# URBAN WATER ENGINEERING AND MANAGEMENT IN ANCIENT GREEK TIMES

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## 1. INTRODUCTION

Ancient Greek civilization has been thoroughly studied, focusing on mental and artistic achievements like poetry, philosophy, science, politics, sculpture. On the other hand, most of technological exploits are still relatively unknown. However, more recent research reveals that ancient Greeks established critical foundations for many modern technological achievements, including water resources. Their approaches, remarkably advanced, encompass various fields of water resources, especially for urban use, such as groundwater exploitation, water transportation, even from long distances, water supply, stormwater and wastewater sewerage systems, flood protection and drainage, construction and use of fountains, baths and other sanitary and purgatory facilities, and even recreational uses of water. The scope of this chapter is not the exhaustive presentation of what is known today about hydraulic works, related technologies and their uses in ancient Greece but, rather, the discussion of a few characteristic examples in selected urban water fields that chronologically extend from the early Minoan civilization to the classical Greek period. Agricultural hydraulic works like flood protection, drainage and irrigation of agricultural lands and drainage of lakes were also in use in ancient Greece starting from the Mycenaean times, but are not covered in this chapter. Scientific advances in water resources as well as invention of hydraulic mechanisms and devices are presented in another entry (Hydrologic and Hydraulic Science and Technology in Ancient Greek Times)

## 2. CLIMATIC AND HYDROLOGIC CONDITIONS

Unlike preceding civilizations such as those in Mesopotamia and Egypt, which were based on the exploitation of water of the large rivers Tigres, Euphrates and Nile, the Greek civilization has been characterized by limited and often inadequate natural water resources. The rainfall regime and consequently the water availability over Greece vary substantially in space. Thus, the mean annual rainfall exceeds 1800 mm in the mountainous areas of western Greece whereas in eastern regions of the country may be as low as 300 mm. Interestingly, the most advanced cultural activities in ancient Greece appeared in semiarid areas with the lowest rainfall and thus the poorest water resources; for example Knossos in Crete, Cyclades islands and Athens have annual rainfall about 500 mm, 300-400 mm and 400 mm, respectively. The potential evapotranspiration exceeds 1000 mm all over Greece, with the highest rates appearing in summer months. Thus, irrigation of cultivated areas during summer is absolutely necessary and becomes the most demanding water use in Greece. Under these climatic and hydrological conditions, Greeks had to develop technological means to capture, store, and convey water even from long distances, as well as legislation and institutions to more effectively manage water.

## 3. THE WATER SUPPLY IN MINOAN CIVILIZATION

Cultural advancements in the Minoan civilization can be observed throughout the third and second millennia BC, which indicates that the main technical operations of water resources have been practiced in varying forms since *ca.* 3000 BC. During the Middle Bronze Age (*ca.* 2100-1600 BC) Crete's population in its central and south regions increased, towns were developed and the first palaces were built. At that time, a "cultural explosion" occurred on the island. A striking indication of this is manifested, inter alia, in the advanced water resources management technologies applied in Crete at that time. The sanitary life style developed at this civilization can be paralleled to the modern standards. It is evident that in Minoan civilization extensive systems and elaborate structures for water supply, sewerage systems, irrigation and drainage were planned, designed and built to supply the growing population with water for the cities and for irrigated agriculture (1).

In the early phases of the Late Bronze Age (*ca.* 1600-1400 BC), Crete appears to have prospered even more, as the larger houses and more luxurious palaces of this period indicate (2). 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, before the island's power collapsed following the destruction of the Minoan palaces (3). The geological catastrophe through the eruption of the Santorini volcano in 1450 BC halted the Minoan civilization.

Our knowledge of how Minoan cities were supplied with potable water is mainly acquired from the Palace of Knossos. A few cisterns, fountains and wells were also found at other archeological sites like Zakros, Mallia, Gortys and other Minoan palaces and cities. At Phaistos some cisterns have been discovered too, but owing to the nature of the ground, no wells or springs have been found there (1).

Even at Knossos, the sources of water and the methods used for supplying it are only partially understood. Several wells have been discovered in the Palace area, 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 (4). In the Protopalatial stage *(ca.* 1900-1700 BC), several wells were used for drawing drinking water. Their depth did not exceed 20 m and their diameter was no more than 5 m (5). At least six such wells have been reported (4). The most important and best known is the one found in the north-west of the Palace in the basement of the House A, which belongs to the first stage of the Middle Minoan period. According to Evans (4), its upper circuit was mostly a patchwork of rubble masonry, recalling the construction of Roman wells in the site. However, below its crudely built upper “collar”, the well was found to be cased in a series of terracotta cylinders of fine clay and of material so hard that it was initially mistaken for some kind of close-grained stone (Figure 1).

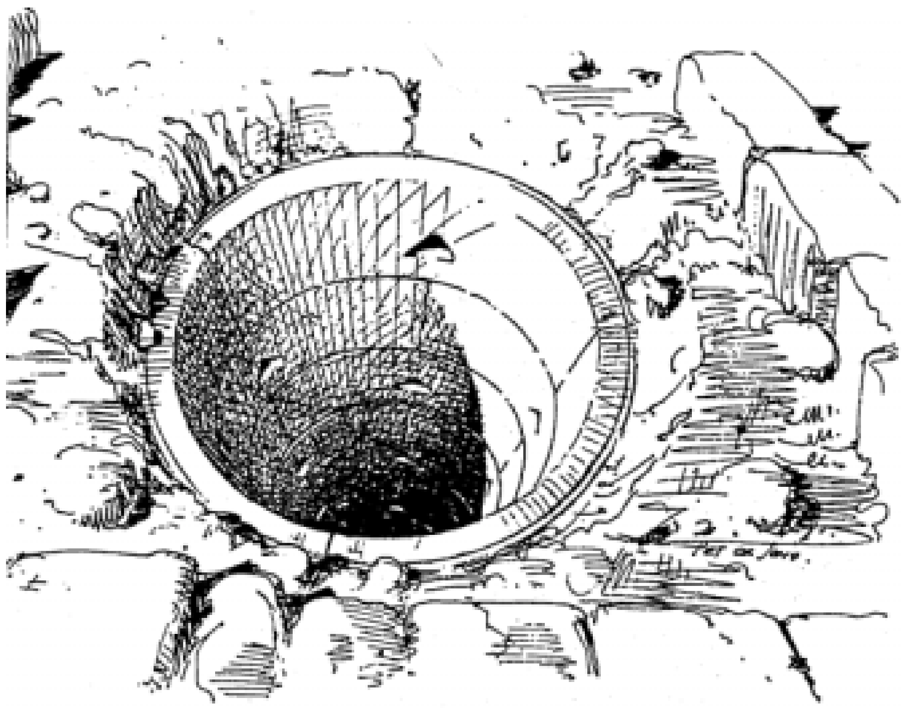


**Figure 1.** Perspective view of well below House A, NW of Knossos Palace (From reference 4).

The inhabitants of the Knossos Palace, however, did not depend on the water of the wells alone. 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 Fundana, and other springs. Mavrokolybos, a pure limestone spring, is located at a distance of 700 m south of the Palace and an elevation of about 115 m, whereas Knossos lies at an elevation of 85 m from sea level; Fundana, a typical karstic spring with excellent quality of water even today, is at a distance of about 5 km from the Palace and at an elevation of about 220 m.

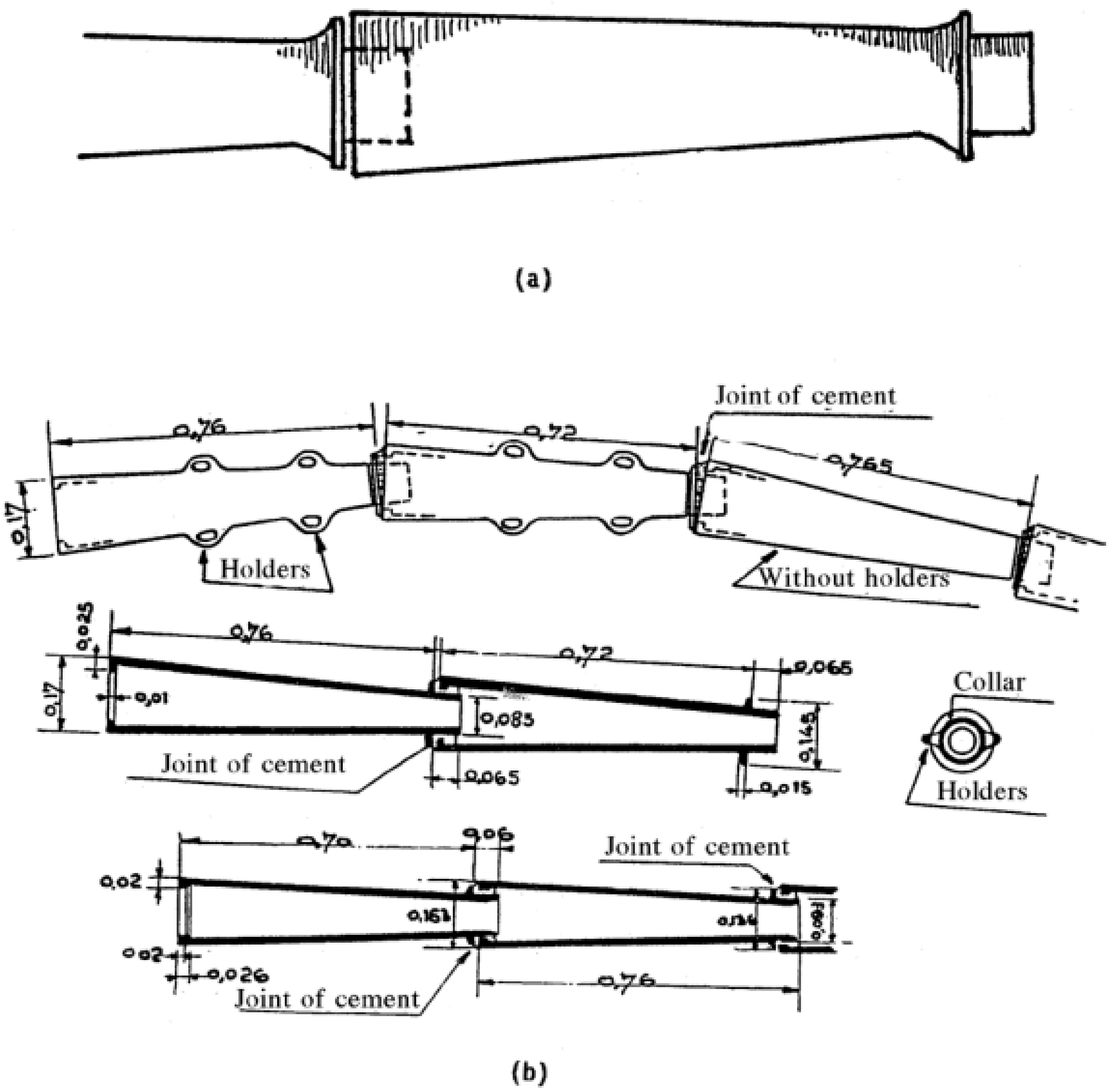



**Figure 2.** Minoan water supply pipes (terracotta pipe sections): (a) overview, and (b) with real dimensions (From reference 5).

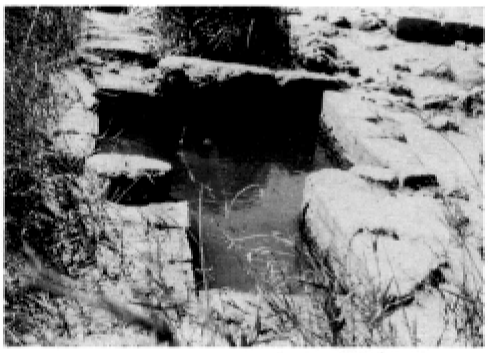
Water supply in the Palace was provided through a network of terracotta piping located beneath the Palace floors. The pipes were constructed in sections of about 60 to 75 cm each. These pipes with their expertly shaped, tightly interlocked sections, date from the earliest days of the building and are quite up to modern standards (Figure 2). The sections of the clay pipes resemble those used in Greece in classical times (Figure 7), 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 (5).

On the basis of their accomplishments, it can be assumed that Minoan hydraulic engineers 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 (4, 6). However, it appears that Minoans had only a vague understanding of the relationship between flow and friction.

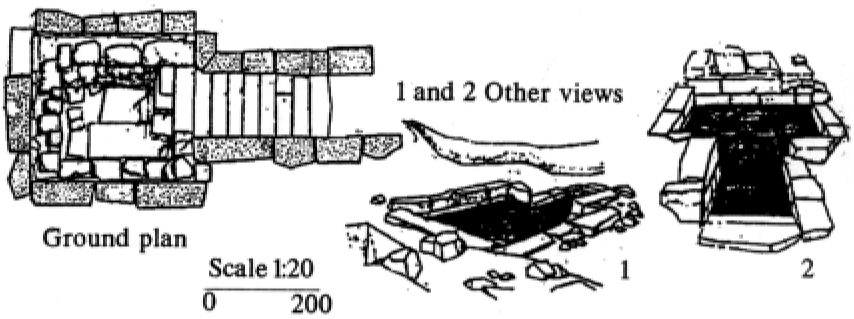
In the Zakros Palace the water supply system depended on groundwater. Here the potable water came from the Main Spring. In the southwest corner of the Cistern Hall an opening leads into a small chamber where the water was collected and channeled into a square underground fountain built on the south; this was thought to correspond with the celebrated man made fountain of the *Odyssey* known as "Τυκτή" fountain (7). The fountain was built of regular limestone, and there is a descending staircase with fourteen steps (Figure 3). The room may also have served as a shrine. The water of the fountain is brackish today, of about 13.00 dS/m EC (Electric Conductivity), due to intrusion of seawater. However, this may well be an indication that some reduction in the distance of the Palace from the coast has occurred.

Another comparable chamber in Zakros is a well-spring located near the southeast corner of the Central Court; here again steps lead down into the chamber. The wood of the windlass was found in the water, along with an offering cup containing olives; this is a unique, remarkable find, since the olives were perfectly preserved, as though they had just been picked from the trees; unfortunately they maintained their relative freshness for only a few minutes after they were taken out of the water (7). A view of this well-spring is given in Figure 4.

In contrast to Knossos, where water was conveyed mainly from springs, and Zakros dependent entirely on groundwater, in Phaistos the water supply system was dependent directly on precipitation: here, the rainwater was collected from the roofs and yards of buildings in cisterns. Special care was given to securing clean surfaces in order to maintain the purity of water. Also, coarse sandy filters were used to treat the rainfall water before it flowed into the cisterns.



(a)




(b)

**Figure 3.** Views of the “Τυκτή” fountain: (a) overall view and (b) scheme (From reference 7).

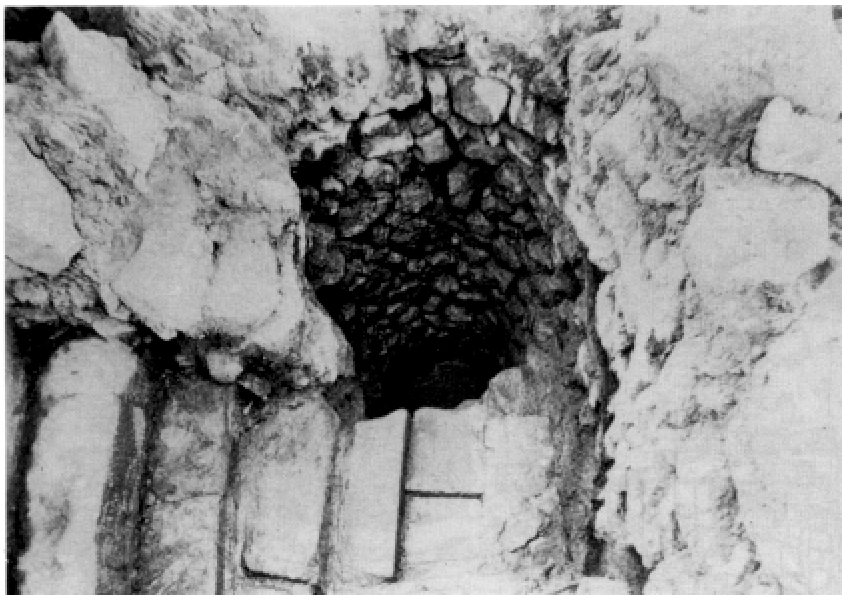


**Figure 4.** Well-spring located in the eastern wing of the Zakros Palace (From reference 7).

## 4. THE WATER SUPPLY OF SAMOS AND THE AWESOME FEAT OF EUPALINOS

The most famous hydraulic work of ancient Greece was the aqueduct of ancient Samos (located where now is the Pythagoreio or Tigani village in the Samos island), which was admired both in antiquity (as recognized by Herodotus) and in modern times (e.g., 8, 9, 10, 11, 12, 13, 14). The most amazing part of the aqueduct is the 1036 m long «Εὐπαλίνειον ὄρυγμα», or "Eupalinean digging", more widely known as Tunnel of Eupalinos. The aqueduct includes two additional parts (Figure 5) so that its total length exceeds 2800 m. The aqueduct was the work of Eupalinos, an engineer from Megara. Its construction was commenced in *ca.* 530 BC, during the tyranny of Polycrates and lasted for ten years. It was in operation until the 5th century AD and then it was abandoned and forgotten. Owing to the text of Herodotus, Guerin (8) uncovered the entrance of the aqueduct. The inhabitants of the island attempted to re-use the aqueduct in 1882 without success. Only ninety years later, between 1971 and 1973, the German Archaeological Institute of Athens undertook the task to finally uncover the tunnel.

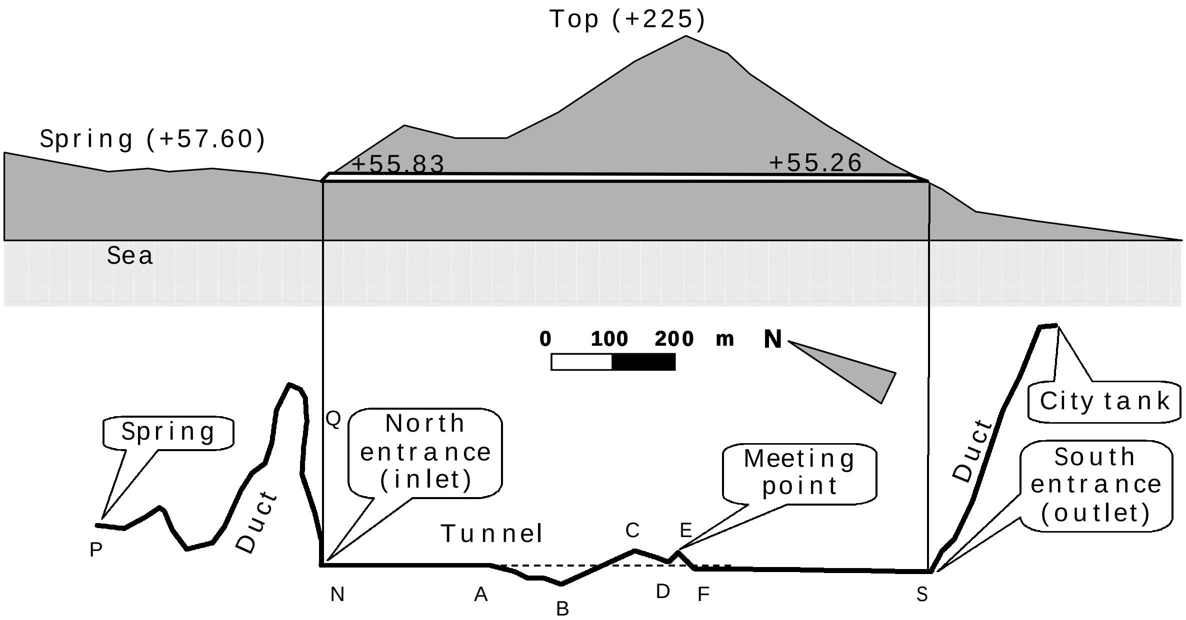



**Figure 5.** Sketch of the Tunnel of Eupalinos (up: vertical section; down: horizontal plan).

Herodotus (History, Γ, 60) called the tunnel «ἀμφίστομον» or "bi-mouthed", a characterization that caused curiosity to the readers (any tunnel has two openings or mouths). Only, when the tunnel was totally explored it was understood that Herodotus meant that the construction of the tunnel was started from two openings. Today, it is very common that water transportation tunnels are constructed from two openings to reduce construction time; high-tech geodetic means and techniques like global positioning systems and laser rays are used to ensure that the two fronts will meet each other. The great achievement of Eupalinos is that it did this using the simple means available at that time; apparently, however, he had good knowledge of geometry and geodesy. Later, in the 1st century BC, his achievement inspired the mathematician and engineer Hero (Heron) of Alexandria (Dioptra, III) who in his geometrical Problem #15 studied how "to dig a mountain on a straight line from two given mouths". His method is based on walking around the mountain measuring out in one direction, then turning at a right angle, measuring again, etc. and finally using geometrical constructions with similar triangles. Moreover, in modern times, it inspired many mathematicians, engineers and archeologists who attempted to reconstruct the methods used by Eupalinos to build the tunnel, as, apart from the mention by Herodotus, no written document was found from that time about the project.

Today, most of the questions have been answered but not all. For example, there is evidence that Eupalinos did not follow Hero's method, which would produce a large error. Most probably Eupalinos walked over the mountain and put poles up along the path in a straight line. When the workers were digging they could try to line themselves up with these poles. This also leaves room for error; as shown in Figure 5, there was a small departure in the two axes that Eupalinos implemented (NA and SF), which is now estimated to 7 m. Another question is: what led Eupalinos to leave the straight line NA at point A and follow the direction AB? A plausible explanation is given by Tsimpourakis (14): Eupalinos found a natural fracture or rift and broadening this rift he was able to proceed much faster. At the end of the rift, he attempted to correct the departure from the initial axis, following the route BC, but C was past this axis. Again according to Tsimpourakis (14), when the two teams of workers (each consisting of two people) were simultaneously at points C and F, they realized (hearing the sounds of the opposite team's excavating tools) that there were close to each other. Then, guided by the sounds of tools they managed to meet at point E. Hermann Kienast of the German Archaeological Institute of Athens proposed a different explanation: the last meters of the two routes of the tunnel (sections CDE and FE) were ingeniously designed rather than coincidentally followed: both teams were directed at points C and F to change direction to the right and then at D the northern one turned to the left on purpose; with this trick it is mathematically sure that the two lines would intersect.

Interestingly, the floor of the tunnel was done virtually horizontal, as observed from the elevations shown in Figure 5; one would expect that it should have some slope for the water to flow. The choice of a horizontal tunnel is related to the excavation from both sides. In a sloping tunnel, the front of the upper section would be inundated (mostly from groundwater), so that the workers could not dig. Another reason is the fact that the horizontal tunnel was easier to control and build with the simple instruments and tools of that time and facilitated the meeting of the two fronts (indeed, the difference in the elevation of the two sections at point F is only 0.60 m).

**Figure 6.** The Tunnel of Eupalinos. The duct is shown to the left.

However, this horizontal tunnel could not operate as an aqueduct, simply because the water would not flow horizontally. Therefore, Eupalinos excavated a slopping duct below the floor of the tunnel, shown in the photo of Figure 6. Its bottom, where clay pipes were arranged, is located 3.5 and 8.5 m in the inlet (N) in the outlet (S), respectively, below the floor of the tunnel; the large depth at the inlet is another question mark of the project, whose discussion is out of the scope of this chapter. At points where the depth becomes too large (in about 2/3 of the tunnel length) Eupalinos preferred to make a second tunnel, the water tunnel, below the main tunnel, the access tunnel. The water tunnel is about 0.60 m wide whereas the access tunnel is about 1.80 × 1.80 m. The construction of the water tunnel was easy and fast, provided that the access tunnel was completed; 28 vertical shafts were constructed for easy access to the water tunnel and many teams of workers must have been worked simultaneously to dig it. The outer parts of the aqueduct, were constructed in a similar manner. Thus, section PQ of the north duct (Figure 5) was constructed as an open channel whereas section QN was a tunnel with five shafts.

What Eupalinos did was not the only solution to the problem of conveying water to Samos. A simple alternative solution was to continue the simple and fast method of section PQN constructing a chain of open channels and tunnels at small depths with shafts. In this solution, the route to from point N to S would be around the mountain. Not only is this alternative solution technically feasible, but also it is technically easier, less expensive and faster. Why

Eupalinos preferred his unorthodox and breakthrough solution? How did he persuade the tyrant Polycrates to support this solution? These are unanswered questions. Probably he wished to build a monument of technology rather than simply solving a specific water transportation problem.

## 5. THE SUSTAINABLE URBAN WATER MANAGEMENT IN ATHENS

Water management in ancient Athens, the most important city of antiquity with a population of more than 200 000 during the golden age (5$^{th}$ century BC), is of great interest. Athenians put great efforts into the water supply of their anhydrous city. The first inhabitants of the city chose the hill of Acropolis for their settlement due to the natural protection it offered and the presence of three natural springs (15), the most famous being “Clepsydra”. However, natural springs in Acropolis and elsewhere were not enough to meet water demand. Therefore, Athenians used both groundwater, by practicing the art of drilling of wells, and stormwater, by constructing cisterns. In addition, the water from the two main streams of the area, Kephisos and Ilissos, whose flow was very limited in summer, was mainly used for irrigation.

Archeological evidence reveals that the city had developed an important system of public water supply consisting of wells, fountains and springs and there were also a number of private springs and wells. There are indications that a primitive distribution system was in place underneath the city, consisting of underground connections of wells (15); this expanded all around the city to the outskirts (16). The most important public work was the Peisistratean aqueduct, built in the time of the tyrant Peisistratos and his descendants (*ca.* 510 BC). The exact location and route of the aqueduct in not well known to date. It is known, however, that it carried water from the foothill of the Hymettos mountain, probably from east of the Holargos suburb at a distance around 7.5 km (17), to the center of the city near Acropolis. The greater part of it was carved as a tunnel at a depth reaching 14 m. In other parts it was constructed as a channel, either carved in rock or made of stone masonry, with depth 1.30-1.50 m and width 0.65 m (18). In the bottom of the tunnel or channel, a pipe made of ceramic sections was placed (Figure 7). The pipe sections had elliptic openings with ceramic covers in their upper part for their cleaning and maintenance; the ends of the sections were appropriately shaped, so that they could be tightly interlocked, and were joined with lead.

In the recent excavations for the construction of the metro, the widespread use of such ceramic pipes was revealed. Similar pipers were also used for sewers. Sewers of large cross section, most probably storm sewers, were built of stone masonry; some of them were natural streams, like Heridanos, that were covered (Figure 8).

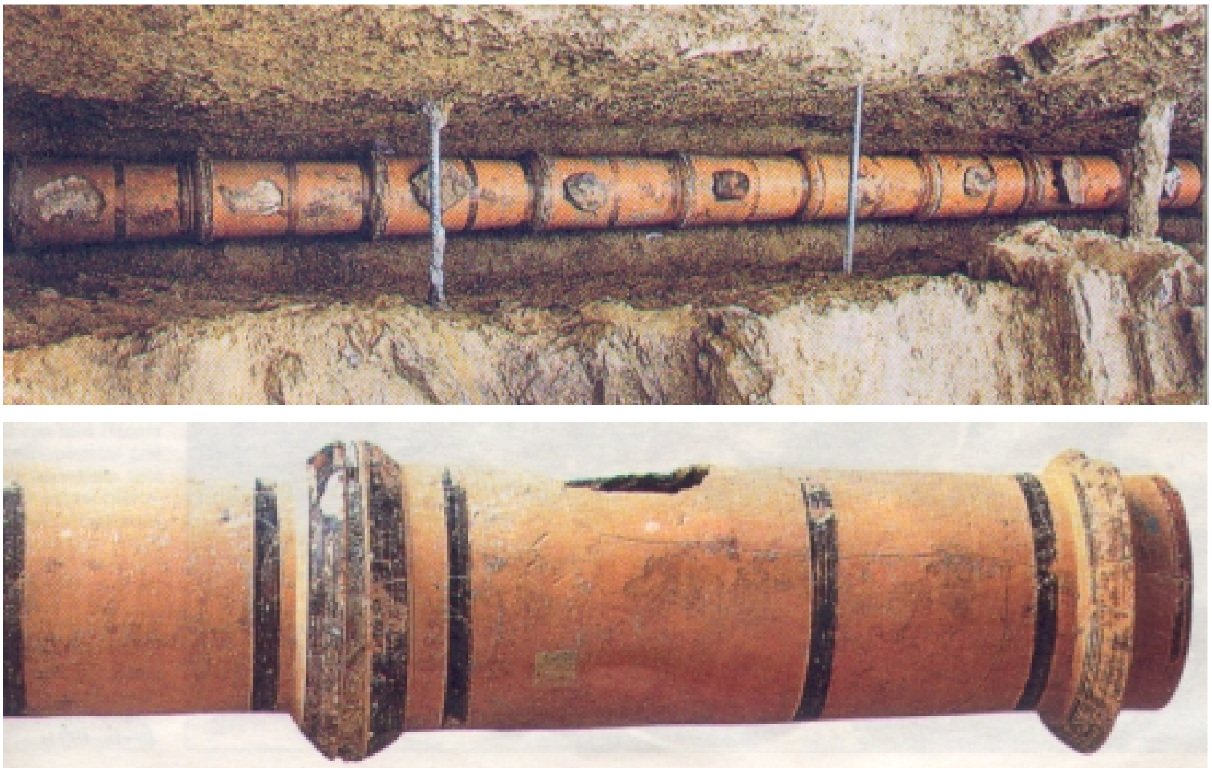


**Figure 7.** Part of the Peisistratean aqueduct (up) and detail of the pipe sections and their connection (down) (photos reproduced from newspaper Kathimerini).

Apart from the structural solutions for water supply and sewerage, the Athenian civilization developed a legislation and institutional framework for water management. The first known laws are due to Solon, the Athenian statesman and poet of the late seventh and early sixth century BC, who was elected archon in 594 and shaped a legal system by which he reformed the economy and politics of Athens. Most of his laws have been later described by Plutarch (47-127 AD), from whom it could be learnt that:

> "Since the area is not sufficiently supplied with water, either from continuous flow rivers, or lakes or rich springs, but most people used artificial wells, Solon made a law, that, where there was a public well within a hippicon, that is, four stadia (4 furlongs, 710 m), all should use that; but when it was farther off, they should try and procure water of their own; and if they had dug ten fathoms (18.3 m) deep and could find no water, they had liberty to fetch a hydria (pitcher) of six choae (20 liters) twice a day from their neighbors; for he thought it prudent to make provision against need, but not to supply laziness." (Plutarch, Solon, 23).

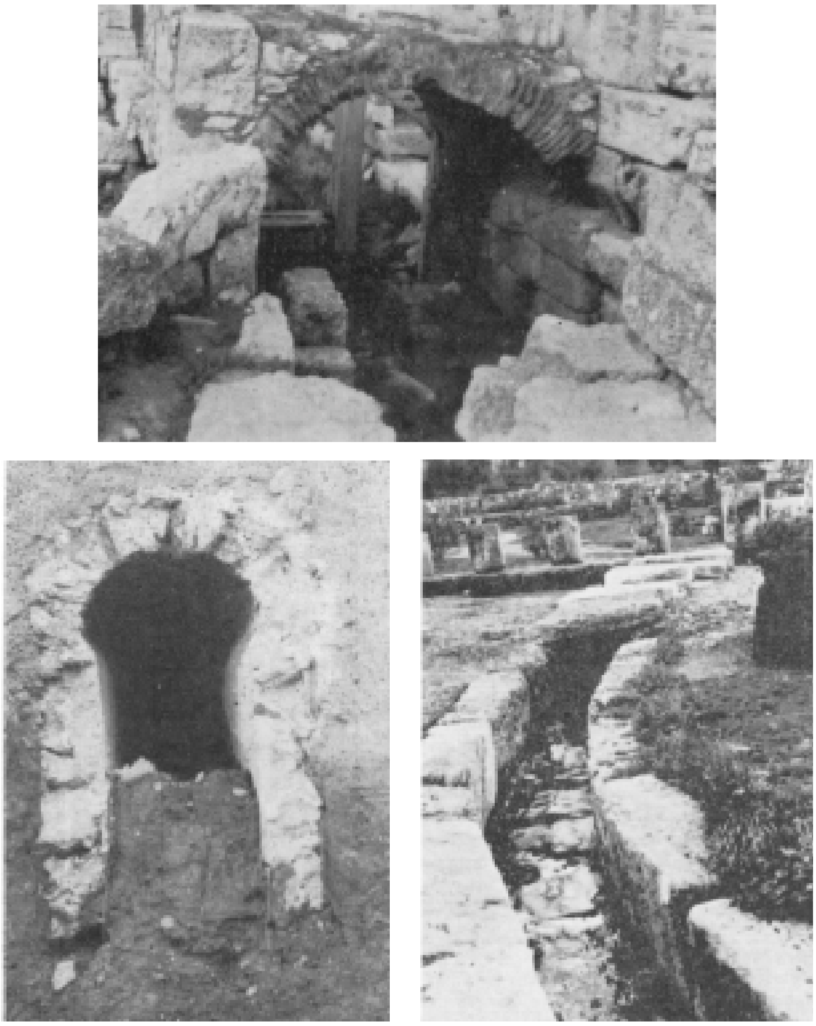


**Figure 8.** The Heridanos stream converted into a sewer at Ceramicos (up) and two tributary sewers (down) at Ceramicos (left) and Agora (right) (From reference 18).

MacDowell (19) conjectures that these laws have been kept unchanged through the classical period. As the city's public system grew and aqueducts transferred water to public fountains, private installations like wells and cisterns tended to be abandoned. But, the latter would be necessary in times of war because the public water system would be exposed; therefore, the owners were forced by decree to maintain their private facilities in good condition and ready to use (20). Other regulations protected surface waters from pollution (19). An epigraph of *ca.* 440 BC contains the "law for tanners", who are enforced not to dispose their wastes to Ilissos river (15).

A distinguished public administrator, called «κρουνῶν ἐπιμελητής», that is, officer of fountains, was appointed to operate and maintain the city's water system, and to ensure keeping of regulations and fair distribution of water. In addition, a number of guards were responsible for the proper daily use of the public springs and fountains. From Aristotle (Athenaion Politeia, 43.1) it is learn that the officer of fountains was one of the few that were elected by vote whereas most other officers were chosen by lot; so important was this position within the governance system of classical Athens (17). Themistocles himself had served in this position. In 333 BC the Athenians awarded a gold wreath to the officer of fountains Pytheus because he restored and maintained several fountains and aqueducts. The entire regulatory and management system of water in Athens must have worked exceptionally well and approached what today we call sustainable water management. For example modern water resource policymakers and hydraulic engineers emphasize the nonstructural measures in urban water management and the importance of small-scale structural measures like domestic cisterns, which reduce the amount of stormwater to be discharged and provide a source of water for private use.

The importance of water in Athens was not only related to the basic uses like drinking, cooking and cleaning. Water was also related to the beauty of the city; this is revealed from the many fountains that Athenians constructed and the depictions thereof on vessels. Given that vessels were used to export goods, they can be regarded as sort of advertisement of the city's beauty. Another important water use in Athens was in public baths, cool or warm, called «βαλανεῖα» (later passed in Latin as balineae or balneae), which, interestingly, at times were common for men and women (what we call today bains mixtes), and were related to enjoyment, health, socialization and culture (21). Later, the Romans took up and extended the Greek water technology including, of course public fountains and balneae, which became a matter of luxury and prestige. As a sort of requital, the Roman emperor Hadrian (117 –138 AD) showed particular interest for Athens; at his time the famous Hadrianic aqueduct was commenced, which conveyed water from mountains Parnes and Pentele to Athens covering a distance of 25 km. This aqueduct was in operation until the middle of the 20$^{th}$ century.

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