water included mainly storm runoff and sewage. Stormwater could be utilized as irrigation water, especially valuable when enriched by sewage placed up along the way, which converted it into fertilizer. Houses and public buildings customarily had gutters and drains that connected with the sewers under the streets. These, like their modern counterparts, existed under the gates and emptied into the dry bed of the nearest river, which served as a drainage channel. Today, it is generally recognized that wastewater was first used for irrigation in Minoan times.

Among the advanced techniques practised in Minoan Crete was the stormwater sewerage system found in the outer stairway of the north-west wing of the Palace at Knossos near the Kairatos river (Evans, 1964). Here on one side of the stairway (Fig. 5), there is a small open sewer that follows a parabolic flow path instead of the line of the stairs. In this manner, the stormwater not only flows down smoothly without causing any erosion, but does not become a nuisance to people using the stairs. These runnels with their parabolic curves following the turns of outer stairways, and the further arrangement of their channels, secure the confinement of sediment in intermediary little tanks, placed at proper intervals, to allow it to settle to the bottom (Michailidou, 1992). This elaborate method of collecting the maximum amount of rain-water, freed from impurities, in a downstream tank for washing or other purposes, is only one indication of the highly skilled hydraulic knowledge attained by the Minoans. The special

Fig. 5. Part of restored stairway with parabolic runnels in Knossos Palace.

suitability of rain-water for washing linen, encourages the assumption that the tank was used for this purpose and that Minoan maidens may have come here from the Palace halls above to do the royal laundry.

Similarly, in the villa of Hagia Triadha, surface water from the stormwater system passed through a rectangular cistern (about $1.6 \times 2.0 \times 6.0$ m). It may be speculated that water from this cistern was probably used for washing or other reuses.

6. Developments during other periods of the Greek civilization

Minoan wastewater technologies are remarkable because they were established at such an early stage of civilization and were so advanced that their counterparts can be found throughout the ancient world, as well as toady in any modern city. The collapse of the Minoan civilization did not cause the disappearance of hydraulic and sanitary technologies for urban wastewater and stormwater management. On the contrary, from archaeological excavations during the 20th century evidence has been accumulated that such technologies existed in continental Greece and in the Aegean islands in several subsequent stages of the Greek civilization. While it is difficult to draw a comprehensive picture of these technologies, some examples are presented to illustrate that sanitation and related technologies were widespread in several stages of the Greek civilization.

6.1. Urban sewer systems

Urban sewer systems have been found in several prehistoric sites of the Aegean civilization (ca. 3400–1200 B.C). Thus, in the prehistoric city of Thera (founded ca. 14th century B.C.) in the homonymous island (today better known as Santorini), which has only been investigated to a limited degree, a sewerage network has been found under the paved streets, connected directly to bathrooms and sanitary facilities, including toilets, that were common in the houses. In cases, these facilities were located in the upper floor. The entire system appears similar to the even older system (ca. 2500 B.C.) at the prehistoric Indus civilization site Mohenjo-daro, India (Gray, 1940).

In historic times, sewer systems were very common in most cities. The value of the sewerage in an ancient Greek city is illustrated by the historian Diodoros Siculus (ca. 90–20 B.C.) in the following quotation from his *Library* (Book 11, Chapter 25, Section 3); here he describes Acragas, the Greek city in Sicily founded ca. 582 B.C. by Rhodio-Cretan colonists:

> … Acragantini, embellished their city and countryside; … Most of these [captives] were handed over to the state, and it was these men who quarried the stones of which not only the largest temples of the gods were constructed but also the sewers were built to lead off the waters from the city; these are so large that their construction is well worth seeing, although it is little thought of because of their lowness.

From this passage it can be concluded that urban sewerage was regarded as a necessary infrastructure for a city, which could be worth seeing, but such works were not of equal importance with the temples of the gods that were related to the beauty and glory of the city. Despite their value in assuring a good quality of life, sewers were regarded as objects of "εὐτέ λεια" commonness or lowness. Interestingly, from the above passage, it is also learned that sewers as well as temples were considered public works and were constructed by war captives.

6.2. Use of ceramic clay pipes

Ceramic clay pipes have been used for small sewer sections, as well as for aqueducts. The technology of ceramic pipes is depicted in Fig. 6. In the upper panel of the figure, referred to an excavation in Amphipolis, an Athenian colony in Thace founded in 437 B.C., it may be observed that the construction of the ceramic sewer pipes was rather rough and primitive. On the other

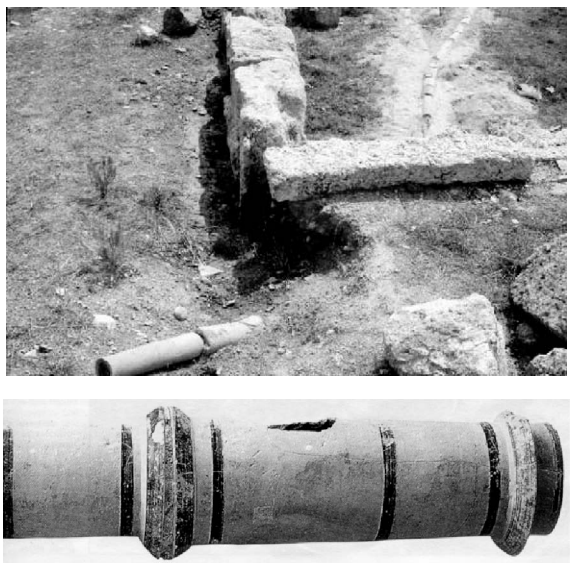

Fig. 6. (Up) Ceramic sewer pipe in the gymnasium at Amphipolis (photo by B. McIntosh and S. Heath, http://www.perseus.tufts.edu/cgi-bin/image?lookup=1990.27.0278). (Down; for comparison) Detail of the ceramic pipe sections used in the Peisistratian aqueduct in ancient Athens and their connection (photo reproduced from the newspaper Kathimerini).

hand, as revealed from the recent excavations for the construction of the metro in Athens, the use of ceramic pipes was widespread for both water supply and sewerage, and in the former case their technology is remarkable (lower panel of Fig. 6). The ends of the sections were appropriately shaped, so that each could be tightly fitted into the next, and were joined with cement or lead. The pipe sections had elliptic openings in their upper part, covered by ceramic covers, for their cleaning and maintenance.

6.3. Stone and masonry sewers

Sewers with larger cross-sections were built of stone in a variety of different ways. In the most sophisticated case, storm drains are of carved stone exposed like a canal. An example is given in Fig. 7 (left), which depicts a drain in the agora of ancient Messene (SW Peloponnesus), a city built in 379 B.C. which was known for its walls, the best preserved in Greece, and the strongest of antiquity (Pausanias, book 4, Chapter 31, Section 5). The excavated drain has two branches 24 and 14 m long, respectively, and at intervals has elliptic cavities for the settling of sediments.

More common were the sewers of stone masonry with rectangular cross section covered by stone blocks; these were used either as stormwater, wastewater, or most probably combined sewers. An example of such a cross section is shown in Fig. 7 (right), which depicts a sewer in the agora of Athens (the similarity with the Minoan sewers of Fig. 2 is remarkable). Very often, such sewers were built beneath paved streets, as is sketched in Fig. 8. The upper panel reproduces a sewer of the ancient Dion, a fortified city inhabited from the 6th century B.C. to the 5th century A.D. The lower panel shows a more interesting style that was used in some of the sewers under paved streets in ancient Cassope. Cassope, the capital of Cassopaea, an area in Epiros, NW Greece, with a climate characterized by significant amount of rainfall (as opposed to the Eastern Greece), was founded before the middle of the 4th century B.C. and its entire road system was designed having in mind the rain water draining; thus, the narrow roads among the houses, as well as main roads were properly formed to carry the water out of the enclosure (Dakaris, 1989).

In most cases of rectangular sewers, it can be observed that no stone blocks were used in the lower side of the sewer cross section. Such construction was not only lower in cost and easier and faster build, but it also allowed infiltration of water into the soil, and, thus, reducing the quantity of flow and simultaneously recharging aquifers. Some techniques of the same type, known as 'source control techniques' have reappeared today, but have not become very common yet (e.g. Butler and Macsimovic, 2001).

Sewers with even larger cross-sections were also built from stone masonry but with a vaulted cross section as illustrated in Fig. 9. The two sewers depicted are located in Athens and in Eretria, a city in Euboea inhabited since the Bronze Age.

6.4. Other parallel developments

It should be noted that hydraulic technologies in ancient Greece are not limited to urban sewerage.

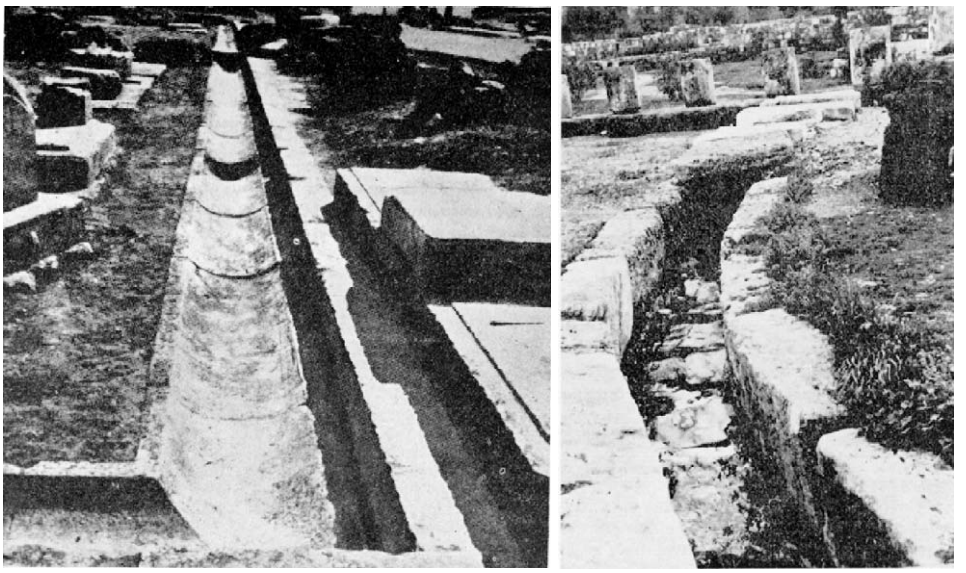

Fig. 7. Drain in the agora of ancient Messene (left) and sewer in the agora of ancient Athens (right) (from Papademos (1975)).

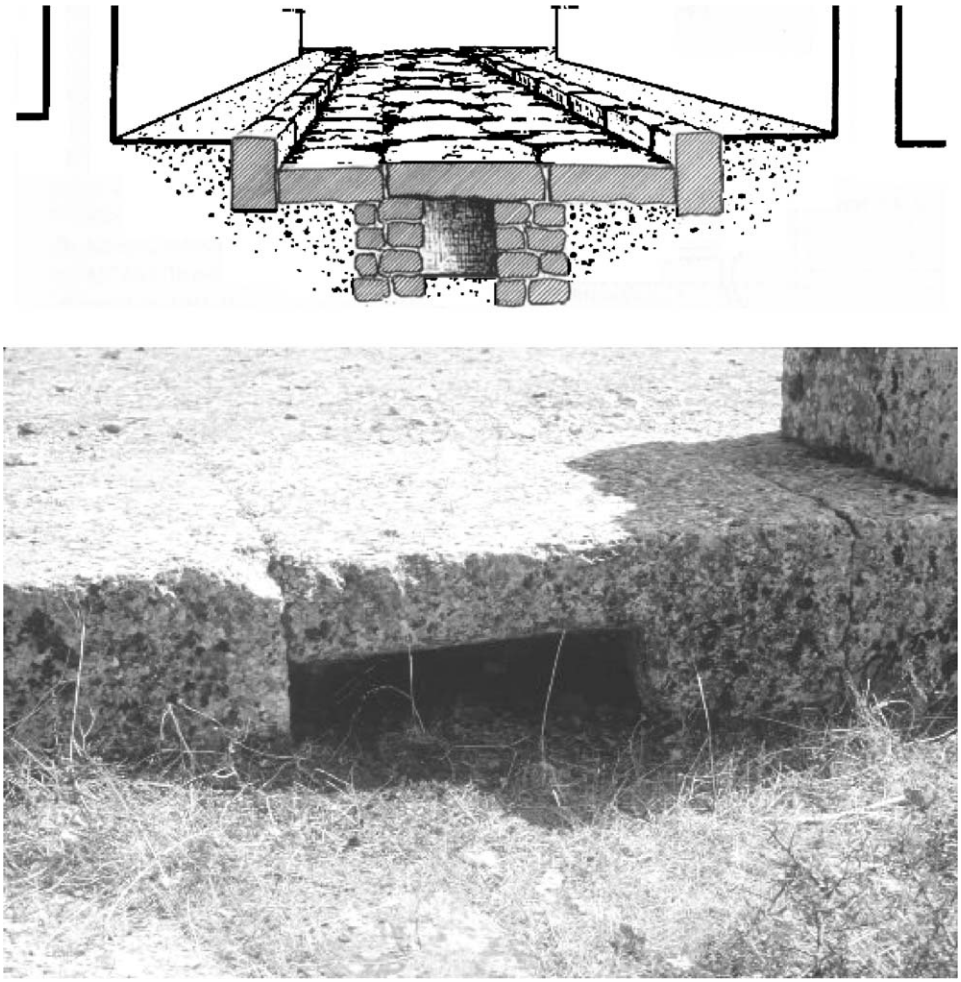

Fig. 8. Sketch of a stone masonry sewer under a paved street in ancient Dion, Macedonia (up; from Karadedos (2002)) and detail of drain in the katagogeion's court in Cassope (down; photo by B. McIntosh and S. Heath, http://www.perseus.tufts.edu/cgi-bin/image?lookup=Perseus:image:1990.27.0758).

The progress in urban water supply was even more admirable (e.g. Angelakis and Koutsoyiannis, 2003), as witnessed by several aqueducts discovered, including the famous tunnel of Eupalinos for the water supply of Samos. In addition, astonishing agricultural hydraulic projects for flood protection, irrigation and drainage were built, including the huge project for the drainage of the Kopais lake constructed in Mycenaean times (e.g. Koutsoyiannis and Angelakis, 2004). This technological progress was coupled with a good understanding of the water related phenomena. Thus, around 600 BC, Greek philosophers developed the first scientific views of natural hydrological and meteorological phenomena. Later, during the Hellenistic period, significant developments were made in hydraulics, which along with progress in mathematics, made the invention of advanced instruments and devices, like the Archimedes's water screw pump, possible (e.g. Koutsoyiannis and Angelakis, 2003).

7. Closing thoughts

Although the above descriptions do not provide a complete picture of urban sewerage and drainage technologies in ancient Greece, they serve to illustrate the fact that such technologies were in use in ancient Greece since about four thousand years ago. These advanced technologies, developed in Minoan Crete, were subsequently transferred to the Mycenaean civilization and then the archaic and classical Greece. In light of this archaeological evidence, the present day progress

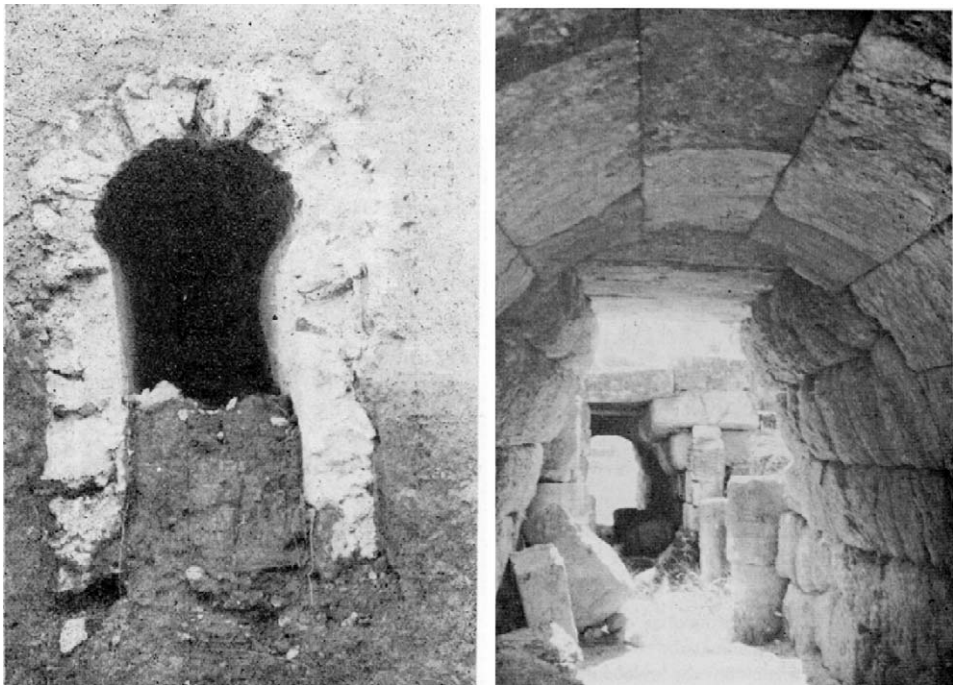

Fig. 9. Sewers of large cross sections located in Athens (left) and Eretria (right) (Papademos, 1975).

in urban water technology as well as in comfortable and hygienic living is clearly not a recent development.

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References

Angelakis, A.N., Koutsoyiannis, D., 2003. Urban water engineering and management in Ancient Greece. In: Stewart, B.A., Howell, T. (Eds.), The Encyclopedia of Water Science. Marcel Dekker, New York, USA, pp. 999–1008.

Angelakis, A.N., Spyridakis, S.V., 1996a. The status of water resources in Minoan times: a preliminary study. In: Angelakis, A.N., Issar, A.S. (Eds.), Diachronic Climatic Impacts on Water Resources with Emphasis on Mediterranean Region. Springer, Heidelberg, Germany, pp. 161–191 (Chapter 8).

Angelakis, A.N., Spyridakis, S.V., 1996b. Wastewater management in Minoan times. In: Proceedings of the Meeting on Protection and Restoration of Environment, August 28–30, Chania, Greece, pp. 549–558.

Butler, D., Macsimovic, C., 2001. Interactions with the environment. Ch. 3. In: Macsimovic, C., Tejada-Guibert, J.A. (Eds.), Frontiers in Urban Water Management—Deadlock or Hope. IWA, London, UK.

Cahill, T., 2003. Sailing the Wine Dark Sea: Why the Greeks Matter. Doubleday, New York, USA.

Castleden, R., 1993. Minoans: Life in Bronze Age Crete. Routledge, 11 New Fetter Lane, London, UK.

Crouch, D.C., 1996. Avoiding water shortages: some ancient Greek solutions. In: Angelakis, A.N., Issar, A.S. (Eds.), Diachronic Climatic Impacts on Water Resources with Emphasis on Mediterranean Region. Springer, Heidelberg, Germany, pp. 129–159 (Chapter 7).

Dakaris, S.I., 1989. Κασσώπη Νεότερεσ Ανασκαφέσ 1977–1983 (Cassope: Newer Excavations 1977–1983). University of Ioannina, Ioannina, Greece (in Greek).

Evans, S.A., 1964. The Palace of Minos at Knossos: a comparative account of the successive stages of the early Cretan civilization as illustrated by the discoveries. Macmillan and Co., London, 1921–1935, vols. I–IV. Reprinted by Biblo and Tannen, New York, USA.

Graham, J.W., 1987. The Palaces of Crete, revised ed. Princeton University Press, Princeton, New Jersey, USA.

Gray, H.F., 1940. Sewerage in Ancient and Medieval Times. Sewage Works J. 12 (5), 939–946.

History of the Greek Nation, 1970. Εκδοτική Αθηνών, Athens, Greece (in Greek).

Issar A.S., 1995. Impacts of climate variations on water management and related socio-economic systems. In: Technical Documents in Hydrology. International Hydrological Programme, UN Educational, Scientific and Cultural Organization, Paris, France.

Karadedos, G., 2000. Υδραυλικές γνώσεις και τεχνολογία–Η περίπτωση του Δίου (Hydraulic knowledge and technology – The Dion case). In: C. Soueref, (Ed.), Υδάτινες Σχέσεις–Το Νερό ως Πηγή Ζωής κατά την Αρχαιότητα (Aquatic Relationships–Water as Source of Life in the Antiquity), University Studio Press, Thessalonike, Greece (in Greek).

Koutsoyiannis, D., Angelakis, A.N., 2003. Hydrologic and hydraulic science and technology in ancient Greece. In: Stewart, B.A., Howell, T. (Eds.), The Encyclopedia of Water Science. Marcel Dekker, New York, USA, pp. 415–418.

Koutsoyiannis, D., Angelakis, A.N., 2004. Agricultural hydraulic works in ancient Greece. In: Stewart, B.A., Howell, T. (Eds.), The Encyclopedia of Water Science. Marcel Dekker, New York, USA, pp. 1–4.

MacDonald, C.F., Driessen, J.M., 1988. The drainage system of the domestic quarter in the palace at Knossos. British School of Athens, Greece, vol. 83, pp. 235–358.

Michailidou, A., 1992. Knossos. A Completed Guide to the Palace of Minos. Ekdotiki Athenon S.A., Athens, Greece.

Mosso, A., 1907. Escursioni nel Mediterraneo e gli scavi di Creta, Treves, Milano, Italy.

Panagiotakis, N.M., 1987. Κρήτη: Ιστορία και Πολιτισμόσ (Crete: History and Civilization). Vikelea Library, Association of Regional Unions of Municipalities and Communities of Crete, Iraklion, Greece, vol. 1, pp. 416 (in Greek).

Papademos, D.L., 1975. Τα Υδραυλικά Έργα Παρά τοις Αρχαίοις (The Hydraulic Works in Ancient Greece). TEE (Ed.), vol. B, Athens, Greece (in Greek).

Platon, N., 1974. Ζάκροζ Το Νέον Μινωϊκόν Ανάκτορον (Zakros, The New Minoan Palace). The Athens Archaeological Society, Athens, Greece, 1974.

Platon, M., 1990. Νέεσ ενδείξεισ για τα προβλήματα των καθαρτηρίων δεξαμενών και του λοντρών στο Μινωϊκό κόσμο (New indications for the problems of purgatory cisterns and bathrooms in Minoan World). Proceedings of the Sixth International Cretologic Congress, Literary Association Chrysostomos, Chania, Greece, vol. A2: pp. 141–155 (in Greek).