

Chapter 2

Water for human consumption through history

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2.1 PROLEGOMENA

In the long history of humankind the basic, most powerful, propelling force that shaped his action was the need to secure food and water. Air was beyond his control. This is shown practically in all excavations of prehistoric human habitations. They all had one thing in common; all were located near sources of a spring, river, lake or stream.

Humans have spent most of their history as hunting and food gathering beings. Only in the last 9000 to 10,000 years did they discover how to grow crops and tame animals. Such revolution probably first took place in the hills to the north of Mesopotamia. From there the agricultural revolution spread to the Nile and Indus Valleys. During this agricultural revolution, permanent villages replaced a wandering existence. About 6000 to 7000 years ago, farming villages of the Near East and Middle East became cities. During the Neolithic age (*ca.* 5700–3200 BC), the first successful efforts to control the flow of water were driven by agricultural needs (irrigation) and were implemented in Mesopotamia and Egypt. Remains of these prehistoric irrigation canals still exist (Mays *et al.* 2007).

Urban hydraulic systems are dated at the Bronze Age (*ca.* 3200–1100 BC). There are several astonishing examples of urban water systems from about the mid-third millennium BC. Mohenjo-Daro, located in the province of Sindh, Pakistan, one of the largest settlements of the ancient Indus Valley Civilization, developed a sophisticated system for water supply and sewage. Built *ca.* 2600 BC, it was one of the world's earliest major urban settlements, existing at the same time as the civilizations of ancient Egypt, Mesopotamia, and Minoan Crete. Water came from more than 700 wells and supplied not only domestic demands but also a system of private baths and a Great Bath for public use (Jansen, 1989). The Mesopotamians were not far behind (Adams, 1981). An example is the city of Eshnunna (80 km northeast of the present Baghdad) dated in the same period, where archaeological excavations exposed sewers constructed of brick, with laterals connecting to houses (Gray, 1940). In the Sumerian city of Nippur the excavations exposed clay pipes as well as tee- and angle-joints. Rainwater harvesting and collection in cisterns for urban water supply was practised at about the same period in Jawa in north-eastern Jordan (Abdel Khaleq & Alhaj Ahmed, this issue). Another collection system, this time for groundwater, was developed in Persia, again in the same period (Hassan, 2003). This is the well-known

“qanat” – a subterranean system of tunnels connecting wells and dug using vertical shafts, designed to collect and transport water, sometimes over long distances, from highlands to low-lying farming land.

Amazing characteristics of the latter technology are its application over a tremendously long period up to modern times and the durability of the systems constructed. For instance, in Iran, over millennia, 22,000 qanat units were constructed, comprising more than 270,000 kilometres of underground channels. In the 1960s, 75% of all the water used in that country for irrigation and domestic consumption was provided by such systems (Wulff, 1968). Over the centuries, the technology was transferred to all civilizations and become known with different names such as “karez” (Afghanistan and Pakistan), “kanerjing” (China), “falaj” (United Arab Emirates) and “foggara/fughara” (North Africa). A “foggara” in Algeria is shown in Figure 2.1. According to UNESCO recommendations, some of those projects are protected as monuments of world heritage (Mays *et al.* 2007).



Figure 2.1 A foggara at Adrar, Algeria: (left) shaft; (right) distribution and metering weir at the foggara outlet (Mays *et al.* 2007)

As in the Indus Valley civilization, the history of water supply engineering on Crete dates back more than ca. 5000 years. From the early Minoan period (ca. 3200–2300 BC) issues related to water supply were considered of great importance and were accordingly developed. Archaeological and other evidence indicate that during the Bronze Age advanced water management and sanitary techniques were practised in several settlements in Crete (Angelakis & Koutsoyiannis, 2003). The emergence of the palaces reveals a remarkable development of water management in the urban context. Moreover, during the Middle Minoan and the beginning of the Late Minoan periods (ca. 2000–1500 BC) a “cultural explosion” occurred on the island. A striking indication of this is manifested, *inter alia*, in the advanced water management techniques practised in Crete at that time (Angelakis & Spyridakis, 1996; Koutsoyiannis *et al.* 2008). These included various scientific fields of water resources, such as wells and ground-water hydrology, aqueducts and domestic water supply according to local conditions in terms of climate and geomorphology. Additionally, the constructions and use of sanitary and purgatory facilities, even the recreational uses of water, signify attitudes of life and taste (Angelakis *et al.* 2005; Antoniou & Angelakis, 2011).

Minoan hydraulic technologies were developed further in Greece during several stages of the Greek civilizations. New more advanced water technologies were also invented there, with a peak in the Hellenistic period which followed Alexander the Great, during which they spread over a geographical area from Greece to India to the east and Egypt to the south. The Romans, whose empire replaced the Greek rule in most part of this area, inherited the technologies and developed them further also changing

their application scale from small to large and implementing them in almost every large city. The Greek and Roman water technologies are not only a cultural heritage but are the underpinning of modern achievements in water engineering and management. The durability of some of the constructions that operated up to modern times, as well as the support of the technologies and their scientific background by written documents, enabled these technologies to pass to modern societies despite regressions that have occurred through the centuries (e.g. in the Dark Ages).

The availability of drinking water is an essential condition for 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 developed close to rivers both for the availability of water suitable for human needs as well as agricultural and 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 hygiene and aesthetic conditions.

Every settlement of the humankind basically depends on a sufficient water supply. This applies especially for arid and semi-arid climate conditions in the regions around the Mediterranean basin and the Near East, where water resources availability is extremely limited mainly during the summer. Meanwhile, in these regions the first cultures rose. The scope of this Chapter is to present the main achievements in selected fields of potable water management chronologically including water supply technological principles and consumption by humans, extending from the earliest to the present. It is not an exhaustive presentation of what is known today about water treatment, related technologies and their uses in water supply since the beginning of humans' quest for water supply systems. Emphasis is given to the periods of great achievements.

2.2 NEOLITHIC AGE

There is an intriguing similarity between the lives of these people in spite of the distances that separated them. Water canals for drinking purposes and irrigation of the land were very much in use by them. Incidentally, and perhaps by coincidence, they were the first to use the land and developed early forms of agriculture instead of depending on nature alone to provide food for them as was the case with primitive man. We find similar man-made water canals and other water-saving devices in ancient Egypt as early as *ca.* 4000 BC.

The Egyptians believed in life after death and spoke freely about it. They prepared themselves all through life for what they would do or what they would say when the time came to go to that unknown after-death world. Water was sacred to the Egyptians. On one of the stone slabs unearthed was inscribed the "confession" of a man who was readying himself for that journey and who was prepared to say that he had not 'held up water in its season' nor had ever 'built a dam against running water'.

During the Neolithic age (*ca.* 10,000–3000 BC), the first successful efforts to control the flow of water were driven by agricultural needs (irrigation). Irrigation probably began to develop at a small scale during the Neolithic age in the so-called "fertile crescent" (Figure 2.2), an arc constituting the hills of Syria – Palestine and the feet of the Taurus and Sagros mountains, as well as the southeast of the Caspian Sea (Viollet, 2006).

Mesopotamia, named by the ancient Greeks as being the land between the Euphrates and Tigris Rivers and its tributaries, is basically the eastern side of the fertile crescent. This area roughly comprises modern day Iraq and Syria. Larger scale irrigation developed when early cultivators settled in the low plains where the Tigris and Euphrates Rivers join. The large alluvial plain between the Tigris and Euphrates Rivers has been occupied by humans since around 5000 BC, with the beginning of the Sumerian civilization. The large scale diversion of water by humans probably had its origin in ancient Mesopotamia.

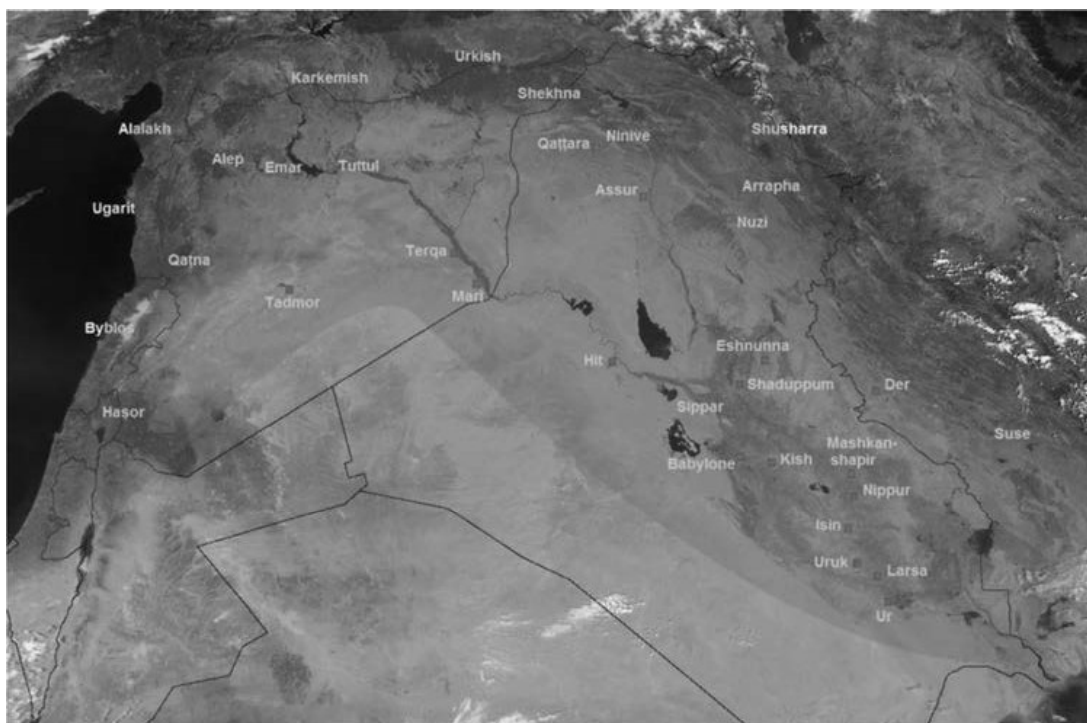


Figure 2.2 Fertile Crescent (*Source: www.Wikipedia.org, GNU Free Documentation Licence*)

2.3 BRONZE AGE

When the human mind overcame the barriers of nature and man was no longer a total slave to its uncontrolled powers, when man had risen to a position that enabled him to harness or manipulate the forces of nature, the basis for a well-conceived and fairly social type of organisation started to develop. Water could be brought from long distances by human effort by detouring streams, using ditches or channels and gradually by constructing cisterns, digging wells or building aqueducts (Phillips, 1972).

One of the early Bronze Age civilizations was Mohenjo-Daro (Mound of the Dead) one of the major urban centres of the Harappa Culture or Indus Civilization (Mays, 2010). Mohenjo-Daro, located on the right bank of the Indus about 400 km south of Karachi, Pakistan, was a deliberately planned city built around 2450 BC over a relatively short time period (Jansen, 1989). This planned city, located in a semi-arid environment, was serviced by at least 700 wells, with an average frequency of one in every third house (Jansen, 1989). The cylindrical well shafts were constructed using wedge-shaped bricks.

The following, from ancient Sanskrit writings (ca. 2000 BC) concerning medical treatment, give evidence of the first writings of water purification. From the *Sus'ruta Samhita*, 'impure water should be purified by being boiled over a fire, or being heated in the sun, or by dipping a heated iron into it, or it may be purified by filtration through sand and coarse gravel and then allowed to cool'. The Sanskrit *Ousruta Sanghita* included, 'It is good to keep water in copper vessels, to expose it to sunlight, and filter through charcoal,' according to Francis Evelyn Place (in 1905) who studied Sanskrit medical lore.

The technologies for water resources for urban areas of Mesopotamia during the Bronze Age included short canals connected to rivers in cities such as Uruk, Ur, Mari, and Babylon (all cities in the Tigris and Euphrates valleys). Other examples including gutters and cisterns for collecting and storing rainwater were used in Mari, and wells were used in Ugarit (Syria). The *shaduf*, a device for lifting water from a

source, a well, or a river, were used in Mesopotamia, as evidenced by a shaduf represented on a cylindrical seal from Mesopotamia dated around 2200 BC.

The Minoan culture flourished during the Bronze Age in Crete. A systematic evolution of water management in ancient Greece began in Crete during the early Bronze Age, for example, the Early Minoan period (ca. 3200–2300 BC). Wells, cisterns, water distribution, fountains, and even recreational functions existed. In prehistoric Crete rivers and springs provided people with water. Starting the Early Minoan period II (ca. 3200–2300 BC), a variety of technologies such as wells, cisterns, and aqueducts were used. Also the Minoan architecture, including flat rooftops, light wells, and open courts, played an important role in water management. The rooftops and open courts acted as catch basins to collect rainwater from which it flowed to storage areas or cisterns.

Historically, drinking water has been considered 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, dated 4000 years ago. It dictates that the dirty water should be exposed to the sun and then a hot copper bar be inserted seven times in it, before filtration, cooling and storage in a clay jar.

Archaeological and other evidence indicate that during the Middle Bronze Age a “cultural explosion”, unparalleled in the history of other ancient civilizations, occurred on 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. 3200–1100 BC) was the treatment devices used for water supply in palaces, cities, and villages from the beginning of the Bronze Age. It is truly amazing that the most common water quality modification technique for providing suitable domestic water supplies was known to Minoan engineers. Thus, according to Dafner (1921), a strange, oblong device with an opening in one of its ends, was used to treat domestic water (Figure 2.3a). The device was constructed in a similar manner and with the same material as the terracotta water pipes. Spanakis (1982) theorised this device as a hydraulic filter which was probably connected to a water supply reservoir by a rope passing through its outside holds. Its operation relied on local, high speed, turbulent conditions in order to continuously clean the porous surface thus allowing the continuous flow of filtered water to the jar. For cleaning purposes after extensive solids accumulation, it was possible to release it from the pipe end by loosening the rope in the holes. Also, an Egyptian clarifying device pictured in the tomb of Amenophis II and later in the tomb of Rameses II is shown in Figure 2.3b. This device allowed impurities to settle out of the water and then the clarified water was siphoned off and stored for later use.

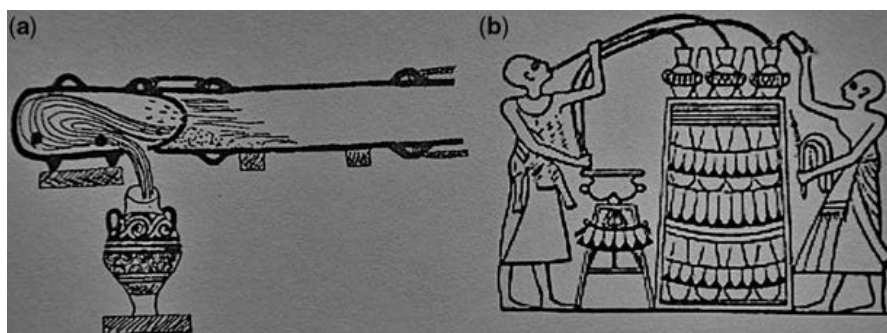


Figure 2.3 Bronze Age water purification devices. (a) Minoan water treatment device (Defner, 1921) and (b) Egyptian clarifying device (Baker & Taras, 1981)

Two other examples are:

- (a) In the Tylissos houses the water was transported through an aqueduct to the three Minoan houses from the Agios Mama Spring, a distance of about 3 km. Terracotta infiltration devices were discovered in Agios Mamas, the location of the spring from where water was transported to the Tylissos village (Figure 2.4). These devices were filled with charcoal, thus playing the role of activated carbon treatment processes for removing both organic and inorganic constituents. In addition to these devices, a terracotta pipeline of 42 m length, similar to those used in Knossos, was discovered in the north-western site of House B. Other remains of the aqueduct are shown in Figure 2.5. A small cistern of stone was used for the removal of suspended solids from the water before its storage in the main cistern (Figure 2.5a). This cylindrical-shaped cistern (Figure 2.5b) was located at the northern site of House C and was considered as a part of the aqueduct (Hatzidakis, 1934).



Figure 2.4 Two terracotta conical tubes probably used as refinery devices from Agios Mamas spring in Tylissos (Archaeological Museum of Iraklion), Iraklion (with permission of M. Nikiforakis, EFIAP)

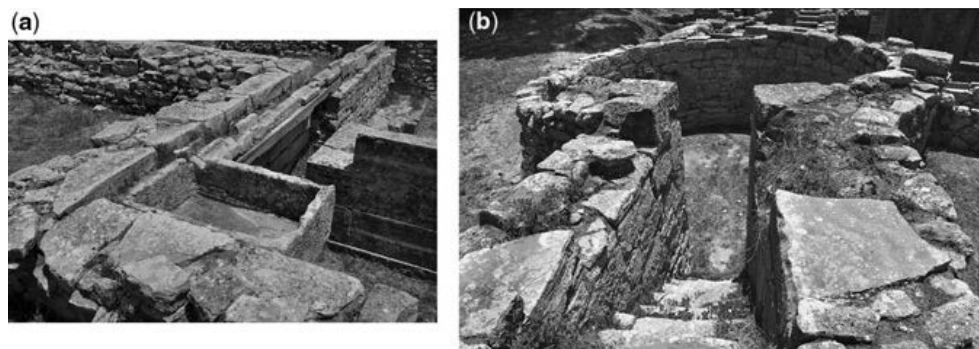


Figure 2.5 Small cistern (sedimentation basin) of stone (a) used for removal of suspended solids of water before it flowed to the main cylindrical-shaped cistern (b) used for water supply of the house (with permission A. N. Angelakis)

- (b) In the palace of Phaestos, as in other cities and villages in Minoan Crete, the water supply system depended directly on precipitation: here, the rainwater was collected from the roofs and yards of buildings and stored 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 with the hygiene of water collection by: (a) cleaning the surfaces used for collecting the runoff water (Figures 2.6a and 2.6b) and (b) filtering the water in coarse sandy filters before it flowed into the cisterns in order to maintain the purity of water (Figure 2.6b) (Angelakis & Spyridakis, 1996). It was estimated that about 8 Mm³ of rainwater were collected in an average year. That water was mainly used for washing clothes and other cleaning tasks.

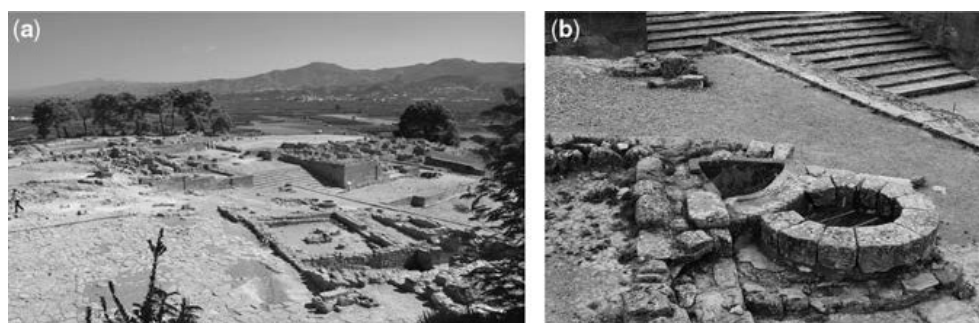


Figure 2.6 Open yard (a) and special cistern (b) with sandy filter in the Phaestos palace (with permission A. N. Angelakis)

2.4 AFTER THE BRONZE AGE (IRON AGE)

In Jerusalem at times of siege (before *ca.* 1,000 BC) or when water from the Gihon spring was not accessible, the water supply was from the cisterns that could possibly supply water only for urgent drinking and cooking purposes alone at 3–5 L/inh · d for as many as 30,000 people (Shuvial, 2009). However, studies by anthropologists in developing countries show that in communities without direct access to potable water sources, the domestic water use is in the range of 10–20 L/inh · d. In such villages all water has to be carried in pots and buckets some distance from the water source to the home. For a family of six that would mean 60–120 L of water each day weighing 60–120 kg. It would hardly be feasible to carry much more water than that every day. Shuvial (2009) is assuming that after *ca.* 1000 BC in ancient Jerusalem, the water requirement for drinking, cooking, washing and minimal other domestic uses was about 20 L/inh · d and that half of the water of the minimum flow Gihon spring (650 m³/d) was for such domestic purposes. Based on this assumption there would be more than enough water to support a population of 20,000–30,000.

Since the prehistoric era the availability of water sources 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 into 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 tunnels under the walls that provided safe underground passages to water sources, in order to secure adequate supply of water during seizures. During the same period important water projects were accomplished such as the draining of Lake Kopaes and the dam near Myticas in west Greece.

2.5 ARCHAIC AND CLASSICAL GREEK PERIODS

In the archaic (750–480 BC) and the classical (480–323 BC) periods of the Greek civilization, aqueducts, cisterns, and wells were similar to those built by the Minoans and Mycenaeans. However, the scientific and engineering progress during those stages enabled the construction of more sophisticated structures. An example is the Peisistratean aqueduct, constructed in Athens during the time of the tyrant Peisistratos and descendents *ca.* 510 BC. This aqueduct carried water from the foothills of the Hymettos mountain (probably from east of the present Holargos suburb for a distance of 7.5 km to the centre of the city near the Acropolis (Tassios, 2002). The pipe segments of the Peisistratean aqueduct are shown in Figure 2.7. For safety reasons, aqueducts were always subterranean, either tunnels or trenches. At the entrance of the city, aqueducts would branch into the city and would feed cisterns and public fountains in central locations. Along the bottom of trenches or tunnels of aqueducts, pipes usually made of terracotta, were laid, allowing for protection. A single pipe, or two or more pipes in parallel, would be used depending upon the flow to be conveyed.

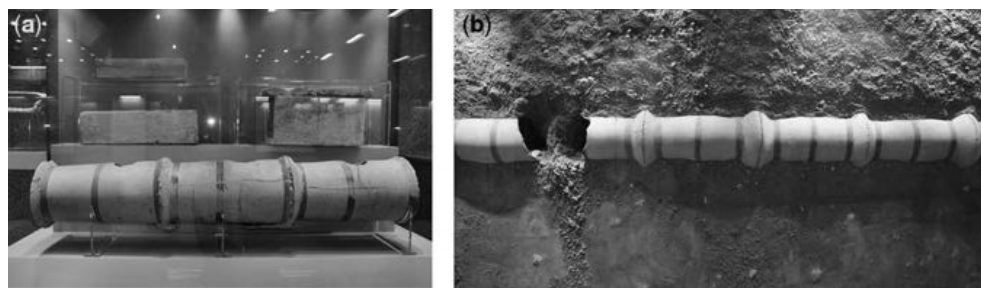


Figure 2.7 Peisistratean aqueduct terracotta pipe segments that were laid in a channel. Pipe joints were made of lead and the elliptical pipe openings were for cleaning purpose (with permission of A. N. Angelakis)

Hippocrates (460–377 BC), the Greek physician, wrote the first work on public hygiene (Air, Water, and Places) in which he noted that water varied in quality (taste and weight) and that it could be purified. His purification process, using what was later called “Hippocrates Sleeve”, was to use a cloth bag through which he poured the water after it was boiled to trap sediments that caused bad taste and smell. This device was used for his patients.

2.6 HELLENISTIC GREEK PERIOD

Later, during the Hellenistic period [323 BC (death of Alexander the Great) – 146 BC (conquest of Greece by the Roman Empire)], further developments were made by the Greeks in hydraulics, such as the construction and operation of aqueducts, cisterns, wells, harbours, water supply systems, baths, toilets, and sewerage and drainage systems. During that period the political and economic situation changed leading to much more architectural development and urban beautification, of which aqueducts played a major role. Progress in science during the Hellenistic period provided a new technical expertise. Hellenistic aqueducts usually used pipes, compared to the late Roman masonry conduit. Furthermore, following the classical Greek tradition, the aqueducts continued to be subterranean for security reasons (not to be exposed to aliens, e.g. in case of war) but also for the safety of the construction during earthquakes which are frequent in the area. Again the Hellenistic technology contrasts with the later Roman technology, whose apparent characteristic was the use of arches and aqueduct bridges.

The water supply system to Pergamon, discussed further in Chapter 12, was built by the Greeks and the Romans (Ozis, 1996). The Madra Dag aqueduct to the acropolis was 42 km long (built by Eumenes II (197–159 BC). The aqueduct was constructed of triple terracotta pipelines of approximately 0.18 m in diameter and a wall thickness of 3.5 cm. The last stretch of 3.2 km of the siphon was under a maximum pressure of 190 m. No sign of lead pipes has survived, however soil samples close to the pipeline location proved to have 50 times higher lead-content than soil samples further away (Fahlbush, 2010).

During the historic years, after the eighth century BC, the settlements and cities obtained drinking water from springs, wells, rivers and precipitating water collected from roofs and stored in reservoirs. The use of remote sources required water transportation. The Hellenes (Greeks is a name imposed later by the Romans) used mostly clay pipes. Since every City-State had a 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 1000 m underground tunnel through the mountain based on the design of the famous engineer Eupalenos. This 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 axes was just 1.8 m. Later the King of Pergamos, Eumenes the 2nd (197–159 BC) constructed the first complete Hellenic water transportation and storage system based on branching pipes. This aqueduct is proved to have been operated for several hundred years. It is looked upon as the peak of Hellenistic water supply technology (Fahlbusch, 2010).

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, for political reasons the organisation 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 upon. 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. This approach has also been adopted by Article 7 of the European Water Framework Directive established in the year 2000 AD (EU, 2000). Moreover, he is credited with the development of the “Hippocrates sleeve” made of cloth and used to filter rainwater.

The small diameter closed water transportation systems had two particular problems, besides the usual structural and leakage problems: calcium carbonate deposits and lead. The predominance of limestone formations in the Balkan Peninsula as well as 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 rates of calcium salts depositions on the surface of pipes, which in practice cannot be removed. So, the pipes gradually had their diameter reduced and the amount of water flow considerably diminished. This problem has been noticed in many excavations of ancient water pipes. Lead was 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 specialised workshops were set up. Their remains have been uncovered in a number of excavations.

2.7 ROMAN PERIOD

Springs were the most common sources of water for the Romans. Water sources included not only springs, percolation wells, and weirs on streams, but also reservoirs that were developed by building dams which is discussed further in Chapter 12. To properly discuss Roman water supply it is important to be aware of the treatises of Marcus Vitruvius Pollio, a Roman architect and engineer who lived in the first century BC. His “Ten Books on Architecture” or “De Architectura” (Morgan, 1914), in Book VIII (Water Supply) discussed the various elements of water supply. In Chapters 5 and 6 of Book VIII, Vitruvius addressed the quality of water.

Chapter III (Various Properties of Different Waters):

- (a) 20. Then there are springs in which wine seems to be mingled, like the one in Paphlagonia, the water of which intoxicates those who drink of the spring alone without wine. ...
- (b) 21. In Arcadia, is the well-known city of Clitor, in whose territory is a cave flowing with running water, which makes people who drink of it become abstemious. ...
- (c) 22. In the island of Zeas is a spring of which those who thoughtlessly drink lose their understanding, and an epigram is cut there to the effect that a draught from the spring is delightful, but that he who drinks will become dull as a stone. ...
- (d) 23. At Susa, the capital of the Persian kingdom, there is a little spring, those who drink of which lose their teeth.
- (e) 24. There are also in some places springs which have the peculiarity of giving fine singing voices to the natives, as at Tarsus in Magnesia, and in other countries of that kind. ...

Chapter IV (Tests of Good Water):

- (a) Springs should be tested and proved in advance in the flowing ways. ...
- (b) And if green vegetables cook quickly when put into a vessel of such water and set over a fire, it will be proof that the water is good and wholesome. ...

Chapter V (Aqueducts, Wells, and Cisterns):

- (a) There are three methods of conducting water, in channels through masonry conduits, or in lead pipes, or in pipes of baked clay. ...
- (b) 10. Clay pipes for conducting water have the following advantages. ... Secondly, water from clay pipes is much more wholesome than that which is conducted through lead pipes, because lead is found to be harmful for the reason that white lead is derived from it, and this is said to be hurtful to the human system. ...

2.7.1 Roman water supply systems

Various components of the Roman water supply system are illustrated in Figure 2.8. Aqueducts were used to transport water from the source to the locations where the water was needed, either for irrigation or for urban water supplies. Rome was an empire, the internal safety was not at danger and therefore the open aqueducts were not a problem for water safety. Roman aqueducts were built to promote quality of life and in general were built to serve existing urban centres, in many cases where prosperous life had existed for centuries before the aqueducts had been built. The Romans built aqueducts largely to supply baths and were an expression of civic pride. Many of the Roman inhabitants obtained their drinking water from wells prior to the construction of the aqueducts. The location and delivery point of the aqueducts were determined

by geographical, economic, and social factors. 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.

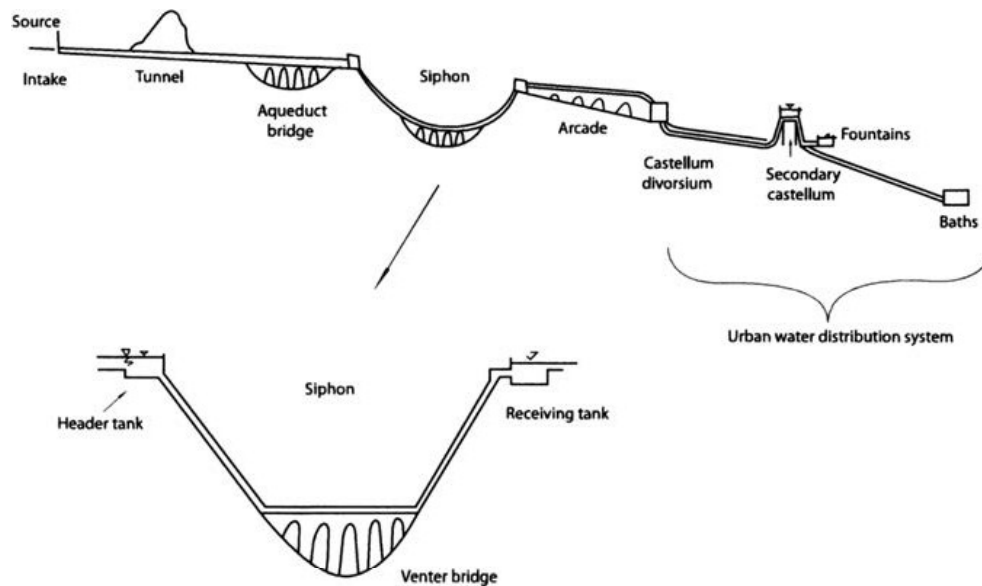


Figure 2.8 Components of the Roman water supply system (copyright with L. W. Mays)

Roman aqueducts included open channels and pipes. The most common was the open channel constructed of masonry conduit. Also open channels were made of cut stone and an open clay-lined leet. Aqueduct bridges were probably the most spectacular feature of the aqueduct systems. The Romans used siphons throughout the empire. The siphons included a header tank for transitioning the open channel flow of the aqueduct into one or more pipes, the bends called *geniculus*, the venter bridge to support the pipes in the valley, and the transition of pipe flow to open channel flow using a receiving tank.

There were many components in the Roman urban water distribution system. Water flowed by gravity through enclosed conduits (*specus* or *rivus*), which were typically 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. These pipes were connected to the *castellum* by a fitting or nozzle (*calix*). These pipes were placed below ground level along major streets. Two approaches to laying out the pipe network were followed: (a) using a main pipe from the secondary *castellum* with smaller branch pipes attached to serve individual customers, and (b) not using main pipes but using individual pipes laid from the secondary *castellum* to the individual customer, which was the normal Roman practice (Hodge, 2002).

The Romans made extensive use of cisterns. Cisterns were used extensively for storing water from rainfall collection and from aqueducts. 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 were made of terracotta pipes and were often set inside the wall.

As the cities and states grew bigger and more confident, especially during the Roman period, they shifted their technology to longer and bigger water transportation systems, namely the open aqueducts. Typically

brick was used for the aqueduct construction. The remains of Patras aqueduct in western Greece are shown in Figure 2.9. 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 BC by Marcus 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 were 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 AD the aqueduct of Rome was destroyed by the Goths and was used as a weak point to enter the city.



Figure 2.9 Sections of the aqueduct of Patras in western Greece (Sklivaniotis & Angelakis, 2006)

The extensive use of open aqueducts was aided by the technology of the strong bonding mixture called pozzolana for bricks, which made the construction of aqueducts both inexpensive and fast to execute.

The distribution of water inside the cities was achieved through pipes: clay and lead for smaller diameters, brickwork sealed with specialised hydraulic plaster for larger diameters (Figures 2.10 and 2.11). 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 with a pressure of 20 atm. Ceramic pipes were usually of cylindrical shape.



Figure 2.10 Lead water pipe of the Roman period, Greece (Sklivaniotis & Angelakis, 2006)



Figure 2.11 Ceramic water pipes from an excavation in Aigio in western Greece (Sklivaniotis & Angelakis, 2006)

Despite the availability of a 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 well was covered with built stones or clay rings, which at regular intervals had holes to facilitate access to the bottom of the well for maintenance (Figure 2.12). They also utilised the rainwater which was collected from the roofs of the houses and stored in cisterns, usually underground. Such a cistern used to collect rainwater is shown in Figure 2.13. This water was mostly used for cleaning the house if running water was available for human consumption.



Figure 2.12 Cylindrical terracotta rings, for coating the walls of a Roman well (Sklivaniotis & Angelakis, 2006)

During the Classic period 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 cold bath called the *frigidarium*, followed by a warm bath called the *tepidarium*, followed by a hot bath called the *caldarium*. The bath houses were heated by hot air passing through clay pipes inside the walls and in the empty space under the false floor. Remains of Roman *thermae* and a public bath in western Greece are shown in Figures 2.14a and b, respectively.



Figure 2.13 House cistern used to collect rainwater in the Atrium of a Roman house in Patras in western Greece (Sklivaniotis & Angelakis, 2006)

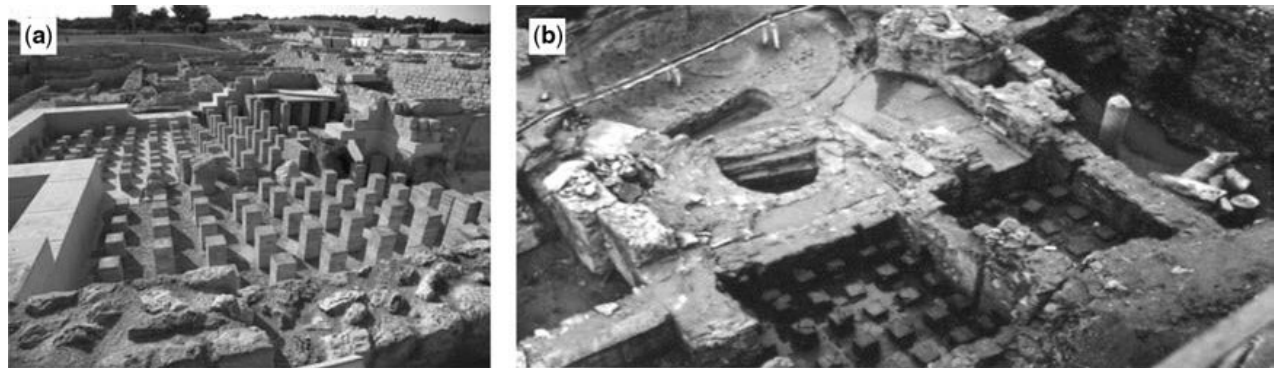


Figure 2.14 Roman baths: (a) Baths Hypocaust columns of Roman bath at Lucentum, near Alicante, Spain (with permission of L. W. Mays) and (b) An early Christian bath in Patras in western Greece (Sklivaniotis & Angelakis, 2006)

2.7.2 Water consumption

As for other ancient periods one unresolved problem, during the Roman period is the quantity of water provided by the aqueducts. In general, data provided by archaeological evidence and written accounts fall short of that required for the computation of either per capita supply or per capita use. The cross-sectional areas of the aqueducts are known, but one cannot be sure that the conduits ever ran at their maximum capacity. Sizing of the channels was probably determined as much by the need for work space as by the volume needed for water (Hansen, 1983). It was certainly a rare occasion when the aqueducts were all working at the same time. Another uncertainty is the population of Imperial Rome. No accurate estimate exists for any particular period. It is generally assumed that during Frontinus era the population of Rome was approximately one million (Parker, 1967).

Hansen (1983) reported that the amount of water delivered by the aqueducts varied from a low of 322,000 to a high of 1,010,623 m³/d. There is also little consensus among more recent estimates. Bruun (1991) prefers a water rate of 600,000 m³/d. This latter figure computes a very high water supply value of

$0.6 \text{ m}^3/\text{d} \cdot \text{inh}$. However, he also makes an estimate of the per capita usage of the middle and lower classes. According to Frontinus, the aqueducts served 591 lacus (or major delivery points), and each, on average, delivered $60 \text{ m}^3/\text{d}$. He estimates that each delivery point served 900 individuals on an average basis. This computes to a water use of $67 \text{ L}/\text{d} \cdot \text{inh}$. This figure is considerably lower than all previous estimates, but it is not too low when it is considered that Romans could also recycle and reuse wastewater from baths, toilets, and other establishments. In addition, they could probably store and use rainwater and/or water directly from Tiber River. A water consumption of $67 \text{ L}/\text{d}$, only includes the water consumed from the lacus. It would seem that for the ordinary Roman, this quantity of water was satisfactory, but not lavish. Contemporary residential customers in the USA require approximately $350 \text{ L}/\text{inh} \cdot \text{d}$ (Hansen, 1983).

Roman water supply in comparison with modern times' water usage rates appears to be problematic. It is commonly felt that water supply in Roman cities was delivered at a constant flow rate instead of on-demand (as with modern systems). For example, water flowed through a latrine in one continual stream, not just when flushed as is the case with the modern toilet. According to Hansen (1983) fountains probably ran night and day. Thus, to compare water use (on $\text{L}/\text{inh} \cdot \text{d}$ basis) in the Roman period with that in 20th century is problematic.

Bruun (1991) disagrees somewhat with the idea that Rome's water supply was constant and continuous. Arguably the Romans considered water flowing day and night as a particular sign of richness and a high standard of living. But this does not necessarily mean that they paid little attention to the storage of water, or to regularising the water flow. In fact there exists sundry evidence that measures for saving water had been adopted. It is often maintained that the Romans did not make use of taps and similar devices in this distribution net; for example Frontinus never even once refers to such objects. But as a matter of fact archaeological discoveries have brought forward a large amount of evidence for their use (Hansen, 1983).

The Romans also diverted water into storage tanks. Archaeologists have uncovered large cisterns in Rome, many received water from the aqueducts. Bruun (1991) argues that Romans were better water managers than we commonly give them credit for. It is safe to assume that Rome received an impressive supply of water, and that the rich and influential received a disproportionate amount. But the water supply for the common Roman was still sufficient. By historic standards, the Romans' water supply was a very impressive accomplishment (Hansen, 1983).

2.8 BYZANTINE PERIOD

The Byzantine Empire and Eastern Roman Empire are names used to describe the Roman Empire during the Middle Ages, with the capital in Constantinople (Istanbul). During the thousand-year existence of the empire the influence spread widely into North Africa and the near East during the Middle Ages. Several water byzantine cisterns are known in various places in Greece (e.g. Athens, Amorgos Island, Mistra, Leontari Arkadias, Monemvasia, and Iraklion Crete). A byzantine cistern at the base of Acropolis in Athens is shown in Figure 2.15a. Another one at the castle of Leontari village in Peloponnesos (Arkadia), known as the cistern of "Goula" is shown in Figure 2.15b. This village was the basis of the brother of Constantine Paleologos (Antoniou, 2011).

The Halkai water conveyance system, dating from the early Byzantine period, was the first of three main systems supplying Constantinople (Ozis, 1987). The most interesting part of the water system of the Byzantine period is the cisterns in Constantinople. During the Byzantine times in Constantinople at least 70 cisterns were constructed (Cinis, 2003). The Basilica Cistern or in Turkish the "Yerebatan Sarayı", is one of the largest ($140 \times 70 \text{ m}^2$ and with a capacity of $80,000 \text{ m}^3$) known covered cisterns, probably

completed in the early sixth century. This cistern, shown in Figure 2.16a, is an underground cistern, having 336 marble columns each 9 m high. The columns are arranged in 12 rows each with 38 columns, spaced 4.9 m apart. The cistern was built underneath the Stoa Basilica which is a large public square on the First Hill of Constantinople during the reign of Emperor Justinianos I in the sixth century. Water was supplied to the cistern by an aqueduct from springs in Marmara, which is west of the city.



Figure 2.15 Byzantine cisterns in Greece: (a) at the base of the acropolis in Athens and (b) at the castle of Leontari village in Peloponnesos (with permission of L. W. Mays & G. Antoniou, respectively)

Another very well known cistern in Constantinople is the Philoxenous cistern located on the opposite side of the present Courthouse close to the Sultanahmet square (Figure 2.16b). The name comes from the Roman Senator Philoxenous who built the Philoxenous palace during the period of Great Constantinus (324–337 AD). Another theory suggests that the cistern was built in the middle of the sixth century by the Emperor Justinianos I based on the style and materials used. The cistern has a rectangular shape of dimensions $64.0 \times 56.4 \text{ m}^2$. It incorporates 16 rows consisting of 14 pillars each (total of 224 pillars) spaced 3.8 m apart. (Cinis, 2003). The pillars are connected via arches and carry diagonal beams and simple pyramid shaped headings. This cistern is also known as the “1001 post” cistern because of the many posts it incorporates. As a result of drying out in subsequent years, the Ottomans used the cistern as a thread-manufacturing workshop until the beginning of the 20th century. Other underground cisterns in Constantinople are those of St. Sophia (five; two of which are below the church), the Grand Palace cisterns (various), the Theodosius cistern, the Forty Martyrs cistern, the Botniates cistern, the Myrelaion cistern, the Fatih cistern, the Studios cistern, the Zeyrek-Pantokrator cisterns (two), and the Sishane cistern.

In addition to the underground cisterns in Constantinople there were at least four open-air cisterns (above ground). The Elephant Dome or Fildami cistern is one of the four biggest reservoirs of antiquity in Byzantium, Constantinople (Figure 2.16c). Different than most of the other cisterns in Constantinople, the Fildami cistern is not situated in the historical peninsula which is covered by Land Walls constructed by Theodosius. It is an extraordinary monument, compared to the others, which have survived until now.

The Fildami cistern is an open-air reservoir of the early Byzantine Empire, 1.5 km away from the coast of the Marmara sea on the west side of the Cirpici stream. It is constructed next to the Magnaura and Jucundianae palaces (Crow *et al.* 2008). The dimensions of the cistern are 127 x 76 m and its depth is 11 m, indicating a total volume of more than 105,000 m³. The walls are visible to a height of about 10 m. Therefore it is estimated that its original shape was deeper than its form today. In total area it is somewhat smaller than the other open reservoirs within the Land Walls. It is only 1000 m² larger in area than the Basilica Cistern. Other known open-air cisterns are Aspar, St. Mocius, and Aetius (Cinis, 2003).

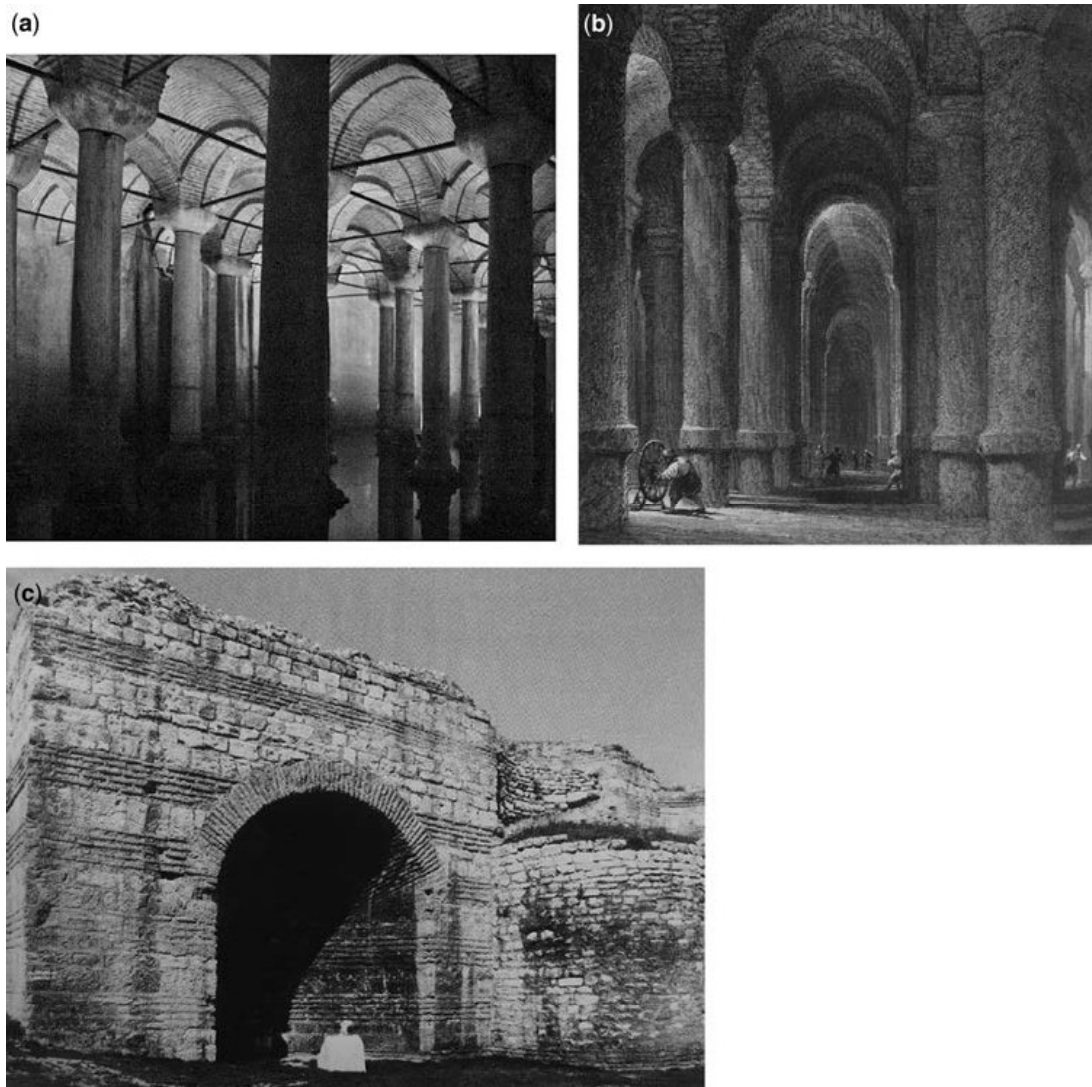


Figure 2.16 Byzantine cisterns in Constantinople: (a) inner view of basilica cistern, (b) an old engraving of Philoxenus cistern and (c) The Elephant Dome or Fildami cistern (with permission of M. Nikiforakis, EFIAP)

The total capacity of the underground cisterns was 200,000 m³ and that of open-air cisterns was 800,000 m³ (Cinis, 2003). With the ancient population of Constantinople estimated to be 50,000 inhabitants, these cisterns were sufficient to provide fresh water for a period of more than one year. Thus, during the Byzantine period an average water consumption of less than 55 L/inh.d is assumed.

2.9 OTTOMAN PERIOD (CA. 1669–1898 AD)

Water was connected to Islam, so that during the Ottoman period there was a water tap in all mosques. Hammams, which are presently also referred to as Turkish bathes, played an important role in the Ottoman culture and served as places of social gathering, ritual cleansing, and as architectural structures, institutes etc. The cleansing of the body symbolises the cleansing of the soul, according to the Koran. The hammam is a very old Ottoman institution and was established in all the regions of the Ottoman Empire. Following the very old Moslem tradition, water supply to hammams and fountains was the major hydraulic works developed during the Ottoman period. Such a domed fountain is shown in Figure 2.17a.

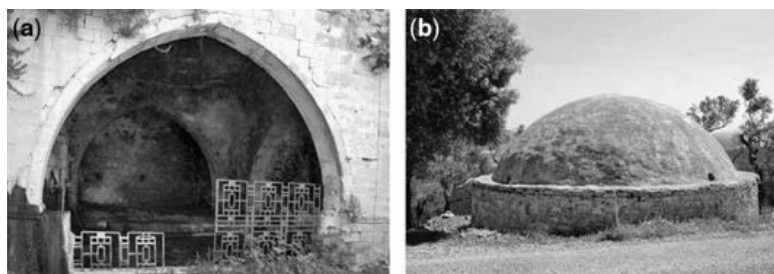


Figure 2.17 Ottoman cistern and fountain: (a) Fountain in Iraklion, Greece and (b) Domed circular cistern in southwest Anatolia (with permission of A. N. Angelakis & L. W. Mays, respectively)

The most remarkable water systems of the Ottoman period served Constantinople (Istanbul). There are also cisterns from this period that were circular-shaped, domed or other (Figure 2.17b) located in several Mediterranean countries. These cisterns were constructed primarily in the 16th century (Ozis, 1987) in various places occupied by Ottomans. Some of these are still in use for livestock water supply. They originally served the Ottoman army at military logistic points.

2.10 MODERN TIMES

As in every other field of art and science, during the Middle Ages there was no progress in the area of water treatment except for limited references in the Arab world. During the eighth century AD the Arab alchemist Gever distilled water to render it free from evil spirits and in the 11th century AD the Persian physician Avicenna advised travellers to boil the water or at least filter it through a cloth.

2.10.1 17th century

The British philosopher and scientist Francis Bacon, who managed to transform nature probing to scientific conclusions, devoted considerable effort to studying water purification techniques. In 1627 he published experimental results on percolation, filtration, distillation and coagulation.

In 1680 Dutch naturalist Antony van Leeuwenhoek discovered the microscope and in 1684 gave a first account of bacteria observed in water which he named “animacules”. These findings were dismissed by the scientific community as unimportant curiosities. It took another 200 years for the importance of the van Leeuwenhoek’s findings for public health to be understood.

In 1685 the Italian Lu Antonio Porzio designed the first multi-pass filter containing a straining section and two sand filtration passes (see Figure 2.18).

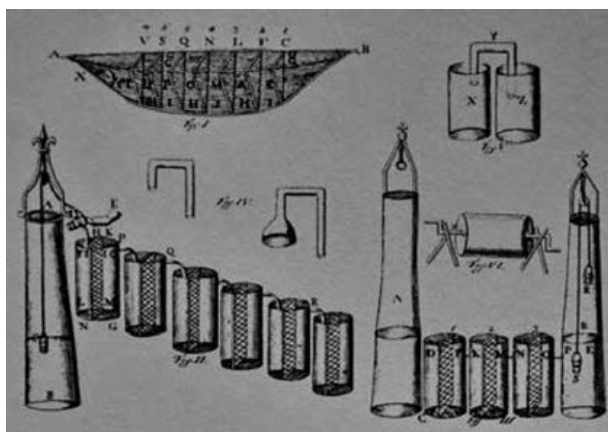


Figure 2.18 Porzio's multiple filter system. Showing the three filters: one floating, and two for land used for well water. (from Militis in Castro Sanitate Tuenda, 1685, translated into English as the Soldier's Vade Mecum, 1747)

2.10.2 18th century

In the 18th century France took the lead. In 1703 the scientist Phillippe La Hire presented a home filter suitable for treating rainwater consisting of a sand filter and a storage tank. He also noticed that the water which came from underground aquifers was rarely polluted. In 1746 Joseph Amy received the first patent for a water filter that in 1750 he put on the market. Figures 2.19 and 2.20 illustrate Amy's filters. The filter was made of sponge, wool and sand. However, it was the British architect James Peacock that managed to claim a patent for a sand filter with backwashing.

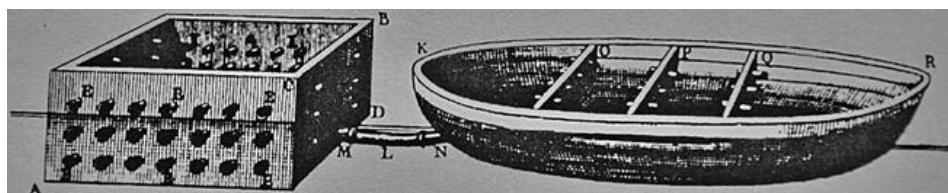


Figure 2.19 Amy's machine to purify water. This filter was approved by the French Academy of Sciences in 1745. The floating filter box and clear-water trailer are shown. Sponges were inserted in the sides of the filter box and if required were placed in the partitions of the trailer. (Source: *Machines et Inventions Approuvees par L'Academie Royale des Sciences*)

2.10.3 19th century

In 1804, Paisley, Scotland, became the site of the first filter facility to deliver water to an entire town. This filter is illustrated in Figure 2.21.

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 pre-filters that were renewed every hour. The main filters consisted of coarse river sand, clean sand, pounded charcoal, and clean Fontainebleau 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.

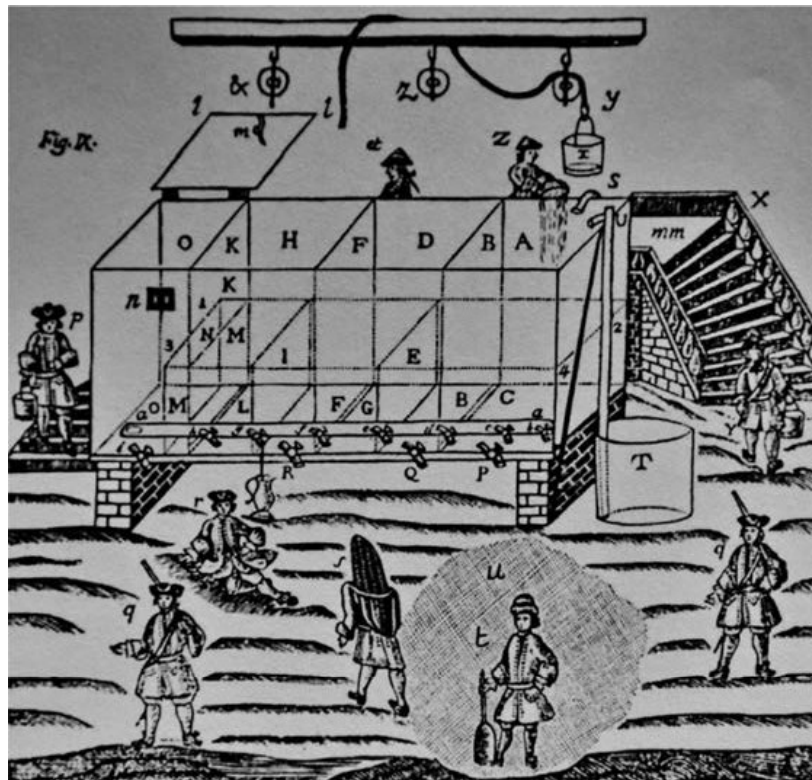


Figure 2.20 Amy's sextifold filter box for army garrisons. This filter system consisted of three pairs of down-up filters. Water flowed through 54 cm of sand. The tank was either lead-lined wood or masonry, 54 x 9 cm² in plan and 18 cm deep. The design closely resembled one described by Porzio in his 1685 book on military camp sanitation (Source: Amy's 1754 book)

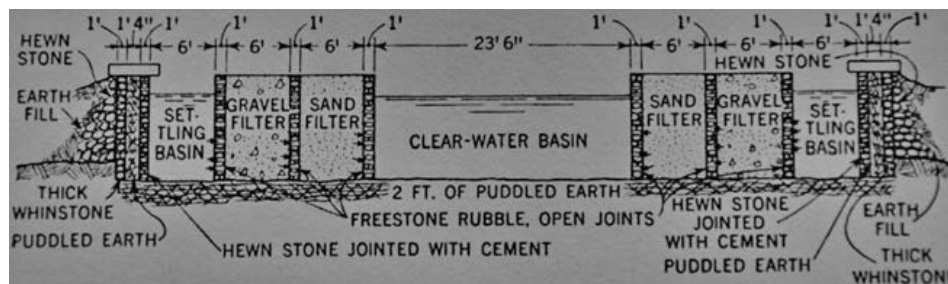


Figure 2.21 Filter system for Paisley, Scotland completed in 1804 by John Gibb. This is the first known filter to supply an entire city according to Baker (1948). Water flowed through a stone-filled trench to a ring-shaped settling chamber followed by flow through two lateral-flow filters to a central clear-water chamber. Water was then delivered to a tank on the hillside from where it was carted to consumers. (From description in Sinclair's Code of Health and Longevity, London, 1807; as presented in Baker (1948))

In 1832 the first slow sand filtration plant in the United States was built in Richmond. In 1833, the plant had 295 water subscribers. A small upward-flow filter of gravel and sand in the water works proved to be a failure for the turbid water of the James River. This was replaced by a downward flow

approach which also failed. The filters were too small to handle the highly turbid water. The next US plant to open was in Elizabeth, New Jersey, 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.

The evolution of rapid filters (Figure 2.22) in the USA began with developments by Patrick Clark and John W. Hyatt. Clark suspended a shallow filter in a river and provided surface-jet wash from a perforated revolving arm, with the loosened dirt being swept downstream (Baker, 1948). This filter was installed at Rahway, New Jersey waterworks around 1880. Hyatt superimposed several Clark filters in a closed tank and serviced them with a common pipe system (Baker, 1948). This method was first applied at Somerville & Raritan Water Co., New Jersey in 1882.

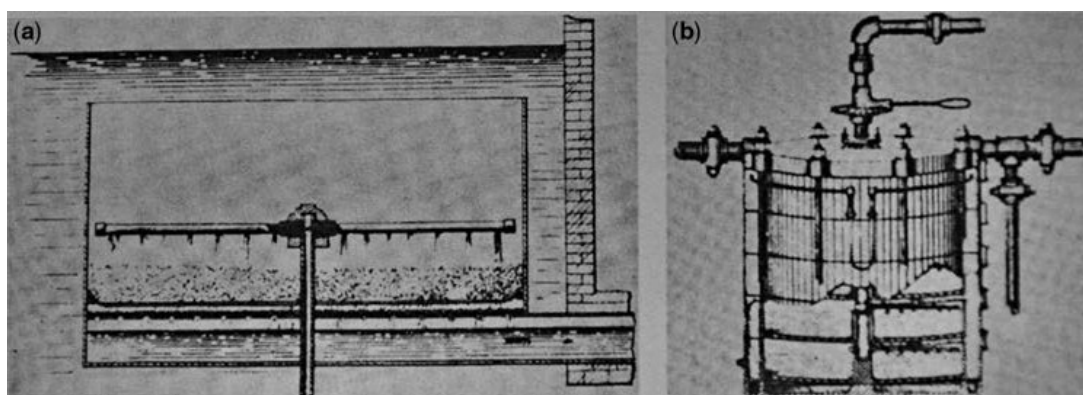


Figure 2.22 Rapid filtration advances by Clark and Hyatt. (a) Clark suspended shallow filter (from US patent drawing, June 21, 1881) (b) Hyatt superimposed several Clark filters in closed tank (from “The multifold water filter,” *Engineering News*, January 1, 1882)

During the decades 1880 and 1890 the rapid sand technology matured and it became evident that in addition to the suspended solids removal, extensive bacteria removal is achieved. The first attempts to use chlorine and ozone for disinfection are made.

Regarding water availability and consumption, a water shortage at the end of 1861 in Athens, Greece was reported by Lambrou (1999). Total available water supplies were 600 *dramia* water in September and October of 1861 whereas the deficit to meet the water requirements of the city during that period was 450 *dramia* of water (one *drami* is equal to about one m³). Lambrou (1999) considered 1.5 *dramia*/family·yr as an indicative water supply for the Athens Municipality. Similar water consumptions were reported by Soulis (1884).

2.10.4 20th century

In 1906 ozone was used for the first time for disinfection in Nice (France) and became very popular in Europe. In the USA, chlorine was 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 chemical warfare during the 1st world war. In 1908 sodium hypochloride was used in Jersey (USA) for disinfection and in 1917 chloramines were used first time for disinfection in Ottawa (Canada) and Denver (USA). The first serious efforts in water desalination technology were made during World War II for the supply of units which encountered difficulties in securing drinking water.

2.11 EPILOGUE

Water for human consumption has had a long and very interesting history. It is closely related to the development of civilization and thus a great deal of related events occurred around the world. All great civilizations had a large chapter written for water transportation, treatment and management of potable water. In this Chapter the evolution of urban water management in ancient civilizations is considered. The important steps in water supply history relevant to water treatment and hygienic technologies are chronologically presented and discussed. During the oligarchic periods the emphasis was on the construction of large-scale hydraulic projects, whereas in democratic periods the focus of water management was on sustainable small scale, safe and cost efficient management practices and institutional arrangements related to both the private and the public sectors. Such practices and institutions are relevant even today, as the water related problems of modern societies are not very different from those in antiquity.

As previously discussed several technologies for improving the water supply of settlements were accomplished very early in recorded history. Few basic principles have been added up to the present. However, the technological skill has been improved steadily such that world records in some fields have been achieved in antiquity for many, many centuries. The water supply of some ancient cities amounted to several hundred litres per day per inhabitant, a number which today is provided for cities only in a few highly industrialised countries. The fact that the water supply systems for many big cities in Central Europe were constructed in the last century, following the Greek and Roman examples, may indicate the high standard, which was achieved in several ancient civilizations (Fahlbusch, 2008). Thus, scientists of the 21st century can admire these achievements and hope that this standard will soon be gained worldwide.

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 had been transferred from Mesopotamia and Syria to Crete by that time since such several works concerning the management of water had already been 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 (Lirintzis & Angelakis, 2006). Thus, the first indication for the development of some technology relevant to the treatment of urban water and hygienic water supply lies in Minoan civilization. It seems likely that these technologies were transferred to the Mycenaeans in continental Greece (Angelakis & Spyridakis, 1996). Classic period Hellenic states and Romans capitalised on this knowledge and made great advances in potable water management (Petropoulos, 2006; Fahlbusch, 2010). The unfortunate Middle Ages, a period of stagnation, was followed by the revival of letters and technology. Slow in the beginning, but 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 usual the problems are emerging from politics in the broad sense. Looking to the future we wonder: What is going to grow faster, the problems or the technology than can solve them?

REFERENCES

- Adams R. (1981). *Heartland of Cities: Surveys of Ancient Settlements and Land Use on the Central Floodplain of the Euphrates*. University of Chicago Press, Chicago, USA.
- Amy J. (1754). *Suite du Livre Intitulé 'Nouvelles Fontaines, Filtrantes Approuvées par l'Académie Royale des Sciences'*. Antoine Boudet, Paris, France.
- Angelakis A. N. and Spyridakis S. V. (1996). The status of water resources in Minoan times – A preliminary study. In: *Diachronic Climatic Impacts on Water Resources with Emphasis on Mediterranean Region*, A. Angelakis and A. Issar (eds). Springer-Verlag, Heidelberg, Germany, pp. 161–191.

- Angelakis A. N. and Koutsoyiannis D. (2003). Urban Water Resources Management in Ancient Greek Times. In: The Encycl. of Water Sci., Markel Dekker Inc., B. A. Stewart and T. Howell (Eds), Madison Ave. New York, N.Y., USA, pp. 999–1008.
- Angelakis A. N., Koutsoyiannis D. and Tchobanoglous G. (2005). Urban Wastewater and Stormwater Technologies in the Ancient Greece. *Water Res.*, **39**(1), 210–220.
- Antoniou G. (2011). Study Rehabilitation buildings of Castle in Leontari Arkadias, Greece. Personal communication (in Greek).
- Antoniou A. and Angelakis A. N. (2011). Evolution of Sanitary and Purgatory Structures in Ancient Greece. *Journal of Early Medicine Issue on Latrines, Hygiene and Health* (in press).
- Baker M. N. (1948). The Quest for Pure Water: The History of Water Purification from the Earliest Records to the Twentieth Century. American Water Works Association (AWWA), Denver, USA.
- Baker M. N. and Taras M. J. (1981). The Quest for Pure Water: The History of the Twentieth Century. Volume 1 and 2. American Water Works Association (AWWA), Denver, USA.
- Bruun C. (1991). The Water Supply of Ancient Rome: A Study of Roman Imperial Administration. Societas Scientiarum Fennica, Helsinki, Finland.
- Cinis N. (2003). Yerebatan Cistern and Other Cisterns in Istanbul. Duru Basim Yayin Remcilik ve Gida San, Tic, Ltd., Sti, Istanbul, Turkey.
- Crow J., Rardill J. and Bayliss R. (2008). The Water Supply of Constantinople. *Journal of Roman Studies Monograph no 11*. Roman Society, London, UK.
- Defner M. (1921). Late Minoan Water Treatment Device. Archaeological Newspaper no 78, Iraklion, Greece (in Greek).
- EU (European Communities) (2000). Framework for Community Action in the Field of Water Policy. The Official Journal of the European Communities L 327/1, 2000/60/EC. Brussels, Belgium.
- Fahlbusch H. (2008). Municipal water supply in antiquity. <http://www.romanaqueducts.info/webteksten/waterinantiquity.htm> (15 accessed August 2011).
- Fahlbusch H. (2010). Water engineering and management in classic civilizations. In: Water Engineering and Management through Time – Learning from History, E. Cabrera and F. Arregui (eds), Taylor and Francis Group, London, UK.
- Gray H. F. (1940). Sewerage in Ancient and Medieval Times. *Sewage Works Journal*, **12**(5), 939–946.
- Hansen R. D. (1983). Water and Wastewater Systems in Imperial Rome. *Journal of the American Water Resources Association*, **19**(2), 263–269, www.waterhistory.org
- Hassan F. A. (2003). Water management and early civilizations: From cooperation to conflict. In: History and Future of Shared Water Resources, F. A. Hassan, M. Reuss, J. Trottier, C. Bernhardt, A. T. Wolf, J. Mohamed-Katerere and P. van derZaag (eds.), (PCCP Series No. 6). UNESCO, Paris, France.
- Hatzidakis J. (1934). Les Villas Minoennes de Tyllissos. Version Francaise de Chapouthier el R. Joly, Etudes Cretoises III, Paris, France.
- Hodge A. T. (2002) Roman Aqueducts and Water Supply. Gerald Duckworth & Co. Ltd., London, UK.
- Jansen M. (1989). Water Supply and Sewage Disposal at Mohenjo-Daro. *World Archaeology, The Archaeology of Public Health*, **21**(21), 177–192.
- Koutsoyiannis D., Zarkadoulas N., Angelakis A. N. and Tchobanoglous G. (2008). Urban Water management in Ancient Greece: Legacies and Lessons. *ASCE, Journal of Water Resources Planning & Manag.*, **134**(1), 45–54.
- Lambrou Y. L. (1999). Fresh Water: A Gift of Gods to Athens. Desmos, Kato Petralona, Athens, Greece (in Greek).
- Lyrantzis A. and Angelakis A. N. (2006). Is the Labyrinth a Water Catchment Technique? People and water management in Minoan Crete. In: Proc. of 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Civilizations, 28–30 October 2006, Iraklion, Greece, pp. 163–174.
- Mays L. W. (2002). Urban water infrastructure: A historical perspective. In: Urban Water Supply Handbook, L. W. Mays (ed.). McGraw–Hill, New York, USA, pp. 1.3–1.66.
- Mays L. W., Koutsoyiannis D. and Angelakis A. N. (2007) A brief history of urban water supply in antiquity. *Water Science & Technology, Water Supply*, **7**(1), 1–12
- Mays L. W. (2008). A very brief history of hydraulic technology during antiquity. *Environmental Fluid Mechanics*, **8**(5), 471–484.

- Mays L. W. (ed.) (2010). *Ancient Water Technologies*. Springer, Dordrecht Heidelberg, London, UK and New York, USA.
- Morgan M. H. (transl.) (1914). *Vitruvius: The Ten Books on Architecture*. Cambridge, Mass. USA.
- Ozis U. (1987) *Ancient Water Works in Anatolia*. Water Resources Development, **3**(1), Butterworth & Co. Ltd, Belfast, Ireland.
- Ozis U. (1996). *Historical Water Schemes in Turkey*. Water Resources Development, **12**(3), Butterworth & Co. Ltd, Belfast, Ireland.
- Parker J. E. (1967). Housing and population in imperial Ostia and Rome. *Journal of Roman Studies*, **57**, 82–91.
- Petropoulos M. (2006). The significance of water in ancient Patra. In: *The Union of Local Authorities of the Prefecture of Achaia “Waterways in Achaia Prefecture”*. Patra, Greece, (pp. 22–39).
- Phillips H. (1972). *History of the Water Supply of the Borough of Beaver*. Published jointly by the Beaver Area Heritage Foundation and the Beaver County Tourist Promotion Agency. Pennsylvania, USA.
- Shuvial H. (2009). The ancient water supply of Jerusalem in the biblical times – some controversial issues. In: *Proc. of the 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Civilizations*, May 28–30, 2009, Bari, Italy.
- Sklivaniotis M. and Angelakis A. N. (2006). Historical development of the treatment of potable water. In: *Proc. of 1st IWA International Symposium on Water and Wastewater Technologies in Ancient Civilizations*, 28–30 October 2006, Iraklion, Greece, pp. 659–666.
- Soulis A. (1884). *Hydraulics*. Andrea Koromila press, Athens, Greece (in Greek).
- Spanakis S. G. (1981). *Water Supply of the City of Iraklion 828-1939*. Technical Chamber of Greece, Dept. of Eastern Crete, Iraklion, Greece (in Greek).
- Tassios T. P. (2002) From “Peisistratean” to Evinos. *Kathimerini news paper*, Athens, Greece (in Greek).
- Viollet P. L. (2010). Water management in the early Bronze age civilizations. In: *Water Engineering and Management through Time: Learning from History*, F. Arregui (ed.), Taylor and Francis Group, London, UK, pp. 29–54.