Climatic Variability and the Evolution of Water Technologies in Crete, Hellas

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Abstract

The Greek island of Crete is one of the southernmost regions of Europe with a long and rich history, which begins as early as *ca*. 3,200 BC with the onset of the Minoan civilization. The archeological findings of well-designed water supply and sewerage systems in the Minoan Palaces and other settlements, with impressive architecture and high-level functionality, suggest a good degree of understanding of the basic water management techniques well before the scientific achievements of our times. Here we document characteristic examples of the ancient hydraulic works and the related hydro-technologies throughout the history of Crete. We summarize the pressures on the water resources in Crete in connection with climatic variability and investigate how and what could be learned from the past using recent findings and paleoclimatology. The reconstructions of the Eastern Mediterranean and more specifically of the Cretan climate using different proxy data (e.g. sediment, pollen, and historical archives) demonstrate a series of alternating periods with varying climatic characteristics with fluctuation lengths spanning from a few decades to many centuries. The synthesis of the on-going research on past climate offers the opportunity to create a picture of the Cretan climatic regime for the last 10,000 years, which could be useful to both hydrologists and archeologists. As the past is the key to the future, the information provided could help in developing modern integrated and sustainable water management plans.

Keywords:

Climatic variability; climatic reconstruction; Crete; hydraulic technologies; wastewater management; water management.

1. INTRODUCTION

During the last few years societies have been increasingly concerned about the possible effects of climatic variability on human prosperity. The simplest way to analyze this complicated relationship is to quantify climatic variability by examining the climate of the past and then studying its impact on human societies. The Mediterranean basin is one of the most appropriate regions for such analysis because (a) it has been the cradle for some of the oldest human civilizations with continuous occupation till today (Finné *et al.*, 2011), and (b) it demonstrates a rich history of climatic variability during the Holocene, with different periods composed by quasi-cyclical patterns and extreme events (Angelakis and Spyridakis, 1996).

One possible way to link the effect of climatic shifts to human development is through the relationship between climate and water resources, as the former influenced agricultural and animal husbandry. In this context, the evolution of water and wastewater management technologies played an important role in the overall advancement, or even survival, of the human societies. Moreover, the study of ancient, historical or even recent hydraulic technologies can be also used as an indirect indicator of past climatic regimes, as it appears to be highly affected by climatic variability. The island of Crete, with its isolated position at the Mediterranean Sea and its abundant archeological and historical evidence, in conjunction to the fact that water resources were never in abundance in the Cretan cites of significant cultural development, constitutes a promising candidate for exploring the relationship between climate and water management.

The island of Crete was the center of Europe's first advanced civilization, the Minoan (Mays *et al*., 2007). The earliest human settlements on the island date back to the ceramic Neolithic period (*ca*. 6,400 BC). Ancient Knossos was one of these major Neolithic (then later Minoan) sites. The Minoan civilization reached its peak during the Bronze Age (*ca*. 3,500–1,400 BC), when several localities on the island grew to cities which further developed into centers of commerce and craftsmanship. Soon its cultural influence and trade relationships extended beyond the borders of the Cretan island reaching destinations as far as Cyprus, Egypt and Anatolia. The Cretans were well-known for their navy which dominated the Aegean Sea, their artistic pottery, and their luxurious palaces and villas.

Although, earlier nearby civilizations were born and flourished in environments where water was abundant, such as large river valleys (e.g. the Egyptian civilization in the Nile valley or the Sumerian in the Tigris-Euphrates river system), the Minoan civilization was different in this respect. As paradoxical it may seem, the majority of the ancient Cretan settlements were established in dry, water-scarce sites with minimal rainfall and not near the small-scale rivers and lakes that did exist on the Cretan island. A possible explanation for this choice could have been that it was based on climatic criteria that affect health: dry climates are generally healthier, e.g. they reduce spread of water–borne diseases. Water scarcity forced the inhabitants of the first Cretan cities, to invent and develop necessary technologies in order to transfer and store water, and at the same time to maintain high hygienic living standards (Angelakis and Spyridakis, 1996; Angelakis and Spyridakis, 2010; Koutsoyiannis *et al.*, 2008; Antoniou and Angelakis, 2015, and others). The progress in urban water supply was even more noteworthy, as witnessed by several aqueducts, cisterns, wells, and other water facilities discovered, including the famous Minoan aqueducts of Knossos and Tylissos, the cisterns of Zakros, Archanes, Myrtos–Pyrgos and Tylissos, the wells of Paleokastro, Zakros, and Itanos (e.g., Koutsoyiannis *et al*., 2008).

Until the end of the Minoan period the technological infrastructures and management solutions were gradually transferred in mainland Greece and to other Aegean islands. During the Classical and Hellenistic periods, they spread from Greece southward to the Arabic world and probably eastward to Persia and India. The next technological steps were taken first by the succeeding Roman Empire, which changed the scale of their application, and afterwards by the Byzantine Empire which further improved urban water management. The Byzantine and the Venetian periods constitute the underpinning of modern achievements in water engineering and management practices (Angelakis and Spyridakis, 2010).

2. CLIMATE AND WATER IN CRETE

2.1 Physical Setting, present day climate and water availability

Crete is a mountainous island located at the eastern Mediterranean, in the southern part of the Aegean Sea (Figure 1). Due to its position between Asia, Africa and Europe it held a strategic location, as it forms a natural and vital bridge between the three continents. This unique geographical position determined its historical course throughout both antiquity and modern times.

The climate of present day Crete is primarily temperate (Figure 2). The island lies between the Mediterranean and the North African climatic zone. The northern part of the island is generally more humid than the southern, and the two parts are separated by a central mountainous region, where snowfall is common in the winter. In the lowlands the winters are milder, while during the summer temperature averages at 30°C, with maxima reaching 40°C. The average and maximum temperatures are higher throughout the year at the south coast of Crete, a region where climate, vegetation and landscape resemble those of Mediterranean Africa.

The precipitation in Crete falls mainly from frontal systems, linked to the interaction of contrasting air masses in eastward moving depressions, and orography due to the existence of three main mountainous formations (Grove and Contario, 1995). Therefore, it exhibits intense spatial and temporal variation; it decreases from west to east and from north to south (Voudouris *et al.*, 2006), while it also increases with altitude. In particular, the average precipitation ranges from 440 mm/yr on the plain of Ierapetra (southeastern Crete) to 2000 mm/yr in the Askifou uplands (northwestern Crete). The mean annual precipitation in eastern Crete measures 815 mm/yr while in western Crete it measures 1050 mm/yr (Decentralized Region of Crete, 2015). Moreover, as can be seen in Figure 2, annual precipitation is divided into a wet and a dry season; the first one lasting from October to March, and the second one from April to September (Angelakis *et al.*, 2012). Approximately 90% of the annual precipitation falls during the wet season, with daily maxima reaching 110 mm in Iraklion (northeastern Crete), 170 mm in Chania (northwestern Crete) and much more in mountainous areas.

Further analysis, based on the available data (Hellenic National Meteorological Service and Platakis, 1964) from the meteorological stations at Iraklion and Sitia located in the northeastern part of the island and Chania (Souda airport) in the northwestern part, showed a small raise in temperature and a slight decline in rainfall. The rise in temperature began in the 1990s after a steady decline, which has been confirmed also by Metaxas (1992) for a longer time series (estimating a drop of 1°C since 1920), and was consistent with the overall cooling observed in the Eastern Mediterranean (Jones and Briffa, 1992).

Within–year daily variability of temperature has remained constant during the last 60 years. In northwestern Crete (Chania) the standard deviation of daily average temperature within a year is approximately 6°C and is slightly lower (5.5°C) further east (Iraklion). Daily maximum and minimum temperature values remain steady as well, with a slight increase in winter minima. In general terms, the precipitation regime demonstrates seasonal stability as well, as there has not been any serious disturbance in the wet/dry season pattern (Figure 3). However episodes of extreme rainfall (purple line in Figure 3) seem to have become scarcer and less intense during the last 25 years, but this could be related to the 1987–99 dry period, because extreme daily precipitation maxima tend to occur during wet periods.

In Mediterranean areas, sustainable water resources management is a major issue, given the semi–arid climate, the variability of hydrological characteristics and the fragile socio–economic conditions (Ganoulis, 2006). Water resources in Crete are characterized by high water requirements for agricultural and tourism during the dry season, when water availability is low. Groundwater is the major source of water in Crete, covering more than 95% of water uses both for domestic and irrigation needs, with the latter being 84.5% of the total (Chartzoulakis *et al.*, 2001). The increase of water demand for irrigation purposes during the last decades is also evident by the increase in the number of boreholes. Moreover, by the 1990s many phreatic aquifers showed signs of depletion and many deep boreholes were opened. As a result, a growing number of the island's coastal aquifer systems are reported to be affected by quality deterioration (salinization and nitrate pollution) due to unsustainable water management practices (Lambrakis, 1998).

2.2 Long–term Climatic Variability

The best source of data for the Cretan climate evolution for the period 10,000 – 2,000 years BC are three paleoceanographic reconstructions of temperature and precipitation presented in Table 1 (Rohling *et al.*, 2002; Geraga *et al.*, 2005; and Triantafyllou *et al.*, 2009). The three records have different time resolutions; the Triantafyllou reconstruction (Tr09) has the highest resolution, followed by Rohling (Ro02) and Geraga (Ge05), and therefore Tr09 can be used more efficiently in order to depict climatic variability.

After the termination of the last glacial epoch, 14,000 years ago, the cold and dry climatic conditions that prevailed in the region (Peyron *et al.*, 1998) were succeeded by an extremely wet period that started at approximately 8,000 BC and ended near 4,500 BC. Moreover, in his pioneering study Bottema (1980) showed that the vegetation in Southern Crete was dominated by oak and pine species, suggesting more humid conditions than present day. This was also in good agreement with the northern Aegean salinity levels (Kotthoff *et al.*, 2008), with the level fluctuations of the lakes Ioannina, Kastoria, Vegoritis and Chimaditislakes in northern continental Greece (Bottema, 1974) and with vegetation changes in western Taurus mountains in south–western Turkey (Bakker *et al*. 2011).

During this warm and wet period, though, an event of abrupt cooling and aridity occurred at the end of the early Holocene in a considerable area of Northern Hemisphere, commonly known as the "8,200-event" (*ca.* 6,200 BC). The drop in temperature reached 6°C in Greenland, while there is also archeological evidence of its impact in the Neolithic settlements in Greece, Adriatic, Sardinia, Southern Italy and Cyprus (Berger and Guillaine, 2009; Weninger *et al.*, 2006; both from Mercuri *et al.*, 2011). This abrupt change was also evident in all three reconstructions in Crete, suggesting that it was a climatic event that affected a large proportion of the Northern hemisphere.

The climatic conditions that prevailed during the period between 4,500 and 3,500 years BC, are rather unclear as there are conflicting results in the scientific literature (Finné *et al.*, 2011 and references therein), which are also reflected in the three proxy-records; two of the time series (Tr09 and Ge05) depict high temperatures, while on the other hand the Ro02 record presents colder water temperatures. Interestingly, this period is considered by archeologists as a time of widespread rapid climate changes that triggered social change in the south–eastern European communities and led to the collapse of the Chalcolithic Age (Weninger *et al*., 2009).

Several observations document moist conditions for the next millennium (3,500 to 2,500 BC), which coincide with the onset of Minoan civilization approximately at 3,200 BC (Angelakis and Spyridakis, 1996; Finné *et al*., 2011 and references therein). This is also supported by a number of studies to nearby locations (Asouti, 2003; Benito, 2003; Migowski *et al*., 2006; Pavlopoulos *et al*., 2006; Hamann *et al*., 2008; Macklin *et al*., 2010; Bar-Matthews and Ayalon, 2011). After this period, a mild aridification of the region is observed (Bar-Matthews *et al*., 1999; vonRad *et al*. 1999; Wick *et al*. 2003; Finné, *et al*., 2011 and references therein).

The pattern of alternating periods of humid and dry periods continued during the Iron Age (*ca*. 1300–600 BC) with another cold and humid period. Following this, during the classical and Hellenistic times (*ca*. 600 – 67 BC), the climate was rather warm and dry. It then returned to colder and moister conditions during the Roman period (*ca*. 67 BC–330 AD) and thereafter (Shilman *et al.*, 2001; Angelakis *et al.*, 2005). In addition, the period of 1350–900 BC, was characterized by rather unstable conditions in Aegean Sea, a time of increase in frequency of floods and droughts and the disruption of cropping cycles (Moody, 2005).

During the Arab period a warm and dry climate prevailed and reached a peak of high temperatures and drought at *ca.* 800AD (Angelakis *et al*., 2005). In the same period, there is large amount of historical references in extensive episodes of drought in the eastern Byzantium (Telelis, 2004), which is supported by paleoclimatic data (Butzer, 1957; and Lamb 1977; from Telelis, 2004) and the limited flood activity of Anapodaris River (Macklin *et al*., 2010). A recent proxy record from the Middle East shows a large drop in precipitation in the time period 100–700 AD (Orland *et al*., 2009), while two other sediment records coming from northern Aegean Sea indicate a dry phase around 300 AD (Kuhnt *et al*., 2008) or 600 AD (Ehrmann *et al.*, 2007), respectively.

In the Medieval Warm Period (MWP; *ca*. 900 – 1300 AD), when hot and dry conditions emerged across northern and central Europe, the climate was quite different in the eastern Mediterranean, where temperatures dropped, harsh winters became more frequent, and precipitation increased, although some extremely dry intervals had been observed (Telelis, 2004; Baker *et al*., 2011; Finné *et al*., 2011). This period of humid conditions is also evident in various locations at the eastern Mediterranean Sea at 1100–1400 yrs AD (Schilman *et al*., 2002); such as the Dead Sea (Enzel *et al*., 2003); the lakes Nar (Jones *et al*., 2006) and Van (Wick *et al*., 2003) at Turkey; coastal Syria (Kaniewski *et al*., 2011) and southern Jordan (Hunt *et al*., 2007).

The Little Ice Age (LIA; *ca*. 1500 – 1850 AD), which followed the MWP, was characterized by the expansion of glaciers globally, having the same impact in Crete and eastern Mediterranean as well (Baker *et al*., 2011; Finné, *et al*., 2011). According to Grove and Conterio's work (1995) based on historical, documentary sources, there was a certain increase in the number of the severe winters between 1547 and 1645. However, the precipitation levels dropped and dry conditions prevailed, as presented in Greek historical documents (Repapis *et al*., 1996); in marine and lake sediments in the Middle East (Issar, 1990; Schilman *et al*., 2002; Enzel*et al*., 2003); and in the Soreq cave record (Bar-Matthews and Ayalon, 2011).

If we sum up all the above sources we can create an overall picture of the climatic fluctations in the eastern Mediterranean and more specifically in Crete during the last 10 thousand years (Figure 4). This reconstruction demonstrates the succession of warm/cold or moist/dry periods, which lasted from a few centuries to some millennia and imply that the climate of the whole region was far from stable. This is in good correspondence with the changes in smaller time scales (i.e. years or decades), which are observed in the instrumental records, as described in the previous section.

3 WATER AND WASTEWATER TECHNOLOGIES IN CRETE THROUGH HISTORY

3.1 Minoan Civilization (*ca*. 3,200–1,100 BC)

Although the island of Crete was first inhabited after *ca*. 6000 BC, the Minoan civilization eventually developed and flourished during the Bronze Age, three thousand years later (Alexiou, 1964). The archeological findings suggest that a highly organized civilization was developed in Crete and in the islands of the south Aegean Sea (e.g. Santorini). At that time the Mediterranean was a contentious region for more than two millennia. In the list of the wars (including those related to water conflicts) before ca. 1000 BC worldwide, one can see that most of them occurred in

Mediterranean region where the Minoan civilization dominated for almost two millennia.

However, it is very interesting to note that in none of these wars and/or conflicts, Minoans were militarily directly or indirectly involved. Not only that, but Minoans, known as sea people, acted as intermediates trying to impose peace. This Minoan Era was called by Arthur Evans (1964) the Pax Minoica or 'Minoan peace' – a period when cities needed no walls, castellum or fortresses, and other military structures. Thus, Minoa had the time and the required knowledge to concentrate on arts, culture, and technologies.

Amongst other evidence, the level of this advanced culture may be demonstrated by the innovative techniques used for collecting, storing, transporting and using surface-water and ground-water resources (Koutsoyiannis et al., 2008; Angelakis and Spyridakis, 2010), suggesting that the engineers of the Minoan times had a good degree of understanding of the basic water management techniques well before the scientific achievements of our times (Angelakis *et al*., 2012). This ancient infrastructure can only be compared to modern hygienic water systems, reestablished in Europe and North America from the second half of the nineteenth century AD. Such hydraulic infrastructures include cisterns used for harvesting and storage of rainwater, toilets flushed by rainwater, water distribution systems, and sewerage and drainage systems.

The hydro-technological advancements created at that era comprised: (a) cisterns and other water harvesting facilities (resembling modern day infrastructure); (b) urban water, wastewater, and storm-water management systems; and (c) aqueducts that ensure superior water quality and safety against pollution and sabotage. Cisterns were used to store rainfall water, while the aqueducts' purpose was to transfer it from springs or surface sources. Two examples which highlight the application of cisterns and aqueducts are illustrated in Figures 5a and 5b (the aqueduct of Tylissos village and the central cistern in Zakros palace), while more cases are also described by Angelakis and Spyridakis (2013). In addition, storm drainage and sewer systems (Figures 6a and 6b), can be found in the palaces to discharge water and wastewater (MacDonald and Driessen, 1990). Open terracotta and stone conduits were used to convey and remove stormwater and limited quantities of wastewater. Pipes, however, were rarely used for this purpose.

Larger sewers, sometimes large enough for a man to enter and clean them, were found in Minoan palaces at Knossos, Phaistos and Zakros. These large sewers may have inspired the genesis of the idea of the labyrinth; the subterranean structure in the form of a maze that hosted the Minotaur, a mythical monster. Some palaces had toilets with flushing systems that were operated by pouring water in a conduit (Shaw, 1973; Angelakis and Spyridakis, 1996). However, the best example of such an installation was found in the Cycladic island of Thera (modern Santorini). This is the most refined and well-preserved pattern belonging to the late (*ca*. 1550 BC) Bronze Age settlement of Akrotiri, which shares identical cultural characteristics with Crete (Angelakis and Spyridakis, 1996).

3.2 The Mycenaean, Classical, and Hellenistic Periods (*ca*. 1,400–67 BC)

As mentioned above, in about 1450 BC there was an abrupt decline at all the centers of Minoan Crete. This was followed by the Mycenaean invasion from mainland Greece to Crete, which perhaps contributed to the dispersion of the advanced Minoan hydro-technologies to the rest of the Greece (Angelakis and Spyridakis, 1996). Crete however did not utterly collapse, and approximately 200 years later, according to

Homer, it participated in the Trojan campaign with a force of 80 ships (*Iliad* 1, 652); while the Mycenaean navy consisted of 100. This could demonstrate some kind of reconstruction of Cretan societies, under the dominance of the Mycenaean kingdoms (*ca*. 1,400 – 1,100 BC). A second invasion at the beginning of the 11th century BC, this time led by the Dorians, ended the Mycenaean dominance by the last years of the Bronze Age (*ca*. 1,100 BC).

During the succeeding Dorian period aqueducts, cisterns and wells similar to the Minoan and Mycenaean originals were constructed. However, the technological progress of that time made the construction of more sophisticated structures a feasible task. A period of prosperity (*ca*. 7th century BC) when trade flourished and Cretan colonies reached as far as Sicily (Italy) Marseille (France) and Cyrene (Libya) was followed by two centuries of economic distress. It is characteristic that during the Classical epoch (*ca*. 500 – 323 BC) the Cretans were unable to participate in the war against the Persian invasion, which united the rest of the Greek cities.

In the Hellenistic period (*ca*. 323–67 BC), there was a significant change in the scale of the hydro-technologies applied. Larger hydraulic works were constructed at several towns (e.g. Eleutherna, Lato, Dreros and Priansos), consistent with the prior Minoan knowledge (Dialynas *et al*., 2006). These included aqueducts, cisterns, wells, water supply systems, baths, toilets, and sewerage and drainage systems. Two such examples of Hellenistic cisterns are shown in Figure 7. However, according to Polybius (*Histories*), this was also a period that Cretan cities contested against each other in establishing trade routes with cities at inland Greece, with other Aegean islands or Egypt and possibly even further east. This rivalry sometimes led to minor hostilities or war (1stand 2nd Cretan wars in 205 and 155 BC). Moreover, many of the residents left the island to enlist as mercenaries to other states due to the economic decline, while others became pirates (Diodorus Siculus, *Bibliotheca historica*).

3.3 The Roman period (*ca*. 67 BC–330 AD)

In 67 BC, after a 3-year campaign, the Romans established their hold at the island, incorporating Crete into the Roman Empire. According to Titus Livius (*AbUrbe Condita*) and other historians of the Roman period this was a time of peace and prosperity under the dominance of the Roman Empire. The Pax Romana and the re-unification of the whole island of Crete under a strong and organized government led to the construction of (a) public buildings, often with fine mosaics, toilets, sewers, drains, and other hydraulic works at many of the main cities of the island including Gortys, Ierapytna, Aptera, Lyttos, and Lebena and (b) public engineering works and even larger scale aqueducts and cisterns, such as Gortys' aqueduct and cisterns in Aptera (Davaras, 1976).

The Romans did not add much to the Greek knowledge of infrastructure management; however, the invention of concrete (*opus caementitium*) by Romans enabled the construction of longer canals, huge water bridges, and long tunnels in soft rocks at lower costs (Fahlbusch, 2010). Furthermore the prior (Minoan and Hellenistic) knowledge in water resources technologies was enhanced by the advanced project management and logistic skills which were quite developed in the Roman Empire. This is the reason behind the 'mega' water supply systems built during the Roman domination, which in terms of functionality and hygienic standards can be compared to the modern urban water systems (Mays *et al*., 2007). During that period, aqueduct, water distribution systems in cities (e. g. water tower and pipelines) and water use (e. g. baths and latrines) were significantly increased.

Roman aqueducts included various components such as channels with an open surface flow following the surface of the land, tunnels, water bridges (Figure 8a) built with arches and inverted siphons. For example water supply of Knossos during the Minoan Age was depended on water from the wells and water from the spring of *Mavrokolybos* located 0.7 km apart from the palace; whereas during the Roman period it was dependent on the *Funtana* aqueduct 11 km in length including a tunnel at Scalani having a cross-section of 1x2 m^2 and length of 1150m (Angelakis et al., 2012). Another example of the changes in scale and functionality is the impressive aqueduct of a total of 22 km length, which was built near ancient Lyttos (Angelakis *et al*., 2012). Its water source was located at the west flank of the present Oropedio Nissimou highlands (its summit is 1148 m high), at Kournias, located at an altitude over 600 m. Stone pipes have been used to build an inverted siphon in the area of the village Tichos, as was also stated by Angelakis *et al*. (2012).

Other sites with ancient aqueducts include Axos, Chersonessos, Falassarna, Minoa, Kissamos, and Gortys (Figure 8a), while several cisterns are located all over the island, e.g. in Dictynna, Lappa, Rhizenia, Eleutherna, and Elyro (Angelakis and Vavoula, 2012). A typical cistern of cylindrical cross–section which lies at Minoa (Marathi) in western Crete is presented in Figure 8b. Also at the town Aptera there are two prominent constructions in both styles of architecture and hydraulic engineering; the public baths, and the thermae. These works are connected by two nearby cisterns of quite different shapes; an L-shaped cistern (3,050 m^3) and a rectangular tri-aisle one (2,900 m^3).

3.4 The Byzantine period and Venetian rule (*ca*. 330–1645 AD)

From *ca*. 330 to 824 AD (Proto-byzantine and First Byzantine periods) minimal development occurred in Crete, and was the case during the next 140 years (824–961

AD) when it was occupied by the Arabs—the pirates known as the Saracens. From 961 to 1204 AD (Second Byzantine period) Crete was again part of the Byzantine Empire. In that period, the technologies applied to assure water supply for the cities were more or less the same as those during the Arabic occupation, i.e. water cisterns and house wells (Figures 9a and 9b). In many cases, collecting rainwater from the roofs of the houses and other open areas in cisterns and wells was a basic practice. A number of water well mouths have been discovered in several rich homes in Iraklion city (Figure 9c).

In 1204 AD the Venetians invaded Crete and there was another shift in the hydraulic works activity. Large-scale water projects were again implemented, such as Morozini's aqueduct, cisterns in Rethymnon and Gramvousa, and older water supply networks reconstructed (Strataridaki *et al*., 2012). The former, named after Francesco Morosini, *Provveditore Generale* (1625) of the city of Candia (Iraklion), was part of the Venetian commander's plan to create an effective water distribution system for the city.

This plan included the interconnection of several minor water springs together into one big aqueduct. The feasibility of this idea was based on two facts: on one hand there was the appropriate elevation difference between the Youktas (where the water springs were located) and Iraklion, and on the other hand there was an abundance of good quality water springs. For the design and construction famous engineers of that era were employed, such as Zorzi Corner, Rafaele Monanni and Francesco Basilicata (Spanakis, 1981), while the expenditures reached 13,000 *regals* (Angelakis and Vavoula, 2012). The overall distance between the two ends of the conduit was approximately 15.5 km (Strataridaki *et al*., 2012) and a few parts of it have been maintained to the present day (Figure 10a). Besides this impressive work, numerous other cisterns and fountains were constructed throughout the island during this period, such as the fountain illustrated in Figure 10b, and can be still found in the city of Rethymnon.

3.5 The Ottoman and the Egyptian periods (*ca*. 1646–1898 AD)

The Venetian rule was ended by the Ottoman occupation in 1645 AD, which was followed by the Egyptian occupation in 1830 and 130 years of intense social unrest with numerous local or widespread rebellions (Detorakis, 1986). Both the Ottomans and the Egyptians mainly operated the existing water infrastructure, which had been developed in earlier times (Angelakis *et al.*, 2012). However, many public fountains were constructed due to the direct link between water and the Ottomans' religious beliefs (Spanakis 1981); thus water was available in almost every district of the major cities. Notably, in Iraklion there were approximately 70 drinking fountains as Evligia Çelebi, a Turkish traveling writer, describes in his books (Strataridaki *et al.*, 2012). However, this was hardly enough, as the fountains could not cover the increasing water demands of the populations, while houses with running water or cisterns were only a few, belonging to the Ottoman officers. A typical drinking fountain is shown in Figure 11a.

In this period some of the existing works were maintained or reconstructed. A typical example is the *Fountana* aqueduct, a part of which is shown in Figure 11b and was still in operation in the middle of the last century.

4. DISCUSSION AND CONCLUSIONS

The climatic and hydrologic conditions in Crete have been characterized by high variability both spatially and temporally through the long history of the island. This had a clear impact to the water availability and thus to the human responses to its fluctuations. The development of the water technologies, whenever the social conditions allowed it, can be considered as one of these responses. Looking back over the long history of human inhabitance of the island, one can clearly outline some principles on which past water technologies were based; notably they were the very same that are used in many applications today.

The evolution of water science and engineering at the island of Crete does not appear to be continuous though. There were some periods, spanning from a few decades to many centuries, when progress halted and only the previous hydraulic works (e.g. the Byzantine Era) were operated and maintained or even left to decay (e.g. the Arab occupation). Still, the existing knowledge of hydro-technologies was not lost during these intermissions, but was preserved to further evolve under more favorable conditions.

Naturally, it is difficult to reconstruct the design principles of the Minoans based on the available archeological findings, but even the fact that several ancient works have operated for very long periods, some until recent times, provides strong evidence that the factor of *durability* was taken very seriously in their design. For example, at the beginning of the 20th century when the Italian writer Angelo Mosso visited the villa of Hagia Triadha at southern Crete he discovered that the sewer system of the villa was fully functional, i.e. stormwater still came out from the sewers, 4000 years after their construction (Angelakis et al., 2005). According to Gray (1940). Mosso was so astonished that made the following statement:

"Perhaps we also may be permitted to doubt whether our modern sewerage systems will still be functioning after even one thousand years."

To our knowledge there is no other case of a sewerage and drainage system functional for more than 4,000 years in the human history. Hence, the existence of several Minoan archaeological sites could be linked to the durability of the sewerage and drainage systems (Angelakis *et al.*, 2014). The principle of durability, and in later periods the support of the technologies and their scientific background by written documents, had also a very important role in the transfer of these technologies to modern societies despite the regressions that have occurred through the centuries (Koutsoyiannis *et al*., 2008).

The evolution of water technologies can also be viewed in regards to the climatic variability and cultural change. Cretan history provides plentiful examples of different social responses to climatic shifts, summarized in Table 2. We can see that the link between society and climate is not deterministic, which is also supported by other examples. Such is the case of the communities that thrived at the Near East near the end of the Early Bronze Age and experienced a series of severe droughts. There is archeological evidence that this coincided with the abandonment of many sites in Syria and in Levant, but at the same time there were also sites that continued to exist (Mercury *et al.*, 2011). This pattern emerged again in the same region a thousand years later when an abrupt fall in temperature led to the demise of many of the big cities (Issar and Zohar, 2009). So what makes some communities more resilient to climatic variability than the others?

Mercury *et al.* (2011) provide three approaches: technological, social and religious. The first one refers to the development of better irrigation practices and water resource management, the second one to a fair food distribution and the construction of large granaries such as the ones discovered at the site of Beit Yerah, and the third one to the establishment of temples or other religious sites devoted to the gods of fertility in order to re–gain the god’s lost grace. Thus, communities which were open to new technologies and/or social institutions were more likely to adapt to climatic change, while the more conservative societies failed to achieve that. From a Darwinian perspective the former societies have evolutionary advantage over the later.

This could also be the case of the technological advancements during the Minoan civilization. The robust social, political and economic structure (minimal internal conflicts and a powerful commercial network) allowed the Cretans to excel in the water resources management during the periods of water scarcity (*ca.* 2100 – 1700 BC) and find innovative methods to deal with it. This reduced its vulnerability during the consecutive even drier years between *ca.* 1700 – 1500 BC, known as Neopalatical period, when waterworks peaked. On the other hand, when similar conditions prevailed during the Classical years (*ca.* 500 – 323 BC) or the Byzantine (*ca.* 330 – 1,204 AD), when socio-political structures were less strong, there is evidence of societal collapse, war and disorder, accompanied with minimal development in hydraulic technologies.

The link between water scarcity, as an outcome of reduced precipitation or/and increased evaporation, and social degradation has been suggested by a number of earlier studies focused to the collapse of the Mayan civilization. (Adams, 1973; Gill, 2000; Brenner *et al.*, 2001; deMenocal, 2001; Haug *et al.*, 2003; Diamond, 2005; Medina–Elizalde and Rohling, 2012). This well–studied civilization reached its peak during a humid period, while its decline coincided with a long-term reduction in precipitation (Gunn and Adams, 1981; Haug *et al.*, 2003). This was not only a cause for hostilities between Mayan cities, but “*also may have undermined the institution of Maya rulership when existing ceremonies and technologies failed to provide sufficient* *water*" (Lucero, 2002). Interestingly, recent research results show that the reduction in annual rainfall was not as high as previously regarded, but only 25 to 40% (Medina–Elizalde and Rohling, 2012).

Similarly to the Mayan civilization, Tsonis *et al*. (2010) argued that a long stretch of drier and warmer conditions that commenced around 1,450 BC could be the reason behind the demise and eventual disappearance of the Minoan civilization. They presented a synthesis of historical, climatic, and geologic evidence which supports the hypothesis that there was abrupt climatic change instigated by an intense El Nino. This is also confirmed by the results of the palynological studies of Moody *et al.* (1996) and Atherden and Hall (1999); suggesting the emergence of extended drought periods during the second half of the Late Bronze Age. In addition, the change in the architecture of the Minoan houses in the Late Minoan Era implies the adaption to more arid, but contrary to Tsonis *et al*. (2010), colder conditions (Moody, 2009).

Our findings, suggest that more research is needed in order to clarify if there is any link between the climate and the fall of the Minoan civilization. The water management infrastructures were designed on a dry climate basis, and as we explained above they were comparable to modern ones. This is also supported by the increase in the scale of Minoan water-management features especially in the eastern Crete (Floods, 2012). The response to the changing climatic conditions (to a more arid regime) observed during the Middle Bronze Age, also shows the importance of water resources management during the period before the abrupt climatic event (Betancourt, 2005).

Thus, it is difficult to support the El-Nino hypothesis, unless the climatic change was so abrupt and intense that it could provoke as an impact a (multi-)decadal crop failure. If this was the case then the short time length and the suddenness of the event could also explain the inconsistency between cold (Moody, 2009) and warm (Tsonis *et al*. 2010) conditions. However, the technological level of the water works and the adaption that the Minoans have developed to the previous periods of dryness makes it rather unlikely that the reason of the Minoan collapse could be linked to a single (climatic) cause.

In the centuries following the fall of the Minoan civilization, a cyclic process seems to emerge. The principles of the hydraulic technologies invented in Crete are dispersed to the rest of Greece (and during the Roman period, to the rest of the Mediterranean region), where they are enhanced by the progress in the techniques of construction and materials and then re-applied to the Cretan cities as more sophisticated or bigger-scale versions.

During all those years it seems that the transition from humid to arid conditions is followed by economic distress (e.g. Classical epoch, Byzantine years and Ottoman period). Specifically, the dryness during the first millennium AD, resulted again to minimal development, occupation from external forces (the Arabs), piracy and social disorder. Thus, it is not surprising that there was not any progress in the implemented water technologies; it could be rather viewed as a setback. One possible reason could be that the Byzantines regarded Crete a distant border state of their empire and therefore abandoned any plans for development, especially in an arid regime; this is a drawback of centralized governance.

The Venetians though, had a quite different approach. As they recognized the importance of the location of Crete in the Mediterranean, for their trade networks between Italy and Middle East, they invaded Crete in 1204 AD. Although, they faced enhanced climatic variability, with extensive droughts followed by out-of-season rain and severe floods, they managed to occupy the island for *ca.* 450 years and coped both with unfavorable climatic conditions and internal social unrest. The enormous hydraulic works of this period should have played a role in both of them.

Finally, the succeeding Ottoman conquerors simply operated the existing Venetian and Roman constructs. The same pattern emerged again: arid climate, water scarcity, insufficient water management, social unrest, rebellions. The Ottomans might have had the military power to occupy Crete, but they lacked the water management technologies or the political will to implement them in order to maintain their occupation in the island. It is impressive that during the last 1500 years almost no innovation in water technologies is observed.

To sum up, we have seen that the Cretan climate has been highly variable. It has transited between cold and warm and between humid and arid conditions several times. These periods lasted from a few decades to over centuries. We can say that social unrest, war and economic shrinkage are more likely to be linked to dry phases, and correspondingly to water scarcity. On the contrary, humid climate is mostly connected with peace and prosperity, due to agriculture and animal husbandry growth. No pattern is evident for temperature; probably because its direct impact to agriculture is lighter compared to water availability in the Eastern Mediterranean region.

The Minoans are the only ones who seem not to follow to this pattern. When they faced a dry period, 900 years after the onset of their civilization, they managed to cope with it by making great innovations in water management, such as the development of cost–effective decentralized, highly durable, water management technologies (e. g. rainwater harvesting). This was combined with their already development of strong and stable social structures, as well as the accumulated economic growth.

The design philosophy of ancient Cretan hydro-technologies has to be further considered in light of its success. Thus, the development of effective water supply management projects, in short–water areas should also include historical knowledge. This rich inheritance of the ancient Cretan, particularly Minoan, hydraulic works should not be restricted to its cultural value alone, but also, and more importantly, viewed as an example for sustainable water technologies.

Acknowledgments

The valuable comments and suggestions of Profs. S. Alexiou and K. Voudouris, are highly appreciated. Moreover, the authors would also like to thank Y. Dialynas for his helpful and creative remarks. Finally, we would like to acknowledge they the constructive suggestions of the anonymous reviewers, which helped us to strengthen our arguments and clarify the obscure points of our work.

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Tables

Table 1: Paleoclimatic reconstructions of Surface Sea Temperature (SST) and Freshwater input (Humidity)

Abbreviation	**Ro02**	**Ge05**	**Tr09**
Reference	Rohling *et al.*, 2002	Geraga *et al.*, 2005	Triantafyllou *et al.*, 2009
Location	N35°39′ E26°34′	N36°32′ E24°12′	N36°38′ E27°00′
Resolution (yr)	125	500 – 2000	50 – 450
Time interval (yr BC)	11,000 – 0	48,000 – 1,000	10,500 – 1,000
SST proxy	Planktonic abundance (Foraminifera)	Planktonic abundance (Foraminifera)	(Alkenone)
Precipitation proxy	$\delta^{18}O$	$\delta^{18}O$, Pollen, Sedimentology	Plactonic abundance (Foraminifera), Pollen

Table 2: Social development, climatic conditions and water technologies evolution in Crete since 3,200 BC.

Period	**Social development**	**Climatic conditions**	**Water technologies**
Early-Minoan (*ca*. 3,200 – 2,200 BC)	Onset of Minoan Civilization.	Warm and humid	First hydraulic water and waste water systems (e.g. cisterns and sewers).
Meso-Minoan (*ca*. 2,200-1,700 BC)	Peak of Minoan Civilization.	Cold and dry	Great innovations in basic infrastructure of palaces and cities (e.g. sewerage and drainage systems).
Late-Minoan (Neopalatial) (*ca*. 1,700-1,450 BC)	Peak of waterworks	Warm and dry	Great innovations in water management (e. g. wells, cisterns and dams)
Late-Minoan and Mycenaean (*ca*. 1,450-1,100 BC)	Demise of Minoan Civilization.	Cold and dry	As above. Also Minoan hydro-technologies transferred to inland Greece.
Dorian (*ca*. 1,100 – 500 BC)	Economic bloom. Colonization of Sicily, Marseille and Cyrene.	Cold and humid	Similar, but more sophisticated structures.
Classical (*ca*. 500 – 323 BC)	Economic distress. Did not participate in the Persian Wars.	Warm and dry	Unknown.
Hellenistic (*ca*. 323 BC –67 AD)	Struggle between cities. Mercenaries in foreign armies.	Warm/cold and dry	Hydro-structures of greater scale.
Roman (*ca*. 67 – 330 AD)	Peace and prosperity.	Cold and humid	Further development of much larger scale water projects (e.g. aqueducts, cisterns, baths and therme).
Byzantine (*ca*. 330 – 1,204 AD)	No development. Piracy.	Warm and dry	Minimal development.
Venetian (1,204 – 1,669 AD)	Strong trade. Rebellions and social unrest.	Cold and humid/dry Enhanced variability	Achievements comparable to modern urban water systems.
Ottoman and Egyptian (1,669 – 1,898 AD)	No development. Rebellions.	Warm and dry	Maintained prior water constructions (emphasis on aqueducts and fountains construction).

Figures

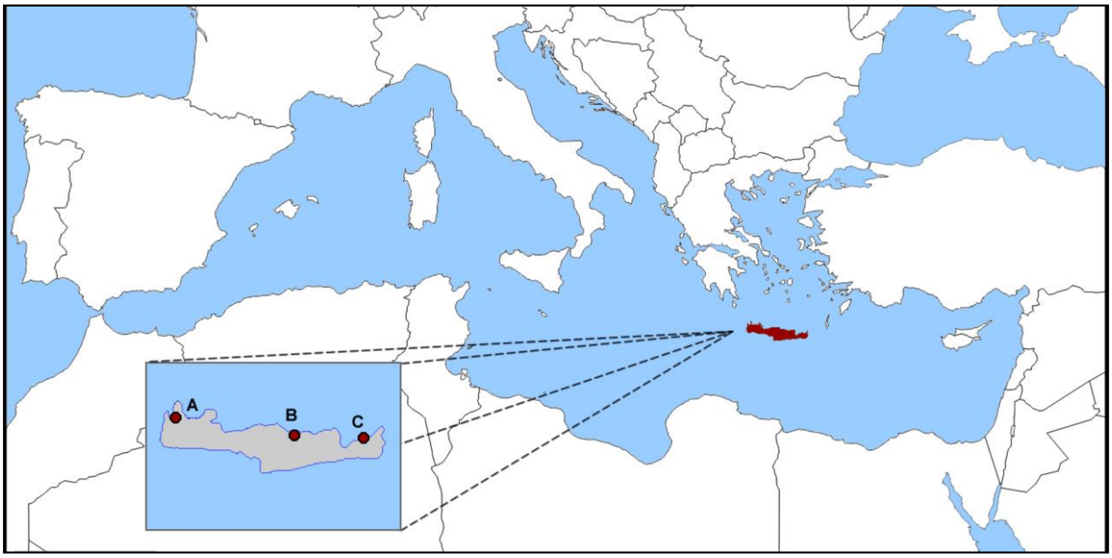

Figure 1. The island of Crete in Mediterranean Sea. The locations of the meteorological stations are shown in the embedded window (A. Chania, B. Iraklion and C. Sitia).

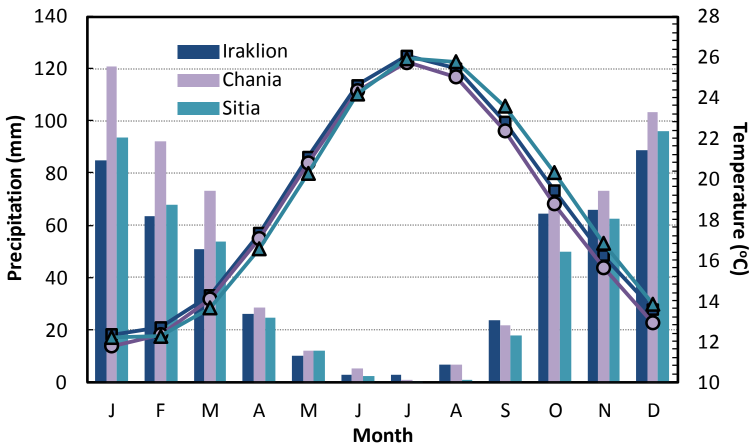

Figure 2. Temperature (lines) and precipitation (bars) of Iraklion, Chania and Sitia (Data from Hellenic National Meteorological Service).

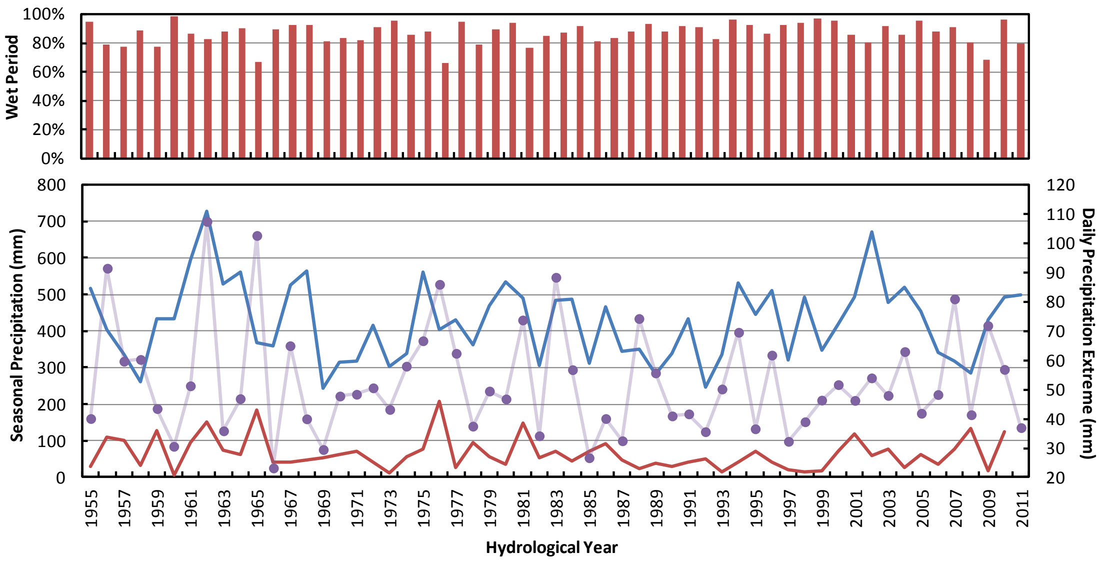

Figure 3. Wet- (blue line) and dry- (red line) season precipitation of Iraklion. Purple line represents daily maxima, while the red bars above show the wet-season precipitation as a percentage of annual precipitation.

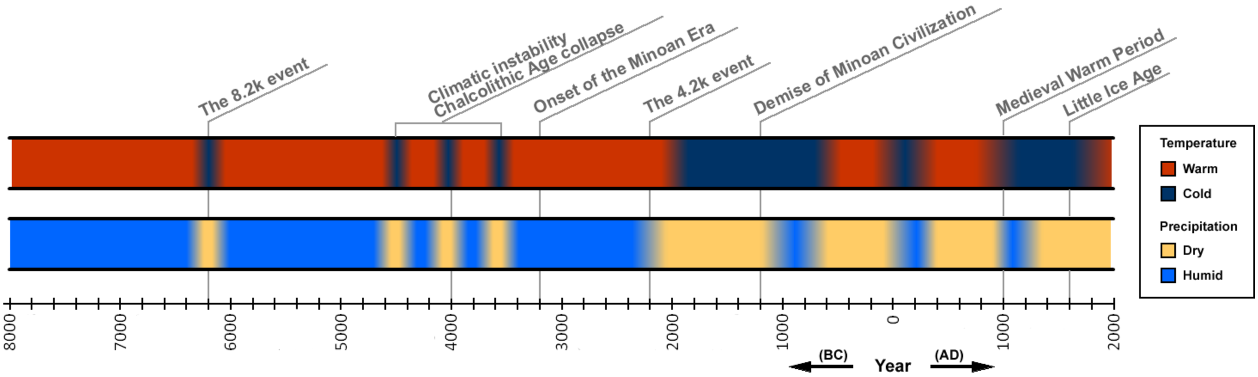

Figure 4. Climate reconstruction of Crete for the last 10,000 years based on proxy and historical data.

(a) (b)

Figure 5. (a) Remains of Minoan aqueduct in Tylissos that brings water from the spring of Agios Mamas to the village and (b) Minoan cistern at Zakros palace (with permission of A. N. Angelakis).

(a) (b)

Figure 6. Minoan sewerage and drainage systems: (a) Part of the central system at the palace of Phaistos and (b) at the Little Palace of Knossos (with permission of A. N. Angelakis).

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(a) (b)

Figure 7. Hellenistic cisterns: (a) at Eleutherna town (excavated) inside view and (b) central cistern at the ancient town of Lato in eastern Crete (with permission of A. N. Angelakis).

(a) (b)

Figure 8. (a) Remnants of Roman aqueduct in the ancient city Gortys (b) Roman cistern (of cylindrical cross–section) in ancient Minoa (Marathi) in western Crete (with permission of A. N. Angelakis).

(a) (b) (c)

Figure 9. Byzantine water cisterns and wells: (a) and (b) Cisterns (of rectangular cross–section) on the right side of the Byzantine church Agios Nikolaos in the homonymous city and Areti Monastery in the eastern Crete, respectively and (c) mouth of water well in the Historical Museum of Iraklion (with permission of A. N. Angelakis).

(a) (b)

Figure 10.(a) Remnants of the Venetian aqueduct (Morozini) in the area of Karidaki, Iraklion and (b) Central fountain in Rethymnon city (with permission of A. N. Angelakis).

(a) (b)

Figure 11. (a) Ottoman fountain outside of the Mosque in Ierapetra city and (b) remains of *Foundana* aqueduct at *Aghia Irini* (with permission of A. N. Angelakis).