Evolution of urban waste- and storm-water management in the region of Crete, Greece: A preliminary Assessment

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ABSTRACT

The history of water supply and wastewater engineering in Crete Island (Greece) dates back more than ca 4,500 years, since the early Bronze Ages. In the Minoan era, it was recognized that the removal of wastewater and storm-water were necessary for communal living. The early Minoan developments in wastewater and storm-water collection and removal are the cornerstones on which modern cities are built. The evolution of wastewater and storm-water management from prehistoric to modern times in Crete is examined briefly in this paper. Information on the current status and future strategies for wastewater and storm-water management is also presented.

Key words: Combined and separated sewerage systems; prehistoric and historic civilizations; modern times and future; urbanization, integrated wastewater management.

1. PROLEGOMENA

The history of man is reflected in the history of sewers.
Victor Hugo (1802-1885), novel Les Misérables

The Island of Crete, with an area of 8,336 km^2, accounts for the 6.36 % of the total area of Greece. Crete has a long history with the first human settlements established in the late Neolithic period (*ca* 9000-3000 BC) (Paschou *et al*. 2014). The first well-organized communities date back to the early Bronze Age in Crete, the Aegean islands, and in the coastal areas of Minor Asia, modern-day Turkey. Throughout human history, two of the most remarkable and advanced achievements are the water supply and sewerage systems of the Minoan period (Evans 1921-1935; MacDonald & Driessen 1990). Following civilizations these early sewerage and drainage technologies, were further developed and improved especially during the Classical and Hellenistic periods (Angelakis, 2017a; Angelakis & Spyridakis 2010). During the Roman period, only the scale of these facilities was expanded due to population growth.

The principal objectives of this paper are to: (a) review briefly wastewater and storm-water management in the island of Crete through centuries, (b) provide information on the current status of wastewater management on the Island, and (c) identify emerging trends and future challenges for wastewater management.

2. FROM PREHISTORIC TO MEDIEVAL TIMES (*ca* 3200 BC-1400 AD)

From prehistoric to medieval times four periods are of special interest: (a) the Minoan, (b) the Classical and Hellenistic, (c) the Roman, and (d) the Byzantine. Significant development and progress during these periods as they relate to modern practice are discussed below.

2.1. Minoan Era in Crete (*ca* 3200- 1100 BC)

During the Minoan Era, extensive systems and elaborate structures for water supply, sewerage and drainage were planned, designed, and implemented to supply the growing population mainly in the urban areas (Angelakis *et al*. 2005). The first water supply and drainage works in the Minoan palaces and towns were probably performed in the Early Minoan period. It has been suggested that the drains at Archanes, excavated by Evans, actually date to the early Minoan period, and were repaired afterwards (Sakellarakis & Sapouna – Sakellaraki 1997). Later some of these facilities were purified and repaired, while others were abandoned (Driessen & Schoep 1994). However, the major hydraulic works (remnants of which we can see today) were implemented later on during the so-called Neopalatical period (*ca* 1700 - 1450 BC) and Late Minoan (or 3rd Palatical) period (*ca* 1450 -1100 BC). Three examples from the Minoan Era are examined below: the wastewater and storm-water drainage systems at the Palace of Knossos, the drainage system at Zakros, and the collection systems of Hagia Triadha.

2.1.1. Wastewater and Storm-waterDrainage Systems at The Palace of Knossos

As the hill, on which the Palace of Minos at Knossos was built, was periodically drenched by torrential rains, the removal of storm-water was a necessity (Shaw 2015). Similarly, if the Palace were to be inhabited, human waste should be removed. The complex wastewater and storm-water drainage systems developed at Knossos were evolved from these concerns (Angelakis 2017a; Antoniou and Angelakis 2015). To illustrate: storm-water collection and drainage systems were installed underneath covering almost all the Palace. Baffles and overflow structures were used to slow the rate of storm-water runoff to prevent flooding. Wastewater was also collected in the storm-water drains (Angelakis *et al*. 2014; Antoniou and Angelakis 2015). A plan of a part of drainage system, about 100 m, under the "Queen's Megaron” (domestic quarters) at Knossos is illustrated in Figure 1. The sophistication of the drainage system is evident from the layout of the system.

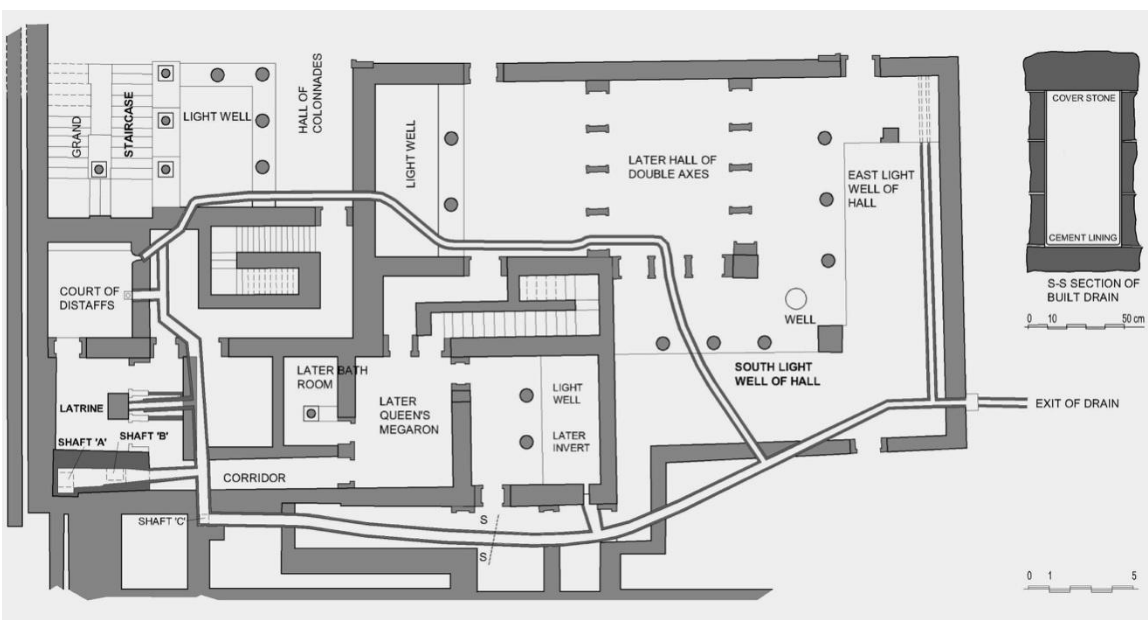

Figure 1. Part of the wastewater and storm-water drainage system in the palace of Knossos beneath the Domestic Quarter (modified from MacDonald and Driessen 1990).

Gutters were used to collect water from the roofs of buildings and most probably this water was used for the toilets located on the lower floor. Generally, drains and sewers were built of dressed stones and were large enough to make it possible to be cleaned and maintained (Angelakis 2017b).

The drainage systems were built of stone blocks lined with cement and measured about 79 to 38 cm per section (as shown in Figure 1, the cross section was rectangular). Probably the upper system was open (Evans 1921-1935). The sewers and drains were large enough to permit people to enter for cleaning and/or maintenance; in fact, access ports were provided for that purpose in the parts that were covered. Airshafts at intervals also helped to ventilate sewers (Graham 1984).

Anyone who has visited Knossos with an interest in evolution of storm-water and wastewater management will be impressed by the high level of knowledge and understanding of the mechanics of fluid and air flow, of the innovative use of construction materials, and of the need to maintain such systems by the ancient Minoans. The many different innovations developed by the Minoans are considered to be the cornerstone for the environmental health of today's cities. It is also interesting to note that the use of combined sewers is still common today in many cities of the world, and the fact that many communities with separate collection systems are now investigating the merits of a combined system.

2.1.2. The Drainage System at Zakros

The drainage and sewerage system of Zakros was quite compact and of the same high water-engineering standards as the ones at the palace of Knossos and other Minoan settlements (Platon 1974). Zakros system provides us with well-preserved remains of sophisticated networks in which descending shafts and well-constructed stone sewers, large enough to permit the passage of a man, play an important role. Part of the drainage system at Zakros is shown in Figure 2a.

2.1.3. The Collection Systems of Hagia Triadha

One of the most advanced Minoan sanitary and storm sewer systems was discovered in Hagia Triadha (close to the south coast of Crete, a few km west of Phaistos) (Angelakis *et al*. 2014). The Italian writer Angelo Mosso, who visited the villa of Hagia Triadha at the beginning of the 20th century and inspected the storm sewer system, noticed that all the sewers of the villa functioned perfectly and was amazed to see storm-water come out of sewers, 4,000 years after their construction (Mosso 1907). He stated that: *I doubt if there is another case of sewerage and drainage system that works 4,000 years after its construction.* Part of the drainage system at Hagia Triadha is shown in Figure 2b.

(a) (b)

Figure 2. Minoan wastewater and storm-water drainage systems: (a) part of the system at Zakros and (b) part of the system in Hagia Triadha (photos of A. N. Angelakis).

2.2. Classical and Hellenistic Periods (*ca* 490-67 BC)

In the beginning of 1420 BC, the Minoan civilization was overrun by the Mycenaean civilization from the mainland of Greece. A beneficial effect of this colonization was that advanced Minoan water technologies were spread to the Greek mainland (Angelakis and Spyridakis 1996). During the Archaic and Classical periods of Greek civilization, sewerage and drainage systems, similar to the Minoan and Mycenaean originals, were constructed. However, the scientific and engineering progress of that time made possible the construction of more sophisticated structures (Angelakis and Vavoula 2012).

2.3. Roman Period (*ca* 67 BC- 330 AD),

During the Roman period, the physical scale of the sanitation technologies significantly increased. For example, large sewers, of which the Cloaca Maxima in Rome is the best known, were used for the removal of surface and underground waters from urban areas. They were not designed to serve as sewers as the Minoans and Indus civilizations had done in the past (*ca* 2,000 years before, Gray, 1940). Except for some connections in

Rome, they were not expected to receive directly excrements. But apparently in Roman cities excrements and other wastes were thrown outside, in the streets. As a result, extensive street washing programs for cleaning purposes were implemented (Angelakis *et al*. 2018). During this period in Crete, public buildings -often with fine mosaics, toilets, sewers, drains, and other hydraulic works-were established in main Greco-Roman cities of the Island including Gortys, Ierapytna, Aptera, Lyttos, Kissamos, and Lebena. The Romans did not add much to the Greek knowledge; however, the invention of concrete by Romans, called "opus caementitium", enabled the construction of longer sewers, canals, huge water bridges, and long tunnels in soft rocks at lower costs (Fahlbusch 2010).

In addition to the lavatories, stone-built central sewers in Roman cities drains and sewers have been developed under the roads, along the central axis, ensuring storm and wastewater sanitation. In Roman period, drains and sewers covered with stone slabs were running below the roads (Fig. 3a). Also, Roman theatres were implemented with sewerage and drainage systems (Fig. 3b).

(a) (b)

Figure 3. Sewerage and drainage system in Roman times: (a) in a road in Kissamos city and (b) in the roman theatre in Aptera (photos of A. N. Angelakis).

3. MEDIEVAL TIMES (*ca* 330-1669 AD)

3.1. Byzantine period

From 961 to 1204 AD, Crete Island was part of the Byzantine Empire. 'Chandax' (present-day Iraklion) was the headquarters of the Duke of Crete. During this period, the technologies applied for water supply as well as sewerage and drainage systems in the urban areas were more or less the same as those in the Roman period. Several drainage conduits, embedded in the fortification walls, were implemented in the fortress of that time. Such an example, located at the northern site of the fortress of Kastelos in Varypetros in western Crete, (in the lateral ceramic bricks that ended up externally) is shown in Figure 4a. Its dimensions are 25x25 cm and it has been built during the 2nd Byzantine period. At the end of the Byzantine period, Crete fell into the hands of the Venetians.

3.2. The Venetian period (*ca* 1204- 1668 AD)

Three major civilizations dominated during this time of period: The Venetians, the Ottomans, and the Egyptians. Although little new innovation occurred during this period, new infrastructures were built, based on past knowledge. It is clear that from the beginning of the Venetian period (*ca* 1204-1668 AD), the Duke of Crete commands the maintenance of the water tank of the Duke's palace, explaining that: *'…because water is a high necessity for the palace and the family of the Duke of Crete'.* Venetians devoted much attention to water supply issues (Strataridaki *et al*. 2012). During this period, large-scale wastewater and storm-water management systems were also implemented. Many of these technologies were related to the protection, operation, and maintenance of the walls and used to protect cities, such as those for Iraklion.

The Venetian occupiers started fortifying the city in 1518 and the construction of the walls lasted approximately 100 years. Thereafter Iraklion was called *Handax* Greek word which means a great channel. On 27 September 1669, *Handax* was conquered by the Ottomans (Fig. 4b). The ground plan of the Venetian city walls of Iaraklion is triangular-shaped with a perimeter of approximately 6.5 km and covered an area more than 20 ha around the old city. The drainage of the storm-waters in the walls were done throughout the two parallel walls, the *Handax* (Fig. 4b).

The Venetian walls of Iraklion remain largely intact to this day and they are considered to be among the best-preserved Venetian fortifications in Europe. The walls protecting Iraklion were one of the greatest fortifications works undertaken in the 16th and 17th centuries in Europe.

(a) (b)

Figure 4. Drainage of fortifications works: (a) of the 2nd Byzantine period (Gigourtakis 2004) and (b) of Venetian walls in Iraklion.

4. THE OTTOMAN AND THE EGYPTIAN PERIODS (*ca* 1669-1898 AD)

Water has a direct connection with the Ottomans' faith, as is the case with most -if not all- religions; in every mosque there was a fountain for the religious needs of the Moslems (Spanakis 1981). Following the Ottoman period (1669-1898 AD), the Egyptians (*ca* 1830-1840) also maintained and operated water supply, sewerage and drainage constructions that have been mainly developed by Romans and Venetians (Angelakis *et al.* 2014).

5. IN CONTEMPORARY TIMES (1898 AD-present)

By the end of the 19th and beginning of the 20th century, water and wastewater technologies, developed in other parts of the world, started to be implemented in Crete. These technologies were partially based on existing traditional ones and on innovative applications including various types of pumps, manufactured pipes, new wastewater treatment plants, septic tanks, etc. Such developments continued after Crete became an administrative province of Greece in 1913, and even more so after World War II and the following Civil War (Angelakis and Vavoula 2012). Progress continued in a rapid way after the World War II, when the first separated sewerage and storm-water drainage systems (SSS) and small wastewater treatment plans were implemented. The current status of wastewater treatment, water reuse, and storm-water management are considered below. Emerging trends and future challenges are considered in the following section.

5.1. Current Wastewater Status

Greece and accordingly Crete have to comply with the EU Urban Wastewater Treatment Directive 271/91/EC (EU 1991). Today, the status of wastewater and storm-water collection as well as wastewater treatment in the Island of Crete has been improved strikingly. The total length of wastewater collection system is estimated to be *ca.* 3,000 km supporting more than 90% of the total population. In contrast to the common practice of the Minoan period, separated systems have been dominant throughout the Island since the middle of the previous century (Tzanakakis *et al.* 2020). At the present time, it is estimated that 90% of the wastewater and storm-water collection systems are separated. There is also a regional plan to replace all the remaining combined systems with separate collections. The rationale is to enhance the performance of existing WWTPs by eliminating the discharge of partially treated wastewater during high rainfall events, which exceed the hydraulic capacity of most treatment facilities.

The status of wastewater treatment in Crete, based on the population served, is presented in Table 1. Today, there are about 100 wastewater treatment plants (WWTPs) that are under operation, most of which serve human communities of less than 2,000 inhabitants. As noted in Table 1, most of the remaining to be built plants in the future is small, in capacity terms. Also, most of these treatment plants will be built in the eastern part of Crete. For the 5-10% of the population that lives in villages of less than 500 inhabitants, onsite sanitation technologies will be applied. It has been estimated that more than 80% of the Island's population will be served after the completion of all plants with

Table 1. Current Status of Wastewater Treatment in Crete (adapted from Tzanakakis *et al*. 2020).

Population served	No of operating WWTPs	Capacity, hm^3/yr	Reused, hm^3/yr	Potential reuse opportunities	Comments
<2000	67	3.90	0.75	Agricultural irrigation	Numerous additional small projects (more than 650[a]) serving less than 2000 persons are in various stages of planning and development. When completed these treatment plants will serve 15-20% of the total population of Crete.
2000-5000	15	4.65	0.90	Agricultural irrigation and landscape irrigation	Two more plants are under implementation and three are under construction.
5000-15000	10	8.90	2.25	Agricultural irrigation, landscape irrigation, and groundwater recharge.	One more plant remains under implementations and another one is under construction. When those treatment plants (including the above) will be completed, the total population served will rise above 80 %.
15000-100000	5	12.00	0.55	Agricultural irrigation, landscape irrigation, groundwater recharge, and indirect and direct potable reuse	
100000 -150000	1	10.20		Agricultural irrigation and landscape irrigation	
>150000	1	14.50	1.00	Agricultural irrigation, landscape irrigation, groundwater recharge, and indirect and direct potable reuse	
Total	99	54.15[a]	5.45[b]		

[a] WWTPs under implementation are not included; [b]The potential for agricultural use is about 10.1% of the total water used for agricultural irrigation.

a capacity above 2000 inhabitant equivalent. Thus far, a number of different WWTP technologies have been adopted for use in Crete. Among the WWTPs serving more than 2,000 inhabitants, 95% are conventional activated sludge and/or extended aeration systems. For populations of less than 2,000 inhabitants, the predominant technologies are gravel and sand filters, textile filters, and wetlands (Tzanakakis *et al*. 2020).

5.2. Water Reuse

Although many regions throughout Greece, especially in the southeast parts are water limited, effluent reuse is not widely practiced (Ilias *et al*. 2014). It has been estimated that 3.20 % of the total water currently used for irrigation could be saved through reusing effluent from the existing WWTPs (Angelakis 2017a). In Greece today more than 75 % of the treated wastewater effluent is discharged by submerged sewers to the sea. In Crete today, about only 1.10 % of treated wastewater is reused mainly for agricultural irrigation (478.39 hm^3/yr) (CMD 2017; Tzanakakis *et al.* 2020). As most of the large cities have WWTPs, the potential for water reuse in Crete is quite high (10.1% of the water used for irrigation) (Table 1). The existing stringent and complex regulations have prevented the development of well-organized water recycling projects (CMD 2011). Nevertheless, concern for effluent reuse has arisen lately, and more recycling projects are being implemented or planned for crop and landscape irrigation. In addition, direct potable reuse (DPR), especially in the eastern urban areas of the inland, should be considered (Angelakis *et al*. 2018).

5.3. Storm-water Management.

Cretan coastal system is characterized by a strong seasonal variability, being typically oligotrophic during the dry summer periods with nutrients delivered primarily during the wet winter periods via pulses associated with high rainfall events. These events are the most important drivers of coastal primary production leading to deterioration of water quality especially near heavily-populated areas. This pattern of nutrient delivery makes coastal systems particularly vulnerable to chronic nutrient inputs as the characteristic wet-dry season periodicity in nutrient inputs can be significantly modified (Gillanders and Kingsford 2002). In Crete, storm-water is disposed to natural recipients, e.g. land, rivers, transitional and coastal waters. As all major cities of the Island are located in coastal areas, storm-water disposal directly to the sea is a common practice. Bathing water quality parameters are monitored from a network of 174 sampling stations in accordance with the provisions of Directive 2006/7/EC (EU 2006). Furthermore, the ecological and chemical status of coastal waters in Crete is seasonally assessed from 6 additional sampling stations according to the Water Framework Directive 2000/60/EC (EU 2000). Results from both monitoring programs reveal a very good water quality and status of the coastal waters around Crete (EEA 2018).

Storm-water management is recognized today as a key climate change adaptation policy response (Moore *et al*. 2016). Rainfall intensity is expected to increase by up to 60% by 2100, which could increase the frequency and volume of storm-water overflows by up to 400% (Willems *et al.* 2012). In Crete, extreme storm events, especially during the wet winter period, can overwhelm WWTPs resulting in massive overflows of sewage into coastal recipients while creating significant public health problems, stress on marine ecosystem and severe water quality concerns. On the 12th of January 2015 a short-term but extreme in intensity weather event has resulted a massive flood over the main WWTP facilities of Iraklion city with a population equivalent to 200,000 inhabitants. Plant remained waterlogged and incapacitated for almost a month resulting in a continuous and massive discharge of untreated sewage in Iraklion bay before restoration. An intense environmental monitoring program conducted by HCMR revealed a gradual recovery of the coastal recipient surface sediment within a period of four to five weeks. It should be noted that Crete is almost by all sides exposed to very strong winds and wave heights, especially during winter, resulting in a high coastal self-cleaning capacity to reduce effectively land-based sources of pollution. In conclusion, though a gradual decrease of nutrient loads has been followed WWTPs installation and function, the coastal area around Crete still remain vulnerable to high nutrient loads associated with heavy precipitation followed by extensive urban flooding events.

6. EMERGING TRENDS AND FUTURE CHALLENGES

In general, future sewerage developments (e.g. wastewater collection and treatment systems) will be governed by the following events: (a) population growth, (b) large urbanization, (c) impacts of climate variability and/or change, and (b) need to replace ageing infrastructure assets. These events will pose 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 and face the future challenges. Both urban and rural areas will be affected.

In the next 30 years it is estimated that the world's population will increase from 7.3 billion today to 9.7 billion by 2050. Also by 2030, roughly 60% of the world's population will be living in urban areas. At the same time, it is anticipated that by 2030, 60% of the world's population will live near a coastal region, creating even more urban sprawl than already exists (UN 2015). As urbanization continues along with anthropogenic climate change, the need to reuse water will become a necessity. Unfortunately, the location of most of the centralized WWTPs in the major cities in Crete is not optimal with respect to the many reuse opportunities. Further, pumping treated effluent where it can be reused effectively for non-portable and potable reuse is generally not feasible economically. Thus, it is anticipated that integrated wastewater management (IWM) strategies will be evolved (Tchobanoglous 2018).

Integrated wastewater management involves the use of various types of treatment facilities located within the service area. Upstream wastewater treatment facilities can be of two types: satellite and stand-alone. The key feature of satellite treatment systems is that they are connected to the centralized WWTP for sludge processing and disposal. Without the need to process sludge and return flows, treatment performance can be optimized for a variety of upstream uses. Large satellite WWTPs, that typically serve a portion of the sewer shed, are utilized where there is a large demand for recycled water. Two notable examples of IWM are: (a) the City of Los Angeles which operates two satellite WWTPs, and (b) the Los Angeles County Sanitation Districts which operate seven satellite WWTPs. Small extraction type satellite WWTPs, where wastewater is withdrawn from a wastewater collection system and treated for specific local reuse applications will also be utilized. As with the large WWTPs, all treatment solids from small extraction type WWTPs are returned to the collection system for downstream processing.

In rural areas, 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 these plants can be used as fertilizer in both rural areas and urban landscape areas (Lyberatos *et al.* 2011). It should be noted here that WWTPs are potentially hot spots for antibiotic resistance contamination in the environment as they offer favourable conditions for proliferation and transfer of antibiotic-resistant bacteria (ARB) and genes (ARG) (Pazda et al. 2019). Strengthening of policies related to ARG dissemination including implementation of regular monitoring and control measures for the usage of antimicrobial drugs, and removal of ARB & ARG during wastewater treatment remain nowadays highly desirable (Sanderson et al. 2016).

All major wastewater treatment plants in Crete are currently located close to the coastline in order to minimize the cost of collecting wastewater and discharging treated effluents to coastal water recipients. They remain vulnerable to rising sea levels and severe storms as most urban regions of the island rely on relatively out-dated infrastructures which were not initially designed to face effectively the forthcoming climate change impacts. WWTPs are likely to experience increased failures and performance decreases over the coming decades with profound potential consequences to public health (Kessler 2011). Local authorities and especially water service providers and consultants should urgently identify adaptation priorities such as infrastructure protection or relocation and further explore relevant local improvements in storm water risk management.

7. EPILOGUE

In this review paper, hydraulic works of urban waste- and storm-water in Minoan, Classical, Hellenistic, Roman, and present times in Crete (Greece) are presented and discussed. In ancient Crete, storm- and wastewater management in urban areas was characterized by simplicity, robustness of operation, and absence of complex controls.

These sanitary technologies are not, in principle, very different, and can be compared with the modern ones, which were established only in the second half of the 19th century in European and American cities (Angelakis 2017a).

The great contribution of the Minoan civilization is the basis of modern technology as well as development of cities and urban centres. Early on, the Minoans recognized that the removal of both wastewater and storm-water was the key to the development of a society that could live in close proximity to each other. The same principles apply to modern civilization. It is difficult to speculate on how modern society would have been developed without these concepts. The American Sanitation Engineer Herold Gray (Gray 1940) stated that: .... *you can enable us to doubt whether the modern sewerage and drainage systems will operate at even a thousand years.* Therefore, the Minoan plumbers planned and constructed projects that have been functional for centuries; unlike today, if a project operates well for 40-50 years, it is considered to be satisfactory (Angelakis 2017b).

Through the ages, innovation has played a key role in ensuring the progress required to face the emerging challenges. However, subsequent civilizations have not contributed, in principle, too much to the original (Minoan) technologies; which mainly increased the scale of them. In the future, waste- and storm-water management systems based on re-application of old practices and scientific approaches and by using new equipment, in order to effectively face the modern emerging challenges, could be of great importance (Rose and Angelakis 2014). For example, an expected increase in decentralized self-supporting, small systems will emerge. In a highly urbanized world, development of cost-effective water supply and wastewater sustainable technologies including water reuse, harvesting and storage rainwater, in order to increase water availability and minimize flood risks, will be of great importance. And remember that: *The sewer is the conscience of the city*. Victor Hugo (1802-1885), novel: *Les Misérables*.

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