Review Paper

History of sanitation and hygiene technologies in the Hellenic world

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ABSTRACT

Sanitation and hygiene technologies have existed in ancient Hellas since the Bronze Age (ca. 3200–1100 BC), when extensive sewerage and drainage and other elaborate sanitary structures were known in Minoan palaces and towns. Classical and Hellenistic periods should be considered as the most progressive eras in the design of sanitary engineering. At that time anatomically shaped toilet seats are found in several sites since many private houses and public buildings have them. As cities grew in size the pressure of larger populations resulted in the construction of communal toilets with seats that were more densely packed together. Drainage and sewerage systems and sanitary installations reflect high cultural and technological levels and they are associated with contemporary observations and ideas about hygiene and medicine. Before the Hellenic advances, medicine was entirely confined to religious beliefs and metaphysical rituals. In the early Roman period, the knowledge of the ancient world on hygienic matter was incorporated in legislative rules. Despite the weakening of this legislation through the ages, the sanitation practices kept being applied even via a technical tradition of the masons. Later various rulers of the Hellenic world (Europeans or Ottomans), introduced their practices (traditional/scientific) sanitation in the greater Helladic regions.

Key words | drains, hygiene, sanitary structures, sanitation, sewers

INTRODUCTION

Knowledge of history and progress of technology may contribute to better understanding of basic human needs and inspire new developments in the future. The geographic region of Hellas has been populated for several thousands of years and has been the cradle of Western civilization since it lies at the gates of Europe in proximity to the crossroads of Asia and Africa. The ancient civilizations that bloomed in different periods in Hellas developed advanced technological and scientific knowledge, which greatly influenced our modern science and technology. As the prolific American writer, historian, and philosopher Will Durant (1939: vii–viii) put it:

‘Excepting machinery, there is hardly anything secular in our culture that does not come from Greece.’

Urban hydraulic technologies first appeared during the Bronze Age (ca. 3200–1100 BC), particularly in the mid-3rd millennium BC, in an area extending from Indus river valley to Mesopotamia and to southeastern Hellas (Angelakis et al. 2005). Cases of very early urban sanitation may be seen in Indus valley (ca. 2600–1900 BC) at Mohenjo-Daro, Harappa and Lothal, indicating an advanced, comfortable, and hygienic lifestyle, as manifest from long term, very efficient drainage and sewerage systems, bathrooms and
flushing toilets, which can only be compared to modern ones, re-established in Europe and North America a century and half ago (De Feo et al. 2014a). It is probable that these two civilizations were connected through Egyptians. Also, in ancient Egypt the homes of rich people included bathrooms and toilets. It is noted that the seats of very early toilets were made of limestone or wood (Antoniou & Angelakis 2015).

Ancient Hellenes appear to have very good knowledge of sanitation. The first sophisticated drainage and sewerage systems in Hellas were constructed by the Minoans in Crete from ca. 2500 to 1650 BC. It should be noticed that in Hellas as in as in other parts of the ancient world drainage and sewerage systems were combined sewerage systems (CSS), since the middle of the last century, when the first separated systems (SSS) were implemented, as known today. The same holds for sewers and drains (Angelakis 2016). Drainage is referred to as the process of collection removing rainwater and stormwater from urban areas. The houses, baths, and flushed toilets were connected to the central drainage and sewerage systems. Similar toilets have been discovered in living rooms in Minoan Crete (e.g. Knossos, Phaistos, Tylissos, Malia, and Gournia). In most cases the evidence for the identification of a toilet derives from the existence of a sewer at the floor level passing through the exterior wall and connecting with the outside central sewerage and drainage system. However, in some homes there are also traces of some sort of provision for a stone or wooden seat (Antoniou & Angelakis 2015). Although the Minoan linear A script has not been deciphered yet, recent DNA studies have shown that Minoan Cretans had the strongest genetic relationships with the modern inhabitants of the Lassithi plateau and other modern Central and Southern Hellas populations, they were also genetically similar to Neolithic and modern European populations (Hughey et al. 2015).

The Mycenaeans in continental Hellas shared similar sanitary technologies with the Minoans. Both had baths and toilets that fitted the human body. However, in Mycenaean culture there was no running water in toilets, and their bathtubs were not portable like the Minoans (Antoniou & Angelakis 2015).

From the 6th until the 1st century BC more sophisticated hydraulic works were developed. The main sewerage and drainage network of Classical and Hellenistic towns delivered stormwater and human wastes to a collection basin constructed outside of towns (De Feo et al. 2014b). Storm and wastewater were conveyed through brick-lined conduits to fields in order to irrigate and fertilize fruit orchards and cultivated crops. In addition to sewers and drains, more advanced public and private baths and toilets were developed during the Classical and Hellenistic times.

The Romans subsequently applied these earlier techniques to larger constructions for a greater number of users at one time, using the advantages of their building methods with concrete based walls and vaulted roofing. In addition, due to their improved aqueduct technology they could provide continuously flowing water to most public toilets. Also, the scale of sewerage and drainage systems was highly increased. Some public toilets survived past the fall of the ancient world and were in use during the first part of the Byzantine period (De Feo et al. 2014b).

The purpose of this paper is to trace the birth and application of sanitation matters in the Helladic regions, not only according to written sources of various kinds but also through the numerous remaining relevant built examples. Historical and archaeological evidence for baths, toilets, sewers, drains, and other sanitary technologies in ancient Hellas are presented and discussed. This will enable us to understand better what facilities were available in different time periods, how design changed over time, and how common such sanitation facilities were at that time.

**PREHISTORIC TIMES (CA. 3200–1100 BC)**

Minoan era

In Prehistoric Hellas, hygienic water supply and wastewater and stormwater used systems, such as net water and sewerage and drainage systems and bathrooms with flushing toilets, were implemented. MacDonald & Driessen (1990), describing the state of the drainage and sewerage in the Minoan palace of Knossos, provided a plan of the original structure. The total spread of the system, including secondary pipelines and drains, exceeds 150 m. Parts of the central drainage and sewerage system of Knossos and Zakros palace are shown in Figure 1(a) and 1(b), respectively. The evidence of these sites is discussed by Antoniou & Angelakis (2015) and Angelakis et al. (2014).
However, one of the most interesting rooms on the ground floor in the residential quarter of the Knossos palace was identified as a toilet. The remains of a clay tube were found just outside the door of the room. It is thought that water was poured through a hole in the floor immediately outside the toilet door, while an under-floor channel linked the hole with the vertical clay pipe under the toilet seat (Castleden 1993). The toilet could thus be flushed even during a rainless summer, either by an attendant outside the toilet or by the user. The toilet in the residential quarter of the palace of Minos in Knossos (Angelakis et al. 2005) is probably the earliest flush toilet in history.

At certain times of the year the drains in the palace of Minos may have been adequately flushed through by the rainfall that fell into the light-wells, but in general it was supposed that water was poured into the toilets to flush them. It was also observed that there was sufficient space at the end of the seat at Queen’s Hall toilet in Knossos for a large pitcher (Graham 1987). The toilet is similar in function to that of the so-called Queen’s Hall, those found in the Phaistos and Malia palaces as well as in some of Minoans cities and houses.

Fortunately, one of the houses near the palace at Malia, known as Da, contains a toilet seat in nearly perfect condition, since it was made out of stone, not of wood like the seat at the palace of Minos in Knossos (Angelakis & Spyridakis 2013). This stone seat was 68.5 cm long by 45.5 cm wide front to back, and its surface was 34–38 cm above the floor (Figure 2(a)).

It was built directly against an outside wall through which a large sewer and drain passed (Graham 1987). Like that in Knossos, the structure was evidently intended for use as a seat rather than a stand. Thus, it resembles the ‘Egyptian’ toilet more than the so-called ‘Turkish’ type found in the palaces at Mari in Syria and Alalakh in Turkey (Angelakis et al. 2005). However, there is a substantial difference between those toilets and the Minoan due to their flushing processes and their connections to the sewerage and drainage system. The toilet at the palace in Knossos mentioned before (Angelakis et al. 2005) may well be the earliest flush toilet in the Mediterranean region identified to date. A similar toilet has been discovered in the west side of the so-called Queen’s Apartment at Phaistos. It was connected to a closed sewer, part of which still exists. Another toilet and sewer was discovered in House C at Tylissos (Angelakis & Spyridakis 1996). In addition, most Minoan toilets were located near or next to the bathrooms, such as those in the Queen’s Hall at Knossos, the Queen’s Apartment at Phaistos, and in Da house at Malia (Figure 2(a)).

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**Figure 1** | Minoan sewerage and drainage systems: (a) at Knossos palace and (b) at Zakros palace (with permission A. N. Angelakis).

**Figure 2** | Minoan toilets: (a) in the Da house in Malia, Crete and (b) and (c) in Thera, West house, sanitary installation on the second floor: photograph and axonometric plan, respectively.
Some palaces had toilets with flushing systems operated by pouring water into a conduit (Angelakis et al. 2005). The best example of such an installation was found in the island of Thera (Santorini) in the Cyclades, at Akrotiri settlement, in a small niche in the wall at the upper floor of the West House (Figure 2(b) and 2(c)). It consisted of two benches on either side of a hole in the floor which corresponded to perpendicular clay pipes embedded in the wall. The pipes ended in a pit outside the house. Its presence had multi functions, that is connection to the main sewer-drain with an even flow, change of level and direction, plus the reduction of gases and odors, which was achieved in combination with a system of oblique and perpendicular slabs (Palyvou 2005). This is the best-preserved example belonging to ca. 1550 BC, which shares the same cultural context with that of Crete and indicates a wide range diffusion of technology, linked to the urban type of livelihood. In addition to the toilets Minoans utilized small bathtubs, wash basins, and foot baths for personal cleanliness. The earliest findings of baths date from the mid-2nd millennium BC in the palace complex at Knossos, Crete, and the luxurious alabaster bathtubs excavated at Akrotiri, Santorini.

In addition to sewerage and drainage systems, baths and toilets, lustral basins and other purgatory facilities were found in several palaces, cities and other Minoan settlements (Platon 1990). Lustral basins were first identified by Arthur Evans (1922–1933) at Knossos in the Throne room, where the sunken area in it was named ‘lustral basin’ by him (Antoniou & Angelakis 2015). Such a facility usually consists of a sunken rectangular room reached by an L-shaped or dog-legged stairway (Figure 3). All of the lustral basins found were lined with gypsum (Angelakis & Spyridakis 1996).

Mycenean era (ca. 1600–1100 BC)

The Mycenaeans in Peloponnese and other parts of mainland Hellas shared several technical similarities with the Minoans. As far as water and wastewater techniques are concerned, both populations had baths that fitted the human body, and drainpipes for vertical water transfer. However, there is a difference of scale between Minoan and Mycenaean water systems. The former were mainly focused on domestic water use at the palatial scale whereas the latter targeted agricultural water use (irrigation and drainage) and were largerscale systems (Zarkadoulas et al. 2012).

Other sanitary structures (e.g. baths) are found in Tyrins Palace, which present the hygienic consciousness of the rulers of the Mycenaean palaces in combination with the luxury of the ruling class (Doerpfeld 1886). Despite these obvious clues, their efforts for sanitation and hygienic practices could be traced on the location of the critical protected water sources of their citadels. These characteristic underground water acquisition spots were constructed at the edges of their fortifications. In Mycenae that feature was built at the higher lever of the fortified settlement (Figure 4(a)). Also, in Tyrins a similar structure is located at the further northern spot of the residential sector of the citadel (Figure 4(b)).

As these water abstraction constructions could also gain water in neighboring places their remote positioning could be possibly related to the efforts of the Mycenaean to keep them away from possible contamination by the wastewater and sewerage fluids of the settlement. More particularly, in Tyrins traces of ducts passing through the thick walls could be sewers-drains, rather than public toilets. The critical feature in this case is their location away from the water spring and actually on a spot having a lower level. It is therefore clear that besides their efforts to provide food and water to the fortified settlement, especially in cases of siege, there were hygiene precautions to prevent contamination of the valuable water source.
In the archaic and classical period the presence of organized towns all over the Hellenic world – mainland, Asia Minor, and colonies – and the improvement of urban planning inevitably led to a major need for effective management of stormwater and human wastes. That is completely natural, since it is well known that as societies moved from nomadic cultures to building more permanent sites, the disposal of human excreta became an important concern (El-Gohary 2014). Moreover, there is no doubt that well-structured (Hippodamian) urban planning and the stabilization of architectural types within the urban grid plan encouraged further development of hydraulic infrastructures and especially sanitation technologies which have been implemented and enriched systematically over Hellenistic and Roman times (Kaiafa 2008). Organized sewerage and drainage systems appeared in ca. 5th century BC in Megara, Rhodes, Olynthos, Miletos, all of Hippodamian grid plan. Nevertheless, both in ca. 5th and 4th century BC serious problems in wastewater and stormwater management have been identified in many cases.

The advent of philosophy influenced Hellenic medicine as well. Hippocrates introduced the foundations of modern medicine, which is based on the observation of clinical signs and rational conclusions, and does not rely on religious or magical beliefs (Yapijakis 2009). Also the documented improvement of the sewerage and drainage network, i.e. in Athens, see below, after the devastating plague of the 5th century BC should be definitely related with know-how related to the waste and wastewater management gained through that plague.

It seems that all scientific knowledge and/or experience produced during that era was applied – or somehow incorporated – in the building and infrastructure technology of these times. That technology could be related to the accumulated tradition of the past, i.e. the Minoan and the Mycenaean. The relation of scientific knowledge and experience, as well as of the tradition of the past to relevant technology of that era, can be traced in surviving ruins and is a matter that should be examined critically.

Early wastewater technologies were based on the development of cesspits land application systems. Notice that a cesspit (cesspool), is a term usually meaning an underground holding tank (sealed or not at the bottom) used for the temporary collection and storage of raw wastewater. Although such sanitation and hygiene systems existed, in many cases they were insufficient. Proper attention was paid to drains and sewers which were large pipe or channels constructed either from ceramic whole or half pipes, often roof tiles and/or large U-shaped channels constructed of stone slabs. Due to the flooding events, these systems were essential in densely settled areas. Drains and sewers are commonly associated with catchment basins, surge chambers, manholes, urinals and toilets, and laundry slabs (Crouch 1995).

In many cases, especially in the cities, drains were combined or used as sewers too. Sewers-drains in ancient
Athens, in particular at the Agora area, were studied carefully (Lang 1968; Thomson & Wycherley 1972). In the classical city, which had up to 600 private houses surrounding Acropolis and Agora, a quite serious hygiene problem existed despite the fact that waste management was a state concern. Toilets were not found, however cesspits have been identified in many house yards. Some of them were abolished in the late 5th century and replaced by a drainage and sewerage system. This system was well improved after the devastating typhoid fever plague in the middle of the ca. 5th century bc (Papagrigorakis et al. 2006).

During the Peloponnesian war the majority of the population of Attica gathered within the fortified area of Athens to avoid the Spartan countryside raids. The increase of inhabitants combined with the old technology waste management formations such as the cesspits etc. and the Spartan seize of the city, were probably the main reasons for the plague. Even though there are not certain testimonies, it seems that the importance of the waste and wastewater management in hygiene matters was properly evaluated – possibly in a scientific rather than practical manner – and resulted in the alternations and improvements of the drainage and sewerage system as presented below.

The main drainage and sewerage network of ancient Athens Agora area, the Great Drain (Figure 5(a) and 5(b)), as it was modified and improved after the era of the ca. 5th century devastating plague, delivered storm water and human wastes to a collection basin outside of town, through Dipylos’ gate. From the collection basin, the storm water and wastes were conveyed through brick-lined conduits to fields of Kifissos’ valley, so as to irrigate and fertilize fruit orchards and field crops (Schladweiler 2002). It seems that that practice was not rare. Besides Athens, wastewater irrigation of agricultural crops to ensure sanitation and benefits of the nutrients contained in wastewater for increasing yield was also practiced elsewhere, as in Dion, Sparti, Cyprus, and other places (Tzanakakis et al. 2014).

The improvement of the Great drain in the ca. 4th century bc was presumably connected with alternations at layouts of some houses, regarding drain and/or sewer outlets as was testified by the archaeological finds in that area (Thomson & Wycherley 1972). The archaeological research also revealed that the residential drain and/or sewers between the private houses often had to skirt the angles of private property. Also it seems that each householder was responsible for the construction of the ducts along his property (Lang 1968).

Most of the finds could lead to the conclusion regarding an increased awareness for more proper drainage and sewerage. As mentioned earlier, the ca. 5th century pestilence along with the scientific approach of sanitation and the rationality of the etiology of diseases could be considered – quite safely – as probable causes for this improvement of these infrastructures. Before the ca. 4th century bc improvements, Athens, as an earlier urban formation, had kept older and technologically inferior drainage and sewerage structures. In contradiction, newer towns such as Olynthos and Amphipolis...
incorporated, along with the ‘Ippodamian’ layout, an improved drainage and sewerage infrastructure.

Olynthus in Chalkidiki, in addition to the long distance subterranean pipeline water supply, was also equipped with storm- and wastewater systems, which were favored by the implementation of the Hippodamian system of the classical city. Many remains of sanitary facilities had been applied, however the hygiene problem was not completely solved. Approximately 30% of the houses had a separate bathroom, with clay bathtubs placed on a cement floor with sewers and drains (Antoniou et al. 2014).

Wastewaters were discharging from the courts by sloping the surface to one point. From there, they were simply conducted away from the houses into the middle of the adjacent streets or alleys, either directly passed through the walls or by means of stone sewers and drains, straight sided or round in section. These were open channels of cobblestones or of channeled stone blocks or of cement faced rubble or of roof tiles.

Frequently, terracotta pipes were evacuating the domestic sewage and drainage to a sewer-drain path between the two rows of houses on each block (Robinson 1938). Nevertheless, nowhere in the city has a separate space used as a toilet been found. Besides, the absence of a separate room or water closet in houses seems to be the rule both in the 5th and 4th century BC. Both in classical and Hellenistic periods many cities, like Athens (Owens 1983), had special groups of employees who released houses from organic wastes and consequently unpleasant smells. The cost of this waste removal process was charged to each owner. Demosthenes called them «ἐπιστάταις κοπρώνων» (caretakers of city ordure) and mentioned that this was a degrading job to do. Still the word ‘koprologoi’ seems to be more common. Aristotle also used this term, and Aristophanes who made clear that koprologoi relieved cities from impurities and bad smells. Inscriptions and written sources used several terms such as ἀμφοδάρχης, κοπροφόρος, κοπρολόγος, κοπροξύστης, κοπρώνης.

A high degree of expertise forms the impressive sewerage and drainage project of the Classical period in the north side of the fortification of Amphipolis, where the banks of the Strymon river were close enough, so as to be very dangerous for the walls to collapse under the pressure of the inner or outer floodwaters. The innovation there was the inclusion of vertical trapezoidal slits in the rampart of 1.65–1.90 m high, with the narrow width side 0.22 m outwardly (Figure 6). Through them the large quantities of storm- and wastewater gathered there, due to the soil inclination, could easily escape out of the town. The system also ensured the safety of the walls in case of the river overflowing. A similar system was also adapted in the Hellenistic period, consisting of drainage and sewerage vertical grilles through the walls, rectangular in shape. It protected the foundations, without allowing the passage of an intruder (Kaiafa 2008; Kaiafa et al. 2014).

During the Hellenistic period there was more interest in sewerage and drainage systems and hygiene installations. These systems were developed within many cities and drains were discharged in the sea or in selected locations outside walls. House wastewater management was the responsibility of the owner, as in the Classical era, while the cleanliness of the streets and the disposal of urban wastes were the concern of the central authority through a special group of professionals, named astynomoi.

In an inscription from ca. 2nd century BC found in Pergamon, concerning astynomous, it is mentioned that among their specified duties was being responsible for the proper functioning of urban sewerage and drainage networks, thus for the supervision of public toilets and maintenance of their sewers and drains: «οἱ ἀστυνομοὶ ἐπιμέλειαι ποιεῖσθαι τῶν τε δημοσίων ἀμφοδράχων καὶ τῶν ἐξ αὐτῶν ἱπονόμων...», lines 64–66) (Kolbe & van Prott 1902).

However, the presence of drainage and sanitation infrastructures was not universal, and thus water closet rooms in
houses were still rare. Smyrna for example had no systematized drainage network, despite the fact that the city was of Hippodamian plan, strictly regulated by horizontal and vertical streets.

Strabo seemed to be disappointed about this serious omission and characterized it as a serious mechanical error (Strabo XIV 1, 37). Delos, in contrast, was equipped with an almost perfect drainage and sewerage network, consisting of numerous channels at different levels, where needed, so as to be more efficient. Each house was outfitted with underground pipelines. In every case they were emptied at central sewers and drains, which were rectangular in cross section and placed about 0.30 m under the streets. Besides, toilets were a necessary part which existed in nearly every house on the ‘sacred’ island of Delos.

The presence of such private sanitary installations is really an exception and not the rule in the Hellenic world and it is due to the fact that the small island was a major commercial and religious center with influences from Eastern civilizations, where disposal technologies were developed. These were small, narrow rooms, consisting of a drainage ditch along one, two or three wall sides which was covered with slabs with holes or gaps. Sometimes defecation seats above the groove were made of wood.

A most complicated sanitation infrastructure has been observed in House D of block VI in Delos (Chamonard 1924). It consisted of an extra drain and sewer running parallel to the main ditch under the defecation seats, so as to collect dirty waters from the floor. Rain waters from house yards were usually channeled in toilet ditches, even since the Hellenistic era. In parallel with the moderately sized domestic toilets, public hygienic installations, which first appeared in Delos and were increasingly used, have been located in baths or Gymnasiums. Public toilets were of the same construction as the domestic ones, but were larger and always made with more diligence (Lapalus 1939).

The importance of Delos regarding the toilets (Figure 7(a) and 7(b)) and sanitation system was probably related to the high living standards of that commercial, rather than pilgrimage, ancient Hellenic town (Antoniou 2007; Trumper 2011; Antoniou et al. 2014). In this case it is once more testified that the improvement of sanitary installations was related to economic and social prosperity.

During the ca. 4th century BC the formation of the typical ancient toilet (Figure 8) took place (Antoniou 2007), a construction which beside other advantages permitted flushing either with buckets or with flowing water (Antoniou 2010). Rainwater was also used for flushing/cleaning toilets.

The predominance of these toilets against the cesspits and ceramic vessels (connected to sewers, as in Olynthos, or not) of previous practices (Figure 9) could be connected to the knowledge gained about hygiene matters related to the rationality of the etiology of diseases mentioned above (Antoniou et al. 2014, 2016). Other features of these installations, such as the underground ducts, the vicinity to the sewerage and drainage city network and

![Figure 7](https://iwaponline.com/washdev/article-pdf/7/2/163/158727/washdev0070163.pdf)

**Figure 7** Delos, houses’ toilets: (a) with flushing hole and (b) L shape toilet, house IV B (the seats were probably wooden, sketches by G. Antoniou).
the anatomic design, could also be connected to the increased knowledge and awareness on hygiene of that period. The presence of such toilets from prosperous communities of merchants such as Delos to hilly small towns such as Dystos (Antoniou 2007) also proves the sanitary value of that structural form.

It is worth mentioning the fact that the desiccation of the lake of Ptecheon next to Dystos – presumably a marsh – referred on an inscription of the ca. 4th century bc (IG XII.9, 191 and Tassios 1997) which was implemented possibly for hygienic reasons, i.e. to limit the disease hazards from that marsh, rather than increasing the cultivated fields. The reference on the inscription that the drainage ducts should pass as far as possible from the cultivated fields of the area testifies that the water of that ‘lake’ (marsh) was not clean and therefore the task was probably an act for sanitary purposes.

In order to ensure the proper outfall of wastewater through the fortification walls, in some cases special features had been constructed, as in Minoa in Amorgos Island. Specifically, these consisted of twin, triple, etc. openings at the walls, usually narrow to prevent the entrance of intruders. The duct in Minoa was mostly a storm water drain since there is a collecting reservoir a few meters away from the gate as its widening size proves (Figure 10). The section outside the fortification was slab covered and the whole formation was incorporated in a network for the reuse of water in that town (Antoniou 2010). As was mentioned earlier, ancient Hellenes utilized (since prehistoric times) small bathtubs, wash basins, and foot baths for personal cleanliness. However, later in the Classical and Hellenistic periods they established public baths only as individual bath buildings (i.e. in Gortyna in Peloponnese and in Chalkis north of Athens) but also within gymnasia for relaxation and personal hygiene. For example, Phalasarna in the western part of Crete was one of the most powerful naval cities of the island in the Hellenistic period. It was a fortified citadel with a southward orientation. Notable finds in the harbor area include public roads, wells, warehouses, an altar, and baths.

A pavement leading from the harbor to the acropolis was discovered next to the second basin as well as five small cisterns which had to do with the public baths of the ca. 4th–3rd century bc (Figure 11). The formation of the
individual bathtubs in array refers directly to the typical formations of the known ancient Greek baths as those in Gortyna in Peloponnese. It is worth mentioning that that type of bath was incorporating both cold and warm-hot water bathing chambers, usually of circular layout.

ROMAN PERIOD (CA. 67 BC—AD 330)

The Romans and other post civilizations did not add fundamental knowledge to the hygienic practices and sanitation technologies. However, the scale of application and the apparatus used was greatly increased during the Roman period. Thus, Romans implemented extensive systems for public and private hygiene, aqueducts for transporting clean water into their cities, baths, toilets, and wash houses, and drainage and sewerage systems for getting rid of stormwater, wastewater, and other wastes. Roman law determined the ways to remove water and impurities from private and public buildings and channel them outside the cities, so as to ensure public hygiene. Legislation relating to sanitation defined the rights and obligations of citizens. These were expressed by servitus cloacae, that means the right to a drain or a sewer from a man’s land or house through a neighbor’s land or house, and servitus stillicidii immittendi, which obliged the owner of an estate to receive,
or his right to turn aside, the droppings or stream from his neighbor’s house (Bruun 2000).

The most characteristic element of Roman sanitation was hygiene. Public baths, toilets, and water fountains were available to even the poorest citizens in all major cities of the Roman empire (Lofrano & Brown 2010). The Romans washed a great deal, to which the use and the number of thermal baths existing at that time bears witness (McGrew 1985). At that time medicine highly influenced by Hellenic physicians such as Asclepiades of Bithynia and Galen of Pergamon extensively used cold and warm baths as treating methods (Yapijakis 2009; Shephard 2015). In the Italian city of Rimini in 2nd century AD, the house of a Greek surgeon named Eutyches had a room for application of bathing treatment in addition to examination and surgery rooms (Jackson 2002).

The strong emphasis of Romans on public health is indicated by the construction of extensive aqueducts to provide clean water. In Rome itself, the aqueduct system spanned a total distance of 350 km (Shephard 2015). The wastewater disposal systems of the Roman cities used a variety of engineering and construction designs of sewers and cesspools, depending on the geological slopes and the distance to the receiving water body (Lofrano & Brown 2010). The responsibility for maintenance, repair and restoration of all kinds of public hydraulic installations was state-owned and was carried out by curatores aquarum. In addition, the riddance of organic wastes by a special group of officials (koprologoi) which started in the Classical era continued in Roman times. Plutarch at the end the 1st century AD used the words πέλεκυρχος or τέλμαρχος, and in contrast to former periods thinks that this job is both ‘great and decent’ («αξιώμα μέγα και αειμόν»).

In the Roman era sewerage and drainage networks consisted of earthen or lead pipes, visible rock cut tunnels, underfloor stone or brick built tunnels, which were discharging to large, invisible, vaulted or flat covered sewers-drains. This is definitely related to the extended use of more complex public baths and toilets, with increasing demands for continuous water flow and the absolute need for channeling away of wastewaters and sewage continually. Roman toilets, usually of rectangular ground plan, have been found all over Hellas, for example in Athens, Corinth, Kos, Gortyn, Thessaloniki, Dion, Philippoi. They were usually embedded into more complex buildings, baths, thermal, palestrae, in the corner of the buildings or across the streets, so as wastes could flow into the urban sewerage and drainage system directly, through a single discharge channel. For example, in the toilets of Great Thermae in Dion, on the southeast corner of the complex, engineers implemented an interesting technological solution for continuous cleanliness and reduction of unpleasant odors. The channel beneath the marble bench with the defecation holes was essentially the continuation of a stone-built vaulted sewer, crossing the complex. It accepted wastewaters from tanks and basins, and stormwater from the roofs, via an elaborate system of clay, lead pipes, stone or brick built conduits, lying vertical and horizontal inside the walls, under the floors or piercing masonries. Rainwaters enriched the arched drain which contributed to public hygiene by leading all the wastes and impurities directly outside the city through the walls nearby (Kaiafa 2008; Karademos 1990).

The toilets of Palaestra in Philippoi in East Macedonia were also equipped with flushing systems connected to urban storm drainage conduits. A conduit running under the side street uninterruptedly supplied the sewage duct. The impurities of urination and defecation under the seats were then flushed by the wastewaters and then they poured in the sewer via a small square cross hole positioned in the northeast corner of the room (Lemerle 1937).

On the other hand, the standalone public toilets in Dion, with a rectangular ground plan, had an impluvium at the centre, which improved the illumination and provided continuous ventilation, hence making the interior somewhat more pleasant for the users (Figure 12(a) and 12(b)). The water from a fountain in the middle of the western side wall of the building rushed in a shallow ditch in front of the defecation seats so people could clean themselves by rinsing a sponge on a stick. Simultaneously, the flowing waters poured into a deeper ditch, passing under the bench type seats along the walls, evacuating into the urban sewerage and drainage system (Pantermalis 1989).

The baths played an important part in the social life of the Roman citizens who would while away hours there almost every day, not only bathing but also exercising. The statues of the children of Asklepios and fragments of a statue of the god himself were found in Dion suggesting
that the baths may have had therapeutic uses (De Feo et al. 2012). Many of the brick pillars of the hypocaust are still visible (Figure 12(b)). The hypocaust is an underground room with a large number of brick pillars supporting the ceiling, through which hot air circulated to heat the floor above. Fires burned in furnaces in the exterior wall.

BYZANTINE PERIOD (CA. AD 330–1500)

The fall of Rome and the Western Roman Empire seemed to be inevitable due to continuous civil wars, social injustice and unrest, and barbarian raids. The Eastern Roman Empire (so-called Byzantine by modern historians) lasted for a thousand more years, gradually losing the loyalty of its people as well as lands due to social injustice, oligarchy and theocratic policies.

The Christian beliefs overshadowed every medical philosophical and scientific thought except Galen’s that shaped views of medicine as well (Fortuna 2010; Jouanna 2010). All hygienic knowledge of the Hellenes was forgotten. The theocratic beliefs of the Middle Ages led to uncivilized extremes because it was considered ‘immoral to view one’s own body’. Therefore, people bathed seldom, wore filthy clothes and used perfumes in order to cover body odors. Their diets were poor and they used spices. The sanitation in cities was ignored, with human and animal waste covering the streets. There were many pandemics during these thousand years (Tsiamis et al. 2011a, 2011b). The Crusades brought cholera from the East back to urbanizing Europe. Leprosy spread from Egypt to Asia Minor and then to Europe. Several incidents of Black Death and plagues occurred periodically in Europe.

During the first ages of the post antiquity era the legacy of the ancient world continued through the Roman legislation and tradition and presented works, descriptions and building regulations mostly of the Eastern part of the Empire, which later was called Byzantine (at least until the ca. 6th–7th century AD). The importance of sanitation can be concluded by these surviving written sources as legislation codes, building regulations, etc. (Karpozilos 1989). In these scripts of the early centuries of the Byzantine Empire is mentioned, for example, the importance of the sewers-drains for the rebuilt of Ephesus by Emperor Justinian after its destruction by the Persians (Downey 1961). The references about the infrastructures of Constantinople made by Emperor Constantine testify their knowledge about the dangers of diseases from the sewерages and drainage (Karpozilos 1989). When Constantine founded Constantinople, he ensured a functional drainage system everywhere in the city because he wanted to avoid the infectious or contagious diseases caused by impurities. Actually, the sewers-drains which were constructed throughout the city were so deep that they could be crossed by men on horses. All drains of the new capital ended up in the sea (Patrīae I.149.4–8). The group of officials (koprologoi) specialized in disposing organic waste continued in Byzantine times.
According to written sources, it is documented that in the Byzantine cities central and secondary sewers and drains, neighborhood ducts network and domestic drainage for rainwater existed. Also, the distinction between public and private sewers is evident, as well as the right of the inhabitants to connect their own sewerage to the central public ducts (Digesta 43.23.1, 3). It seems that the knowledge mentioned at the legislation of Digesta, written in Latin, refers to the hazards from the waste of the sewers-drains which contaminate the air and threaten public health. It definitely survived until the era of the dynasty of Macedonian Emperors (ca. 9th–11th century AD) since references were written in 995 (Karpozilos 1989). Moreover, the legal code of the Byzantine Empire mentions that it was necessary to occasionally change the clay pipes of toilets (Prochiron 38.23–24). The public drainage network was cared for and cleaned by a special team of employees, named καναλοπλύται or καναλοπλύτα, the profession of which was considered inferior compared to others (Patrologiae Graecae, Chrysostomus, 61, 331, 414).

The sewers and drains of ordinary houses were mostly of ceramic pipes and they differentiated from the public ones due to their size and probably their construction. Relevant references about residential cesspits conclude that there were also domestic sewer-drains not connected to a public network. In addition there are clear references about separate domestic drains. After several detailed references it is also testified that there were vertical sewer-drains serving the toilets of the upper floors of residential blocks. According to the scripts it can also be assumed that sewerage and drainage networks existed only in towns where the disposal of the wastewater in a river, lake or the sea was possible (Karpozilos 1989). All the detailed discussion about the sewerage and drainage network and the public and private responsibility emphasize the knowledge of the sanitary importance of these structures and their role in limiting the hazards of diseases, especially in densely populated cities. Despite that, most scholars assume that during the last centuries of the Byzantine state the actual condition of the sewer-drain network was not relevant to the contemporary detailed legislation about these sanitation matters and was much decayed or even extinct.

Two early interesting sanitary installations with connected sewerage and drainage systems of the Byzantine period were found together, in Thessaloniki, on the ruins of a luxurious villa of ca. 4th and 5th century bc, which was abandoned during ca. 6th century bc (Karydas 1999). They both served the needs of a public building, probably an identified monastery of the town. In particular, two toilets were found, one individual and another one available to more than one user simultaneously. The first one was constructed in an arch which was formed in the thick south wall of the east portico of the abandoned previous villa (Figure 15(a)). It was characterized by typical features known since prehistory; a built pedestal on which a perforated wooden seat would have been located. Human excreta were emptied to the duct of the other larger toilet, northern, via a built square pipe. The second toilet was constructed of marble troughs which formed bench type seats with defecation holes. It was cleaned by a constant flow of water so that hygiene would be ensured, while another pipe at a lower level carried the waste away (Figure 15(b)–15(d)).

Despite there being several examples of multiple position toilets in monastic buildings (Antoniou et al. 2016), single toilets were the common feature in Byzantine houses. Even though limited examples have survived, the cases at Mystras (Orlandos 1937, some of them in Figure 14) probably present the typical formation. This is relevant to references for vertical ducts (as in Karpozilos 1989) but in the case of Mystras they were built of masonry. The presence of similar constructions in monasteries of the middle Byzantine era (Orlandos 1927) and on reveals the common character of the formation. It is interesting though that the surviving examples show both squatting and sitting toilets.

**MODERN TIMES**

During the post Byzantine era efforts and precautions related to sanitation and hygiene can be also traced through the water harvesting constructions and their features aimed at the purity of the harvested water. Most of the rainwater cisterns at the Venetian and Frank ruled settlements had a walled runoff surface preventing access to people and livestock and therefore possible contamination was limited (Angelakis et al. 2012).

Regarding the medieval sanitation system, it should be remarked that rivers were used as cloacae during centuries.
Figure 13 | Byzantine toilets: (a) on the ruins of an abandoned Roman villa, (b) apsidal toilet and (c) and (d) multiple position toilet.

Figure 14 | Two mansion house Chambers (a) and (b) in Mystras with toilet (Orlandos 1937).
For example, in Muslim Al-Andalus, in spite of the fact that river water was consumed for human needs, river courses were used as sewers and drains and also as garbage disposal places. Nevertheless, the employment of watercourses as open sewers and drains had been common in the entire Islamic world, even in such cities as Damascus or al-Basra (Reklaityte 2012, p. 275).

In spite of sanitation problems, which were common in medieval Islamic cities, such as water contamination, accumulation of garbage within the city walls or the accumulation of cesspools near the living space, the existence of sewer-drains networks in the urban environment along with the presence of a toilet within domestic spaces demonstrates that medieval Islamic sanitation was much more advanced in comparison with contemporary Christian cities. The simple formations of the preindustrial past reassuring the purity of the collected rainwater also continued at the beginning of the industrial age. Walled runoff surfaces above rainwater cisterns were built in many islands of the Aegean (Antoniou 2009). Moreover, relevant constructions in the Ionian Islands present a better designed approach. There exists a path-corridor, stepped or not, for the access of the orifice without stepping on the runoff which must remain clean (Antoniou 2014).

After World War I, at the beginning of the 20th century the state of Greece was established as it is known today and 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 was continued with an advanced manner after World War II and the following Civil War, when the first SSS and small wastewater treatment plans were implemented. More on this can be found in Angelakis (2016).

**CONCLUSIONS**

Based on existing evidence, the historical examination of sanitation and hygiene technologies in the same region over a great span of time may provide important information to engineers, archeologists and historians. The analysis of sanitary engineering and hygiene elements of each period may contribute to a better understanding of basic human needs, draw conclusions regarding past triumphs and mistakes, as well as possibly inspire new developments in the future.

In Hellas, extensive drainage and sewerage systems and elaborate sanitary infrastructure such as baths and flushing toilets have been in use since the Minoan Era. Such technologies were developed in prehistory, as early as ca. 2100–1650 BC in Crete and the Aegean islands. Influenced by the advent and progress of philosophy in the Classical and Hellenistic periods, sanitation became gradually based more on scientific investigations.

The Hellenistic period (ca. 4th–1st century BC) should be considered as the most progressive time in the design of sanitary and sewerage engineering during antiquity. By the ca. 4th century BC, anatomically shaped toilets seats were found across Greece, and by the 2nd century BC many private houses and public buildings had toilets (Antoniou & Angelakis 2015). Heavily influenced by Hellenic philosophy and sanitary engineering, the Romans subsequently applied these earlier sanitary techniques on a larger scale by constructing an infrastructure serving a greater number of users at one time, using the advantages of their building methods with concrete based walls and vaulted roofing. In addition, due to their improved aqueduct technology, they could provide continuously flowing water to most public toilets.

Some public toilets survived past the fall of the ancient world and were in use during the first part of the Byzantine period. Apart from the continuation of constructions of the Roman and generally the ancient world, the knowledge about the danger of diseases from sewerages survived through rules and regulations, at least during the early Byzantine times. Only after the Hellenic liberation from the Ottoman occupation in the early 19th century and the gradual introduction of new, enlightening and scientific ideas regarding medicine and sanitation was the improved infrastructure of Hellenistic times reached again and was surpassed only recently with modern engineering technology (Angelakis et al. 2005).

In conclusion, although the above descriptions do not provide a complete picture of urban sanitation technologies in ancient Hellas, they serve to illustrate the fact that such technologies were in use in this European region for about 5000 years. These advanced technologies, developed originally in Minoan Crete, were subsequently transferred to...
the Mycenaean civilization and then the Archaic, Classical, Hellenistic, and Roman Greece. Thereafter, minimal progress in developing sanitary technologies was gained until the end of the 19th century. In light of this archaeological evidence, the present day progress in urban water technology, as well as in comfortable and hygienic living, is clearly not an entirely recent development.

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