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Hydro-technologies in the Minoan Era

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ABSTRACT

Significant characteristics of the Minoan civilization were: (a) their peaceful living with their environment and neighbors (although the Minoans dominated in the Mediterranean for almost two millennia, in none of the numerous wars and/or conflicts that occurred in the region were they directly or indirectly involved) and (b) technological developments that are unprecedented in world history, as shown by the numerous paradigms on water resources technologies used and water, wastewater, and stormwater management. These paradigms are relevant to water supply, fountains, cisterns used to store rainwater or spring water, aqueducts, dams, wells, water treatment systems, baths and toilets, sewerage and drainage systems, irrigation and drainage of agricultural land, and water use for recreation. Significant hydrologic and hydraulic achievements in Minoan Crete are considered and discussed.

Key words | aqueducts, baths and toilets, cisterns, dams, irrigation and drainage, wells

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INTRODUCTION

The Minoan civilization, the first known European civilization, developed mainly on and ruled the island of Crete and the Aegean islands during the Bronze Age (from about 3200 to 1100 BC). Surprisingly little is known about it, although it flourished for nearly two millennia; not even the name used for this 'nation' at that time is known. The term Minoan is a modern one, firstly used by A. Evans who discovered the palace of Knossos and derived it from the legendary King Minos, first King of Crete (son of Zeus and Europa) who, according to Greek mythology, ruled the island of Crete (Figure 1). An ancient civilization rich in trade of all kinds of goods, with access to amenities, such as plumbing, paved roads, and well-planned towns, that would not be seen again for several centuries, the Minoans had little need of weapons, and life revolved around grand palace complexes (http://saylor.org/site/wp-content/uploads/2012/10/HIST101-2.3.2-MinoanCrete-FINAL1.pdf).

The basic characteristics of the Minoans were briefly described by Evans (1921–35) as: 'The colorful frescoes in Minoan palaces reflect a life full of creativity, good taste and coexistence in harmony with the natural environment.' Also, recently Hirschfeld (2013) reported that: 'This culture [Minoan] is an amazing paradox: A great power without military aristocracy, a palace was a royal residence, where neither glorified the King, a religion without greatness and that women were equal to men.'

In the list of wars worldwide before *ca.* 1000 BC (including those related to conflicts over water resources), and especially during the Bronze Age (*ca.* 3200–1100 BC), one can observe that most occurred in the eastern Mediterranean region, where the Minoans dominated (http://en.wikipedia.org/wiki/List_of_wars_before_1000). For example, in the Early Minoan period Libyans and Egyptians fought against the Levante and others, in the Middle Minoan period Sumerians fought against Babylonian cities, Babylonians against Elamites, Sumerians and Assyrians, and Hittites against Babylonians and Hurrians, and finally during the Late Minoan period, Egyptians fought against Libyans, Persians and Phoenicians. However, it is remarkable that in none of these wars and/or hostilities did the Minoans have any direct or indirect military engagement. Not only that, but the Minoans, known as naval, were

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Figure 1 | The major archaeological sites with major hydro-technologies in Minoan Crete.

always playing a conciliatory role between the warring parties (Angelakis 2015a). Thus, the Minoan Era was named by Evans (1921–35) as *Pax minoica* or *Minoan peace*, a period in which cities did not have walls.

The control of water resources in ancient Greece was affected by its geophysical characteristics and climate (Koutsoyiannis & Patrikiou 2013). Earlier civilizations bloomed in large river valleys, which had water in abundance (Mesopotamia near the Tigris and Euphrates, Egypt near the Nile, and India near the Indus). However, the island of Crete does not have large rivers, and it is divided by mountains into small plains; it is in these plains where the major part of land cultivation takes place. Historically, Minoans preferred to settle and grow in these plains with dry microclimates, which led to the development of urban centers, mainly palaces and villas (Angelakis *et al.* 2014). The locations of nearly all major cities of Cretan civilizations, for millennia, are in areas with low precipitation (<500 mm), which seems to be a paradox (Markonis *et al.* 2016). Whilst there are only small rivers and lakes in Crete, the Minoan palace and other urban areas were established apart from them. This could suggest that the Minoans preferred to install their palaces, towns and other urban areas in places with hot and dry climatic conditions for hygienic reasons and for protection from diseases and natural hazards (such as floods and droughts) (Koutsoyiannis *et al.* 2008).

Finally, an interesting feature of Minoan culture was the remarkable architectural and hydraulic adequacy of infrastructures for the management of water resources, such as water supply, fountains, dams, aqueducts, the sewerage and drainage systems, baths and toilets, and irrigation and drainage of agricultural land (Angelakis & Spyridakis 1996a, 2013; Koutsoyiannis & Angelakis 2003). Thus, the remarkable progress in the Minoan Era, especially during the Neopalatial period (*ca.* 1700–1450 BC) when Minoan technology peaked, appears to be linked inextricably with peaceful coexistence with the natural environment and neighboring cultures as well as with the highly hygienic standards and comfort of living (Angelakis 2015a). To achieve these, the Minoans developed the appropriate hydrological and hydraulic technologies and water, wastewater, and stormwater management infrastructures.

The scope of this paper is to present the main achievements in hydrological and hydraulic works in Crete, Hellas, in prehistoric times. Emphasis is given to the great achievements by Minoan civilization (*ca.* 3200–1100 BC) and the importance of this not only to following civilizations but even to the present times. Water resources management and use in Crete and examples of hydro-technologies in Minoan Crete follow.

PHYSICAL SETTINGS

Crete has a strategic location, positioned between Asia, Africa and Europe and forming a natural and vital bridge between the three continents. This unique geographical position has determined its historical course throughout both ancient and modern times. The total population of Crete is 623,065 inhabitants or 5.8% of the total population of the country. In addition, more than 5 mil. tourists/yr have visited the island in recent years. In 2011, more than 73% of the total population was living in urban areas (i.e. the five major cities located on the north coastal area of the island. Of this, 225,000 or 36.11% of Crete's permanent population is living in three coterminous municipalities (Iraklion, Gazi, and Chersonissos) located in an area of 809.4 km^2 (or 9.7% of the total area of Crete) in the north central regions (Hellenic Statistical Authority 2011).

Climate

In the Eastern Mediterranean, and especially in the island of Crete, fluctuations show increasing and decreasing cycles of climatic conditions alternating chronologically, lasting from a few decades to more than centuries. The climatic and hydrologic conditions in Crete have been characterized by high variability both spatially and temporally through the long history of the island by Markonis *et al.* (2016), who summed up all the available sources and presented a picture of the climatic variability in Crete during the last 10,000 years which is shown alternating between warm/cold and moist/dry periods, which lasted from a few centuries to millennia (Figure 2). This picture demonstrates clearly the instability of the climatic conditions of the whole region (Markonis 2016).

In present days, the climate in Crete is primarily temperate. The western and northern parts of the island are generally more humid than the eastern and southern, and the two parts are separated by a central mountainous region, where snowfall is common in the winter. The three main mountains (White, Ida, and Dikti) play an important role in the rainfall and runoff regimes of the island. In the lowlands the winters are milder, while during the summer the temperature averages at 30 °C, with maxima reaching 40 °C. The average and maximum temperatures are higher throughout the year on the south coast of Crete, a region where climate, vegetation and landscape resemble more Mediterranean Africa (Angelakis 2016a).

Hydrology

Today, the atmospheric precipitation in Crete shows intense spatial and temporal variation. Generally the precipitation decreases from west to east and from north to south, and also it increases with altitude. In particular, the average precipitation of 927 mm/yr ranges from 440 mm/yr on the plain of Ierapetra in southeastern Crete to 2,000 mm/yr in the Askifou highlands in western Crete (Angelakis 2016a). Potential

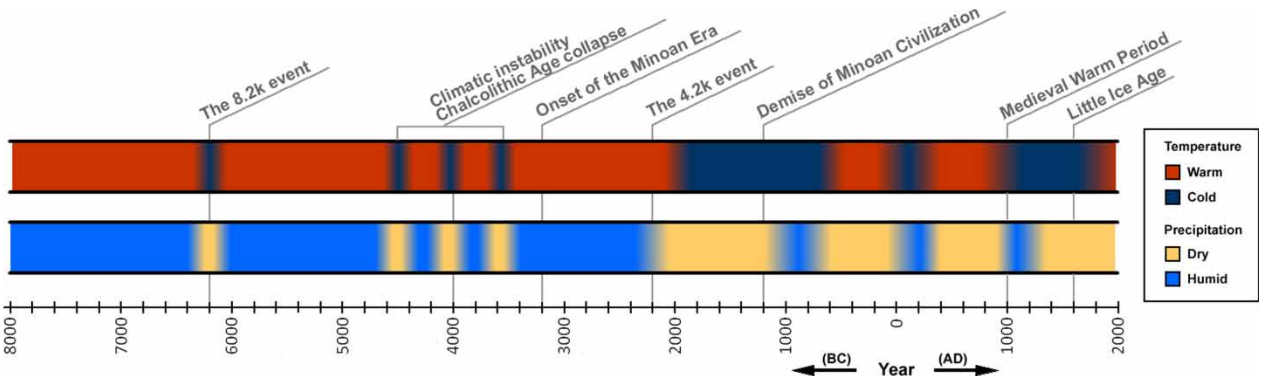

Figure 2 | Climate reconstruction of Crete for the last 10,000 years based on proxy and historical data (with permission of Markonis 2016).

evapotranspiration (ET), as estimated using the Penman–Monteith method, a system which provides the most accurate estimates, varies from 1,240 mm/yr to 1,570 mm/yr. The mean annual actual ET has been estimated to represent 75% to 85% of the mean annual precipitation in low elevation areas (less than 300 m absl) whilst it drops to 50% to 70% in high elevation areas (Decentralized Region of Crete 2015).

The island of Crete has been characterized by a significant increase in urban and touristic activities, especially in the past 20 years. As a result, the majority of the population is concentrated in the coastal areas. In many cases the infrastructures required to support this type of economic development are inadequate (Angelakis 2016a). However, agricultural water demand continues to be the major water consumer on the island, accounting for over 86% of the total use as based on both surface and underground water resources. Although underground water resources are estimated to be sufficient to satisfy all water needs, the lack of proper management and infrastructures has led to serious problems, particularly during dry periods when water demand is high (Angelakis 2016a).

Water resources availability and use

Water consumption and use in Crete is less than 7% and 18% of the annual precipitation and total water potential, respectively (Table 1). However, in many cases there is a severe water imbalance due to the temporal and regional distribution of precipitation. This worsens during the summer months when water demand rises due to the needs of agriculture and tourism. Furthermore, a high percentage of the annual precipitation occurs in the mountainous areas of western Crete and transport of water to the rest of the island suffers from technical, social, and economic limitations. An alternative, integrated water resources management plan is needed by which non-conventional sources (e.g. rainwater harvesting, treated wastewater, desalinated water, brackish water) should be considered (Angelakis 2016a).

The available water resources and water uses for Crete are shown in Table 1 (Hellenic Central Water Agency 2008, 2013). The real water use in 2010 was 421 Mm^3/yr, and the total water potential 2,941 Mm^3/yr, resulting in a consumption index of 14.31%. Note that the desirable water demand in 2010 was 515 Mm^3/yr (Decentralized Region of Crete 2015). Thus, water resources are more than adequate to meet the current and future needs of the islands several times over by reconsidering the management plan, which should include traditional practices (e.g. rainwater harvesting and water recycling and reuse).

WATER SUPPLY NETWORKS IN THE MINOAN ERA

In the Minoan palaces, towns, and villages water supply was differentiated according to the local conditions. Thus, the water supply at the Minos palace in Knossos was originally dependent mainly on the Mavrokolybos spring and later on the Karidaki and Fundana springs. In Zakros palace, it was entirely dependent on groundwater. On the other hand, in Phaistos palace the water supply system was dependent directly on surface runoff, where rainfall water was collected in special cisterns from the roofs and yards of urban areas.

The Minoans developed a special water pipe technology. They used terracotta pipes, approximately 76 cm long with a conical geometry (Figure 3). In Knossos palace, closed terracotta pipes were used (Angelakis *et al.* 2007). It seems that the geometry of the pipes was not based on hydraulic principles, but on manufacturing and assembly. The possible reasons for the conical shape of Minoan pipes could be: (a) the construction of the pipes was easier with cylindrical ones; (b) the conical shape served better for the connection; (c) the pressure could be more easily

Table 1 | Available water resources and water uses in Crete (adapted from Angelakis 2016a)

	Precipitation			Water potential (Mm^3/yr)			Water use in 2010 (Mm^3/yr)				
Area (km^2)	Height (mm/yr)	Volume (Mm^3/yr)	ET in volume (Mm^3)	Surface	Ground	Total	Agricult	Domestic	Industr	Total	Consumption index (%)
8,335	927	7,727	4,799	774	2,167	2,941	340	77	4	421	14.31

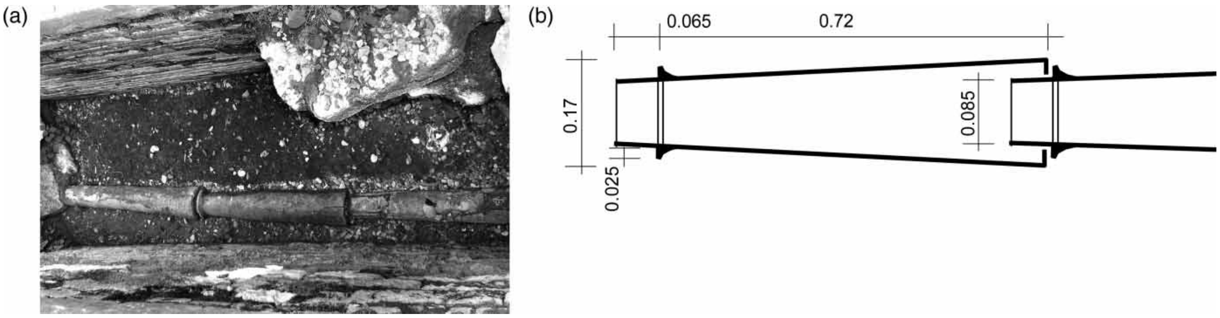

Figure 3 | Water supply terracotta pipes: (a) a real network segment and (b) pipe dimensions (Koutsoyiannis *et al.* 2008).

controlled on rough terrain; (d) the design of the network was easier in the case of curved walkways; and (e) precipitation and deposition of sediments on the walls of the pipes, particularly in the case of water with high pH, could be avoided (Angelakis *et al.* 2012).

FOUNTAINS

Minoan fountains were very sophisticated structures. Most of them are fed above ground with water from local sources or from other water sources through conduits (Angelakis 2015b). The most typical examples are the fountains known as *tyktes* (new). They refer to a type of fountain of the late Classical and/or Hellenistic period known as *ayrkrene* (from the Greek word *avrokrene*). Such a fountain is found in the 'Caravanserai' of Knossos, consisting of a rectangular basin with dimensions 2.0×1.6 m (Figure 4(a)). The basin is accessible by three steps and the water comes directly from a source located in the floor of the house (Evans 1921–35).

Another characteristic *tykti* fountain was found in the southwest corner of the room of the palace of Zakros (Figure 4(b)). An opening leads into a small chamber where the water is collected and lifted under the floor at the base of a square underground fountain (Angelakis 2015b). Its dimensions are 3×4 m and it is dated to the Late Minoan period (*ca*. 1500 BC).

CISTERNS

The Minoan cisterns were basically cylindrical. The total volume of each Minoan cistern ranged from 5 to 100 m^3. The most well known were presented by Angelakis (2013). In terms of form, cisterns were holes with irregular shapes

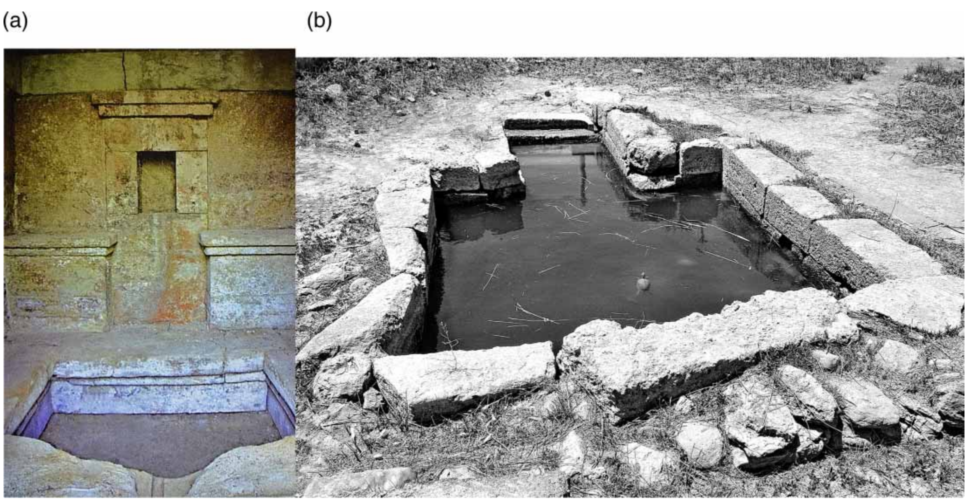

Figure 4 | Minoan *tyktes* fountains: (a) in the 'Caravanserai' of Knossos and (b) in the central square of the palace of Zakros.

dug out of sand and loose rock and lined with waterproof plaster (stucco), resulting in sophisticated structures (Gorokhovich *et al.* 2012). Two basic types are distinguished: (a) those used for collecting and storing rainwater and (b) those storing water that is transferred from spring sources or other surface sources through aqueducts (Mays *et al.* 2013). In areas with relatively high altitude and lack of aquifers and other water sources, the water economy was based on the collection and storage of surface runoff in underground reservoirs during rainfall (cisterns) (Figure 5(a)). Squares, courtyards, roofs, and other open spaces or even small watersheds were properly arranged for collecting rainwater. These sites were cleaned thoroughly before the collection process (Antoniou *et al.* 2014). Also, special structures were used for collection of rainwater, which did not affect other functions of the sites (Angelakis 2013). Special terracotta pipes were also used to convey rainwater to cisterns. In Myrtos-Pyrgos, such a terracotta pipe of rectangular cross-section supplied the nearby cistern system with stormwater collected from the rooftops (Cadogan 1977–78, 2007).

In addition to the cisterns used for water supply, lustral basins were sacred spaces necessary in Minoan settlements for cleansing, something similar to Christian cleansing places (Figure 5(b)). This type of 'cistern' was necessary in all Minoan settlements because Minoan religion required believers to always wash themselves before the religious ceremonies (Platon 1990). Also the facilities at the Caravanserai located opposite the main entrance of the palace of Knossos are characteristic. There was always water available from the aqueduct of Knossos for washing the visitors. It was the so-called sacred fountain (Pendlebury 1965).

AQUEDUCTS

As already mentioned, in areas with water springs, water was transported to palaces and other habitable spaces mainly by open stone-made conduits, unlike the closed conduits used during the Venetian and later during the Ottoman period. A typical example is the Tylissos aqueduct of a total length of 1.40 km in an open conduit (Figure 6), unlike the aqueduct of Knossos, where the water was transferred originally from the Mavrokolymbos spring and later from neighboring springs by a combination of open conduits and terracotta pipes (Angelakis *et al.* 2007; Nikolaou *et al.* 2016). Later on during the Neopalatial period the water supply of Knossos was transferred from springs located in the Jiouchtas area, 10 km south of the palace. More evidence of Minoan aqueducts can be found in Angelakis *et al.* (2007) and De Feo *et al.* (2013).

WELLS

As mentioned before, in the Minoan Era the water supply conditions of palaces and other residential areas were

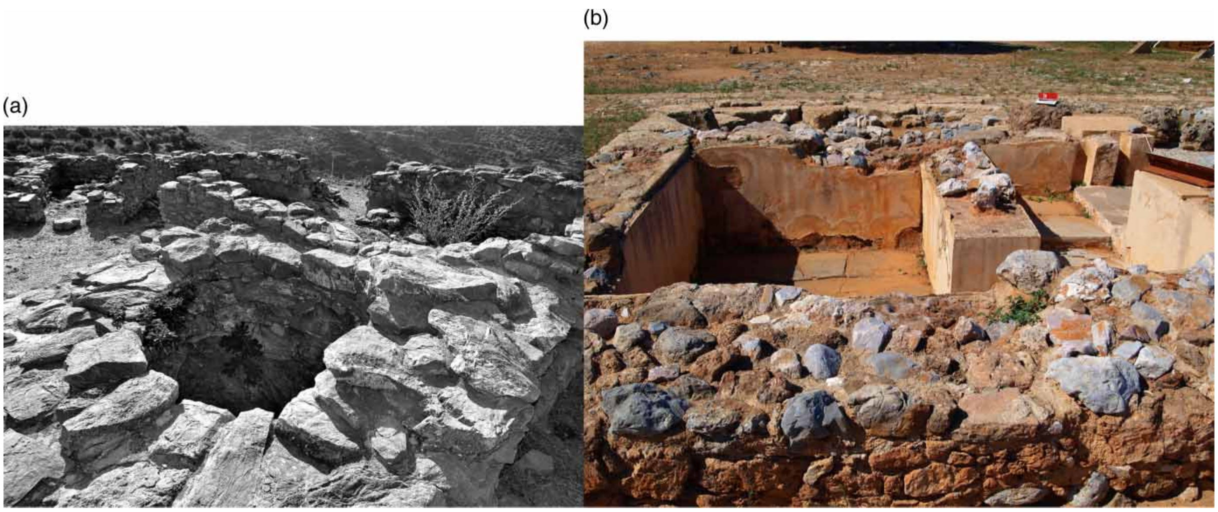

Figure 5 | (a) Typical Minoan cistern in Chamezi village and (b) lustral basin in Malia palace.

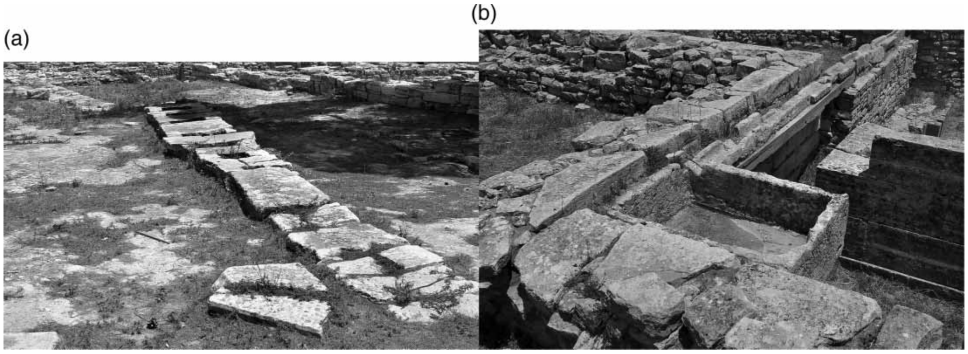

Figure 6 | Parts of the Tylissos aqueduct: (a) central conduit located at the entrance of the three villas and (b) secondary conduit and a small lithic cistern used for removal of suspended solids from the water before its storage in the main cistern.

differentiated not only according to time periods, but were also dependent on the hydrological conditions of each region (Koutsoyiannis & Angelakis 2003; Koutsoyiannis *et al.* 2008; De Feo *et al.* 2011). In places in southeastern Crete with limited surface water available underground, such as in the Minoan village of Agios Ioannis and the town of Palaikastro, digging and use of groundwater practices were implemented (Figure 7). The depth of Minoan wells was less than 20 m, usually 12 m, and their diameter less than 5 m, usually 1.5 m (Mays *et al.* 2007; Floods 2012). The practice used to lift the water was remarkable. Yannopoulos *et al.* (2015) reported that there is evidence that the Minoans were using the device known as the *shadoof* (in Greek *κηλώνειον ή γεράνι*). More on groundwater utilization in Minoan Era is given in Angelakis & Voudouris (2014) and Angelakis *et al.* (2016).

DAMS

Dams were constructed in various parts of the world from the Bronze age. In the Minoan Era, the best known are those found in the valley of Choiromandres, located at the eastern end of Crete, with a strong slope and direction from east to west (Tsatsanifos 2015). In the *ca.* 2nd millennium BC, the Minoans attempted to regulate the flow of the stream through a system of two dams, in order to protect arable land from erosion after heavy rainfall, and also to irrigate their fields (Figure 8(a)). It seems that the construction started in the Palaiopalatial period (*ca.* 1900–1700 BC), whereas the dams rescued today were constructed of megalithic materials during the Neopalatial period (*ca.* 1700–1450 BC). The higher has length 27 m, height 3.10 m, whilst the thickness of the base is greater than that of the

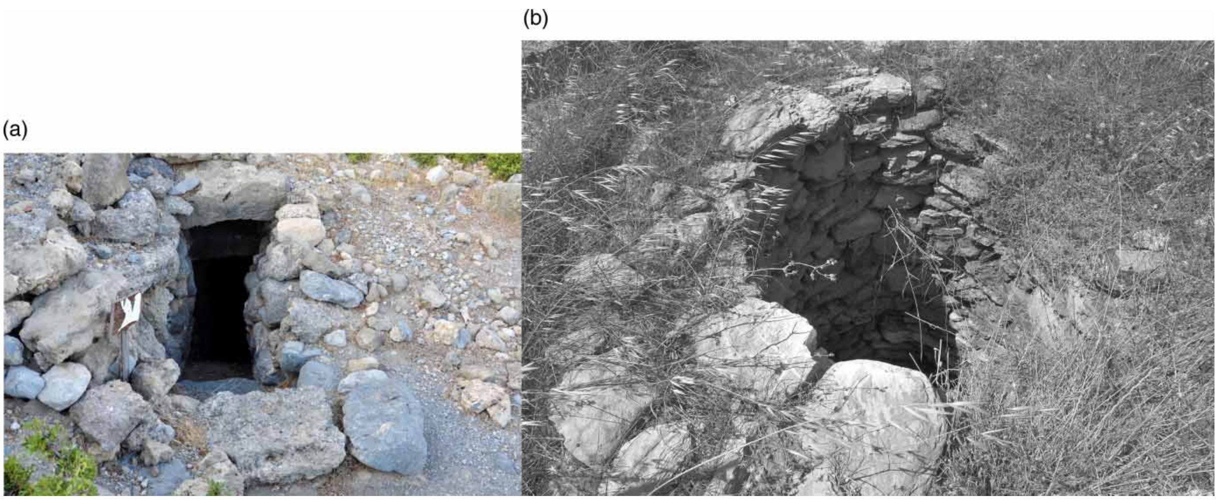

Figure 7 | Minoan wells: (a) in the village of Agios Ioannis and (b) in the town of Palaikastro in south eastern Crete.

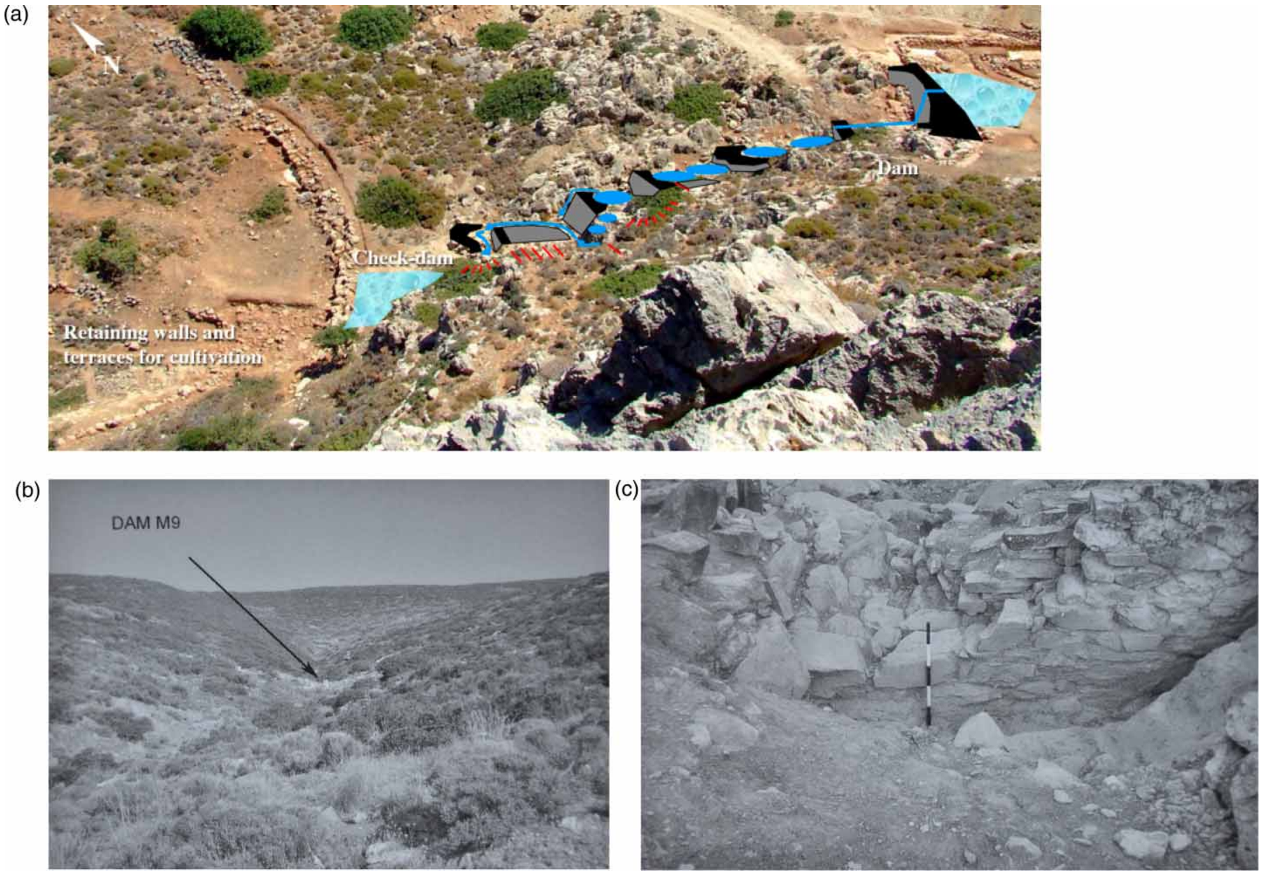

Figure 8 | Minoan dams: (a) plan of irrigation practices in the valley of Choiromandres, Zakros (Vokotopoulos *et al*. 2014); and the basic dam (M9) in Pseira (b) upstream in 2010 and (c) from the top in 1990 (Betancourt 2012).

crest (Tsatsanifos 2015). A channel in the eastern surface of the rock functioned probably as a spillway (Figure 8(a)). The upper part of the dam was built in the late Classical and early Hellenistic periods.

Similar hydraulic structures are found on the island of Pseira (Mochlos), located in the gulf of Mirabello in north-eastern Crete (Betancourt 2012). The Minoans, in order to ensure water for irrigation of agricultural crops and livestock on the island, built two water management systems: (a) small dams to intercept runoff waters in the seasonal streams and (b) a larger dam for storing water (Tsatsanifos 2015). The dams were made of stones and clay mortar (Figure 8(b) and 8(c)). The first had a length of 15.5 m, height 3.6 m, thickness 2.5–2.8 m, and a capacity of 500–600 m^3 (Betancourt 2012). They were constructed in the Neopalatial period (*ca*. 1700–1450 BC). The upper part of the main dam was built in the Byzantine period (*ca*. 6th–8th century AD).

WATER TREATMENT

Next to the water storage cisterns, well-protected sandy filters were used for treatment of surface water before storage (Angelakis & Koutsoyiannis 2003). Such facilities are found in Phaistos, where the water supply of the palace was dependent on rainwater harvesting (Figure 9(a)). Also, Defner (1921) describes clay-made oblong structures (hydraulic filters) with small holes in one end, possibly used as small filters at the outputs of the water from the water reservoirs (cisterns) (Figure 9(b)). In such a filter, the turbulent water flow created relatively small pressures in the external perforated walls due to the high flow rate. Thus, the outflow released suspended and maybe some dissolved solids. In addition to the terracotta filters, in some cases cisterns were associated with small canals collecting water from rainfall and from mountain streams (Viollet 2003, 2007).

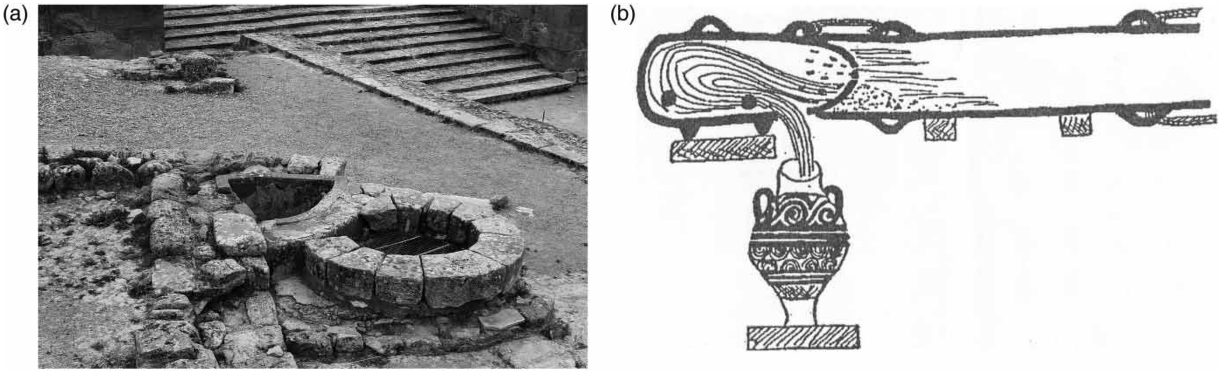

Figure 9 | Minoan water treatment system: (a) sand filter next to a water storage cistern in the palace of Phaistos and (b) water filter (Spanakis 1981).

SEWERAGE AND DRAINAGE SYSTEMS

One of the salient characteristics of Minoan civilization was the architecture and operation of the hydraulic drainage and sewerage systems in palaces and other settlements (De Feo *et al.* 2014). Of the total infrastructure of the Minoan palace at Knossos nothing was more remarkable than the complex but very functional sewers and drains, passing through the municipal facilities of the palace and its neighboring districts. Evans (1921–35) and MacDonald & Driessen (1988) described these hydraulic structures and proposed their original form, with particular reference to their architecture and performance. This plan provides the visitor with a basic orientation of the site and helps for a full understanding of the whole network. The total length of the sewerage and drainage system, including the central and secondary conduits beneath the domestic quarter, exceeds 150 m (Angelakis *et al.* 2005).

In a part of the central Government house of the palace of Minos, rainwater in large capacity was collected in underground stone-made drains, which passed down the corridor that led to the north entrance (Angelakis *et al.* 2014). Sewage was also collected in the same drains. Gutters collected water from the roofs of buildings and probably sent it to the toilets of the last floor. Generally, drains and sewers were built of dressed stones and were large enough to make them possible to clean and maintain (Angelakis 2016b). The central drainage and sewerage system of the palace of Phaistos is similar to that of Knossos (Figure 10(a)).

The most advanced ancient Minoan drainage system seems to be that in the villa of Hagia Triada (Figure 10(b)). This system was admired by several visitors, including the Italian writer Mosso (1907), who visited the area in the early 20th century. During heavy rain, he noticed that the pipes functioned perfectly and he recorded the incident saying: ‘I doubt if there is another case of a stormwater drainage system that works 4000 years after its construction.’ Also, the American Gray (1940), said: ‘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 functioned for centuries, unlike today, when if a project operates well for 40–50 years it is considered satisfactory (Koutsoyiannis *et al.* 2008).

BATHS AND OTHER PURGATORY INFRASTRUCTURE

In Minoan palaces, drainage in the baths was not necessary, but useful. Evans (1921–35) recognized the existence of three such baths in Knossos palace.

The basic type of Minoan bathroom is that found next to the dining room of the Queen. This type of bath is basically similar to those found in Phaistos and Malia (Figure 11(a)). However, in Knossos palace its floor was not at the lower level. Portions of clay pipes were found just outside the room’s door. Obviously water was passed through a small canal on the floor, outside the door of the bathroom. The toilet could be purified even during the dry summer, by somebody else or by the user himself. In Knossos there was a second bathroom with toilet on the upper floor, just

Figure 10 | Minoan sewerage and drainage systems: (a) the output of the central system of the Phaistos palace and (b) part of the central system of the villa Hagia Triada.

above the room of the stone throne in the southwest corner of the palace.

Toilets, similar to those of Knossos, were found in Phaistos, in Malia, and in other settlements (Graham 1987). A house in the area of the palace of Malia (Figure 11(b)) has a toilet seat in almost perfect condition, built of solid stone, as in the palace of Knossos. This stone seat had dimensions of 68.60–45.70 cm width and 35–38 cm height (Graham 1987). It was built opposite an exterior wall, through which passes a spacious drain. It is evident that its use was for seating and not for support, more like the Egyptian toilets than those of 'Turkish type' (Antoniou & Angelakis 2015), found in the

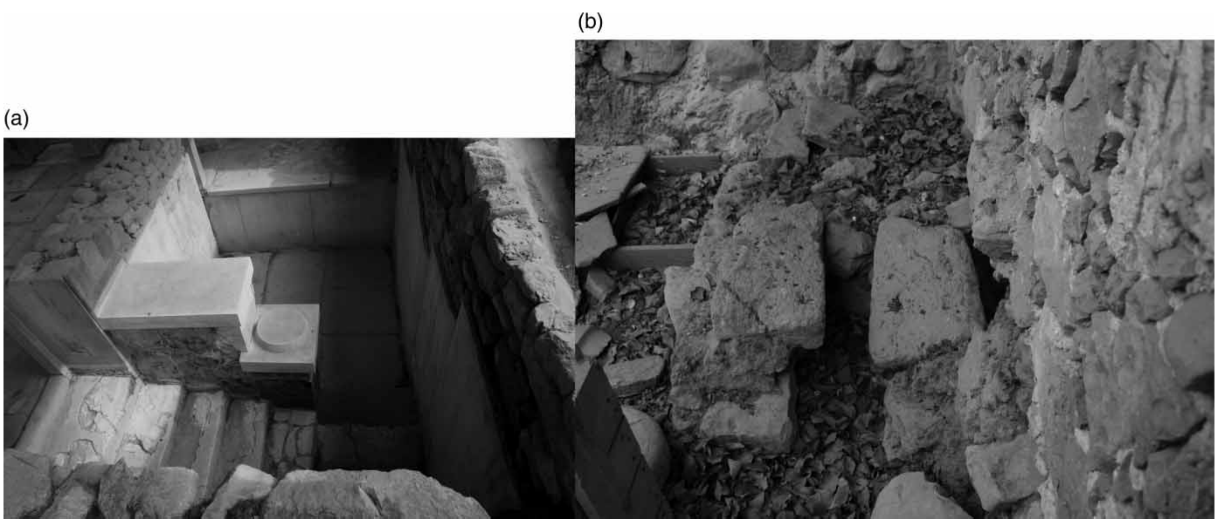

Figure 11 | (a) Royal bath in the palace of Phaistos and (b) Minoan toilet in the house known as Da in the palace at Malia.

palace of Mari on the Euphrates. A similar toilet was discovered on the west side of the so-called Department of the Queen in Phaistos palace, connected with a small drain, part of which still survives, and another in house C, in Tylissos.

A room of interest was identified by Evans (1921–35) as a toilet with a wooden seat. As with today's toilets, it had a flushing/washing system. The flushing and outflow tube from the outer entrance crossed along the toilet, passing under the seat and ended at the outside sewer (Castleden 1993). In the palace of Minos and probably in other Minoan settlements, sewers and toilets more likely were cleaned thoroughly for some days of the year, with rainwater that was collected in tanks.

IRRIGATION AND DRAINAGE OF AGRICULTURAL LANDS

In Minoan Crete agricultural development was necessary to support the population explosion. At that time population growth, combined with economic, technological and cultural development, contributed to increasing agricultural productivity (Koutsoyiannis & Angelakis 2003). In the Neopalatial period (*ca.* 1700–1450 BC), the practice of irrigation was very important. Thus, irrigation and drainage of agricultural lands seem to have developed at that time.

On Lassithi Plateau there exists a very famous drainage system called Linia (from the word *linea* = straight line), which was in use from Venetian times, with numerous drainage canals and irrigation ditches intersecting and creating a remarkable network (Figure 12). It is probable that its roots come from the Minoan Era since the Lassithi Plateau has been irrigated since that time (Angelakis & Spyridakis 1996a). This technique is considered to have subsequently been transferred by Minyes to central Greece (Angelakis & Spyridakis 1996a). Generally, it seems that irrigation and drainage technologies were also practiced during the Mycenaean period with even greater pace and contributed to further economic progress and of course the creation of the basis of Classical civilization (Koutsoyiannis & Angelakis 2004).

Finally, in the valley of Choiromandres in eastern Crete, there are strong indications of irrigation (Figure 8(a)). Downstream of the dam, walls were constructed parallel or perpendicular to the bed, in order to achieve containment and proper channeling of water flow (Tsatsanifos 2015). At the lower end of the stream there was a permeable barrier through which irrigation water was controlled in the downstream terraces.

Figure 12 | Drainage channels on the Lassithi plateau.

REUSE OF MUNICIPAL WASTEWATER

The outputs of sewer systems in palaces and towns, like Knossos, Phaistos and Malia seem to be similar. Wastewater and rainwater were discharged in existing rivers (streams or creeks) or in the sea, as in Knossos and Zakros palaces, respectively. In the palace of Phaistos, raw collection facilities instead diverted the sewage and stormwater to the farmland. Similarly, in the villa of Hagia Triada sewage and rainwater were collected in a typical rectangular storage cistern (dimensions $1.6 \times 2.0 \times 6.0\ m^3$) from where it was possibly used for washing or other household uses or irrigation. Such collection techniques have been found in other towns and palaces of Minoan Crete (Angelakis & Spyridakis 1996b). Crete and especially the eastern regions are under low water availability and several periods of the Minoan Era seemed to be characterized by severe water shortages (Markonis *et al.* 2016). Accordingly, the reuse of water was a necessary practice. Thus, it appears that bath water could be reused for irrigation of gardens and farmlands (Antoniou & Angelakis 2015). Also Tzanakakis *et al.* (2014) propose that Minoans should be considered as pioneers in the recycling and reuse of water.

WATER FOR RECREATION AND ENVIRONMENTAL USE

The first indications of the use of water for recreation are reported for the Minoan Era. The hydraulic engineers seem to have had enough knowledge and had developed water use technologies even for recreation and environmental improvements. Various findings suggest the existence in the palaces of 'jet d'eau' (jets or jet of water), fish farms, aquaria and other related facilities. The first serious indication in ancient Greece of water use for recreation is one type of 'jet d'eau' discovered in the House of Frescoes at Knossos palace (Figure 13(a)), found in the Archaeological Museum of Iraklion (Angelakis & Spyridakis 1996a).

Another indication of such water use is the underground cistern, with a diameter of 7 m, which was discovered in the central part along the so-called royal apartments of the palace of Zakros (Figure 13(b)). The room is called Tank Room (Platon 1974). For the use of this pool several theories and opinions have been reported, such as use for swimming, as an aquarium, and for religious ceremonies (Alexiou 1964). Today, it is believed that this pool had multiple uses, including recreational (Angelakis & Spyridakis 2010).

CONCLUSIONS

It should be noticed that Minoans lived in harmony with nature and their environment; others that did not, failed. 'The multicolored wall-paintings in Minoan Palaces depict a life full of creativity, good taste and in complete harmony with the natural environment' (Evans 1921–35). Local water supply sources were first used by the ancient Cretans of the Minoan Era. When these were exhausted, local and temporary transfers were instituted and the necessary hydraulic structures built such as water cisterns (Angelakis 2016a).

Archaeological and other evidence suggests that mainly during the Middle Minoan period a cultural explosion, unprecedented in the history of ancient civilizations, occurred in Crete. This is demonstrated by the advanced techniques applied to water, wastewater, and stormwater management. These techniques include various disciplines of water resources, water networks, especially those in urban areas, recovery and use of surface resources, construction of baths and other sanitary and purification structures, drainage and disposal of wastewater and rainwater systems, rehabilitation projects and farmland irrigation and drainage and finally water use for recreation (Angelakis 2015a).

One of the most prominent features of the Minoan civilization was the hydraulic architecture, the construction and operation of water supply systems and those for collection and disposal of waste and rain waters in the palaces and towns. In most Minoan palaces and towns nothing was more remarkable than the complex and highly functional water supply, drainage and sewerage systems. Moreover, the use of wastewater for irrigation of agricultural lands is also indicated. The design philosophy of Minoan hydro-technologies has to be further considered in light of its success.

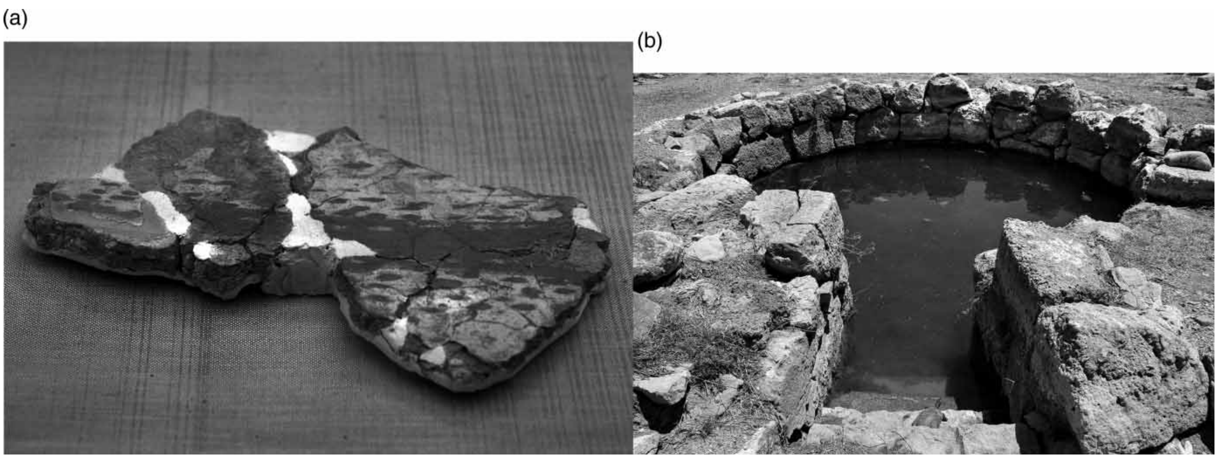

Figure 13 | Projects used for recreation water: (a) fresco representing a type of diffuser at Knossos (from the Archaeological Museum of Iraklion, Greece) and (b) circular tank in a central square of the palace of Zakros.

Thus, the development of effective water supply management projects in short–water areas should also include historical knowledge. This rich inheritance of Minoan hydraulic works should not be restricted only to its cultural value, but also, and more importantly, be viewed as an example for sustainable water hydro-technologies (Markonis *et al.* 2016).

From these and other reports on technologies related to water resources and wastewater in the Minoan Era, we can conclude the following:

(a) The Minoans lived in harmony with the environment.
(b) No fundamental differences are noticed in the design and construction of water projects since then. The main differences concern the scale, and the available equipment.
(c) In many cases, these constructions operated efficiently for millennia.
(d) There was integrated management of water resources, with provision for matching demand and supply and possible future increased needs.
(e) Looking back to the long past of human habitation on the island, one can clearly outline some principles on which past water hydro-technologies were based; notably they are the very same that are used in many applications of the present.

RECOMMENDATIONS

Research priorities based on past hydro-technologies that have the potential to advance the sustainable management of water resources should be identified. To put in perspective the ancient water management principles and practices discussed in this paper, it is important to investigate Minoan hydro-technologies in terms of the following:

(a) Evolution. An important question to be considered is whether all Minoan technologies were entirely developed by the Minoans or whether some of them existed during Neolithic times. The same holds for the technologies later on used in Archaic and Classical Greece. We cannot be sure whether or not the Minoans' knowledge of water resources survived after the collapse of Minoan civilization about 1100 BC (Angelakis *et al.* 2013).
(b) Technological advances. To some extent, the differences between Minoan and modern hydro-technologies are mostly found in the apparatus and the scale of applications with practically no differences in the fundamental principles used. For example, flushing toilets equipped with seats resembling present-day toilets and drained by sewers existed from Minoan times.
(c) Design and construction principles. Naturally, it is difficult to estimate the design and construction principles of Minoan 'engineers' but it is notable that several ancient works have operated for very long periods, some until recent times. For example, waste- and stormwater drainage systems functioned for millennia. On the other hand, engineers in our times typically design constructions to function for about 40 to 50 years, as dictated by economic considerations. Thus, the sustainability and durability of Minoan water technologies should be further studied.
(d) Today's applicability. Minoan hydro-technologies could be updated by considering today's apparatus and knowledge and looking for possible applicability particularly in regions under water shortage.

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REFERENCES

Alexiou, S. 1964 *Minoan Civilization*. Sons of S. Alexiou, Iraklion, Greece (in Hellenic).
Angelakis, A. N. 2013 Evolution of rainwater harvesting and use in Crete, Hellas through the millennia. In: *13th International Conference on Environmental Science and Technology (CEST2013)*, 5–7 September 2013, Athens, Hellas, paper no. 0202.
Angelakis, A. N. 2015a Hydrological and hydraulic technologies in Minoan Era. In: *Common Conference of HHA, HWA, and*

HCoMWR, 10–12 December 2012, Athens, Greece, II: pp. 599–612 (in Hellenic).

Angelakis, A. N. 2015b The history of fountains and relevant structures in Crete, Hellas. *Journal for Global Environmental Issues* **14** (3/4), 200–215. DOI: http://dx.doi.org/10.1504/IJGENVI.2015.071865.

Angelakis, A. N. 2016a Evolution of rainwater harvesting and use in Crete, Hellas through the millennia. *Water Sci. and Techn.: Water Supply* **16** (5). DOI:10.2166/ws.2016.084.

Angelakis, A. N. 2016b Evolution of urban waste- and storm-water management through the centuries focusing on Hellenic civilizations. In: *13th IWA Specialized Conference on Small Water and Wastewater Systems (SWWS) and the 5th IWA Specialized Conference on Resources-Oriented Sanitation (ROS)*, 14–16 September 2016, Athens, Greece. http://swws2016.gr/proceedings/proceedings.html.

Angelakis, A. N. & Koutsoyiannis, D. 2003 Urban water resources management in ancient Greek times. In: *The Encyclopedia of Water Science* (B. A. Stewart & T. Howell, eds). Markel Dekker Inc., CRC Press, Madison Ave., New York, NY, USA, pp. 999–1007.

Angelakis, A. N. & Spyridakis, S. V. 1996a The status of water resources in Minoan times: a preliminary study. In: *Diachronic Climatic Impacts on Water Resources with Emphasis on Mediterranean Region* (A. N. Angelakis & A. S. Issar, eds). Springer-Verlag, Heidelberg, Germany, Ch. 8, pp. 161–191.

Angelakis, A. N. & Spyridakis, S. V. 1996b Wastewater management in Minoan times. In: *Proc. of the Meeting on Protection and Restoration of Environment*, 28–30 August, Chania, Hellas, pp. 549–558.

Angelakis, A. N. & Spyridakis, D. S. 2010 A brief history of water supply and wastewater management in ancient Greece. *Water Sci. and Techn.: Water Supply* **10** (4), 618–628.

Angelakis, A. N. & Spyridakis, S. V. 2013 Major urban water and wastewater systems in Minoan Crete, Greece. *Water Sci. and Techn.: Water Supply* **13** (3), 564–573.

Angelakis, A. N. & Voudouris, K. 2014 Evolution of geohydrology through the centuries with emphasis on the Hellenic civilizations. In: *Proc. of the 10th Hydrogeology Conference*, 8–10 October 2014, Thessaloniki, Hellas, pp. 71–96.

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

Angelakis, A. N., Savvakis, Y. M. & Charalampakis, G. 2007 Aqueducts during the Minoan Era. *Water Sci. and Techn.: Water Supply* **7** (1), 95–101.

Angelakis, A. N., Koutsoyiannis, D. & Papanikolaou, P. 2012 On the geometry of the Minoan water conduits. In: *Proc. of the 3rd IWA International Symposium on Water and Wastewater Technologies in Ancient Civilizations*, 22–25 March 2012, Istanbul, Turkey, pp. 172–177.

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

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

Angelakis, A. N., Voudouris, K. & Mariolakos, I. 2016 Groundwater utilization through the centuries focusing on the Hellenic civilizations. *Hydrogeology Journal* **24**, 1311–1324. DOI 10.1007/s10040-016-1392-0.

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

Antoniou, G., Kathijotes, N., Angelakis, A. N. & Spyridakis, D. S. 2014 Historical development of technologies on water resources management and rainwater harvesting in the Hellenic civilizations. *Inter. Journal of Water Resources Development* **14** (8), 1–14.

Betancourt, P. P. 2012 *The Dams and Water Management Systems of Minoan Pseira*. INSTAP Academic Press, Philadelphia, PA, USA.

Cadogan, G. 1977–78 Pyrgos, Crete, 1970–7. *Archaeological Reports* **24**, 70–84.

Cadogan, G. 2007 Water management in Minoan Crete, Greece: the two cisterns of one Middle Bronze Age settlement. *Water Sci. and Techn.: Water Supply* **7** (1), 103–111.

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

Decentralized Region of Crete 2015 *River Basin Management Plan for Water Region of Crete, Hellas (ΦΕΚ Β'570/2015)*. Iraklion, Greece (in Greek).

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

De Feo, G., Angelakis, A. N., Antoniou, G. P., El-Gohary, F., Haut, B., Passchier, C. W. & Zheng, X. Y. 2013 Historical and technical notes on aqueducts from prehistoric to medieval times. *Water* **5** (4), 1996–2025.

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

Defner, M. 1921 *Διϋλιστήριο Υστερομινωϊκής Εποχής. Αρχαιολογική Εφημερίδα* 78, Iraklion, Greece (in Hellenic).

Evans, S. A. 1921–35 *The Palace of Minos at Knossos: A Comparative Account of the Successive Stages of the Early Cretan Civilization as Illustrated by the Discoveries*. Macmillan and Co., London, 1921–35, vols I–IV. Reprinted by Biblo and Tannen, New York, NY, USA.

Floods, J. 2012 *Water Management in Neopalatial Crete and the Development of the Mediterranean Climate*. MA Thesis, Faculty of the Graduate School at the University of North Carolina, Greensboro, NC, USA.

Gorokhovich, Y., Mays, L. W. & Ullmann, L. A. 2012 Survey of ancient Minoan water technologies. *Water Sci. and Techn.: Water Supply* **114**, 388–399.

Graham, J. W. 1987 *The Palaces of Crete*. Revised edn. Princeton University Press, Princeton, NJ, USA.

Gray, H. F. 1940 Sewerage in ancient and medieval times. *Sewage Works Journal* **12** (5), 939–946.

Hellenic Central Water Agency 2008 *Water Framework Directive (2000/60/EC). Article 5: The Characterization and Analysis of the Greek River Basin Districts*. Hellenic Ministry for the Environment, Energy, and Climate Change, Athens, Greece (in Hellenic).

Hellenic Central Water Agency 2013 *Preliminary Plan of Water Resources Management of the Water Region of Crete*. Ministry of Environment, Energy and Climate Change, Athens, Greece (in Hellenic).

Hellenic Statistical Authority 2011 *Census of Population in 2011*. Hellenic Statistical Authority, Athens, Hellas (Hellenic).

Hirschfeld, E. 2013 Minoan Cretan thalassocracy. In: *Periplus* (A. Muge & M. Loucanicas, eds). https://peripluscd.wordpress.com/tag/minoan-art/.

Koutsoyiannis, D. & Angelakis, A. N. 2003 Hydrologic and hydraulic sciences and technologies in Ancient Greek times. In: *The Encyclopedia of Water Science* (B. A. Stewart & T. Howell, eds). Taylor & Francis, New York, NY, USA, pp. 415–417.

Koutsoyiannis, D. & Angelakis, A. N. 2004 Agricultural hydraulic works in Ancient Greece. In: *The Encyclopedia of Water Science* (B. A. Stewart & T. Howell, eds). Taylor & Francis Group, New York, NY, USA, pp. 1–4.

Koutsoyiannis, D. & Patrikiou, A. 2013 Water control in Ancient Greek cities. In: *Water and Urbanization* (T. Ostigard, ed.). National Technical University of Athens, Athens, Greece, pp. 130–148.

Koutsoyiannis, D., Zarkadoulas, N., Angelakis, A. N. & Tchobanoglous, G. 2008 Urban water management in ancient Greece: legacies and lessons. *Journal of Water Resources Planning & Manag.* **134** (1), 45–54.

MacDonald, C. F. & Driessen, J. M. 1988 The drainage system of the domestic quarter in the palace at Knossos. *Annual of the British School of Athens* **83**, 235–258.

Markonis, Y. 2016 *Stochastic Investigation of Large-Scale Hydroclimatic Correlations Over the Mediterranean*. PhD Thesis, National Technical University of Athens, Athens, Greece (in Hellenic).

Markonis, Y., Angelakis, A. N., Christy, J. & Koutsoyiannis, D. 2016 Climatic variability and the evolution of water technologies in Crete, Hellas. *Water History* **8** (2), 137–157. DOI:10.1007/s12685-016-0159-9.

Mays, L. W., Koutsoyiannis, D. & Angelakis, A. N. 2007 A brief history of urban water supply in antiquity. *Water Sci. and Techn.: Water Supply* **7** (1), 1–12.

Mays, L., Antoniou, G. P. & Angelakis, A. N. 2013 History of water cisterns: legacies and lessons. *Water* **5** (4), 1916–1940.

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

Nikolaou, T. G., Christodoulakos, I., Piperidis, P. G. & Angelakis, A. N. 2016 Evolution of Cretan aqueducts and their potential for hydroelectric exploitation. *Water* **9** (1), article 31.

Pendlebury, J. D. S. 1965 *The Archeology of Crete: An Introduction*. The Norton Library, New York, USA.

Platon, N. 1974 *Zakros, The New Minoan Palace*. The Athens Archaeological Society, Athens, Hellas.

Platon, M. 1990 New indications for the problems of purgatory cisterns and bathrooms in Minoan World. In: *Proceedings of the 6th International Cretologic Congress*. Literary Association Chrysostomos, Chania, Greece, A2, pp. 141–155 (in Hellenic).

Spanakis, S. 1981 *The Water Supply of Iraklion, 828–1939*. The Technical Chamber of Hellas, Iraklion, Greece (in Greek).

Tsatsanifos, Ch. 2015 Ancient Greek dams. In: *Common Conference of HHA, HWA, and HCoMWR*, 10–12 December 2015, Athens, II, pp. 997–1004 (in Hellenic).

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

Viollet, P.-L. 2003 The predecessors of European hydraulic engineers: Minoans of Crete and Mycenaeans of Greece (2100–1200 BC). In: *XXX IAHR Congress, Theme E: Linkage between Education Research and Professional Development in Water Engineering*, August 2003, Thessaloniki, Hellas.

Viollet, P.-L. 2007 *Water Engineering in Ancient Civilizations: 5000 Years of History*. Int. Assoc. of Hydraulic Research (IAHR). Originally in French, *L'Hydraulique dans les Civilisations Anciennes*. Taylor & Francis. Translated into English by Forrest M. Holly, Jr. IAHR, Madrid, Spain.

Vokotopoulos, L., Plath, G. & McCoy, F. W. 2014 The yield of the land: soil conservation and the exploitation of arable land at Choiromandres, Zakros in the New Palace Period. In: *Physis. L'environnement naturel et la relation home-milieu dans le monde égéen protohistorique* (G. Touchais, R. Laffineur & F. Rougemont, eds). Actes de la 14e Rencontre égéenne internationale, Paris, Institut National d'Histoire de l'Art (INHA), 11–14 December 2012, Aegaeum 37, Liège, Belgium, pp. 251–262.

Yannopoulos, S. I., Lyberatos, G., Theodossiou, N., Li, W., Valipour, M., Tamburrino, A. & Angelakis, A. N. 2015 Evolution of water lifting devices (pumps) through the centuries worldwide. *Water* **7**, 5031–5060.

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