Water resources technologies in the ancient Greece

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Parts of the presentation

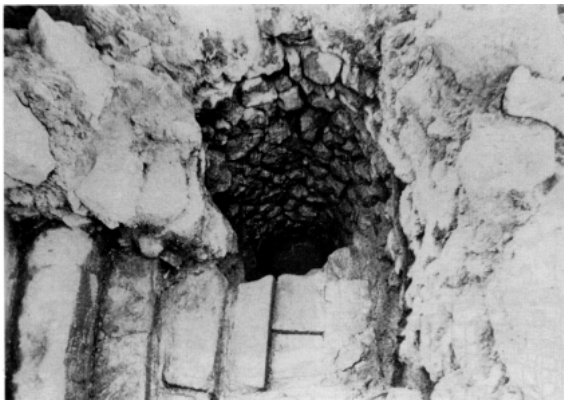
- The Minoan civilization and its "modern" sanitary life style
- Major agricultural and flood protection hydraulic works
- The water supply of Samos and the awesome feat of Eupalinos
- Athens and the sustainable urban water management
- Greek inventions for hydraulic mechanisms and devices
- Institutions for building public hydraulic works
- Epilogue: From application to understanding

The Minoan civilization and its "modern" sanitary life style
1. A note on history of Minoan civilization

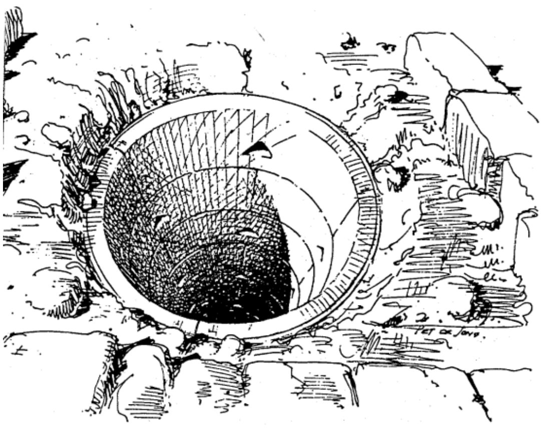
- Located in Crete island
- First cultural achievements since *ca*. 3000 BC
- Progressed especially in the Middle Bronze Age (*ca*. 2100-1600 BC)
- Prospered even more in the early phases of the Late Bronze Age (*ca.* 1600-1400 BC)
- Mostly known from large houses and luxurious palaces (e.g. Knossos, discovered by Evans, Zakros, Mallia, Gortys, Phaestos)
- Halted after the geological catastrophe through the eruption of the Santorini volcano (1450 BC)

The Minoan civilization and its "modern" sanitary life style
2. Water resources exploitation

- Groundwater exploitation (Knossos, Zakros)
  - Springs combined with aqueducts and/or cisterns
  - Wells
- Rainwater collection (Phaestos)
  - Cisterns



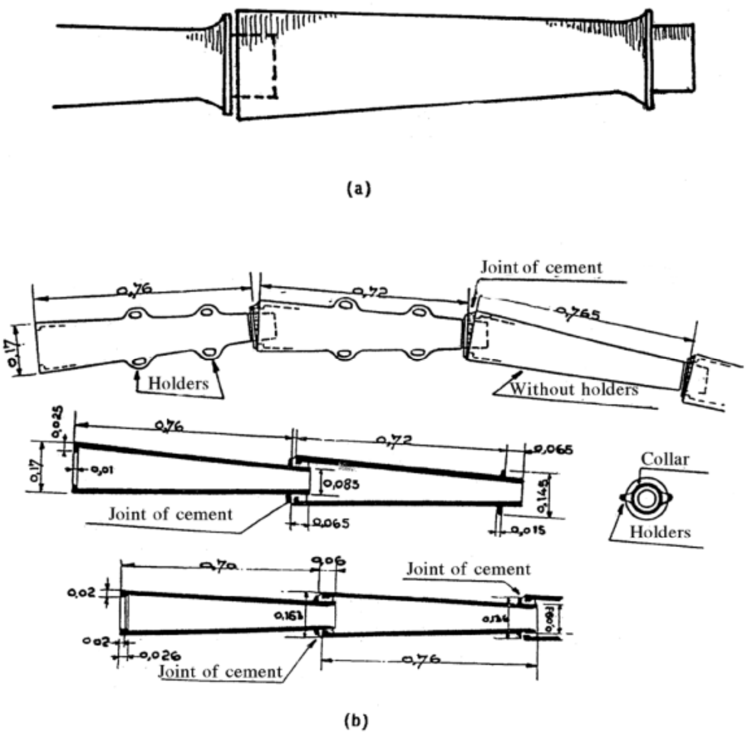
Well-spring located in the eastern wing of the Zakros Palace (Platon, 1974)



Perspective view of well below House A, NW of Knossos Palace (Evans, 1921-1935)

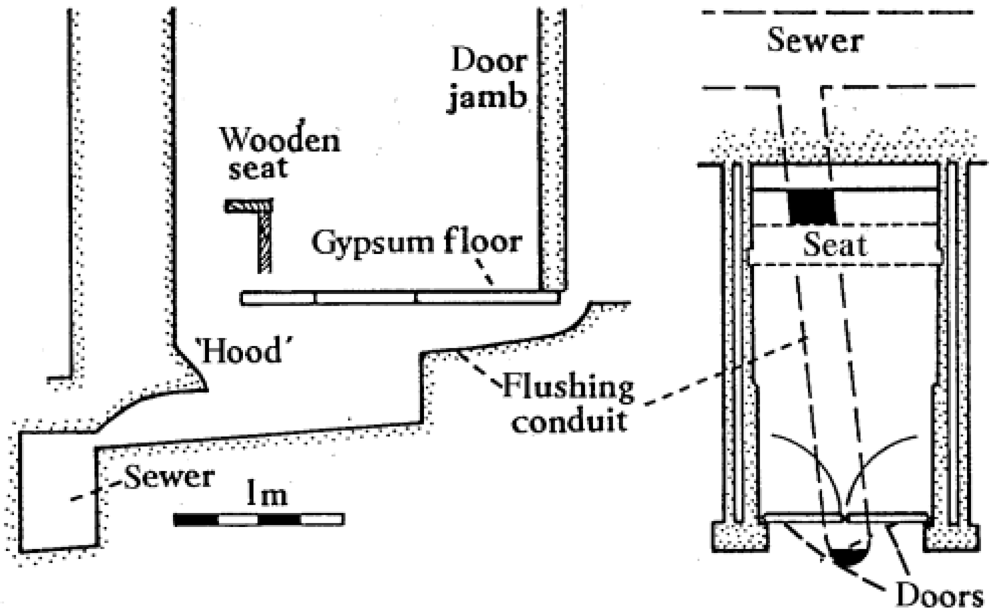
3. Minoan water supply systems

In the Knossos Palace, water was conveyed from springs at distances 700 m – 5 km using terracota pipes



Terracotta pipe sections (Buffet and Evrard, 1950

4. Minoan toilets



Section and plan of ground-floor toilet in the residential quarter of Palace of Minos (Graham, 1987).

5. Minoan sanitary and storm sewers

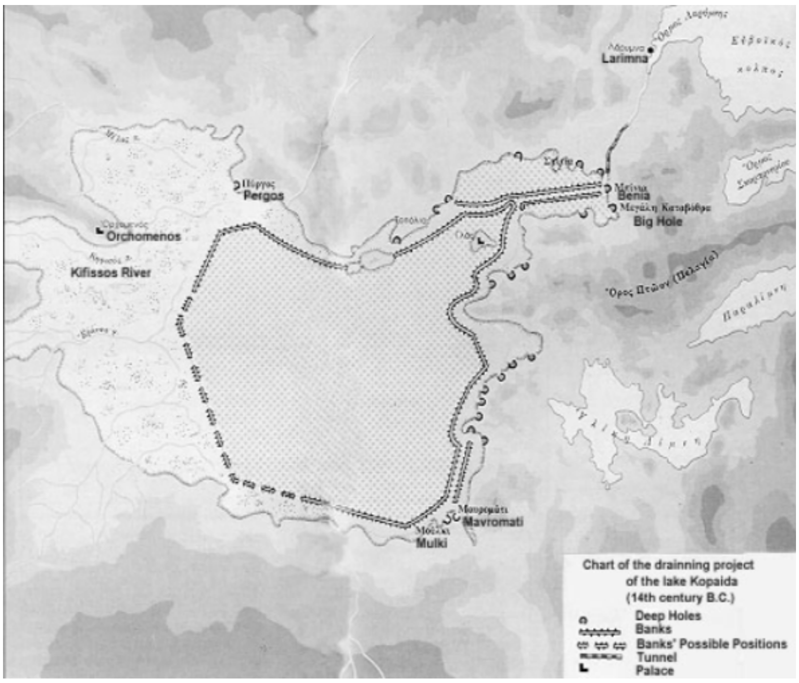
Part of restored stairway with parabolic runnels in Knossos Palace

Parts of the sanitary and storm sewer systems in Agia Triadha (Angelakis and Spyridakis, 1996)

Note
At the beginning of the 20th century, when the Italian writer and scientist Angelo Mosso visited the villa of Agia Triadha during a heavy storm, he noticed that all the sewers of the villa functioned perfectly and was amazed to see storm water come out of sewers. Mosso concluded that in the entire history of humankind there exists no other example of a sewerage system still functional today, 4000 years after its original construction (Spanakis, 1981).

Major agricultural hydraulic works: The Copais Mycenaean project

Massive hydraulic engineering works that most probably drained the lake Copais were built in late Mycenaean times (*ca.* 1450-1300 BC). Huge earthen dykes furnished with Cyclopean walls were built along the sides of Copais. Three main canals with length 40-50 km, width 40-80 m and parallel walls up to 2-3 m thick traverse the former lake area (Papademos, 1975; Lazos, 1993). The scale of this vast project dwarfs any other Mycenaean building project. The area became reflooded sometime later (probably due to earthquakes, *ca.* 1100 BC).

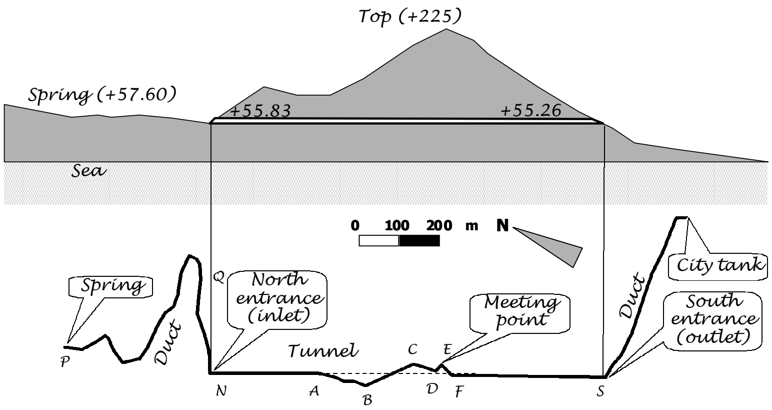


Major flood protection works: The Tiryns dam

During a flood (ca. 1250-1200 BC), a stream south of Tiryns abandoned its bed and shifted to the north of Tiryns. To protect the lower town from future floods the inhabitants of Tiryns installed an artificial river diversion consisting of a 10 m high and 300 m long dam and a 1.5 km long canal. The dam is a huge earthen embankment lined with Cyclopean masonry across the earlier western streambed

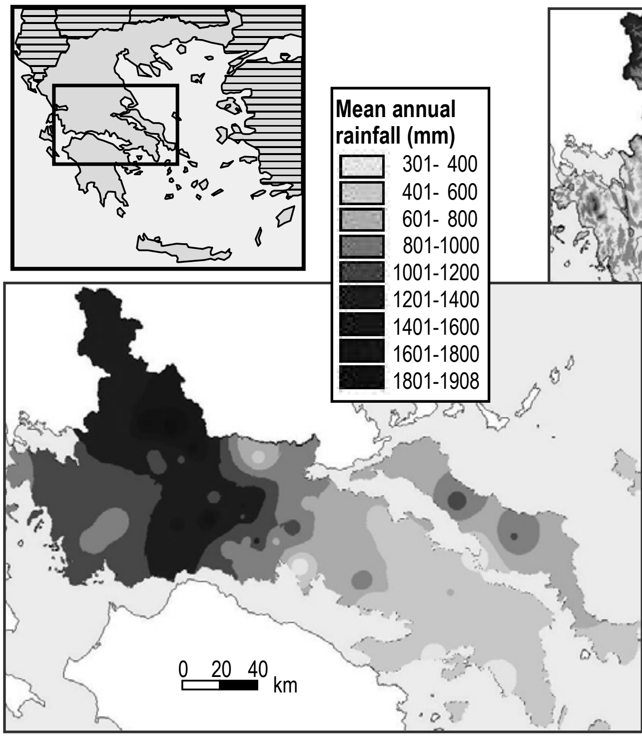
Remnants of the Tiryns dam; east face and detail of Cyclopean lining of east face (photos from http://devlab.cs.dartmouth.edu/history/bronze_age/)

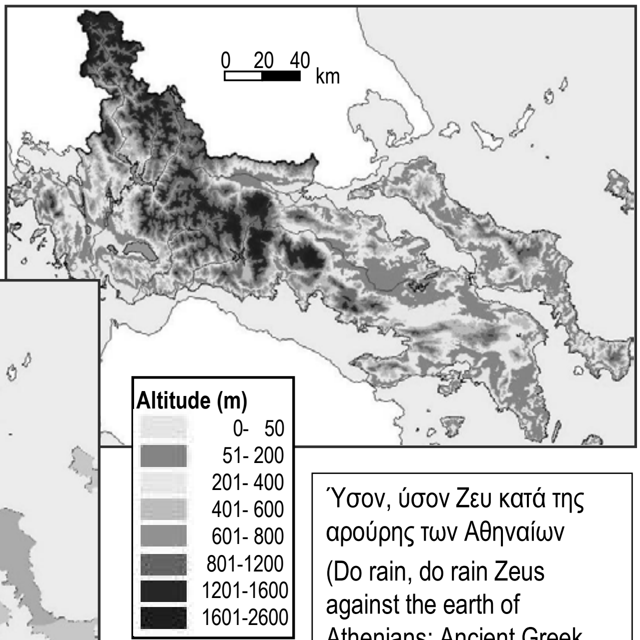
The water supply of Samos and the awesome feat of Eupalinos



The most famous hydraulic work of ancient Greece was the aqueduct of ancient Samos, which was admired both in antiquity (e.g. Herodotus) and in modern times. The most amazing part of the aqueduct is the 1036 m long, dug from two openings, «Ευπαλίνειον όρυγμα», or "Eupaninean digging", after Eupalinos, an engineer from Megara. Its construction started in 530 BC, during the tyranny of Polycrates and lasted for ten years. Owing to the text of Herodotus, Guerin (1856) uncovered the entrance of the aqueduct. Only ninety years later, between 1971 and 1973, the German Archaeological Institute of Athens uncovered the entire tunnel (Kienast, 1977; Tsimpourakis, 1997).

Athens and the sustainable urban water management
1. The climatic conditions

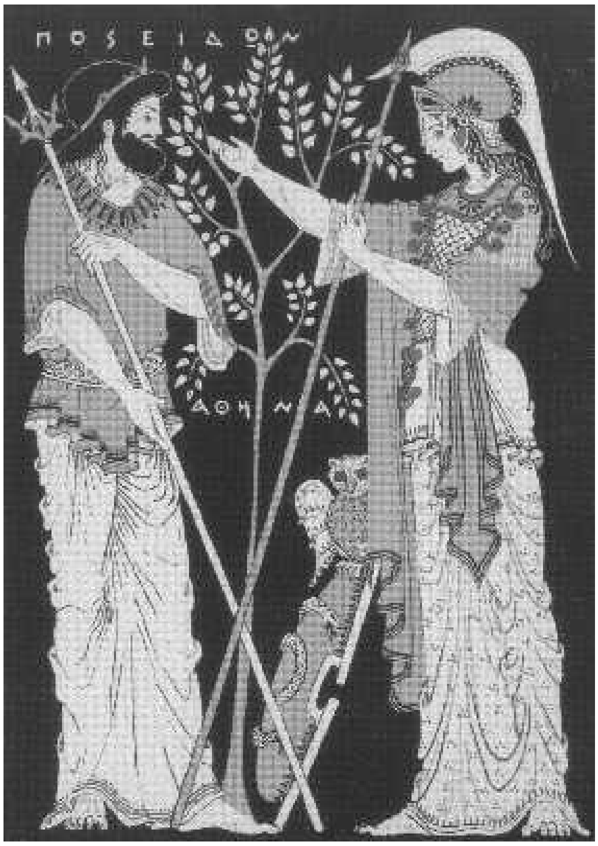




Ύσον, ύσον Ζευ κατά της αρούρης των Αθηναίων

(Do rain, do rain Zeus against the earth of Athenians; Ancient Greek prayer)

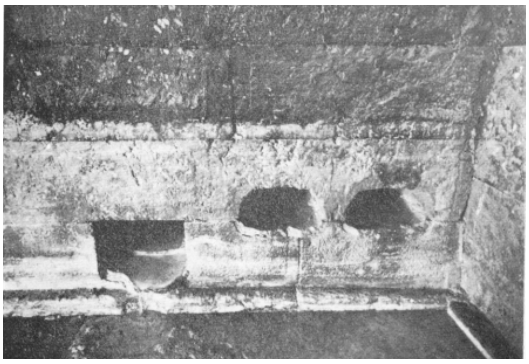
2. The myth



Water shortage in Athens has been characteristically reflected in the well-known myth of 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.

After many centuries, the symbolic character of the myth 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.

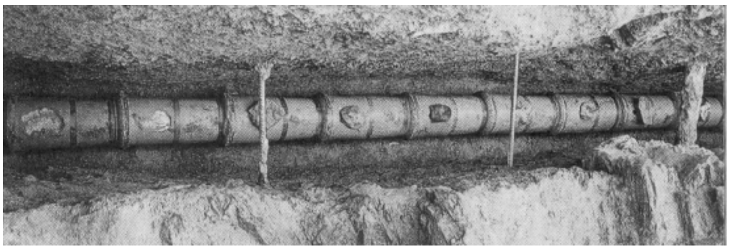
3. The initial stage of water supply

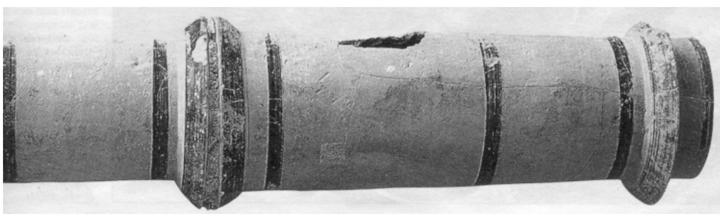


The interior of the tank of the Clepsydra spring at Acropolis (photo from Papademos, 1975).

- Athens was the most important city of antiquity with a population of more than 200 000 during the golden age (5th century BC)
- Athenians put great efforts into the water supply of their anhydrous city. The first inhabitants of the city chose the hill now known as Acropolis for their settlement due to the natural protection it offered and the presence of three natural springs (Pappas, 1999), the most famous being "Clepsydra".
- Natural springs were not enough to meet urban water demands. 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.

4. The Peisistratean aqueduct





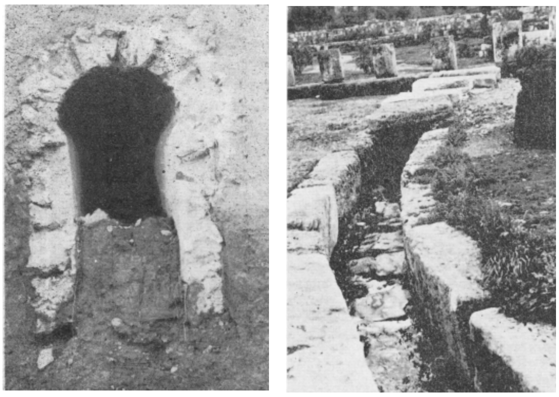
Part of the Peisistratean aqueduct (up) and detail of the pipe sections and their connection (down) (photos reproduced from newspaper Kathimerini).

- The most important work was the Peisistratean aqueduct, built in the time of the tyrant Peisistratos and his descendants (*ca.* 510 BC).
- It carried water from the foothill of the Hymettos mountain (probably from east of the Holargos suburb at a distance around 7.5 km; Tasios, 2002a), 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 from stone masonry, with depth 1.30-1.50 m and width 0.65 m (Papademos, 1975).
- In the bottom of the tunnel or channel, a pipe made of ceramic sections was placed.

5. The sewer system

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. However, sewers of large cross section were built of stone masonry. Most probably these were storm sewers; some of them were natural streams, like Heridanos, that were covered and converted into sewers

The Heridanos stream converted into a sewer at Ceramicos (photo from Papademos, 1975)



Two tributary sewers at Ceramicos (left) and agora (right) (photos from Papademos, 1975).

6. Legislation

- Apart from the structural solutions for the water supply and sewerage of Athens, the Athenian civilization developed a framework of laws and institutions for water management.
- The first known regulations were designed by Solon, the Athenian statesman and poet of the late seventh and early sixth century BC, who 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 we learn:

  > "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 liiters) twice a day from their neighbours; for he thought it prudent to make provision against need, but not to supply laziness." (Plutarch, Solon, 23).

- As the city's public system grew and aqueducts transferred water to public fountains, private installations like wells and cisterns tended to be abandoned. As the latter would be necessary in times of war because the public water system would be exposed, the owners were forced by regulation to maintain the wells at a good condition and ready to use (Korres, 2000).
- Other regulations protected surface waters from pollution (MacDowell, 1978). An epigraph of *ca.* 440 BC contains the "law for tanners", who are enforced not to dispose their wastes to Ilissos river (Pappas, 1999).

7. Institutions

- A distinguished public administrator, called «κρουνών επιμελητής», that is, officer of fountains, was appointed to operate and maintain the city's water system, to monitor enforcement of the regulations and to ensure the fair distribution of water.
- Reporting to the officer of fountains there were a number of guards, responsible for the proper daily use of the public springs and fountains.
- From Aristotle (Athenaion Politeia, 43.1) we 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 (Tasios, 2002a).
- 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 have in recent international conferences emphasized the nonstructural measures in urban water management and the importance of small-scale structural measures like domestic cisterns. Such cisterns have two advantages: They reduce the amount of stormwater to be discharged and provide a source of water for private use (like watering of gardens).

Greek inventions for hydraulic mechanisms and devices

- Today's hydraulic projects are typically equipped with electromechanical equipment, e.g. pumps.
- Although in antiquity several devices were in use to lift water to a higher elevation, the first pump with the modern meaning is Archimedes's helix or water-screw. Archimedes was a Syracusian mathematician and engineer (287-212 BC) considered by many to be the greatest mathematician of antiquity or even of the entire history. The invention of the water screw is tied to the study of the spiral, for which Archimedes wrote a treatise entitled On Spirals, in 225 BC.
- This pump is an ingenious device functioning in a simple and elegant manner by rotating an inclined cylinder bearing helical blades around its axis whose bottom is immersed in the water to be pumped. As the screw turns, water is trapped between the helical blades and the walls, thus rises up the length of the screw and drains out the top.

Archimedes's water screw in its original form as depicted in an Italian stamp along with a bust of Archimedes (from http://www.mcs.drexel.edu/~crorres/Archimedes/Stamps/)

Archimedes's water screw in its modern form, as implemented in the wastewater treatment plant of Athens (1 of 5 screws that pump 1 million m^3 per day).

Institutions for building public hydraulic works

- It was a common practice in ancient Greece that competition announcements, project specifications and project contracts were written on marble steles erected in public sites so that everyone would have known all project details and, simultaneously, the breach of contract would be difficult. As Tassios (2002b) puts it, if someone wished to violate some terms, he would "stumble on them".
- To validate the fact that *scripta manent*, the contracts of certain projects were revealed in excavations. As a typical example, the contract for draining and exploitation of the lake Ptechae (probably identified with the Dystos Lake in Southern Euboea), which is between the Eretrians and the engineer-contractor Chairephanes (2nd half of 4th century BC), was revealed in Chalkis (1860) and is kept in the Athens Archaeological Museum. The project is what we call today BOT – Build, Operate, Transfer. The rather wordy (like construction contracts of today) contract is written on a Pentelian marble stele with dimensions: $87 \times 47 \times 9$ cm (Papademos, 1975). On the surface relief sculptures show the Gods that were worshiped in the region, Apollo, Artemis and Leto. A carved scripture in 66 verses signed by more than 150 people contains the construction contract, which starts as follows:

  «Κατά τάδε Χαιρεφάνης επαγγέλλεται Ερετριεύσιν εξάξειν και ξηράν ποιήσειν την λίμνην την εν Πτέχαις ...» (In this, Chairephanes promises to the Eretrians that he will drive away the Ptechae lake and make it land …)
- The first 35 verses are the main contract. In the continuation two resolutions of the parliament are given. With the first one asylum is granted to Chairephanes and his collaborators for the whole duration of the contract and in the second resolution the keeping of the contract is confirmed by oath to Apollo and Artemis; against misdemeanors moral and material sanctions (penalty for breach of contract) are foreseen such as the confiscation of their property and the dedication of it to Artemis.

Institutions for building public hydraulic works (2)

A summary of the main contract for draining of the lake Ptechae (adapted from Papademos, 1975)

1. Between the city of the Eretrians representing the 31 municipalities of the Eretrian region and the contractor Chairephanes, a contract is made concerning the draining of the Ptechae Lake.
2. The draining works include the construction of drainage canals, sewers, and wells for the drainage of water to natural underground holes or cracks, and miscellaneous protection works including wooden or metallic railings.
3. In addition, irrigation works, such as the construction of a reservoir with side length up to 2 stadia (360 m) for storing irrigation water, and sluice gates, are included in the contract.
4. It is agreed a 4-year construction period that could be extended in case of war.
5. The contractor is granted the right to exploit the dried fields for 10 years (extended in case of war), starting by the finishing of the drying works.
6. The contractor is granted the privilege of custom free import of materials (stones and wood).
7. The contractor is obliged (a) to pay all labor costs without any charge for the people Eretria; (b) to pay the amount of 30 talents in monthly installments as a rental for the permission to exploit the lake for 10 years; (c) to maintain all works for the exploitation period, in order to be in good condition after the finishing of the contract; (d) to compensate the land owners by one drachma per foot of land area that is to be the expropriated for the construction of works; and (e) to avoid harm on private property as much as possible by locating the works in non cultivating areas.
8. In case of death of the contractor, his heirs and collaborators will substitute him in the relations to the city.
9. Penalties are enforced against any person trying to annul the contract.
10. The contractor is obliged to submit a good construction guarantee up to the amount of 30 talents.

Epilogue: From application to understanding

- The approach typically followed in problem solving today is represented by the sequence Understanding – Data – Application, in this order. However, the historical evolution in the development of water science and technology (and other scientific and technological fields) followed the reverse order: application preceded understanding (Dooge, 1988).
- It has been believed by many water scientists that ancient Greeks had not achieved understanding of the water related phenomena, and had a wrong conception of hydrological cycle. This belief is mainly based on Plato, whose dialogue Phaedo (14.112) indeed reveals misconception of the natural water cycle.
- However, long before Plato, as well as much later, several Greek philosophers had developed correct explanations of hydrological cycle, which reveal good understanding of the related phenomena. Here is a catalog of a number of ancient Greek contributions revealing correct understanding of water related phenomena (adapted from Koutsoyiannis and Xanthopoulos, 1999).
- The Ionian philosopher Anaximenes (585-525 BC) studied with ingenuity the meteorological phenomena and presented correct explanations for the formation of clouds, and the cause of winds and rainbow.
- The Pythagorean philosopher Hippon (5^{th} century BC) recognizes that all waters originate from the sea.

Epilogue: From application to understanding (2)

- Anaxagoras, who lived in Athens (500-428 BC) and together with Empedocles, is recognized as the father of experimental research, clarified the concept of hydrological cycle: the sun raises water from the sea into the atmosphere, from where it falls as rain; then it is collected underground and feeds the flow of rivers. He also studied several meteorological phenomena, generally supporting and completing Anaximenes's theories; his theory about thunders, which fought the belief that they are thrown by Zeus, probably cost him imprisonment (430 BC). In particular, he correctly assumed that winds are caused from differences in the air density: the air, heated by the sun, moves towards the north pole and leaves gaps that cause air currents. He also studied Nile's floods attributing them to the snowmelt in Ethiopia. The "enigma" of Nile's floods (which, contrary to the regime of Mediterranean rivers, occur in summer) was also thoroughly studied by Herodotus (480-430 BC), who seems to have clear knowledge of hydrological cycle and its mechanisms.
- Aristotle (384-323 BC) in his treatise Mereorologica clearly states the principles of hydrological cycle, clarifying that water evaporates by the action of sun and forms vapor, whose condensation forms clouds; also, he recognizes indirectly the principle of mass conservation within hydrological cycle.
- Theophrastus (372-287 BC) adopts and completes the theories of Anaximenes and Aristotle for the forming of precipitation from vapor condensation and freezing; his contribution to the understanding of the relation between wind and evaporation was significant.

Epilogue: From application to understanding (3)

- Epicurus (341-270 BC) contributed to physical explanations of meteorological phenomena, contravening the superstitions of his era.
- Archimedes (287-212 BC), among other significant contributions, founded hydrostatics introducing the principle named after him.
- Hero of Alexandria (after 150 BC) is recognized (U.S. Committee on Opportunities in the Hydrological Sciences, 1992) as the first who formulated the discharge concept and made flow measurements.
- Unfortunately, many of these correct explanations and theories were ignored or forgotten for many centuries, only to be re-invented during Renaissance or later. This was not restricted to water related phenomena.
- For example, the heliocentric model of the solar system was first formulated by the astronomer Aristarchus of Samos (310-230 BC) who also figured out how to measure the distances to and sizes of the Sun and the Moon. Copernicus, who re-invented that, acknowledges this in his book.
- In addition, not only did ancient Greeks know that Earth is spherical, but also Eratosthenes (276-194 BC) calculated, 1700 years before Columbus, the circumference of the earth with an error of only 3% by measuring the angle of the sun's rays at different places at the same time; in addition Strabo had defined the five zones or belts of Earth's surface (torrid, two temperate and two frigid) that we also use today.

References

- Angelakis A.N. and S.V. Spyridakis (1996). Wastewater Management in Minoan Times. Intern. Proc. of the Meeting on Protection and Restoration of Environment, August 28-30, Chania, Greece, pp. 549-558.
- Buffet, B., and R. Evrard. (1950). L'Eau Potable a Travers Les Ages. Editions Soledi, Rue de la Province, 37, Liege, Belgium.
- Dooge, J. C. I., (1988). Hydrology, past and present. Journal of Hydraulic Research, 26(1), 5-26.
- Evans, S.A. (1921-1935). The Palace of Minos at Knossos: A comparative account of the successive stages of the early Cretan civilization as illustrated by the discoveries. Vols. I-IV, Macmillan and Co., London (reprinted by Biblo and Tannen, New York, 1964).
- Graham, J.W. (1987). The Palaces of Crete. Revised Ed. Princeton University Press, Princeton, New Jersey.
- Guerin, V. (1865). Description de l'Ile Patmos et de l'Ile Samos, Paris.
- Kienast, H. J., Der Tunnel des Eupalinos auf Samos, *Architectura*, Zeitschrift für Geschichte der Architektur, 97-116, 1977.
- Korres M. (2000), Water supply of Athens in antiquity (in Greek). Workshop: "Water and Environment", EYDAP, Athens.
- Koutsoyiannis, D., and T. Xanthopoulos (1999). Engineering Hydrology (in Greek). 3rd edition, 418 pages, National Technical University of Athens, Athens.
- Lazos, C. D. (1993). Mechanics and Technology in Ancient Greece (in Greek). Aeolos, Athens.
- MacDowell, D. M. (1978). The Law in the Classical Athens. Thames and Hudson, London.
- Papademos, D.L. (1975). The Hydraulic Works in Ancient Greece, Vol. B (in Greek). Ed. TEE, Athens.
- Pappas, A. (1999). The Water Supply of Ancient Athens (in Greek). Eleuphtheri Skepsis, Athens.
- Platon, N. (1974). Zakros, The New Minoan Palace (in Greek). The Athens Archaeological Society, Athens.
- Spanakis, S. G. (1981). The Water Supply of Heracleion 828-1939 (in Greek). TEE/TAK, Heracleion.
- Tassios, T. P. (2002a). From "Peisistratean" to Evinos (in Greek). Kathimerini, 24 March 2002.
- Tassios, T. P. (2002b) Transparency and ancients (in Greek). To Vima, 5 May 2002.
- Tsimpourakis, D. (1997). 530 BC, The Digging of Eupalinos in Ancient Samos (in Greek). Editions Arithmos, Athens.
- U.S. Committee on Opportunities in the Hydrological Sciences (1991) Opportunities in the Hydrologic Sciences. National Academy Press, Washington, DC.