Evolution of urban waste- and storm-water management through the centuries focusing on Hellenic civilizations

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ABSTRACT
The urban wastewater and storm management has a long history which coincides with the appearance of the first organized human settlements (*ca*. 3500 BC). It begins in Prehistoric Crete during the Early Bronze Ages (*ca*. 3200 BC) when many remarkable developments occurred in several stages as Minoan civilization. One of its salient characteristics was the architectural and hydraulic 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, though they do not give a complete picture of wastewater and storm water technologies in ancient Greece, indicate nevertheless that such technologies have been used in Greece since Prehistoric times. Minoan sanitary technologies were diffused to the Greek mainland in the subsequent phases of Greek civilizations, i.e. in the Mycenaean, Classical, Hellenistic, Roman, and Ottoman periods. The scope of this article is the presentation and discussion of the evolution of wastewater and stormwater management through the long history of Greece focusing on hydraulic characteristics of sanitary infrastructures. Also present and future trends of wastewater and storm water management are considered. Practices described in this paper may have some relevance for wastewater engineering even in modern times.

Key words: baths; Bronze Age; combined sewerage systems; historic and prehistoric civilizations; separate sewerage systems; toilets.

PROLEGOMENA

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 Aegean islands, hygienic technologies were practiced as early as in the Minoan period of the island (*ca*. 3,200–1,100 BC) and were followed in several other cases in mainland Greece, the Aegean islands and Cyprus (Angelakis *et al*. 2014).

Control of urban wastewater and stormwater is known since the first large urban development period in mankind's history (*ca*. 3,500-1,100 BC). By *ca*. 3,500 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 costal Syria. In this small city, known as Habuba Kebira, wastewater and rainwater was collected and carried outside the city walls by U-shaped terracotta pipes and sewers 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 civilisation of the Indus valley (*ca*. 3,000 – 1,900 BC),

and westward as far as in the Aegean sea, with the Minoan civilization in Crete (*ca*. 2,700-1,400 BC), and the Mycenaean civilization in continental Greece (Viollet 2000).

Minoan civilization is universally considered to be one of the grandest and most brilliant one. The architectural and hydraulic function of storm water and wastewater sewerage systems were of special significance in the construction of the principal Minoan centres. Archaeological and other evidence indicate that, during the Middle Bronze Age, advanced water management and sanitary techniques were practiced in Minoan settlements (Angelakis and Spyridakis 2010). These include the construction and use of bathrooms and other sanitary and purgatory facilities relevant to sewerage and storm water systems. It should be noticed that throughout this paper sewerage systems referred to combined sewerage and/or storm water systems (CSS). Same holds for sewers and/or drains. The hydraulic and architectural function of sewerage systems in palaces and cities are regarded as one of the salient characteristics of the Minoan civilization (Angelakis and 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 seweragesystems, including disposal sites of the effluent, have been practiced in varying forms (Angelakis and Spyridakis 1996; Tzanakakis *et al*. 2014).

The status of urban wastewater and stormwater technologies in ancient Greece is reviewed, based on the results of archaeological studies of the 20th century. The emphasis is given to the evolution of sewerage systems construction, operation and management in the Hellenic civilizations. The achievements of this period, in order to support the hygienic and the functional requirements of palaces and other settlements, were so advanced that could be paralleled only to modern urban water systems. Many remains of sanitary and purgatory structures have been found in Minoan sites (e. g. Knossos, Phaistos, Mallia, Gournia, and Tylissos). The installations of hygiene can be classified as a characteristic factor of living's standard and economic prosperity, in both domestic and public uses (Angelakis *et al*. 2005). Due to these reasons lavatories had become, and often still are, shown off luxury elements (Antoniou and Angelakis 2008; Antoniou and Angelakis 2009). These advanced technologies were further developed during the Classical, Hellenistic, and Roman periods. In parallel, these advanced Minoan technologies were expanded to all over Greece in later periods of the Greek civilizations, i.e. in Mycenaean, Archaic, Classical, Hellenistic, and Roman periods (Angelakis and Koutsoyiannis 2006).

By this review study, the basic status of the wastewater and storm water management in ancient Crete, Greece is attempted. It is evident that extensive systems and elaborate structures for urban wastewater and storm water were designed, constructed, operated and managed properly, in order to support the hygienic and functional requirements of palaces, cities, and other settlements in ancient Greece. Significant developments relevant to the hygienic lifestyle in the Minoan era, and thereafter in Archaic, Classical, Hellenistic, and Roman civilizations, the Middle Ages, and the present times. The evolution of the major sanitary achievements during the long history of Greece is considered. Thus, the main objectives of this study are: (a) to review briefly the wastewater and stormwater management in Greece through the centuries, (b) to provide information on the status and to present and compare sanitation technologies among several Greek civilizations including the modern times, and (b) to briefly present the trends and the developments in sanitation technologies in future Greece. The information provided is expected to contribute to *how to learn from the past*.

BRONZE AGE (*ca*. 3,200-1,100 BC)

Minoan Era

Minoans had developed remarkable technologies relevant to wastewater and stormwater management such as sewers, baths, and toilets. Several Minoan cities and palaces had well established sewerage systems, which are in good functional condition even today (Fig. 1). The existence today of several Minoan archaeological sites is mainly due to their very advanced systems. The most advanced Minoan sewerage system seems to be advanced as that in the villa of Hagia Triada (Fig. 1b). This system caused the admiration of several visitors, including the Italian writer A. Mosso (1907), who visited the area in the early 20th century. During a heavy rain, he noticed that the pipes functioned perfectly and recorded the incident saying: *I doubt if any other case of stormwater drainage system that works 4,000 years after its construction.*

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

(a)

(b)

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.

Others Prehistoric civilizations

In Boeotia, on the other hand, at Orchomenos, large quantities of surface waters 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, in 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 the wastes. A little further north intownship in central Greece dating of both the Neolithic period and the Mycenaean period (*ca*.14-13th centuries BC) in northeastern of ancient Iolkos, the city of Jason has been discovered (Antoniou *et al*. 2014). A well-constructed wide road with *megaroid* houses were built with the same orientation on either side of a wide street have been excavated. In addition a very well preserved sewerage system has been recently discovered. 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).

HISTORICAL TIMES (*ca*. 490 BC-330 AD)

Classical and Hellenistic periods

The technological progress developed in Greece during the Historical times was accompanied with good understanding of the water and wastewater related phenomena. 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 done in hydraulics, which along with progress in mathematics allowed the invention of advanced instruments and devices, like the Archimedes's water screw pump (Koutsoyiannis and Angelakis 2003).

The realization of the importance of water sanitation is 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* examines the effects of the climate and the environment, in general, to the human health (Galanaki, 2014). In the Hippocratic medicine, every disease has its natural logical causes. Thus, the importance of water for the public health for first time was recognized and the first well organized baths, toilets, and sewerage systems appeared (Angelakis *et al*. 2005).

The lavatories of the Hellenistic period are concerned, they present clearly the typical formation of the ancient Greek lavatory, which consists of single or multiple benches, wooden or stone-made, having defecation keyhole shaped openings (Antoniou 2007). The benches are 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 Minoa Amorgos and at Corinth and the U shaped as in Epidauros and Philippoi. More on this are 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.

As far as the sewers in Athens delivered storm water, human wastes and other effluents, to a collection basin outside the town, implementing for that also the Eridanos river. From that basin, the storm water and wastes were conveyed through brick-lined conduits to fields to irrigate and fertilize fruit orchards and other agricultural field crops. The known as 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 also constructed in various ways; one for example had carefully built stone walls and was covered with tiles and flat slabs; others were simply made of inverted roof tiles (Thomson and 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 2. 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).

A quite significant feature of the sewers during the Hellenic antiquity is the sewer system for the drainage of ancient theatres. The problem of the rainwater management

of the spacious open areas of the ancient Hellenic theatres is an aspect which was incorporated into their design since 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 importance and necessity, the drainage of the theatres built in stone was constructed at the beginning. Cases where the drain conduits were added later, seem to refer mostly to originally wooden constructions, as in Dionysus theatre in Athens, which was rebuilt or reformed into stone constructions. 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 Aegean island Delos are given by Kollyropoulos *et al*., 2015.

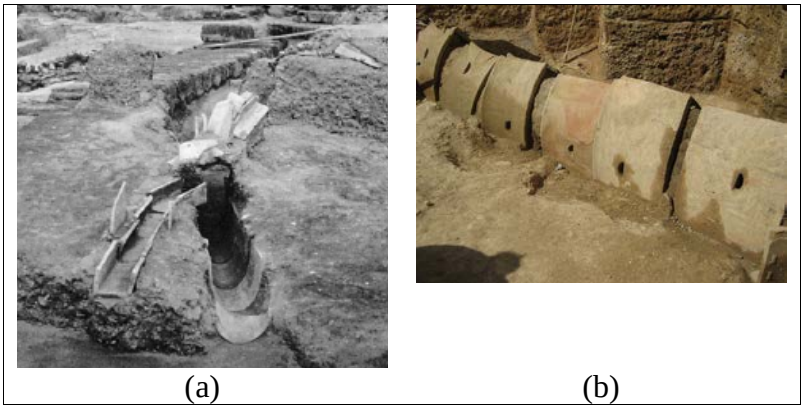

Figure 2. Remains of sewers in Hellenistic Athens: (a) Sewers south of the Middle Stoa and (b) Duct covered with prefabricated ceramic well ring sectors in south foothills of Acropolis (De Feo *et al.,* 2014).

Roman period

Baths and lavatories in Macedonia and other Roman domestic canters were playing a major role in the life style. Roman engineers were 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 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 was ensuring uninterrupted cleanliness, by supplying continually water 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 waste water sanitation. They were all of rectangular section, made of materials of second use (Kaiafa 2008). Their walls were made of stones and mortar, while slabs, used for the drainbeds. Also in the Roman cities of Veria, Dion, and Philippoi in north 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. Also in Roman Thassos, massive slabs of the road surfaces were set

onto the rims of underground sewers functioning simultaneously as covers (Grandjean 1994) (Fig. 3).

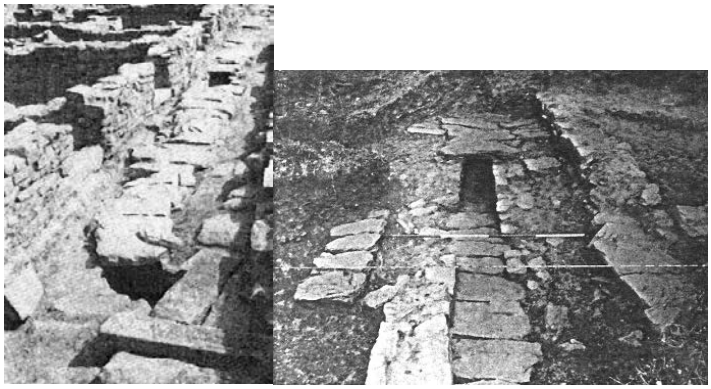

Figure 3. Sewers in island of Thassos (Antoniou *et al.*, 2014).

BYZANTINE TIMES (*ca*. 330-1453 AD)

The decline of the ancient world influenced not only the technological achievements accumulated by that time, but also the relevant skills and constructional abilities. In addition to that, the morals and the social habits introduced by Christianity influenced the practices and management of storm and wastewater management. Not only that the design and construction of the lavatories and baths and particularly the importance of privateness, not only referring to defecation, but also the bathing were highly influenced (Antoniou *et al*. 2014). 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, there were several common lavatories, mainly in monasteries, facilitating multiple users at the same time. Despite that, storm and wastewater management seems somehow neglected by the communities and was mostly resolved privately. The private character of lavatories resulted to the reduction of their size and to the possibility for their placement in spaces closer or next to main rooms (Orlandos 1937).

OTTOMAN PERIOD (*ca*. 1453-1828 AD*)*

During the Ottoman period, water and wastewater constructions that has been mainly developed by Romans were still maintained, operated and used (Angelakis *et al*. 2014). 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 enough. Only a few houses had running water or cisterns and they usually belonged to Ottoman officials.

Examples of lavatories have been evidenced in a few Ottoman hammams still existing in Greece, where sanitary installations actually consist of a small cell just to fit a 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 still existing hammam in Chania, Crete, the hammam of the Winds, Athens, and that of Karavangeli hammam in Lesvos (Antoniou *et al*. 2014). There is a tap or a full sewer inside the cell for cleaning purposes (Fig. 4). Usually openings set 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 the Mecca. No flushing system has been traced, and

the waste was removed from the toilet through ceramic pipes, placed under the key-hole shaped slab, connected most probably with a sewage pit (Dimitriou 2002).

(a) (b)

Figure 4. Ottomann toilets (a) In the women's section, Abid Efendi or Hammam of the Winds, Athens and (b) in Lesvos, Mytilene in Karavangeli hammam (Antoniou *et al.*, 2014).

MODERN TIMES (1828 to present times)

The history of modern Greece covers the history of the country from the recognition of its autonomy from the Ottoman Empire in 1828. After the World War I, beginning of the 20th century, Greece state was established as it is known today and 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 was continued with an advanced manner after the World War II and the following Civil War, when the first separate sewerage and drainage systems (SSS) and small wastewater treatment plans were implemented.

Today Greece, with a population of approximately 11 million inhabitants, has to comply with the EU Urban Wastewater Treatment Directive (271/91/EC). The total length of sewage system is estimated to be *ca.* 50,000 km and more than 90 % of the total population is covered with it. To the contrary of the ancient Greece, SSS are dominant throughout the country, since the middle of the last century. At the present times the most of sewerage and drainage systems (80 %) are SSS. Also there is a tendency for the remaining of CSS, about 20 % of the total, which is mostly located in the centers of the big cities, to be replaced with SSS. Today Greece is bound to connect all urban agglomerations serving above 1000 pe (population equivalents) to more than 500 WWTPs which cover about 85% of pe. The total effluent produced is 700 M m^3/yr, which is mainly discharged to the Mediterranean sea and to the rivers (Ilias *et al*., 2014).

FUTURE TRENDS

The future collecting, conveying and treatment of sewage will be governed by the following macro drivers: (a) faster population growth, (b) higher urbanization, (c) climatic variability, and (d) ageing infrastructure assets. These will present both a challenge and an opportunity on how to re-configure the sewers and treatment processes as well as financing of water and wastewater infrastructure to meet the future challenges. Thus, Greece will follow, the development of proper decentralized water and wastewater management technology, due mainly to the expected increased urbanization. Also septic tanks are to be replaced with efficient small-scale systems

that will allow environmental protection, while at the same time producing energy, water and/or sludge for reuse. 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). Also SSS will be dominant in all over Greece. In addition, 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).

EPILOGUE

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

In conclusion, through the ages, innovation has played a key role, in ensuring the progress required to meet the emerging challenges. There is a lot to be learnt from studying the technological progress that has been historically the result of the need to address sanitation infrastructures. It is obvious that ideas, technologies, and practices developed during most periods of Hellenic civilizations greatly influenced our today knowledge. In addition, more than 2.6 billion people do not use improved sanitation thus there is a huge need for sustainable and cost-effective water supply and sanitation facilities, particularly in cities of the developing world (Bond *et al.*, 2013). Applicability of selected ancient Hellenic sanitation systems for the contemporary developing world should be seriously considered. Thus, much we learn from the past technologies and practices implemented (e. g. design philosophy, adaptation to the environment, and decentralization management of water and wastewater projects, architectural and operation aspects, and sustainability as a design principle).

In the future, water and wastewater management systems based on reapplication of old practices using new equipment could be of great significance. 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 series impacts to the future wastewater management and especially to treatment infrastructure. Therefore, an expected increase in decentralized self-supporting, small systems will emerge (De Feo *et al*. 2014).

Probing the past, forging the future (Theodore Kolokotronis, 1770 -1843).

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The same techniques for urban drainage were widely used in the 3rd millennium BC, both in the Indus valley and in Crete, with the introduction of bathrooms and latrines in palaces and private houses.

Urban drainage and water supply in bronze age cities (Euphrates and Indus Valley, Syria, Minoan Crete, Mycenaean Greece, 3500 – 1200 BC)

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The Oriental Bronze Age, between 3500 BC and 1200 BC, is known as the first large urban development period in mankind's history. Referring to the first article of this series (see IAHR Newsletter 4, 2002), the reader may recall reading about the link between controlling the Tigris and Euphrates rivers and the development of the Sumerian civilization in Mesopotamia. Technologies for urban water control were also developed to a high degree : in Mesopotamia and Syria, in the Harapean civilisation of the Indus valley (3000 – 1900 BC), and westward as far as in the Aegean sea, with the Minoan civilisation in Crete (2700-1400 BC), and the Mycenaean civilisation in continental Greece (1600-1200 BC). By 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 littoral of Syria. In this small city, known as Habuba Kebira, wastewater was collected and carried outside the city walls by U-shaped terracotta pipes and drains covered with stone slabs, running below the streets. The same techniques for urban drainage were widely used in the 3rd millennium BC, both in the Indus valley and in Crete, with the introduction of bathrooms and lavatories in palaces and private houses. Architecture encompassing flat roofs and terraces, and large courts with stone or brick pavements, made the question of rainwater management even more important in those countries where rainfall had damaging potential. Terracotta pipes descending from roofs and terraces were connected with pipes from lavatories (sometimes situated on the second floor!) and joined down to the first floor with covered drains made of terracotta pipe elements, baked bricks or

stone slabs. This pipes would run below streets and courts, towards larger sewage collectors, sometimes large enough for a man to enter (Fig. 1). In Mohenjo Daro (lower
Indus valley), bottomless terracotta jars were used as infiltration drains in streets which were too far from the collector network. In Mari (2800 – 1780 BC), in the middle Euphrates valley in modern Syria, deep vertical drains for excess rainfall evacuation were coated with bitumen. Those same water drainage techniques were used later during the 2nd millennium BC in Mycenaean Greece (Mycens, Tyrins in the Peloponese) and in the littoral of Syria (Ugarit, close to modern Lattaqieh), as well as in the ancient city of Akrotiri in Santorini island. Terracotta tubs in bathrooms were used in Minoan Crete and Mycenaean Greece during the same period. Of course, water was also a resource.

Cities in The Euphrates and Nile valley were directly provided with water through canals connecting to rivers. Wells were found in many Indus valley cities (700 wells existed in Mohenjo Daro, both public and private, about 15 m deep), and to a lesser extent in Syria and Crete. Cisterns were used for rainwater conservation, and advanced hydraulic systems for collecting water from the terraces down to the cisterns were implemented in Ugarit and Mari (Syria) as well as in Cnossos (Crete) – see Fig. 2 and 3. There is no evidence of the use of aqueducts before the Minoans in Crete, and there have been debates regarding the water supply of the palace of Cnossos, where clay pipes made with conical elements, -obviously used for water distribution- were found in different places in the palace. It is probable that a terracotta-made aqueduct was used to provide the palace with running water from a source situated on a hill a few kilometers away. This aqueduct may have crossed a small brook upon a bridge which was used for the road between the guest house and the palace. In later Mycenaean palaces, in continental Greece, aqueducts existed for sure : in Pylos, the aqueduct was two kilometers long and made partly of U-shaped terracotta elements, partly of wood. Thus, the ancient bronze age civilisations were not only brilliant for their palaces and temple architecture and treasures, but also for the knowledge they developed on urban water management. When those civilisations disappeared, in the chaotic end of the 2nd millennium BC, this knowledge was somehow maintained. Much later, in the classical antiquity, when the Greek philosopher Plato (by 400 BC) wrote about Atlantis, the legendary lost civilisation, he mentioned how the people of Atlantis developed high skills in hydraulic technologies. This may be a memory of the ancient hydraulic engineers from the lost Mari, Ugarit, Cnossos, and Tyrins cities.

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Fig 1. Exit of the main sewage collector of the palace of Cnossos (Crete). About 80 cm high and 40 cm wide (photo by the author). Fig 3. Canals made of baked bricks for rainwater
collection from terraces down to a cistern in Mari, Syria (photo by the author). Fig 2. A large stone drain for rainfall collection inside the palace of Cnossos (photo by the author)