Urban waste- and stormwater management in Greece: past, present and future

A. N. Angelakis

ABSTRACT

Urban wastewater and storm management has a long history which coincides with the appearance of the first organized human settlements (*ca*. 3500 BC). It began in prehistoric Crete during the Early Bronze Age (*ca*. 3200 BC) when many remarkable developments occurred in several stages known as Minoan civilization. One of its salient characteristics was the architecture and function of its hydraulic works and especially the drainage and sewerage systems and other sanitary infrastructures in the Minoan palaces and other settlements. These technologies, although they do not give a complete picture of wastewater and stormwater technologies in ancient Greece, indicate that such technologies have been used in Greece since the Minoan times. Minoan sanitary technologies were transferred to the Greek mainland in the subsequent phases of Greek civilization, i.e. in the Mycenaean, Classical, Hellenistic, Roman, and present times. The scope of this article is the presentation and discussion of the evolution of waste- and stormwater management through the long history of Greece, focusing on the hydraulic characteristics of sanitary infrastructures. Also, the present and future trends of wastewater and stormwater management are considered. Practices achieved in prehistoric Greece may have some relevance for wastewater engineering even in modern times.

Key words | baths, combined and separated sewerage systems, drainage and sewerage systems, prehistoric and historic civilizations, toilets, urbanization

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INTRODUCTION

Most Greek civilizations were closely linked to hygienic living standards and a comfortable lifestyle. These developments were driven by the necessities to make efficient use of natural resources, to make ancient Greeks more resistant to destructive natural elements, and to improve the standards of life, both at public and private level. To achieve these, both technological infrastructures and management solutions were developed. In Crete and the Aegean islands, hygienic technologies were practiced as early as in the Minoan period (*ca*. 3200–1100 BC) and were transferred to mainland Greece, the Aegean islands and Cyprus (Angelakis *et al.* 2014; De Feo *et al.* 2014a).

Management of urban waste- and stormwater has been known since the first large urban development period in mankind's history (*ca*. 3500–1100 BC). By *ca*. 3500 BC, people from the Sumerian country created a new city, on the upper course of the Euphrates in modern Turkey, in order to control trade with the coastal Syria. In this small city, known as Habuba Kebira, wastewater and rainwater were collected and carried outside the city walls by U-shaped terracotta pipes and sewers and/or drains covered with stone slabs, running below the streets (Vallet 1997; Viollet 2000). Technologies for control of waters in urban areas were also developed to a high degree in Mesopotamia and Syria, in the Harapean civilization of the Indus valley (*ca*. 3000–1900 BC), and westward as far as in the Aegean sea, during the Minoan civilization in Crete (*ca*. 2700–1400 BC), and the Mycenaean civilization in continental Greece (De Feo *et al.* 2014b; Viollet 2000).

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Previous studies on waste- and stormwaters were limited to ancient management and institutional aspects in several civilizations (Lofrano & Brown 2010; De Feo *et al.* 2014a, 2014b; Angelakis & Zheng 2015; Brown & Lofrano 2015). Also, Angelakis *et al.* (2005) reviewed the status of urban sewerage and stormwater drainage systems in ancient Greece, based on archaeological studies. However, the evolution of sewerage and drainage systems construction, operation and management in the Hellenic civilizations up to modern times, and the future trends can be a challenge. The technological achievements in some periods of ancient Greece were so advanced that they could be compared only to modern urban water, wastewater and rainwater systems.

The luxurious hygienic infrastructures in Minoan Greece can be considered characteristics of high living standards and economic prosperity, in both domestic and public places (Antoniou & Angelakis 2008, 2009, 2015). These advanced technologies were further developed during the Mycenaean, Classical, Hellenistic, and Roman periods (Angelakis & Koutsoyiannis 2006; De Feo *et al.* 2011). The long-term sustainability of the ancient sewerage and drainage systems and other sanitary structures is justified by the fact that these techniques are still practiced today in rural areas.

The chronological sequence of hydro-technological achievements in Greece is interesting. The development of water science in ancient Greece was not linear but often characterized by discontinuities and regressions. Many historians, archaeologists, and engineers believe that the Minoans, by means of their Mediterranean naval fleet and commercial trade networks, had contacts all around the Mediterranean, e.g. Mesopotamians and Egyptians (Black 2013). Thus, during the so called 'dark ages' (e.g. *ca*. 1100–650 BC), bridges were probably built with neighboring civilizations (e.g. Etruscans and Egyptians) (Angelakis *et al.* 2013).

It is evident that in ancient Greece, extensive systems and elaborate structures for urban wastewater and stormwater were designed, constructed, operated and managed properly, in order to support the hygienic and functional requirements of palaces, cities, and other settlements. Thus, the main objectives of this study are: (a) to review briefly the waste- and stormwater management in Greece through the centuries in the Minoan era, and thereafter in Archaic, Classical, Hellenistic, and Roman civilizations, and the Middle Ages; (b) to provide information on the status and to present and compare sanitation technologies among several Greek civilizations up to modern times; and (c) to briefly present the trends and the developments in sanitation technologies in the future. The information provided is expected to contribute to *how and what we could learn from the past*.

BRONZE AGE (*CA*. 3200–1100 BC)

Minoan era

Minoan civilization, the first European civilization, was a sophisticated and very advanced culture which blossomed from about 3200 BC to 1150 BC, on the island of Crete and the Aegean islands. It was followed by a long period (*ca*. 1150–650 BC), usually referred to as the 'dark ages' before Archaic-Classical Greece. It seems to have combined the characteristics of monarchy and city-state democracy.

The architectural and hydraulic function of stormwater and wastewater systems were of special significance in the construction of the principal Minoan centers. Archaeological and other evidence indicate that, during the Middle Bronze Age, advanced water management and sanitary techniques were practiced in Minoan settlements (Angelakis & Spyridakis 2010; Antoniou & Angelakis 2015). These include the construction and use of bathrooms and other sanitary and purgatory facilities relevant to waste- and stormwater systems. It should be noticed that throughout this paper 'sewerage systems' refers to combined sewerage and/or stormwater systems (CSS). The same holds for sewers and/or drains. The hydraulic and architectural function of sewerage and drainage systems in palaces and cities are regarded as one of the salient characteristics of the Minoan civilization (Angelakis & Spyridakis 1996). It is not by chance that during the Minoan Era the main technical and hydraulic operations associated with catchment basins, surge chambers, manholes, urinals and toilets, laundry slabs and basins, and sewerage systems, including disposal sites of the effluents, were practiced in varying forms (Angelakis & Spyridakis 1996; Tzanakakis *et al.* 2014).

Minoans had developed remarkable technologies relevant to waste- and stormwater management such as sewers, baths and toilets. Several Minoan cities and palaces had well established sewerage and drainage systems, which are in good functional condition even today (Figure 1). The preservation of several Minoan archaeological sites is largely due to well operating drainage systems. The most advanced Minoan sewerage system seems to be in the villa of Hagia Triada (Figure 1(b)). This system prompted the admiration of several visitors, including the Italian Physiologist and Archeologist Mosso (1907), who visited the area in the early 20th century. During a heavy rain, he noticed that the drainage system functioned perfectly and recorded it by saying: '*I doubt if any other case of stormwater drainage system exists that works 4,000 years after its construction*.'

In addition to sewers, bathrooms, toilets and other purgatory structures were considered necessary in most Minoan palaces. A room of interest was identified in the palace of Knossos by Evans (1921–1935) as a toilet with wooden seat. As with today's toilets, it had flushing system. The flushing and outflow tube leading from the outer entrance, crossed along the toilet, passed under the seat and ended at the outside sewer (Castleden 1993). Toilets in the palace of Minos and probably in other Minoan settlements were cleaned thoroughly for some days of the year, with rainwater that was collected in tanks.

Mycenaean civilization (*ca*. 1600–1100 BC)

In the last phase of the Bronze Age, from *ca.* 1600 to 1100 BC, the Mycenaean civilization blossomed in the mainland of Ancient Greece, representing the first advanced civilization in mainland Greece. In Orchomenos, one of the centers of the Mycenaeans, large quantities of surface water were controlled and channeled in dikes and canals, during the Late Bronze Age (Knauss 2003). The development of hydraulic engineering during the Late Bronze Age on the Greek mainland is also evidenced by the existence of bathtubs associated with sewerage infrastructures, e.g. in Pylos. Engineers were able to drain stormwaters, and control and dispose of the wastes. In central Greece, ancient Iolkos, the city of Jason was discovered, with *megaroid* houses built with the same orientation on either side of a wide street and a very well preserved sewerage system (Antoniou *et al.* 2014). Also in Dimini Iolkos, a permanent settlement classified as urban, three of the houses had bathtubs with sewers in separate rooms, implying advanced knowledge of wastewater management and high living standards (Antoniou *et al.* 2014). Finally, in Mycenae, the major center of the Mycenaean civilization, a large open drain parallel to and just inside the outer wall of the citadel, probably as a part of the central sewerage and drainage system drained down the steep hillside outside the defensive wall (Figure 2).

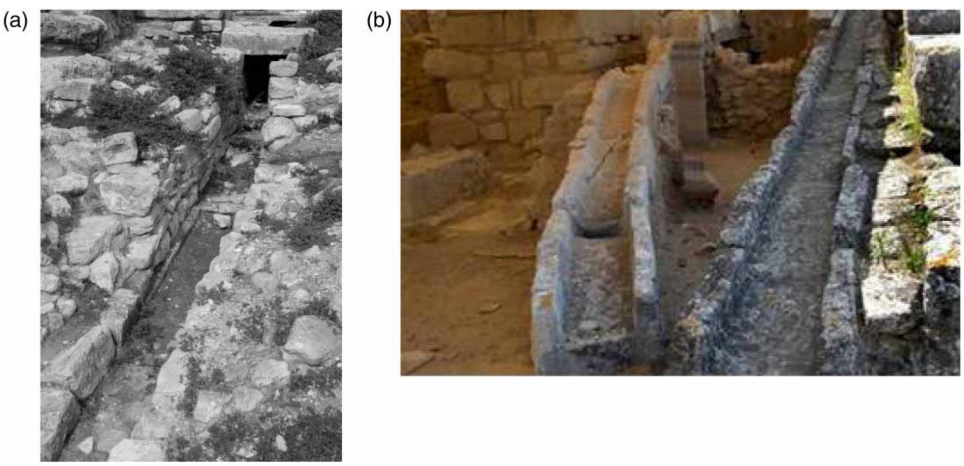

Figure 1 | Minoan sewerage systems: (a) the output of the central system of the Phaistos palace and (b) part of the central system of the villa Hagia Triada.

Figure 2 | Part of the central drainage system in Mycenae (http://toilet-guru.com/mycenae.php).

HISTORICAL TIMES (*CA*. 490 BC–330 AD)

Classical and Hellenistic periods

The technological progress in Greece during the Historical times was accompanied by a good understanding of the water and wastewater related aspects. In *ca*. 600 BC, Greek philosophers developed the first known scientific views on natural hydrological and meteorological phenomena. Later, during the Hellenistic period, significant developments were achieved in hydraulics, which along with progress in mathematics allowed the invention of advanced instruments and devices, like the Archimedes' water screw pump (Koutsoyiannis & Angelakis 2003).

The realization of the importance of water sanitation was evident already from the early Archaic period. Later, Alcmaeon of Croton (floruit *ca.* 470 BC) was the first Greek doctor to state that the quality of water may influence the health of people. Also the Hippocratic treatise: *Airs, Waters, and Places* examined the effects of the climate and the environment, in general, on human health (Galanaki 2014). In Hippocratic medicine, every disease had its natural logical causes. Thus, the importance of water for public health was recognized for the first time and the first well organized baths, toilets, and sewerage systems appeared (Angelakis *et al.* 2005).

The lavatories of the Hellenistic period consist of single or multiple benches, wooden or stone-made, having defecation keyhole-shaped openings (Antoniou 2007). The benches were supported by cantilever stone blocks, and were situated over the main ditch, where flushing water was running, continuously or periodically. According to the type and the layout of the benches, the shape of the supporting beams and the keyhole openings could be categorized as a type of typology. The more usual layouts are the L-shaped, as in Minoan Amorgos and in Corinth, and the U-shaped, as in Epidaurus and Philippoi. More on this is given by Antoniou *et al.* (2014). Depending on their use, they are distinguished in domestic lavatories and public ones, usually related with public buildings or complexes.

Regarding sewers, in Athens stormwater, human wastes and other effluents, were delivered to a collection basin outside the town. From that basin, the stormwater and wastes were conveyed through brick-lined conduits in fields to irrigate and fertilize fruit orchards and other agricultural field crops. The known epidemic in Athens (*ca.* 430–426 BC), probably contributed to the enhancement of the sewerage system of the town during the *ca.* 4th century. Holes were left in the walls of the drain channel (main sector and/or branches) as inlets for the effluents of the adjacent houses. These house sewers were constructed in various ways; for example one had carefully built stone walls and was covered with tiles and flat slabs; others were simply made of inverted roof tiles (Thomson & Wycherley 1972). Several manholes at the covered sectors of that network reveal the provision for cleaning and maintenance. Remains of sewers in Hellenistic Athens are shown in Figure 3. Also, in Classical Olynthus, terracotta pipes were frequently evacuating the domestic sewage to a drain-path between the two rows of houses on each block (Robinson 1938).

Kassope in the north west of Greece is considered as one of the best examples of a city built on a rectilinear street grid of a Hippodamian plan. The city flourished in the 3rd century BC, when large public buildings were built. The city's waste- and stormwater system is also a remarkable point of the Hippodamian plan of the city (Figure 4). Interestingly, the drains/sewers in several locations were open facing the ground, which can be considered as a novelty, so that water could come in contact with soil. In addition to the simpler construction of the

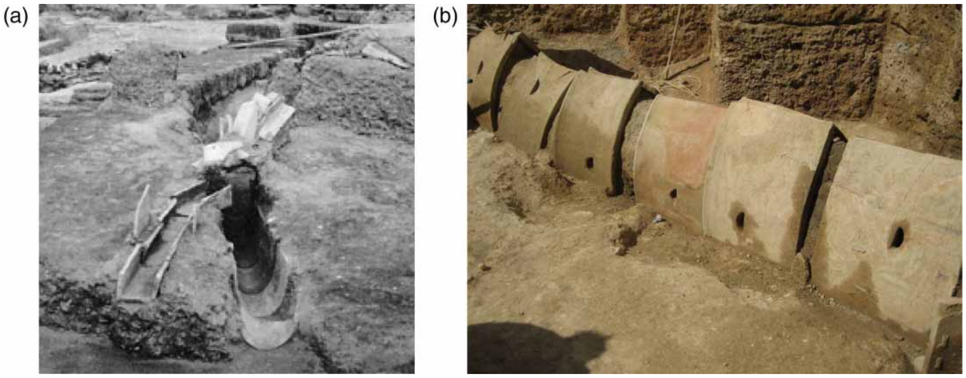

Figure 3 | Remains of sewers in Hellenistic Athens: (a) sewers south of the Middle Stoa and (b) duct covered with prefabricated ceramic well ring sectors in south foothills of Acropolis (De Feo *et al.* 2014a).

system and the lower cost, the particular feature resulted in water absorption by the soil and in reduction of its flow rate while it could also recharge the underground aquifers.

A quite significant feature of the sewers during the Hellenic antiquity is the sewer system for the drainage of ancient theatres. The rainwater management of the spacious open areas of the ancient Hellenic theatres is an aspect which was incorporated into their design from the earliest years of their appearance, due to the nature of these unroofed constructions. Their shape functioned as a typical runoff surface and therefore the necessity for the drainage of the rainwater was essential. Due to that important necessity, the drainage of the theatres built in stone was constructed from the beginning. Cases where the drain conduits were added later, seem to refer mostly to originally wooden constructions, as in the Dionysus theatre in Athens, which was rebuilt or reformed into stone construction. Representative examples of drainage systems in ancient theatres, including their hydraulic characteristics at Knossos and Phaistos in Minoan Crete, Dionysus in Athens, Arcadian in Orchomenos, Ephesus in Turkey, and that in the Aegean island Delos are given by Kollyropoulos *et al.* (2015).

Figure 4 | Remnants of sewerage and drainage system in Kassope.

Roman period

Drainage and sewerage systems were used by Romans for the disposal of surplus water, and were found both in cities, to carry rainfall, overflow from fountains and bathrooms and in the country, to prevent flooding in the fields. Sewage and rainwater were conveyed to domestic systems, and were only found in cities, where they were necessary due to a high population density (De Feo *et al.* 2011). However, in most cases, combined systems of flow rates composed mainly of rainfall runoff and wastewater were applied.

Baths and lavatories in Macedonia and other Roman domestic centers played a major role in life style. Roman engineers had developed water supply and sewerage systems and other impressive sanitary achievements, such as public baths and toilets (Kaiafa 2008). At least five lavatories have been found in Dion, Thessaloniki and Philippoi. They all had a rectangular ground plan and were usually embedded into more complex buildings, such as baths, thermae, and palestrae. Also in Dion, public lavatories are also found outside the walls joining the Sanctuary of Demeter, during the *ca*. 2nd century AD. The ditch under the defecation bench ensured uninterrupted cleanliness, by supplying water continuously from a source in the sanctuary of Asclepius through an underground stone-built conduit (Pingiatoglou 2003).

In addition to the lavatories, stone-built central sewers in Roman Macedonia have been developed under vertical and horizontal streets, along the central axis, ensuring storm and wastewater sanitation. They were all of rectangular section, made of materials of second use (Kaiafa 2008). Their walls were made of stone and mortar, while slabs were used for the drainbeds. Also, in the Roman cities of Veria, Dion, and Philippoi in northern Greece, central sewers had no extra coverage, as they were covered directly with road plaques, which had slits in the joints, enabling the percolation of rainwater. Sewers of Philippoi had impressive dimensions, ranging from 0.55 m to 1.00 m in width from 0.90 m to 1.70 m in height. Somewhat smaller were the sewers in Roman Veria. A central sewer covered with a stone-built apsis has been discovered in the city of Thessaloniki (Figure 5(a)). Also in Roman Thassos, massive slabs of the road surfaces were set onto the rims of underground sewers functioning simultaneously as covers (Grandjean 1994) (Figure 5(b)).

BYZANTINE TIMES (*CA*. 330–1453 AD)

The decline of the ancient world influenced not only the existing technological achievements, but also the

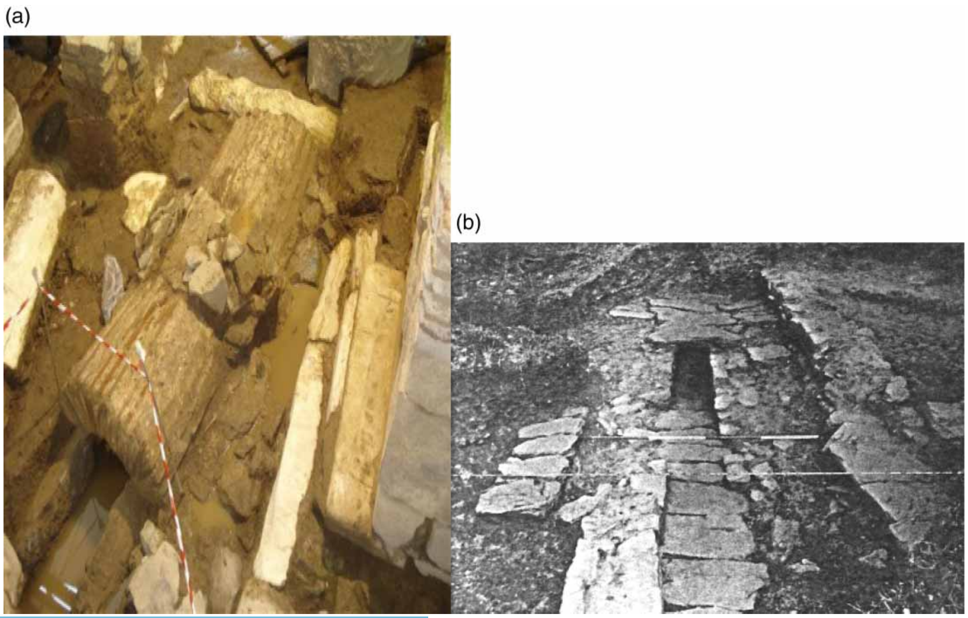

Figure 5 | Roman sewers: (a) central sewer covered with stone-built apsis in Thessaloniki and (b) on the island of Thassos (Antoniou *et al.* 2014).

relevant skills and constructional capacities. In addition, the morals and the social habits introduced by Christianity influenced the practices and waste- and stormwater management (Antoniou *et al.* 2014). Moreover, the remains suggest that lavatories were simultaneously used by many people, despite their use almost two centuries after the official end of the ancient religion and the prevalence of Christianity, which promoted privacy (Antoniou *et al.* 2016). During that period, single seat toilets were constructed in old buildings, justifying privacy, but also single bathing chambers were incorporated in pre-existing Roman baths, which originally had only common bathing pools (Yannopoulos *et al.* 2016). On the other hand, the vivid tradition of the ancient world, especially in the East, permitted the continuation of earlier relevant habits. In the early centuries of the Byzantine Empire, several common lavatories, mainly in monasteries, facilitated multiple users at the same time. Despite that, waste- and stormwater management was somehow neglected by the communities and was mostly resolved privately. The private character of lavatories resulted in the reduction of their size and in their position closer or next to main rooms (Orlandos 1927). Examples of Byzantine sewers in Thessaloniki are shown in Figure 6.

OTTOMAN PERIOD (*CA*. 1453–1828 AD)

Water is an element of the Ottomans' religion. According to the Koran, cleaning of the body symbolizes the cleanliness of the soul. Thus, a water tap is located outside mosques and hammams. Fountains and water supply to hammams were the major hydraulic works developed during the Ottoman period. Also, water and wastewater constructions developed mainly by Roman, Byzantine and post-Byzantine civilizations were maintained, operated and used (Chalkiadakis 2012; Angelakis *et al.* 2014). During the first period of the Ottoman conquest, many Turkish neighborhoods in major cities had fountains. However, with Christians and Moslems living side-by-side, the water was not sufficient. Only a few houses, mostly of the Ottoman officials, had running water or cisterns.

In the Islamic world, hydraulic hygiene facilities, such as latrines connected to a sewer or cesspit were widely used and found in most of the houses. The importance of defecation hygiene etiquette related to religion, should not be excluded as an aspect to the evolution of the toilet.

Examples of lavatories have been evidenced in a few Ottoman hammams still existing in Greece, where sanitary installations actually consist of a small cell sized to fit a

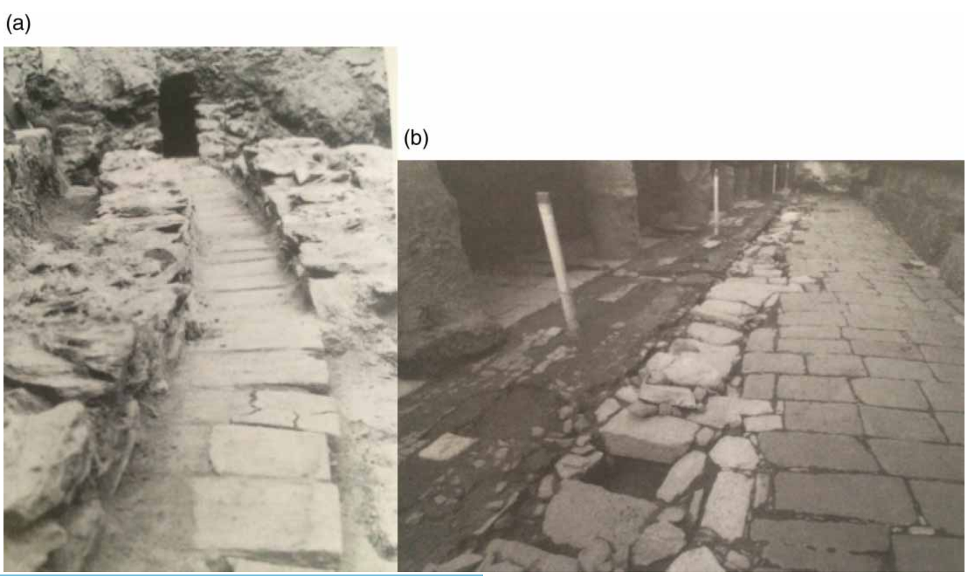

Figure 6 | Stone-built sewers of Byzantine times (6th c.) in Thessaloniki: (a) in Pastier road and (b) in Egnatia road.

man, who may squat down on his heels, located close to the disrobing hall, just before entering the warm part, e.g. Bey hammam in Thessaloniki, the hammam in Chania, Crete, the hammam of the Winds, Athens, and Karavangeli hammam in Lesvos (Antoniou *et al.* 2014). A tap or a full sewer is located inside the cell for cleaning purposes (Figure 7). Usually openings on the roof provided the necessary ventilation of the lavatory. The direction of the cells in Ottoman toilets is very important, because they are oriented as much as possible towards the opposite direction of Mecca. No flushing system has been traced, and the waste was removed from the toilet through ceramic pipes, placed under the keyhole-shaped slab, connected most probably with a sewage pit (Dimitriou 2002).

MODERN TIMES (1828 TO PRESENT TIMES)

The history of modern Greece starts from the recognition of its autonomy from the Ottoman Empire in 1821. After World War I, at the beginning of the 20th century, the modern wastewater technologies started to be developed, as in other parts of the world. They were based on the technologies of the past as well as on the development of improved septic tanks and land application systems. It continued rapidly after World War II, when the first separate sewerage and drainage systems (SSS) and small wastewater treatment plans were constructed.

Greece, with a population of approximately 11 million inh. (UN 2015), has to comply with the EU Urban Wastewater Treatment Directive (271/91) treatment (EU 1991). The total length of the sewage system is estimated to be *ca.* 55,000 km, serving more than 90% of the total population. To the contrary of ancient Greece, after the 1950s and up to now, SSS are dominant throughout the country. Presently most of the sewerage and drainage systems (80%) are SSS, with the tendency for the about 20% remaining of CSS, mostly located in the centers of the big cities, to be replaced with SSS.

According to the EU Urban Wastewater Directive, Greece as a member of EU, was bound to connect all urban agglomerations with more than 2,000 p.e. (population equivalents) to wastewater treatment plants (WWTPs) by the end of 2005. In 2005, approximately 350 WWTPs served over 75% of the country's permanent population (Tsagarakis *et al.* 2004). In 2010, the Greek Ministry of Environment, Energy and Climate Change reported that 100%, 93%, 74% and 32% of the population living in agglomerations of over 150,000 p.e., 15,000–150,000 p.e., 10,000–15,000 p.e., and 2000–10,000 p.e., respectively, were covered by complying to the EU regulations for WWTPs (MEECC 2010). The evolution in compliance rates of this Directive, since reference year 1998 (based on incomplete – datasets available) is shown in Figure 8 (EC 2016).

Today, Greece is bound to connect all urban agglomerations serving above 2,000 p.e. (population equivalents) to

Figure 7 | Ottoman toilets (a) in the women's section, Abid Efendi or Hammam of the Winds, Athens, and (b) in Karavangeli hammam in Lesvos, Mytilene (Antoniou *et al.* 2014).

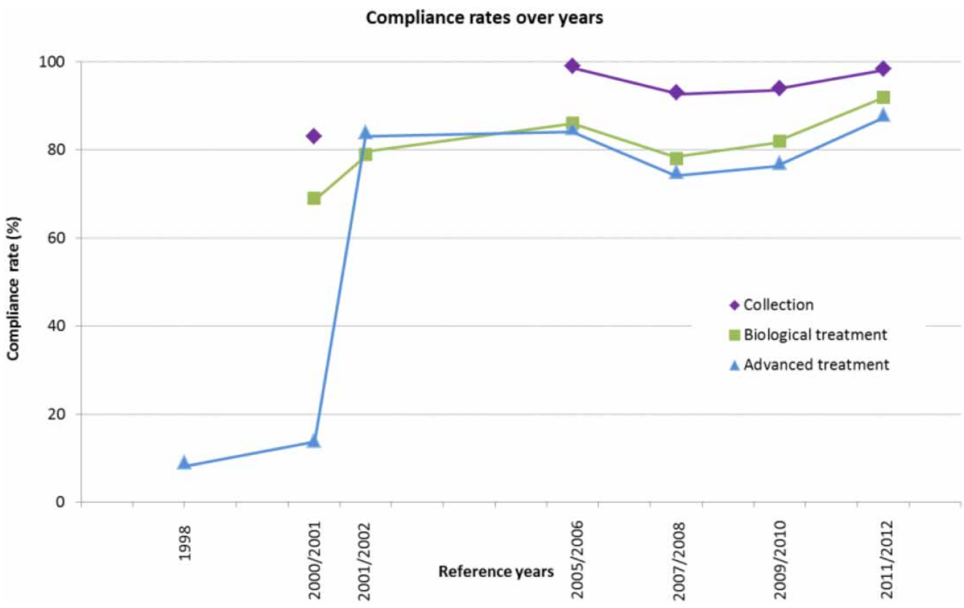

Figure 8 | Evolution of compliance rates since reference year 1998 (based on incomplete – datasets available) (EC 2016).

about 500 WWTPs, which cover more than 85% of the country's p.e. The total numbers of WWTPs in 2015 are shown in Table 1. Thus far, a number of different technologies for municipal wastewater treatment have been adopted (e.g. activated sludge systems, extended aeration, natural treatment systems, and attached growth systems) (Tsagarakis *et al.* 1998).

Table 1 | Total WWTP in Greece (adapted from EC 2016)

Category (p.e.)	No. of WWTP	Comments
<2,000	650–750[a]	Implementation of effective non-conventional treatment systems to a large number of projects, serving 20% of the total p.e. of the country.
2,000–10,000	370	With completion of the projects under implementation the p.e. serviced p.e. with such projects will be 16% of the total.
10,000–15,000	39	
15,000–100,000	72	Still to be implemented 3–4 (Eastern Attica).
100,000–150,000	5	
>150,000	6	
Total	1,192	

[a]Estimation.

Regarding water reuse, although many regions of Greece, especially in the southeast regions, are under water shortage, effluent reuse is not practiced widely. Tsagarakis *et al.* (2001) estimated that 3.2% of the total water currently used for irrigation could be saved by reusing effluent from the existing WWTPs, in order to increase water availability for crop irrigation and ensure environmental protection. This percentage has actually been increased to 4.5% (Paranychianakis *et al.* 2009). However, the existing stringent and complex regulations have prevented the development of well-organized water recycling projects (CMD 2011). Nevertheless the concern for effluent reuse has arisen in the last few years, and many recycling projects are being implemented or planned in Greece, mainly for crop and landscape irrigation. Today the total effluent produced is 650 M m^3/yr, which is mainly discharged to the Mediterranean Sea and to the rivers (Ilias *et al.* 2014). Only 4% of it (included that of indirect reuse) is estimated to be reused.

FUTURE TRENDS

Collecting, conveying and treatment of sewage in the future in Greece, as in many other parts of the world, will be governed by the following macro drivers:

(a) Faster population growth. In Greece, as in other EU countries, population growth will mainly come from Middle Eastern and African refugees. This increase will play a vital role in the future waste- and stormwater treatment and sewerage and drainage systems (e.g. they should be highly decentralized, reduce their lengths, increase their diameter and reuse effluents) (De Feo *et al.* 2014a).
(b) Higher urbanization. The great majority of these people will settle in urban areas further stressing the pollution pressures and health risks in these areas. A characteristic example of urbanization is the region of Metropolitan-Athens with an area 3,500 km^2 (2.65% of the total area of Greece), where 35% of the total permanent population of the country is living. In such cases it will not be possible to simply extend existing centralized water and wastewater systems to cope with the extra water demand and waste loads. The increasing volume of wastewater and the inadequate infrastructure and management systems will be at the heart of the wastewater crisis (UN 2010). The expected increase in urbanization will impose a series of impacts to the future philosophy of waste- and stormwater management.
(c) Climatic variability. Climate variability 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 (e.g. expected increase of floods events) with appropriate techniques for capturing and distributing water, protecting soil, recycling, and optimizing energy use. These techniques constitute a great reserve of biological diversity and sustainable knowledge (Angelakis *et al.* 2012).
(d) Ageing of infrastructure assets. Many networks and installations in mature economies are ageing and deteriorating. In Greece, as in other European countries, upgrading of water and wastewater treatment systems to comply with EU environmental legislation is necessary (De Feo *et al.* 2014a). In the developing world, the pace of growth and urbanization, combined with rising environmental expectations, is creating the need for costly new investments (UNESCO 2009). This will present both, a challenge and an opportunity on how to re-configure the sewers as well as other wastewater management infrastructures, regarding financing, in order to meet the future challenges, e.g. the existing wastewater collection system should be modified to be adapted to the source separated resource streams (Figure 9).

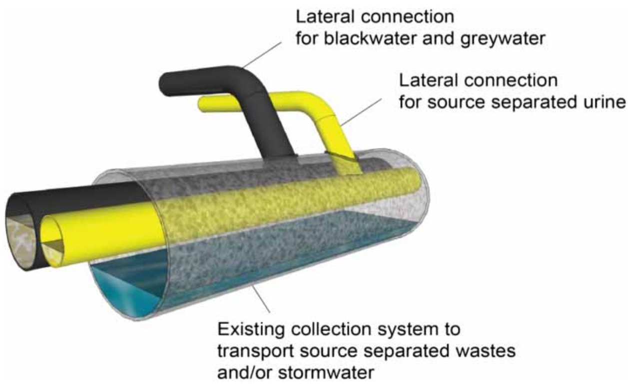

Figure 9 | Use of existing collection system for source separated resource streams (with permission of G. Tchobanoglous).

In the future, small-scale WWTPs mainly those of <2000 p.e., should be implemented. Greece will focus on the best possible decentralized water and wastewater management technologies, mainly due to the expected increased urbanization. Non-conventional technologies for collection, conveyance, and treatment, e.g. land application, wetland, packed bed filters (such as sand, textile and pumice) in small-scale plants will prevail. Raw wastewater should be pre-treated in cost-efficient septic tanks in which more than 60% of the applied organic load should be removed. Treated wastewater can be easily reused locally for various purposes such as toilet flushing, watering gardens or car washing or even for direct potable use (Leverenz *et al.* 2011). Sludge from decentralized plants can be used as fertilizer in both rural areas and urban landscape areas (Lyberatos *et al.* 2011).

Regarding rain/stormwater management, SSS will be extended all over the country. Thus, rain/stormwater will continue to be directly disposed of to natural sites, e.g. rivers, sea and land, and in the coastal areas disposal to the sea will be a common practice. This practice has not created any major problems to the bathing waters, which retain very good quality. Recently, EEA (2016) reported that 97% of bathing sites in Greece are of excellent quality. This is mainly due to the fact that most of the sea regions around Greece are oligotrophic, characterized by low nutrient levels, impoverished phytoplankton populations and low primary productivity (Karydis 2009). Finally, measures and technologies for harvesting of rainwater in order to reduce the flood risk and increase water availability should be developed (Haut *et al.* 2015).

CONCLUSIONS

In this paper, hydraulic works of waste- and stormwater in Minoan, Classical, Hellenistic, Roman, and present times are presented and discussed. In ancient Greece, storm- and wastewater management in urban areas, including disposal practices, were characterized by simplicity, robustness of operation, and absence of complex controls. These sanitary technologies are sometimes not too different from the modern ones, and can be compared with the modern systems, which were established only in the second half of the 19th century in European and American cities. On the other hand, the present day technologies directly descend from the ancient ones.

Through the ages, innovation has played a key role in ensuring the progress required to meet the emerging challenges. In the future, waste- and stormwater management systems based on reapplication of old practices and philosophical approaches, using new equipment, in order to effectively meet the modern emerging challenges could be of great significance (Rose & Angelakis 2014). It is obvious that ideas, technologies, and practices developed during several periods of ancient civilizations greatly influenced our current knowledge. Today, 2.6 billion people lack adequate sanitation and 1.8 million people die every year from diarrheal diseases, of which 90% are children (Bond *et al.* 2013). This situation is no longer bearable and there is an urgent need for sustainable and cost-effective water supply and sanitation facilities, particularly in cities of the developing world. Thus, applicability of selected ancient water techniques for the contemporary developing world should be seriously considered. Learning from technologies and practices implemented in the past, such as design philosophy, adaptation to the environment, and decentralization management of water and wastewater projects, architectural and operation aspects, and sustainability as a design principle remain open.

The goals of sustainable wastewater management will be the collection, treatment, and reuse of water in a way that does not adversely impact the health of humans or other species, preserves environmental quality and the integrity of ecological systems, recovers energy and nutrients present in waste, and utilizes resources efficiently. The rapid growth and development in and around urban areas has increased both the importance of sustainable wastewater management and the complexity of implementation. The expected increase in urbanization will have impacts for the future wastewater management philosophy and especially for the treatment infrastructure. Therefore, an expected increase in decentralized self-supporting, small systems will emerge (De Feo *et al.* 2014a). In a highly urbanized world, development of cost-effective water supply and wastewater sustainable technologies including water reuse and harvesting and storage rainwater in order to increase water availability and to minimize flood risks, will be of great significance. And remember that:

Όμοια γάρ ως επί το πολύ τα μέλλοντα τοις γεγονόσιν, i.e.
The events to come extensively resemble to those of the past
UNESCO's 'Aristotle Anniversary Year' 2016.

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REFERENCES

Angelakis, A. N. & Koutsoyiannis, D. 2006 Wastewater management in Minoan civilization. In: *2nd Conf. on Ancient Technologies*, 17–21 October 2005, Athens, Greece. Technical Chamber of Greece, Athens, Greece, pp. 751–756 (in Greek).

Angelakis, A. N. & Spyridakis, D. S. 2010 Water supply and wastewater management aspects in ancient Hellas. *Water Science and Technology, Water Supply* **10** (4), 618–628.

Angelakis, A. N. & 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*, Ch. 8 (A. N. Angelakis & A. S. Issar, eds). Springer-Verlag, Heidelberg, Germany, pp. 161–191.

Angelakis, A. N. & Zheng, X. Y. 2015 Evolution of water supply, sanitation, wastewater, and stormwater technologies globally. *Water* **7** (2), 455–463.

Angelakis, A. N., Koutsoyiannis, D. & Tchobanoglous, G. 2005 Urban wastewater and stormwater technologies in the ancient Hellas. *Water Res.* **39** (1), 210–220.

Angelakis, A. N., Mays, L. W., De Feo, G., Salgot, M., Laureano, P. & Paranychianakis, N. 2012 Water and wastewater in ancient civilizations. In: *A Compendium of Hot Topics and Features from IWA-SG on Water and Wastewater in Ancient Civilizations (WWAC). Global Trends and Challenges in Water Science, Research and Management* (H. Li, ed.). IWA, London, UK, pp. 90–94.

Angelakis, A. N., De Feo, G., Laureano, P. & Zourou, A. 2013 Minoan and Etruscan hydro-technologies. *Water* **5**, 972–987.

Angelakis, A. N., Kavoulaki, E. & Dialynas, M. G. 2014 Sanitation and stormwater and wastewater technologies in Minoan era. In: *Evolution of Sanitation and Wastewater Management through the Centuries*, Ch. 1 (A. Angelakis & J. Rose, eds). IWA Publishing, London, UK, pp. 1–24.

Antoniou, G. P. 2007 Lavatories in ancient Greece. *Water Science and Technology, Water Supply* **7** (1), 155–164.

Antoniou, G. & Angelakis, A. N. 2008 Sanitary and purgatory structures in ancient Greece. In: *5th Symposium on Archaeometry of the Hellenic Society of Archaeology*, October 8–10, 2008, Athens, Greece, no. 19, p. 1.

Antoniou, G. & Angelakis, A. N. 2009 Historical development bathrooms (toilets) and other sanitary and purgatory structures in Greece. In: *Proc. of the 2nd IWA International Symposium on Water and Wastewater Technologies in Ancient Civilizations*, May 28–30, 2009, Bari, Italy.

Antoniou, G. & Angelakis, A. N. 2015 Latrines and wastewater sanitation technologies in ancient Greece. In: *Sanitation, Latrines and Intestinal Parasites in Past Populations*, Ch. 4 (P. D. Mitchell, ed.). Taylor & Francis Ltd, Imprint: Ashgate Publishing Ltd, Farnham, UK, pp. 41–68.

Antoniou, G., Lyberatos, G., Kanetaki, E. I., Kaiafa, A., Voudouris, K. & Angelakis, A. N. 2014 History of urban wastewater sanitation technologies in Hellas. In: *Evolution of Sanitation and Wastewater Management through the Centuries*, Ch. 6 (A. Angelakis & J. Rose, eds). IWA Publishing, London, UK, pp. 101–148.

Antoniou, G., De Feo, G., Fardin, F., Tamburrino Tavantzis, A., Khan, S., Fie, T., Ieva Reklaityte, I., Kanetaki, E., Zheng, X. Y., Mays, L. & Angelakis, A. N. 2016 Evolution of toilets worldwide through the millennia. *Sustainability* **8** (8), 779. doi:10.3390/su8080779.

Black, J. 2013 Traces of the Minoan civilization from Egypt to Syria, http://www.ancient-origins.net/news-history-archaeology/traces-minoan-civilization-egypt-syria-00581?nopaging=1 (accessed 22 January 2017).

Bond, T., Roma, E., Foxon, K. M., Templeton, M. R. & Buckley, C. A. 2013 Ancient water and sanitation systems – applicability for the contemporary urban developing world. *Water Science and Technology* **67** (5), 935–941.

Brown, J. & Lofrano, G. 2015 Overview of wastewater management through the Ages. In: *World Environmental and Water Resources Congress 2015. Floods, Droughts, and Ecosytems: Proc. of the 2015 World Environmental and Water Resources Congress*, May 17–21, 2015, Austin, Texas (K. Karvazy & V. L. Webster, eds). American Society of Civil Engineers, Reston, Virginia, USA, pp. 125–135.

Castleden, R. 1993 *Minoans: Life in Bronze Age Crete*. Routledge, London, UK.

Chalkiadakis, E. 2012 The water supply to Heraklion, Crete, Greece from the Ottoman period (1669) to the present; the modern aqueduct and the ancient springs. In: *Proc. of the 3rd IWA Specialized Conference on Water & Wastewater Technologies in Ancient Civilizations*, March 22–25, 2012 (I. Koyuncu, Z. Sen, S. Ozturk, M. Altinbas & I. Ozturk, eds). Technical Univ., Istanbul, Turkey, pp. 459–466.

CMD (Common Ministerial Decision) 2011 *Measures, Limits and Procedures for Reuse of Treated Wastewater, No. 145116*. Ministry of Environment, Energy and Climate Change, Athens, Greece (in Greek).

De Feo, G., Mays, L. W. & Angelakis, A. N. 2011 Water and wastewater management technologies in ancient Greek and Roman civilizations. In: *Treatise on Water Science*, vol. 1 (P. Wilderer, ed.). Academic Press, Oxford, UK, pp. 3–22.

De Feo, G., Antoniou, G., Fardin, H. F., El-Gohary, F., Zheng, X. Y., Reklaityte, I., Butler, D., Yannopoulos, S. & Angelakis, A. N. 2014a History of sanitary sewers worldwide. *Sustainability* **6**, 3936–3974.

De Feo, G., Antoniou, G. P., Mays, L., Dragoni, W., Fardin, H. F., El-Gohary, F., Laureano, P., Kanetaki, E. I., Zheng, X. Y. & Angelakis, A. N. 2014b Historical development of waste water management. In: *Handbook of Engineering Hydrology*, Vol. 2, Ch. 9 (S. Eslamian, ed.). Taylor & Francis Group, Florida, USA, pp. 163–217.

Dimitriou, O. 2002 Latrines and sanitation facilities in Greek houses of ancient, byzantine and modern times. Doctoral Dissertation, Dept. of History-Archaeology, Aristotle University, Thessaloniki, Greece.

EC 2016 *Eighth Report on the Implementation Status and the Programmes for Implementation (as required by Article 17) of Council Directive 91/271/EEC Concerning Urban Waste Water Treatment. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*. Brussels, Belgium, 04/03/2016.

EEA (European Environment Agency) 2016 *25/05/2016: The European Environment Agency and the European Commission have Published Today the Report on European Bathing Water Quality in 2015*. http://ec.europa.eu/environment/water/water-bathing/index_en.html# (accessed 30 January 2017).

EU 1991 *Council Directive of 21 May 1991 Concerning Urban Wastewater Treatment (91/271/EEC)*. 'Official Journal of the European Communities' L135/40 (30 May).

Evans, S. A. 1921–1935 The Palace of Minos at Knossos: a Comparative Account of the Successive Stages of the Early Cretan Civilization as Illustrated by the Discoveries. Macmillan and Co., London, vols I–IV. Reprinted by Biblo and Tannen, New York, USA.

Galanaki, M. 2014 Water borne diseases and Hippocrates: the treatise on airs, waters, and places. In: *Evolution of Sanitation and Wastewater Management through the Centuries*, Ch. 21 (A. N. Angelakis & J. B. Rose, eds). IWA Publishing, London, UK, pp. 419–428.

Grandjean, Y. 1994 L' eau dans la ville de Thassos. L' eau, la santé et la maladie dans Le Monde grec. *Bulletin de Correspondance Hellénique Supplément* **28**, 283–296 (in French).

Haut, B., Zheng, X. Y, Mays, L., Han, M., Passchier, C. & Angelakis, A. N. 2015 Evolution of rainwater harvesting, heritage in urban areas through the millennia: a sustainable technology for increasing water availability. In: *Water, Heritage: Material, Conceptual, Spiritual connections*, Ch. 3 (W. J. H. Willems & H. P. J. van Schaik, eds). Sidestone Press, Leiden, The Netherlands, pp. 37–56.

Ilias, A., Panoras, A. & Angelakis, A. N. 2014 Water recycling and reuse in Hellas with emphasis on the Thessaloniki project. *Sustainability* **6**, 2876–2892.

Kaiafa, A. 2008 Urban Water Supply and Drainage Systems in Hellenistic and Roman Macedonia. Doctoral dissertation, Dept. of Architecture, Aristotle University, Thessaloniki, Greece (in Greek).

Karydis, V. 2009 Eutrophication assessment of coastal waters based on indicators: a literature review. *Global NEST Journal* **11** (4), 373–390.

Knauss, J. 2003 Arcadian and Boiotian Orchomenos, centres of Mycenaean hydraulic engineering. *Irrigation and Drainage Systems* **5**, 363–381.

Kollyropoulos, K., Antoniou, G., Kalavrouziotis, I., Krasilnikoff, J., Koutsoyiannis, D. & Angelakis, A. 2015 Hydraulic characteristics of the drainage systems of ancient Hellenic theatres: case study of the theatre of Dionysus and its implications. *ASCE, Journal of Irrigation and Drainage Engineering* Doi: 10.1061/(ASCE)IR.1943-4774.0000906, 04015018.

Koutsoyiannis, D. & Angelakis, A. N. 2003 Hydrologic and hydraulic sciences and technologies in Ancient Greek Times. In: *The Encyclopedia of Water Science* (B. A. Stewart & T. Howell, eds). Markel Dekker Inc., New York, NY, USA, pp. 415–418.

Leverenz, H. L., Tchobanoglous, G. & Asano, A. 2011 Direct potable reuse: a future imperative. *Journal of Water Reuse and Desalination* **1** (1), 2–10.

Lofrano, G. & Brown, J. 2010 Wastewater management through the ages: a history of mankind. *Science of the Total Environment* **408** (22), 5254–5264.

Lyberatos, G., Sklyvaniotis, M. & Angelakis, A. N. 2011 Sewage bio-solids management in EU countries: challenges and prospective. *Fresenius Environmental Bulletin* **20** (9A), 2489–2495.

MEECC (Ministry of Environment, Energy and Climate Change) 2010 *Greek State Conformation to the EU 271/91 Directive*. MEECC, Athens, Greece (in Greek).

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

Orlandos, A. 1927 Monasterial Architecture (Μοναστηριακή Αρχιτεκτονική), 1st edn. E. A. E., Estia, Athens, Greece.

Paranychianakis, N. V., Kotselidou, O., Vardakou, E. & Angelakis, A. N. 2009 *Greek Regulations on Wastewater Reclamation and Reuse*. Hellenic Union of Municipal Enterprises for Water Supply and Sewage, Larissa, Greece, p. xxiv, 160 (in Greek).

Pingiatoglou, S. 2003 The sanctuary of Demeter in Dion. *The Archaeological Work in Macedonia and Thrace*, Vol. 17, pp. 425–434 (in Greek).

Robinson, M. D. 1938 *Excavations at Olynthus, Part VIII, The Hellenic House, A Study of the Houses Found at Olynthus With a Detailed Account of Those Excavated in 1931–1934*. John Hopkins Press, Baltimore, MA, USA.

Rose, J. & Angelakis, A. N. 2014 The evolution of sanitation and wastewater management throughout the centuries: past, present, and future. In: *Evolution of Sanitation and Wastewater Management through the Centuries*, Ch. 27 (A. Angelakis & J. Rose, eds). IWA Publishing, London, UK, pp. 507–528.

Thomson, H. A. & Wycherley, R. E. 1972 *The Agora of Athens: The History, Shape, and Uses of an Ancient City Center (Athenian Agora)*, Volume XIV. American School of Classical Studies, Princeton, NJ, USA, pp. 170–204.

Tsagarakis, K. P., Mara, D. D. & Angelakis, A. N. 1998 Evaluation of municipal wastewater treatment plants in Greece. *Tech. Chron.* **18**, 97–109 (in Greek).

Tsagarakis, K. P., Tsoumanis, P., Chartzoulakis, K. & Angelakis, A. N. 2001 Water resources status including wastewater treatment and reuse in Greece: related problems and prospectives. *Water International* **26**, 252–258.

Tsagarakis, K. P., Dialynas, G. E. & Angelakis, A. N. 2004 Water resources management in Crete (Greece) including water recycling and reuse and proposed quality criteria. *Agricultural Water Management* **66**, 35–47.

Tzanakakis, V. E., Koo-Oshima, S., Haddad, M., Apostolidis, N. & Angelakis, A. N. 2014 The history of land application and hydroponic systems for wastewater treatment and reuse. In: *Evolution of Sanitation and Wastewater Management through the Centuries*, Ch. 24 (A. Angelakis & J. Rose, eds). IWA Publishing, London, UK, pp. 459–482.

UNESCO 2009 *World Water Assessment Programme 2009. The United Nations World Water Development Report 3: Water in a Changing World*. Earthscan Ltd, Earthscan, Paris, France; London, UK.

UN (United Nations) 2010 Sick water? The central role of wastewater management in sustainable development. In: *A Rapid Response Assessment* (E. Corcoran, C. Nellemann, C. Baker, R. Bos, D. Osborn & H. Savelli, eds). United Nations Environment Programme, UN-HABITAT, GRID-Arendal, Birkeland, Norway.

UN (United Nations) 2015 *World Population Prospects: The 2015 Revision, Key Findings and Advance Tables*. UN, Department of Economic and Social Affairs/Population Division, p. 14 (Retrieved 18 January 2017).

Vallet, R. 1997 Habuba Kebira ou la naissance de l'urbanisme. *Paleorient* **22** (2), 45–76.

Viollet, P. L. 2000 *L'hydraulique Dans les Civilisations Anciennes: 5000 Ans d' Histoire*. Presses des Ponts et Chaussées, Paris, France.

Yannopoulos, S., Yapijakis, C., Kaiafa-Saropoulou, A., Antoniou, G. & Angelakis, A. N. 2016 History of sanitation and hygiene technologies in the Hellenic world. *Journal of Water, Sanitation and Hygiene for Development*. doi: 10.2166/washdev.2017.178.

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