Evolution of water supplies in the Hellenic world focusing on water treatment and modern parallels

A. N. Angelakis, K. S. Voudouris and G. Tchobanoglous

ABSTRACT

Advanced, well organized, and operated urban water supply systems existed in Greece from the Bronze Age (*ca.* 3200–1100 BC). At the dawn of human history, surface water and groundwater, principally springs, were the most common water supply sources. As the population grew, periodic water shortages occurred. In Early Minoan times (*ca.* 3200–2100 BC), these water shortages led to the development of sophisticated hydraulic structures for importing water and for the harvesting and storage of rainwater. In addition, the water treatment technologies and water distribution techniques developed at that time served as the basis for the advanced technological progress in the development of the urban water supply systems in the centuries that followed. In this paper, an overview of the evolution of public water supplies and water treatment technologies in the Hellenic world through the centuries up to modern times is presented. Some of the most significant innovations in the provision of water, its treatment, and distribution are highlighted. The overview is followed by a discussion of the contemporary situation, emerging trends, and future challenges, and parallels are drawn between historical developments and the water supply problems faced today.

Key words | ancient Greece, ancient hydraulic technologies, future trends, modern times, urban water systems, water treatment devices

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PROLEGOMENA

> '… *the principle of all things is water, out of water is all and into water goes all things back* ….'
>
> Thales of Miletus (624–546 BC)

Modern humans (*Homo sapiens*) have dwelled on earth for over 200,000 years, originally as hunter–gatherers, and with the population began to expand faster than ever before (Vuorinen *et al.* 2007). A new era started about 10,000 years ago when humankind adopted a rural way of living and established permanent small settlements (i.e. villages) scattered over wide areas. Because their settlements were highly dependent on water, a new relationship developed between humans and water (Rose & Angelakis 2014). When people lived as hunters and/or collectors, river water was used for drinking purposes. Also, the first permanent settlements were usually near a river or lake (e.g. China, Egypt, Mesopotamia). However when settlements were established in areas where there were no rivers or lakes, groundwater sources were used for drinking water purposes. At that time, waterborne diseases became a very serious health risk for the prehistoric agriculturists (Vuorinen *et al.* 2007).

The earliest known permanent settlement, which can be classified as urban, is Jericho, a city in the Palestinian Territories, located near the Jordan River. There is evidence of a settlement dating back to *ca.* 10,000 BCE (before the common era or before Christ, BC) (Mithen 2006). In Greece, the Neolithic settlement of Sesklo, located in northeastern Thessaly, is considered as one of the earlier Neolithic settlements of Europe. It covered an area of approximately 20 ha (1 ha = 10,000 m^2) during its peak period at *ca.* 5000 BC and comprised about 500–800

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houses with a potential population of 5,000 people. It is located near springs and other bodies of water.

Dating from the early Bronze Age (*ca.* 3000 BC), in the city of Mohenjo-Daro, located in modern Pakistan, archaeologists have found numerous ancient wells, water pipes and toilets (Angelakis & Zheng 2015; Khan *et al.* 2020). At the same time there is the first evidence of the purposeful construction of water supply and drainage and sewerage systems including water treatment devices in Europe, developed in Minoan Crete. In Egypt, there are traces of wells, and in Mesopotamia of stone rainwater channels, from 3000 BC (Vuorinen *et al.* 2007). Also the first primitive water supply treatment systems developed (Angelakis *et al.* 2012; Mays 2013; Antoniou *et al.* 2014).

In ancient Greece, because of a rapid increase in urban population, settlements were forced to transport water through aqueducts, to store water in cisterns and dams, and to distribute it to the people through networks. The produced wastewater was carried away through sewers, along with the rainwater. In cases of unfavorable terrain the water was lead through hills under pressure. The Greeks were among the first people to express an interest in water quality (Kosso & Scott 2009). They used aeration tanks and other devices for water purification. All major ancient cities in the Hellenic world, which lasted for millennia, were established in dry areas under water scarcity, in contrast to other ancient civilizations (Egyptians, Mesopotamians, Indus), which developed in regions with high surface water availability (close to rivers e.g. Nile, Tigris, Euphrates) (Zarkadoulas *et al.* 2008). Moreover, for reasons of safety, to avoid occupying fertile lands, and for hygienic reasons, especially those of water, most settlements were built on the top of hills and/or on dry areas (Angelakis *et al.* 2005; Koutsoyiannis & Patrikiou 2013).

In the early prehistoric times of a siege or when water from a spring or a well was not accessible, the water supply was from cisterns, which was only used for drinking and cooking purposes at 3–5 litres per person per day (l/p · d) (Mays *et al.* 2012). Studies by anthropologists in developing countries have found that in communities without direct access to potable water sources, the domestic water use is in the range of 10–20 l/p · d (Shuvial 2009). The average water demand in classical Miletus during its best times was 18 l/p · d (Kramer 2002).

In the Hellenistic period (*ca.* 323–146 BC) hand-dug wells and springs were used to meet water demands. In addition, the construction of cisterns became a widespread practice in many Greek cities during this period (Voudouris 2012). Furthermore, following the classical tradition, aqueducts continued to be subterranean. The cleaning of water took place in sedimentation tanks and sand filters. Romans were famous for their knowledge, craftsmanship, and ability to implement engineering projects, e.g. aqueducts, sewers and drains. They developed very advanced technology for sanitation, including baths with flowing water and underground sewers and drains. In rich and well-developed urban regions of Roman civilization, the scale of hydraulic works was highly increased (De Feo *et al.* 2011).

The purpose of this paper is to present a brief review of the basic development of water supply and treatment in ancient Greece with modern parallels. It is evident that urban systems and hydraulic works were designed, constructed, operated and managed properly, to support the water requirements of cities, and other settlements, from the early Bronze Age. Contemporary and future developments are also considered. In addition to the following discussion, an Appendix of important developments in the evolution of public water supplies in the Hellenic world from Early Minoan times is included online.

IN PREHISTORIC TO MEDIEVAL TIMES (*CA*. 3200 BC–AD 1400)

In this and the following section the evolution of public water supplies and treatment in the Hellenic world is traced from *ca*. 3200 BC to AD 1900 (Anno Domini or Current Era, CE). Contemporary and the future developments are considered in the fourth and fifth sections, respectively.

Prehistoric times (*ca.* 3200–650 BC)

Water treatment originally focused on improving the aesthetic characteristics of drinking water (EPA 2000). The prehistoric Greek and Indian civilizations, dating back to *ca.* 2000 BC, were the first to consider water supply treatment methods (Sklivaniotis & Angelakis 2006). People at that time knew that boiling water might in some way purify it. Also, they were aware of the benefits of sand and gravel filtration. During that time, the clarity of the water (i.e. turbidity) was the principal driving force for the earliest water treatments. Minoans had a good working knowledge of the benefits of sedimentation and sand filters (Angelakis & Spyridakis 1996). Not much was known about microorganisms or chemical contaminants (Enzler 2018). The Egyptians first (after *ca.* 1500 BC) discovered the principle of coagulation (EPA 2000). They applied chemical alum for suspended particle settlement. Pictures of these purification devices were found on the walls of the tombs of Amenophis II and Ramses II (Mays *et al.* 2012).

In prehistoric Greece the first water supply systems, based on rainwater harvesting, appear in the Early Minoan period (*ca.* 3200–2100 BC), e.g. in Minoan Chamaize and Trypiti settlements in eastern Crete. These systems were further improved in the Neopalatial period (*ca.* 1650–1450 BC), when, in several Cretan settlements (e.g. Phaestos, Troullos and Fournou Korifi) the water supply depended directly on atmospheric precipitation. In these locations, rainwater was collected from the yards and roofs of buildings (harvesting) and stored in water cisterns. In Phaistos palace, for example, rainfall water was collected in cisterns. Special care was taken with the hygiene of water collection by: (a) cleaning the opened surface (e.g. yards and roofs) used for the collection of the runoff water (Figure 1(a)) and (b) filtering the water in coarse sandy filters before it flowed into the cisterns (Figure 1(b)) (Mays *et al.* 2012).

Also in the Middle Minoan period, aqueducts delivered water to Knossos Palace from Mavrokolympos spring originally and in Kephala Hill from spring water sources at Archanes, which are also the source of the Kairatos River (Hogan 2007). Archanes was likely a summer palace for the Knossos kings. Also, to some houses in Minoan Tylissos the water was transferred via an aqueduct from a distance of 3 km. The source of the water was from the Agios Mama spring, where terracotta infiltration devices were discovered (Figure 2(a)). These devices were filled with charcoal, which correspond to modern day activated carbon treatment

Figure 1 | Water supply system in Phaestos palace: (a) open yard used to collect rainwater, which was diverted to a series of small cisterns, and (b) special cistern with coarse sandy filter (photographs: A. N. Angelakis).

Figure 2 | Water treatment devices in Minoan Tylissos: (a) two terracotta pairs of conical tubes probably used as refinery devices in Agios Mamas spring (from the Archaeological Museum of Iraklion, Crete) and (b) small stone-made cistern used for sedimentation of suspended solids (photographs: A. N. Angelakis; J. Hatzidakis).

processes, for removing both organic and inorganic constituents (Mays *et al.* 2012). To remove the suspended solids from the water as sediment, a small cistern of stone (sedimentation tank) was used before the collected water was stored in the main cistern (Figure 2(b)). A representative cylindrical-shaped cistern is shown in the background of Figure 2(b) (Hatzidakis 1934).

In the Late Minoan period, clarity and/or turbidity was the main criterion for classifying water as suitable for potable use, similarly to today considerations (Mays *et al.* 2012). It is truly amazing that the most common water quality modification technique for providing suitable domestic water supplies was known to Minoans. Thus, according to Defner (1921), a strange, oblong device with an opening in one of its ends was used to treat domestic water (Figure 3).

The device was constructed in a similar manner and with the same material as the terracotta water pipes. Spanakis (1981) considered this device to be a hydraulic filter which was probably connected to a water supply reservoir by a rope passing through its outside handles. Its operation relied on turbulent conditions to continuously clean the porous surface thus allowing the continuous flow of filtered water to a container. After extensive use and solids accumulation, it was probably released from the pipe end for cleaning purposes.

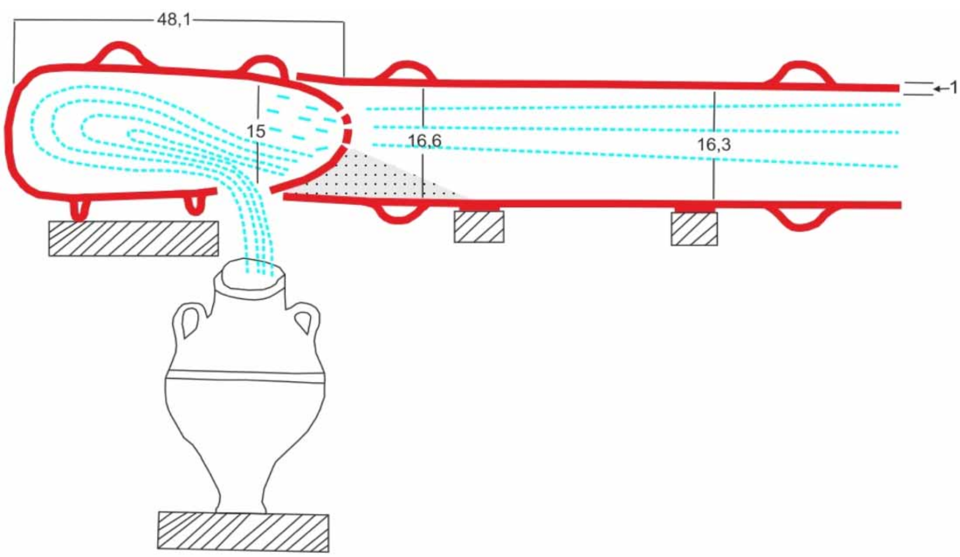


Figure 3 | Minoan water ceramic filter (units in cm) (Spanakis (1981), with modifications).

As mentioned before, during the Minoan Era, in several Cretan settlements (e.g. Phaestos, Chamezi, and Fournou Korifi) the water supply depended primarily on atmospheric precipitation, mainly on rainfall. In such a place, the rainwater was collected from the roofs of buildings and via conduits into cisterns for storage.

Mycenaean settlements in the *ca.* 14th century BC used aqueducts to transfer water over long distances, ensuring autonomy against siege for the acropolis of Mycenae and the fortifications at Tiryns (Argolida, South Greece). It should be noted that the first sophisticated long-distance canal systems were constructed in the Assyrian empire in the *ca.* 9th century BC (http://www.ancient.eu/aqueduct/).

In historical times (*ca.* 650 BC–AD 330)

Historical sources and archaeological excavations provide evidence of the cultural explosion that occurred in Greece from the very early times of the classical period (*ca.* 480–336 BC), including various disciplines of the water sciences such as dams, aqueducts, water networks, and other sanitary and purification structures, especially those in urban areas (Angelakis *et al.* 2005).

Classical and Hellenistic times (480–146 BC)

The advancement of water technology and management is demonstrated in numerous hydraulic works at several archaeological sites (e.g. Athens, Pella, Miletus, Delos, Crete, and Samos). Furthermore, rainwater harvesting systems were expanded in areas with low water availability, including sedimentation and/or filtration devices, e.g. on Aegina Island. In addition, water treatment systems were applied, and some representative examples are next presented.

Hippocratic sleeve. Hippocrates, who is considered one of the most famous in the history of medicine, invented and used the first water filtering system, in the form of a cloth bag about 500 BC, known today as the Hippocratic sleeve (Figure 4). It was used for removing the impurities from drinking water after it was boiled. This early method consisted of a piece of cloth, folded at the corners, into which water could be poured, usually after being boiled, and then passed through to increase cleanliness for use in medical procedures and treatments (Mays 2013). Hippocrates is still revered for many of his contributions to health, and this dedication to clean water should be considered a major accomplishment.

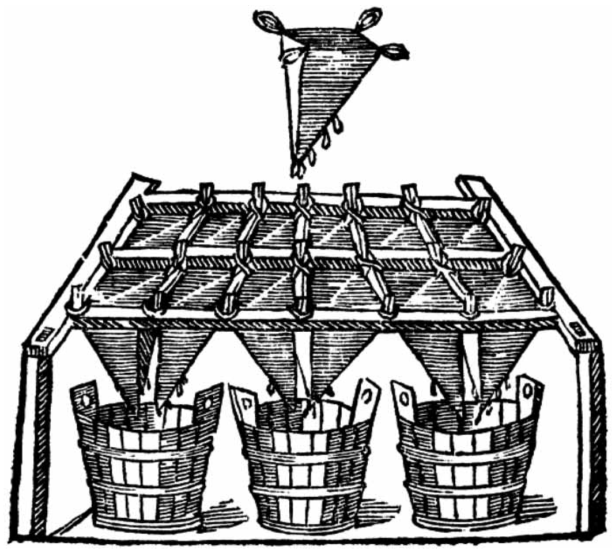


Figure 4 | Hippocratic sleeve (Mays 2013).

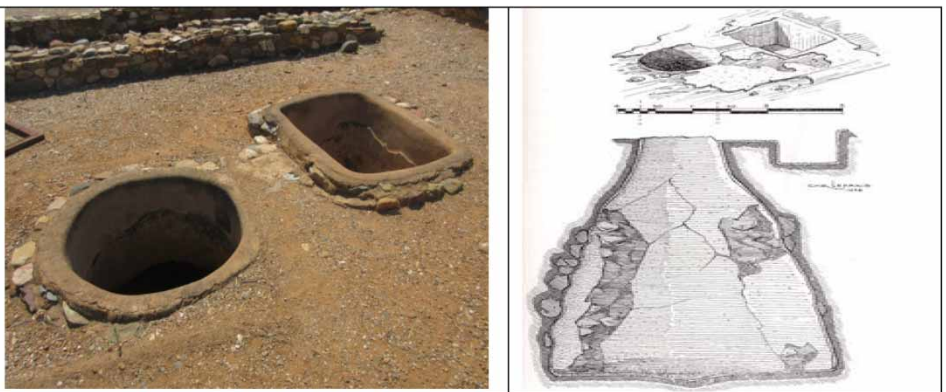
Pella. Pella, located 40 km from Thessaloniki, is one of the first known cities in ancient Greece to have had an extensive and a sophisticated water supply and sewerage system. Pella was the capital of the ancient Greek kingdom of Macedon and birthplace of Alexander the Great. Pella's infrastructure is based on a Hippodamian city-planning system. Hippodamus of Miletus is known as the father of urban planning. The streets are from 9 to 10 m wide, except for the central east–west arterial, which is up to 15 m wide. The water supply system, as part of the urban design, includes wells, cisterns, fountains, etc (Kaiafa *et al.* 2014). The city was supplied by an extensive distribution network of terracotta piping. Water supply pipes and sewers were located under the pediments, which unfortunately are not preserved today. These were connected to individual houses and wastewater disposal from most of the city (Tamiolakis 2018).

Olynthus. Olynthus is located in the first Peninsula of Halkidiki (Kassandra) in northern Greece. The accuracy of the urban plan of Olynthus city as well as in other classical cities (e.g. Pella, Kassiopi, Miletus) helps to explain how the Hippodamian city-planning system was being implemented (Kaiafa *et al.* 2014). Each square block usually contained ten houses, which had an internal courtyard and besides the necessary rooms, auxiliary areas with running water and sewerage and drainage systems (Cahill 2002). Regarding the water supply in Olynthus as well as in other classical cities, the importance of cisterns and well technologies has been severely underestimated. Cisterns have been found in 15% of the excavated houses (Klingborg 2017).

According to Kaiafa *et al.* (2014) there were few wells or springs in the wider area to cover the public water supply. Recently Klingborg & Finné (2018) reported 'that it is impossible to explore the ancient water supply system as a whole, and therefore to understand how it is related to factors such as climate change, social development, demographic variation, technological advance and economic prerequisites, unless we obtain a more holistic understanding of the water supply systems, including these installations'. Similar to Minoan technology, in Olynthus the water supply system was based on the use of coarse sand filters in the ground, which were used for filtering the rainwater before it flowed into underground cisterns, aiming at water purity (Figure 5). Cisterns are, however, not intended to receive a constant inflow, because they are not primarily designed to facilitate a continuous outflow.

Emporiae, Spain. Asclepius was a popular and influential healing deity-figure throughout the Mediterranean region (Morehouse 2012). He also became so popular across the ancient Hellenic world and its colonies for his extraordinary healing skills, that he was worshipped everywhere. There were sanctuaries located in remote but beautiful areas, well known as *Asclepieia* or *Asclepieions* (in ancient Greek: *Ασκληπιεία*), dedicated to the healer-god, which functioned as medical centers for prognosis, advice, healings, and therapy (Risse 1999). More than 400 *Asclepieia* operated in the ancient Hellenic world, offering their valuable services to the ancient people. In all *Asclepieia* the role of water and its cleanliness were crucial and there was no *Asclepieion* without a source of water. In the *Asclepieion* in the Hellenistic city of Emporiae in the northwestern coastal area of Catalonia (Spain), the major water source was rainwater, which was stored in cisterns (Figure 6(a)). The stored water in the cisterns was treated by ceramic filters of the *ca.* 3rd century BC, before its use in the *Asclepieion* (Figure 6(b)). It is probably the first use of ceramic filters for water treatment in the world.

Pergamon. Hellenistic Pergamon, near modern-day Izmir, Turkey, was supplied by aqueducts. Around 200 BC, as the city began to expand, water demand exceeded that used from a system of cisterns where rainwater was stored. At that time, three aqueducts were installed to carry water from the mountains to Pergamon city (Fahlbusch 2010). In addition, an inverted siphon more than 3 km long with a maximum pressure head of about 180 m was used to transfer water via aqueduct. This siphon was constructed using lead pipes anchored with large stones (Koutsoyiannis *et al.* 2008). In the upstream end of the inverted siphon a sediment-settling chamber was built in order to avoid clogging from the sediments (Garbrecht & Garbrecht 2005; Mays 2013).



(a) (b)

Figure 5 | Olynthus bottle-shaped cistern with a small tank for pretreatment including the capture of debris and sediment: (a) plan and (b) cross-section (Klingborg & Finné 2018).

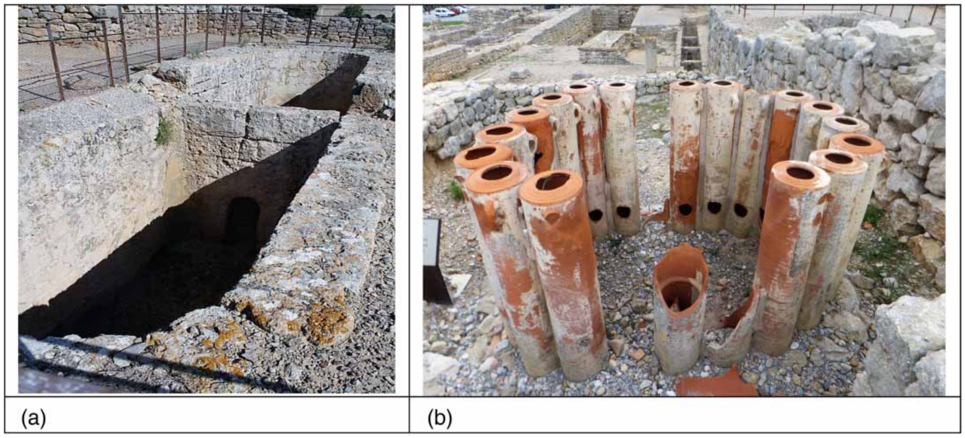


Figure 6 | Cistern and ceramic water filters from the *Asclepieion* in the Hellenistic city of Emporiae in northwestern Catalonia, Spain (with permission of S. Manolioudis).

Roman period (146 BC–AD 330)

The Romans developed and improved the technology of the Hellenistic period from small to large scale. Aqueducts were the most common technology of water supply in Roman cities. Water sources included springs, percolation wells, dams, and weirs on streams. These facilities are discussed extensively in the treatises of Marcus Vitruvius Pollio, a Roman architect and engineer who lived in the *ca.* 1st century BC (Mays 2013). A model of the two-story, four-chambered settling tanks (*piscina limaria*) in the Virgo Roman aqueduct on the Pincian Hill in Rome is illustrated in Figure 7(a). An ellipsoid ceramic device used for separating water from oil and fats is shown in Figure 7(b). It consists of a vertical compartment with two smaller compartments inside. Two semicircular openings on the upper part and at the base of the compartment were used to connect the two sections. The first section was filled with the water mixed with oil. The oil, which was lighter, would flow through the upper opening into the next department while the water remained in the bottom of the first one. The device was used mainly for the separation of oil from water during the production of olive oil.

Medieval times (*ca.* AD 330–1400)

After the fall of the Roman period, during the Middle Ages (*ca*. AD 400–1400), little progress was made in water treatment and its connection to the field of public health. During these centuries, known also as the Dark Ages, technological development was minimal due to the lack of scientific innovations and experiments (Enzler 2018).

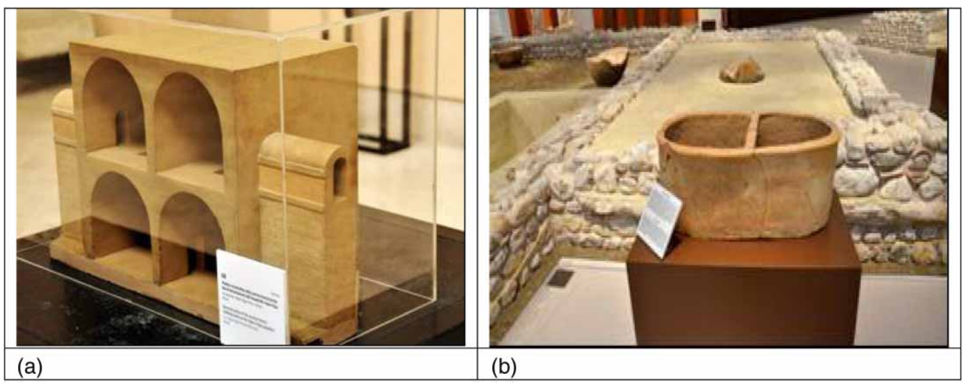


Figure 7 | Roman-era devices: (a) model (reconstruction) of the settling tanks (*piscina limaria*) on the aqueduct Virgo in Rome (Roman Civilization Museum in Rome, photograph is by permission of L. W. Mays) and (b) ceramic device used for separating water from oil and fats dated to the end of the *ca.* 1st century AD (Archeological Museum of Patras, Greece, photograph: A. N. Angelakis).

Water was extracted from rivers or wells, which became highly polluted due to the waste and excrement which were discharged into the rivers. To face that problem, people started to bring water from outside the cities, where rivers where unpolluted.

IN EARLY AND MID-MODERN TIMES (*CA.* AD 1400–1900)

During this period very little progress was made in Greece, which was under Ottoman occupation. Sedimentation tanks were used mainly for improving drinking water quality. Nevertheless, new developments were occurring in other parts of the world. In Italy, the Italian physician named Lu Antonio Porzio designed the first multiple filter in 1685. However, the first documented use of sand filters to purify drinking water dates to 1804 by John Gibb in Paisley, Scotland, when the owner of a bleachery installed an experimental filter, selling his unwanted surplus to the public (Baker 1981). In the next three years, filtered water was transported to Glasgow. In 1806 a large water treatment plant operated in Paris (Hall & Dietrich 2000). The plant's filters consisted of sand and charcoal. The raw water was settled for 12 hours, before it was filtered. Thereafter, in 1827, the Englishman James Simpson built a sand filter for drinking water purification. Today, it is still considered as the number-one contribution to public health (Crittenden *et al.* 2005).

IN CONTEMPORARY TIMES (AD 1900–PRESENT)

For the first time, in the mid-19th century, the social reformer Sir Edwin Chadwick (1800–1890) noted the relation between disease (such as cholera and typhoid) and water and the correlation between water quality and sanitation with mortality rates and life expectancy (Chadwick 1842, 1965). He estimated that by implementing proper sanitation and supplying clean water, an extra 13 years of life could be added to the labouring class. Chadwick's ideas on the public health movement originated from his report, starting with the Public Health Act of 1848 (Prasad 2007). In the 1850s, building water supply and sewerage and drainage networks became a prestigious symbol of the public health of a city (Breyer 2006).

In the beginning of the 20th century, several cities in the United States began routine WTPs (water treatment plants) including disinfection of community drinking water. Over the next decade, thousands of cities and towns across the United States followed suit in routinely disinfecting their drinking water, contributing to a dramatic decrease in water-borne disease across the country (CDC 1999). Thereafter, water treatment technologies were expanded to western European cities. By the First World War these technologies had become routine in cities in the developed world.

There are other factors in addition to water quality that affect the quality of life and life expectancy, e.g. child mortality, diseases, medicines, pharmacology, nutrition, environmental and other risks and standards of life. However, some authors (e.g. Dietrich 2006; Reiter 2012) suggest that the increase in life expectancy in the last century (from 30 years to over 80) is mainly due to water quality. For several millennia (since prehistoric times) it was *ca*. 30 years. It is noteworthy that life expectancy in Greece during the Minoan Era (*ca.* 5,000–3,000 years ago) was a little less than 30 years, in classical and Hellenistic times (*ca.* 2,500–2,100 years ago) it was just over 30 years, in 1947 it was 45 years and in 2016 the life expectancy for women was 84 years and for men 78.9 years and today it is 81.5 years. Currently it is probably over 82 years. The significant increase in life expectancy immediately after the Second World War is probably due to the improvement of potable water quality and hygiene conditions. At that time, water disinfection was introduced and the first WTPs were implemented.

In Athens, the capital of Greece, water for drinking and domestic demands is supplied mainly from surface water reservoirs (Marathonas, Yliki, Mornos, Evinos). Of these reservoirs, only Yliki is natural, while the others have been created by the construction of dams in the appropriate places on the respective rivers Evinos, Mornos and Harados (Marathon dam). Groundwater via boreholes is also used for water supply (www.eydap.gr). In Athens, the first WTP was implemented at the end of 1931 in Galatsi (Figure 8(a)) at an elevation of 159 m. Its capacity is 540,000 m^3/d. Chlorine is used for disinfection. Additional

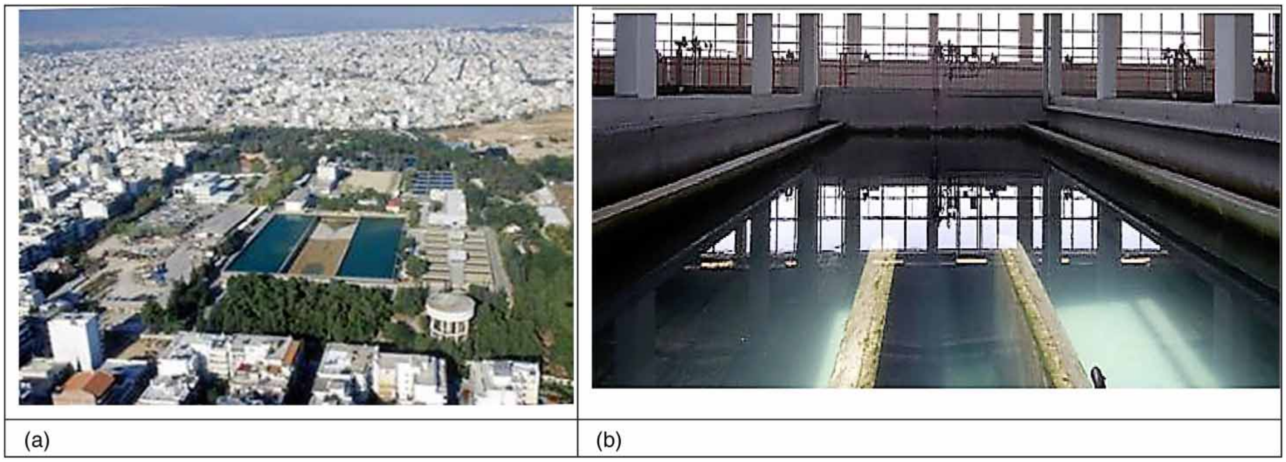


Figure 8 | WTPs: (a) in Galatsi, Athens (photograph: G. Stefanakou, EYDAP, Athens, Greece), (b) the Thessaloniki Water Treatment Facility (Refinery) (www.eyath.gr).

WTPs were implemented in Acharnes (1970), in Polydentri (1986) and in Aspropyrgos (1997).

In Thessaloniki (the second biggest city of Greece), at the Kalochori aqueduct, a sedimentation reservoir, was constructed in 1888. In 1917 the Hellenistic-era aqueduct of Chortiatis was restored and the first WTP was implemented in which calcium hypochlorite was used (Yannopoulos *et al.* 2017; Tamiolakis 2018). Today, the city's domestic-water-needs (250,000 m^3/d) are met using the karst spring of Aravisos and the reservoir on the Aliakmonas River. The Thessaloniki Water Treatment Plant (Refinery) is located in Sindos, west of Thessaloniki, and the water treatment entails the following stages (www.eyath.gr): pre-ozonization, pH adjustment–rapid mixing, flocculation–sedimentation, filtering through sand beds, ozonization, and filtration through granular-activated-carbon beds. Chlorination is used for disinfection and pH adjustment is with lime (Figure 8(b)). Clean drinking water is then directed to storage tanks and distributed via a network of pipes to existing water supply tanks. Later water supply and sewerage enterprises were established in all the major cities throughout the country by which similar WTPs were implemented. The disinfection is mainly done by chlorine in storage tanks.

CURRENT ISSUES AND CHALLENGES

While the history of water supply in modern Greece was discussed in the previous section, it is appropriate now to consider some current issues and challenges that will affect the long-term sustainability of water supply systems in Greece. Future trends and challenges are considered in the following section.

Major current issues and challenges highlighted in the following discussion include: (a) long-term water sustainability, (b) aging infrastructure, (c) non-revenue water (d) water reuse, (e) impacts of climate change, (f) development of a single water management agency, and (g) development of region-wide water resource management programs. In effect, the current issues and challenges are the modern parallels of those faced by the Minoan civilization. Their solution will take the same ingenuity and inventiveness exhibited in Minoan times.

Long-term water sustainability

The long-term availability and sustainability of existing and new water supply sources are perhaps the most serious issues faced by most water agencies in Greece today. Factors that will impact public water supplies are population growth, population demographics, limited availability of new natural water sources, the distribution of existing freshwater sources, increased contamination of existing water sources with trace organics and nanoparticles, aging infrastructure, and climate change.

By 2030, roughly 60% of the world's population will be living in urban areas. At the same time, it is also predicted that 60% of the world's population will live near a coastal region, creating even more urban sprawl than already exists (UN 2015). The same situation applies in Greece. In Greece, as in other EU countries, population growth will mainly come from Middle Eastern and African refugees. This population increase will play a critical role in the implementation of future water, sewerage and drainage systems. The great majority of these refugees will settle in urban areas, further stressing the existing water supply systems. For example, 35% of the total permanent population of the country lives in the Metropolitan-Athens region with an area of 3,500 km^2 (2.65% of the total area of Greece) (Angelakis 2017). With the anticipated growth in the Athens region, it will not be possible to simply extend the existing centralized model of water and wastewater systems to cope with the extra water demands and waste loads.

Alternative strategies for providing water supply and sewerage must be developed. Decentralized water treatment facilities and integrated wastewater management systems employing satellite treatment systems will be needed (Leverenz & Tchobanoglous 2009; De Feo *et al.* 2014).

Aging infrastructure

Many of the water distribution and sewage collection systems installed in the first part of the last century are in constant need of repair or replacement. Clearly, an effective operating strategy is needed to deal with aging water distribution systems to protect public health. As noted above, dealing with population growth and urban sprawl further complicates this issue. The replacement of aging infrastructure must also be coordinated with the implementation of decentralized water treatment facilities (De Feo *et al.* 2014; Tchobanoglous 2018).

Non-revenue water

Dealing with non-revenue water is a major problem in Greece today. Non-revenue water is water which is lost from the system and is not paid for. Non-revenue water can result from: (a) losses due to deteriorating supply and distribution networks, (b) apparent losses due to illegal connections, and (c) unbilled authorized use. In Greece, non-revenue water can exceed 60% of the available potable water supply. The largest percentage of water that is lost is due to leaks in the distribution system.

Water reuse

In Greece as in all the EU, increase in effluent reuse is a priority goal to alleviate water scarcity across Member States, to preserve water resources and to protect the environment and public health (EC-COM 2018). It is also in full compliance with EU policies dealing with circular economy and adaptation to climate change. Recently, the European Commission published criteria describing minimum quality requirements for crop irrigation and aquifer recharge, monitoring requirements, and key risk-assessment tasks. However, these criteria only deal with agricultural irrigation and groundwater recharge. For Greece, in earlier estimates it was found that 3.2% of the total water currently used for irrigation could be saved by reusing effluent from existing wastewater treatment plants (WWTPs) (Tsagarakis *et al.* 2004).

Recognition that withdrawing water from inland areas, transporting it to urban population centers, treating it, using it once, and discharging it to coastal waters is unsustainable and given the difficulties of developing new water sources and the high percentage of non-revenue water, most water agencies have concluded that various forms of water reuse, including planned potable reuse, can play a vital and crucial role in helping to alleviate water shortage problems (Angelakis *et al.* 2018). Unfortunately, most existing WWTPs are not located near potential water reuse opportunities (Ilias *et al.* 2014; Tchobanoglous 2018). The infrastructure costs and social disruption associated with the transport and storage of water from advanced treatment to or near the point of use are significant impediments to both non-potable and potable reuse. Solutions employing decentralized water and wastewater facilities, as noted above, must be implemented.

Climate change

Climate change is not a new phenomenon. People have always had to cope with the uncertainty of natural phenomena and the unpredictability of the environment. Precisely these conditions have shaped knowledge and adapted it locally to respond to adversity in the increase of flood events, particularly in increased urban areas, with appropriate techniques for capturing and distributing water, protecting soil, recycling, and optimizing energy use (Angelakis 2017). Today, while areas that are wet are getting wetter and areas that are dry are getting drier, what is different is the intensity of the rainfall events. Most existing water and wastewater management facilities were never designed to deal with the volume of water that now occurs within hours of an intense rainfall event.

Development of a single water management agency

Historically, the agencies responsible for water supply and wastewater management in Greece were separate entities. There is, however, a growing recognition that long-term water sustainability problems cannot be by individual agencies. Separate municipal water and wastewater agencies must be merged into one agency with the responsibility for managing both drinking water and wastewater as 'one water'.

Development of region-wide water resource management programs

Because of the increasing volume of stormwater and wastewater due to infiltration, existing infrastructure and management systems have proven to be inadequate. The need to develop integrated region-wide sustainable water resource management programs has become apparent to workers in the water sector. If regional solutions are to be developed, all water agencies will have to work together (Angelakis 2017).

FUTURE TRENDS AND CHALLENGES

In addition to the issues discussed above, there are also a number of trends and challenges that will further tax the resources and capabilities of water agencies throughout the world and Greece including: (a) the need to examine all potential sources of water including local surface water, local groundwater, imported water, potable reuse (direct potable reuse, DPR, and indirect potable reuse, IPR), desalination (brackish and sea water), stormwater and other more limited sources; (b) recognition that conventional water treatment technologies may not be adequate for the treatment of trace organics, including most recently perfluoroalkyl and polyfluoroalkyl (PFAS) compounds and nanoparticles now found in almost all water supply sources and also that the water quality of some new water sources may be significantly deteriorated, requiring extensive treatment; (c) development of an ongoing effective risk management program taking into account system reliability, robustness, and resilience; (d) implementation of voluntary and mandatory water conservation measures including the use of low flow fixtures, alternating landscape watering days, and the implementation of desert-type landscaping.

Which of the above measures will be pursued in depth will vary from location to location, but what is important is that each of these measures must be evaluated in the development of a long-term water management strategy.

CONCLUDING REMARKS

The evolution of water supply and treatment to enhance water quality in the Hellenic world are examined in the paper. In ancient Greece the water supply was progressive. In most cities every house had its own water supply with cisterns or pumping wells. In some cases, sophisticated piping for water supply systems applied which was connected to individual houses. The technology developed and applied was designed for optimal water supply. Also, hygienic aspects were decisive for water supply in the ancient Greece to prevent the spreading of sicknesses and epidemics. At the same time, the ancient Greeks also thought about the quality of water supply and they built systems to transport sewage out of the towns. The most important steps in water supply history relevant to water treatment, consumption and hygienic practices are chronologically presented and discussed in Appendix 1.

The concerns that led to the development of water treatment processes in the Hellenic world are at play today. In the Hellenic world, the clarity of the water was taken as a measure of its safety. The quest for clean water led to the development of sedimentation facilities, and anthracite filtration, cloth filtration and ceramic membrane filtration. Today there are similar concerns about the safety of water, but instead of water clarity, the concerns are with trace organics and nanoparticles. New treatment processes including ion-selective membranes and resins are being researched and developed to deal with these constituents, as was the case in the Hellenic world. In addition, long-term water sustainability, aging infrastructure, non-revenue water, water reuse, impacts of climate change, development of a single water management agency, and development of region-wide water resource management programs are issues that must also be addressed. The solution of these problems will require the same dedication that the Minoans exhibited in finding solutions to water supply and wastewater management issues.

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SUPPLEMENTARY MATERIAL

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