

## Article

# Evolution of Cretan Aqueducts and Their Potential for Hydroelectric Exploitation

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**Abstract:** In this article, several archaeological, historical and other aspects of aqueducts in Crete, Greece, since the prehistoric times until today, are reviewed and presented. In Crete, since the Minoan era, various water management techniques that are found in modern water technologies were developed and applied. One of the most significant features of the Minoan civilization was the architecture of water supply systems in the palaces and other settlements. These technologies were continued and improved mainly during the Classical, Hellenistic and Roman periods and at the same time spread to other towns in the mainland and islands. The aqueduct technologies developed during the Classical and Hellenistic periods were further developed by Romans, mainly by enlarging their application scale (e.g., water bridges). Several paradigms of Cretan aqueducts are considered by which the significance of those technologies for water supply in areas with limited water resources is justified. A brief presentation and discussion of climatic conditions, the karst hydrogeology and the water resources management in Crete is also included. The article also describes the present water management profile of the island, in terms of the water plants, water supply–irrigation networks, and water renewable energy exploitation of dams and water pipelines.

**Keywords:** aqueducts; Minoan era; Classical–Hellenistic periods; Roman–Ottoman period; modern times; hydroelectric exploitation

## 1. Introduction

The Island of Crete is located in the eastern Mediterranean area and is characterized by low water availability due to the intense spatial and temporal variation of precipitation. The island is a rather mountainous region with three main mountains (i.e., White, Ida, and Dikti) which play an important role to the hydrogeology of the island [1,2]. Thus, the technology of transporting of water from the higher watersheds to the urban areas located in downhill areas with low water availability has been known since prehistoric times. The mean atmospheric precipitation ranges from 1800 mm in the mountainous areas of western Crete to about 300 mm in the southeastern coastal areas [3].

The Island of Crete was the center of Europe's first advanced civilization, the Minoan [4]. In Crete, the earliest human settlements on the island date back to the Neolithic period (ca. 7000–3200 BC). However, Crete was the center of Europe during the Bronze Age when the Minoan civilization developed (ca. 3200–1100 BC), one of the most important civilizations of mankind and the first European civilization. At that time, several localities on the island grew to cities, which further

developed into centers of commerce and craftsmanship. Minoan was peaceful and equal cultural society, characterized by Evans [5] as *pax minoica* (i.e., Minoan peace) *a period that cities did not have walls*. Thus, Minoans were concentrated to arts, cultures and technologies.

One of the major achievements of the Minoans was the advanced water resources technologies developed in Crete at that time [6]. Archaeological and other evidence reveal that, in the Island of Crete since the Minoan times, various water management techniques (water networks; construction, exploitation and use of surface water; sanitation; and irrigation), that are found in modern scientific fields of water resources, waste water and hydrology of groundwater, were developed and applied. Angelakis et al. [7] suggested that the advanced water distribution systems in Minoan “palaces” and other settlements located in areas of pure water sources, i.e., aqueduct technology, was originally developed by Minoans (e.g., Knossos, Malia, Gournia, Tylissos and Mochlos). In the structures of most Minoan palaces and towns are remarkably complex and highly functional water supply systems. Thereafter, aqueducts were used by the Mycenaens in continental Greece. These technologies were continued and improved during Classical and Hellenistic Crete (ca. 490–67 BC) and Roman (ca. 67 BC–330 AC) periods and at the same time spread to other towns in the mainland and islands. Typical examples are the aqueducts, cisterns and other water supply plants in Polyrhinia, Eleuthera, Falassarna, Elyros, Chersonisos, Lyttos, Gortys, Minoa (Marathi), Kissamos, and other sites [8–10].

Nowadays, the bodies related to water in Crete are: the Direction of Water of the Decentralized Administration of Crete; the Organization for the Development of Crete (OAK, sa), which has continued to be active in the water infrastructures and networks since 1979; and municipalities and research institutes, which are responsible for the optimal implementation of the approved Water Management Plan of Crete, in terms of the development, construction and improvement of water plants and networks, in order to meet the water needs in Crete in the most efficient and environmentally friendly way [11,12].

In this article, several characteristic examples in selected archeological sites that chronologically extend from the prehistoric times to the present times are presented and discussed. By those examples, the evolution of the aqueduct technology on the Island of Crete through its long history is presented. In addition, some of significant recent renewable energy projects, based on water exploitation, are presented in the article, pointing out another significant role of water resources in “green development” [13–15].

The article is organized as follows: In Section 2, the historical variation of climate of Crete, as well as the water resource status is presented. Section 3 deals with presentation of the characteristics of major aqueducts in Minoan Crete. In Section 4, the known aqueducts in Crete from the Classical and Historical periods and Roman period are presented. Section 5 refers to Byzantine period, while Section 6 deals with the modern times, focusing on present large hydraulic infrastructure like dams, reservoirs, water treatment plants and the water supply–irrigation networks in the Island of Crete. In Section 7, some renewable energy projects that are based on the exploitation of water infrastructures and networks are analyzed and presented. Section 8 summarizes the historical evolution of Cretan aqueducts and indicates the most significant future water measures that have to be planned for the most efficient exploitation of water resources on the Island of Crete.

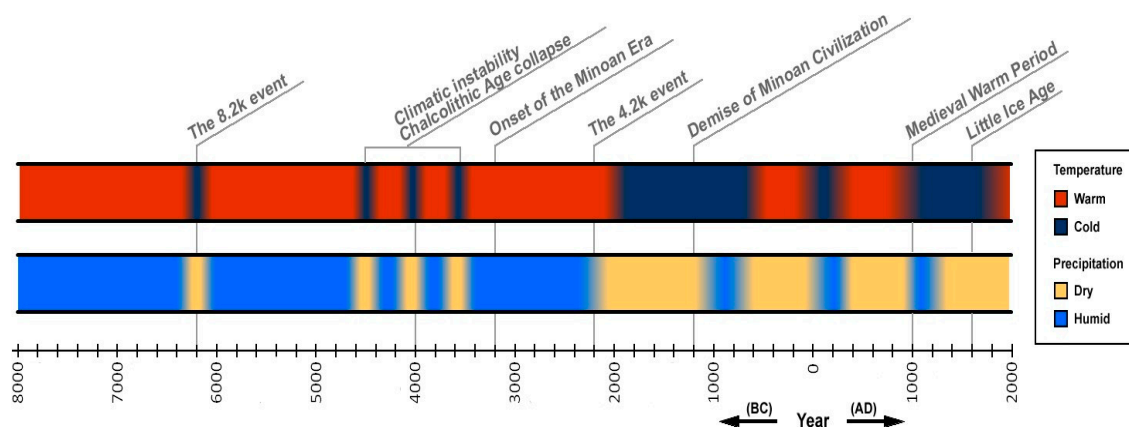
## 2. Physical Settings

Crete is a mountainous island in the eastern Mediterranean, located in the southern part of the Aegean Sea, separating the Aegean Sea from the Libyan Sea. Crete, the largest Greek island and the fifth largest in the Mediterranean, washed North from Cretan Sea and south of the Aegean Sea, located 160 km south of the Greek mainland, is the southernmost border of the EU and is surrounded by numerous small islands (Gavdos, Gavdopoula, Golden, Koufonisia, Dia, Dionysases, etc.), which are uninhabited, except the island of Gavdos. The total area of the island is 8335 km<sup>2</sup>. It is 260 km long, with width ranging from 12 to 57 km and a coastline of 1306 km (including the islands) [11,12].

Crete forms an important bridge between Europe, Asia, and Africa. The unique geographical position of Crete in the eastern Mediterranean basin has determined its historical course throughout the centuries. The total population of Crete is 623,065 or 5.8% of the total population of the country. In addition, more than 4.5 million tourists visited Crete in 2013. A further increase is expected in the coming years [16].

### 2.1. Climate of the Island of Crete

In eastern Mediterranean, and especially in the Island of Crete, climatic fluctuations during the last 10 thousand years were recorded [17]. These fluctuations show increasing and decreasing cycles of climatic conditions alternating chronologically, lasting from a few decades to over centuries. Recently, Markonis [18] summarize all available sources and presented a picture of the climatic variability in the eastern Mediterranean and more specifically in Crete during the last 10 thousand years which showed alternating warm/cold and moist/dry periods, lasting from a few centuries to some millennia (Figure 1). This picture demonstrates clearly the instability of climatic conditions of the whole region.



**Figure 1.** Climate reconstruction of Crete for the last 10 thousand years based on proxy and historical data (with permission from Markonis [18]).

Tsonis et al. [19] indicates that wetter conditions during the middle Holocene were warm and wet periods were followed by cool and arid conditions. The climatic conditions that prevailed during the period ca. 4500–3500 BC, are rather unclear as there is contradicting information in the literature [20]. Some indications suggest moist conditions for the next millennium (ca. 3500 to 2500 BC), which coincide with early Minoan era [20,21]. Floods [22] indicate that the Mediterranean dry-season became more pronounced on Crete during the Neopalatial period (ca. 1700–1500 BC). He reported that the Late Minoan IB (ca. 1500–1450 BC) was perhaps a particularly dry period with more pronounced summer temperatures or perhaps less winter precipitation. Thereafter, a mild acidification of the region followed and around 1450 BC a long stretch of drier conditions started, ending around 1200 BC [23]. Tsonis et al. [19] presented a synthesis of historical, climatic, and geological evidence which supports that climatic changes instigated by an intense El Nino activity contributed to the demise and eventual disappearance of the Minoan civilization. Thereafter, during the Iron period (ca. 1300–600 BC), there was another cold and humid period. Then, during Classical and Hellenistic periods (ca. 500–67 BC), the climate was rather warm and dry. During the Roman period (ca. 67 BC–330 AD), a colder and more humid period prevailed. Finally, a warm and dry climate prevailed during the Arab period (ca. 800–1000 AD) reaching a peak of high temperatures and drought [24].

Presently, the climate in Crete is primarily temperate. The island lies in the Mediterranean basin between the southeastern Europe and the North African climatic zones. Its western and northern parts are generally more humid than the eastern and southern, and the two parts are separated by a central mountainous area, where snowfall is common during the winter [17]. The climate is

considered mild with relatively warm winters (with average temperature 10 °C) and hot summers (with average temperature 30 °C). In general, the Mediterranean climatic zone influences a large part of Crete and makes spring and autumn short in comparison to the longer summers and winters seasons. The temperature in the southeastern regions is quite high with summer maxima occasionally reaching 40 °C, resembling North Africa.

## 2.2. The Karst Hydrogeology of the Island of Crete

The geology of the Island of Crete creates major karst formation as it is composed of carbonate rocks, such as limestone, marble and dolomite, which allow water to penetrate [25]. The carbonate rocks cover the total area of the island for more than 30%. The majority of these rocks are located in the mountains: Lefka Ori, Idi, Dikti and Sitia. The total karst area in Crete covers about 2730 km<sup>2</sup>. The water contribution to the karst aquifer is estimated around 2000 Mm<sup>3</sup>/year which charges out in many springs [3]. Regarding the springs, in the Island of Crete there are 47 gauged springs in Crete, which are subdivided in three main classes: freshwater springs, brackish water springs and undersea springs. Most springs are karst springs and refer to the same karst hydrogeological system (Lefka Ori, Idi, Dikti and Sitia) discharging around 500 Mm<sup>3</sup> freshwater annually into the rivers [26]. The use and exploitation of water resources in karst through the centuries, especially in the Mediterranean area has been widely studied in the literature [27–32]. The knowledge of the historical techniques of karst water exploitation is significant for better management and planning of water resources under scarcity in the island.

## 2.3. Water Resource Status

Today, the atmospheric precipitation in Crete shows intense spatial and temporal variation. Generally the precipitation decreases from northwest to southeast and decreases with altitude. In particular, the average precipitation ranges from 400 mm/year on the southeastern plains to over 2000 mm/year in the northwestern mountainous area. In addition, the mean annual precipitation ranges from 816 mm/year in eastern Crete to 927 mm/year in the west [11]. Potential evapotranspiration (ET), as estimated using the Penman–Monteith method [33] which provides the most accurate estimates, varies from 1240 to 1570 mm/year. Within the annual cycle, the monthly ET rate changes from about 25 mm in winter to 225 mm in summer. The mean annual actual ET has been estimated to represent 75% to 85% of the mean annual precipitation at low elevation areas (less than 300 m a.s.l.) whilst it drops to 50% to 70% at high elevation areas [12].

The Island of Crete was characterized by a significant increase in urban and touristic activities, especially in the past twenty years. As a result, the majority of the population is concentrated in coastal areas. In many cases, the infrastructures required to support this type of economic development are inadequate. However, agricultural water demand continues to be the major water consumer on the island, accounting that over 86% of the total uses is 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 the dry periods when water demand is high.

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 temporal and regional distribution of precipitation. This worsens during the summer months when water demand rises due to the increased demand for agriculture and tourism. In addition, the highest percentage of the annual precipitation occurs in the mountainous areas of western and central Crete. Transport of water from mountains to the coastal areas and to the agricultural lands in the south and east plains of the island suffers of technical, social, and economical limitations. Thus, the management of water resources including rainwater harvesting, treating wastewater and utilizing other non-conventional sources requires an alternative integrated plan. Such a plan would



not only provide additional water, but could also contribute significantly to reduce flood risks and coastal pollution.

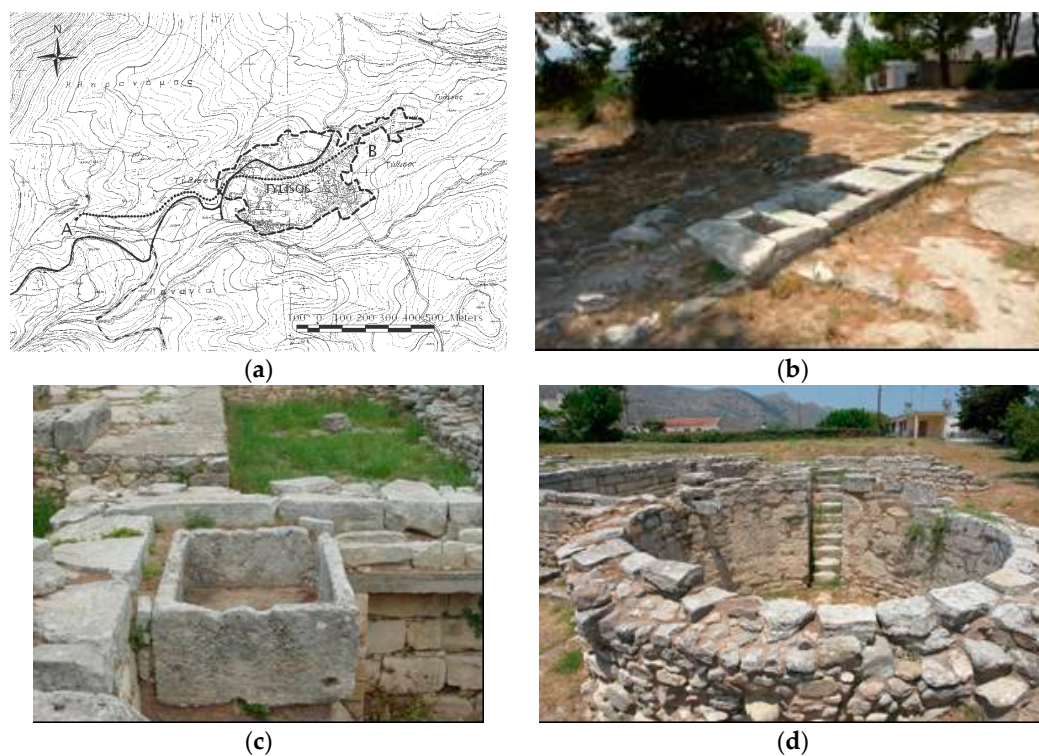
The available water resources and water uses for Crete are shown in Table 1 [11]. The real water use in 2010 was 421 Mm<sup>3</sup>/year, and the total water potential was 2941 Mm<sup>3</sup>/year, resulting in a consumption index of 14.31%. Note that the desirable water demand in 2010 was 515 Mm<sup>3</sup>/year [12].

**Table 1.** Available water resources and water uses in Crete (adapted from Angelakis [16]).

Area (km <sup>2</sup> )	Precipitation		ET in Volume (Mm <sup>3</sup> )	Water Potential (Mm <sup>3</sup> /Year)			Water Use in 2010 (Mm <sup>3</sup> /Year)				Cons. Index (%)
	Height (mm/Year)	Volume (Mm <sup>3</sup> /Year)		Surface	Ground	Total	Agricult.	Domestic	Industr.	Total	
8335	927	7740	4799	774	2167	2941	340	77	4	421	14.31

### 3. Minoan Civilization (ca. 3200–1100 BC)

Aqueducts have been useful in Crete with its anomalous terrain since the Minoan era. Several aqueducts of the Minoan era have been identified thus far [5,34]. There are two basic types of Minoan aqueducts: (a) closed/pressurized terracotta pipes; and (b) opened or covered terracotta conduits or channels of various dimensions and sections. Closed terracotta pipes were used for the distribution of the water in the Minoan “palaces”. In addition, terracotta pipes were found in the palace of Knossos and some other Minoan settlements [34]. Most renowned are the aqueducts in Gournia, Karphi, Knossos (Mavrokolymbos), Malia, Mochlos and Tylissos (Table 2). As an example, the aqueduct in Tylissos houses is shown in Figure 2. Technique was further developed during the Classical, Hellenistic and Roman periods in Crete and expanded to continental Greece and other areas of the Mediterranean and Near East.



**Figure 2.** Tylissos aqueduct: (a) Possible layout (“A” spring of Agios Mammias); (b) part of the central conduit located at the entrance of the archaeological site; (c) secondary conduit and small stone cistern used for removing solid particles from water before storage in the main cistern; and (d) central cistern in which the water was stored (with permission of A. N. Angelakis).

**Table 2.** Characteristics of major aqueducts in Minoan Crete [7].

Aqueduct Name	Location	Construction	Reconstruction	Length (km)
Gournia	Faneromeni, Asari	Minoan	-	7
Karphi	Karphi, Lassithi	Minoan	-	not available
Knossos ( <i>Mavrokolympos</i> )	Knossos	Minoan	Roman	0.7
Malia	Profitis Ilias, Malia	Minoan	Hellenistic, Roman	0.85 or 1.15
Mochlos	Mochlos, Lassithi	Minoan	-	3
Tylissos	Tylissos	Minoan	-	1.4

## 4. Historical Times

### 4.1. Classical and Hellenistic Period (ca. 490–67 BC)

Hydrotechnologies including aqueducts developed by Minoans and Mycenaeans were transferred to neighboring civilizations such as Egyptians, Etruscans and Dorians and later transferred by them to Archaic and Classical Greece, with which they had “built bridges” [35]. Classical Greeks inherited the Minoan technologies and developed them further, mainly by changing their application scale from small to large and implementing them mainly in urban areas. Minoan aqueduct technology was further developed and spread all over Greece during the Classical and Hellenistic periods [8]. The advancement of aqueduct technology and water management is illustrated by several paradigms shown in Table 3. In some cases, ancient aqueducts derived water only from springs, whereas others combined water from springs and underground capture. The ancient aqueducts in Greece were intentionally designed to capture additional underground water in order to increase their capacity and reduce the effect of periodic fluctuations of the springs in summer, especially during the dry years [8,9].

Eleuthera was a Dorian town in central Crete located in a natural crossroads, as it lay between Cydonia on the northwest coast and Knossos. It evolved during the Archaic period in a similar way as did Lato and Dreros in the eastern island and on various occasions was both an enemy and ally of Knossos. However, the town flourished in Roman period and early Christian times and became the seat of the Diocese. The ruins of the town include mainly the tower, an aqueduct, several huge and impressive pillared cisterns, forty-meter deep cuts in the rock, and two bridges built without an arch [6]. The water supply of the town was transported from the spring of Sfartiakes to the city on the eastern part of the hill by a vaulted aqueduct about 0.8 km long to two cisterns of dimensions 40 m × 25 m excavated in rock. The cisterns were inter-connected. Part of the aqueduct was also cut into the rock (Figure 3a). A schematic representation of the pipes and cisterns used for storage of the water supply in the ancient Kissamos is shown in Figure 3b.

**Table 3.** Characteristics of Classical and Hellenistic aqueducts (adapted from De Feo et al. [10]).

Aqueduct Name	Location	Period	Age of Construction	Length (km)
Polyrrhenia 1 <sup>a</sup>	Polyrrhenia, Chania	Classical	4th century BC	≈0.09
Polyrrhenia 2 <sup>a</sup>	Polyrrhenia, Chania	Classical	4th century BC	≈0.07
Eleuthera <sup>b</sup>	Eleuthera, Rethymnon	Hellenistic	-	3.00
Kissamos	Kissamos, Chania	Hellenistic	-	4.50

Notes: <sup>a</sup> Underground was brought to the surface through tunnels parts of which have been discovered. Water was flowing through channels and stored in rock-cut cisterns. For further details see Voudouris et al. [8];

<sup>b</sup> The cistern is probably dated to the Roman period but an even earlier date should not be excluded [36].



(a)



(b)

**Figure 3.** (a) View of the cistern used for water storage in Eleuthera (with permission of A. N. Angelakis); and (b) schematic representation of the pipes and cisterns used for storage of the water supply in the ancient Kissamos (from the files of Ephorate of Antiquities of Chania).

#### 4.2. Roman Period (ca. 67 BC–330 AD)

Aqueduct construction on the Island of Crete reached an apex in the Roman Imperial Age, when many aqueducts were built in a time of great economic prosperity. Aqueducts were very common technologies during the Roman period, and larger in size and in capacity and capable of transporting a greater water volume longer distances than those used by Minoan, Classical, and Hellenistic predecessors. Roman aqueducts are found in several places on the island, e.g., Gortys, Lyttos, Chersonisos, Elyros, Falasarna, and Minoa (Marathi) (Table 4). In Elyros, water supplied to the the Roman town was stored in rock-cut cisterns (Figure 4a). In addition, conduits of the Falasarna and Minoa (Marathi) aqueducts are shown in Figure 4b,c. Further details about the aqueducts are given below.

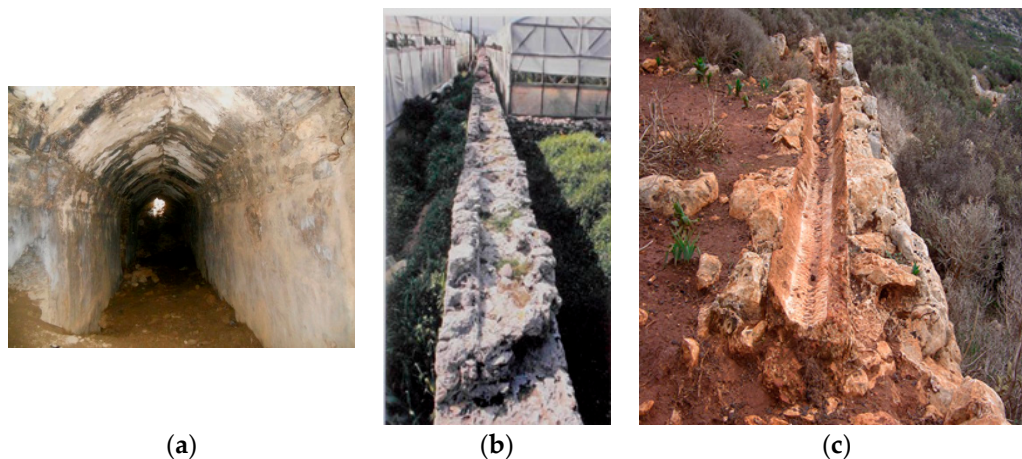
**Table 4.** Characteristics of a selected of Roman aqueducts (adapted from [10,37,38]).

Aqueduct Name	Location	Period	Age of Construction	Length (km)	Flow Rate (m <sup>3</sup> ·Day <sup>−1</sup> )
Axos	Axos, Rethymnon	-	-	-	-
Arkadia	Ini, Iraklion	-	-	-	-
Chersonisos	Hellas	Roman	First half of the 2nd century AD	13	-
Elyros <sup>a</sup>	Rodovani, Chania	Roman	2nd century AD	2	-
Fountana	Skalani, Iraklion	Roman, Egyptian	-	1.15	682.56
Ierapytna	Ierapetra	Roman	-	-	-
Syia <sup>b</sup>	Souyia, Chania	Roman	2nd century AD	8.10	-
Falassarna <sup>c</sup>	Falassarna, Chania	-	2nd century AD	1.40	-
Lefki (Koufonissi)	Island Lefki Island	Roman	-	-	-
Lebena (Lentas)	-	-	-	-	-
Gavdos Island <sup>d</sup>	Gavdos Island	Roman	2nd century AD	1.10	-
Gortys	Crete, Hellas	Roman	Late Roman	15	-
Lyttos	Hellas	Roman	33 BC–14 AD	22	-
Minoa (Chania) <sup>e</sup>	Crete, Hellas	Roman	2nd century AD	1.77	-

Notes: <sup>a</sup> Section of clay pipes 0.25 m × 0.22 m and 0.13–0.18 m (int.) on the wall and underground, respectively;

<sup>b</sup> Pipe section on the wall is 0.20 m × 0.28 m; <sup>c</sup> Pipe section on the wall is 0.26 m (with; height not preserved);

<sup>d</sup> Pipe section on the wall is 0.20 m × 0.18 m; <sup>e</sup> Pipe section on the wall is 0.20 m × 0.12 m.



**Figure 4.** Parts of Roman aqueducts: (a) cistern in Elyros; (b) conduit in Falassarna; and (c) conduit in Minoa (Marathi) (with permission of J. Christodoulakos).

Elyros: the 1st part of the aqueduct which is close to the source: the water pipe was put into a shallow pit. It was covered with stone slabs. The 2nd part of the aqueduct: clay pipes (tubuli), 13 cm in diameter, were partly subterranean and partly ran on a wall up to the cisterns.

Syia: Open water pipe on wall following the contour lines. About 8 km long, with three arcs crossing the ravines.

Falassarna: Open water pipe on wall.

Kissamos: Open water pipe on wall, with wells for cleaning.

Marathi (Minoa): Open water pipe on wall, with one arc.

Gavdos: Open water pipe on wall, with wells for cleaning.

Polyrrhenia: Two independent subterranean tunnels, measuring 2.0 m × 0.80 m, led to the town, each ending to a surface fountain and a subterranean cistern. Midway to one of these tunnels stood a subterranean fountain.

## 5. Byzantine Period and Venetian Rule (ca. 330–1669 AD)

After the end of Roman period, water supply and other hydraulic works experienced fundamental changes in Europe. In Medieval times, towns, villages, castles and monasteries, and other settlements had their own wells, cisterns, and fountains [39]. From 961 to 1204 AD, Crete was part of the Byzantine Empire. “Handax” (present-day Iraklion) was the headquarters of the Duke of Crete. During this



period, the city was under water stress. At the end of the Byzantine period, Crete fell into the hands of the Venetians.

In the period of 1612–1614, Francesco Morosini, named the Duke of the city, recognized that one of the biggest problems of the city was the water shortage [40]. He was the first Venetian that gave much attention to water supply issues. He undertook the responsibility of implementing the so-called Morosini aqueduct, the construction of a 15.64-km line from which the water was transferred from three surface springs (*pelekita*, *Agios Ioannis* and *miristi*) in the area of *Karydaki* (Archanes area, south of the city) into the city center (Figure 5a). The project began at the beginning of 1627 and progressed at a remarkable speed, completed within 15 months. Thousands of workers were utilized (e.g., builders, sculptors, and others specialized technicians), which had been spread out the whole distance of the aqueduct, from the initial spring to the center of the most important square of the city [40].



**Figure 5.** (a) Water bridge of Morosini's aqueduct in Karidaki; and (b) one of its water bridges in the area of Agia Irini (with permission of A. N. Angelakis).

## 6. Modern Times

### 6.1. The Ottoman and the Egyptian Periods (ca. 1669–1898 AD)

Water is part of the Ottoman religion. The cleansing of the body symbolizes the cleansing of the soul, according to the Koran. Thus, a water tap was located in all mosques and hammams. However, during the Ottoman period, in Crete, with the exception of a short period of Egyptian rule, there was no significant water supply work at that time in urban areas (e.g., Iraklion, Rethymnon and Chania). The Ottoman's hydraulic works concentrated on maintaining in good condition the Venetian water supply works [8]. For example, they repaired the Venetian Morosini aqueduct in Iraklion, as they had successfully cut off the water flow from Archanes springs and/or Youktas Mountain during the siege [41]. In addition, during the Ottoman period, numerous fountains were implemented in urban areas throughout the island. Thus, fountains and water supply to hammams were the major hydraulic works developed during the Ottoman period.

The Egyptian rule in Crete followed the Ottoman period (1830–1840 AD). The Egyptians also maintained and operated the water constructions developed by the Venetians. The most known new hydraulic work developed by them is the reconstruction of Foundana aqueduct through which water was transferred to Iraklion from Foundana. At that time, the tunnel at Scalani (1 m × 2 m cross-section and 1150 m in length) was cleaned up by Egyptian soldiers, many of whom died by suffocation while working [42]. The water bridge at Aghia Irini was constructed at the end of this period (ca. 1839) (Figure 5b).

By the end of 19th and the beginning of 20th century, the independent Hellenic-state was established, Crete was united with the mainland and serious progress in new water supply projects was made on the island, despite the difficult economic, political and social conditions. As in other parts of the world, they were based on past technologies as well as new ones such as deep wells, pumps,



pipes, and so on. At that time, the population growth required increased water and the steep terrain of the island highly increased the scale and cost of the required hydraulic projects [16,43].

## 6.2. Present Times (1898–Today)

### 6.2.1. Organization for the Development of Crete, sa (OAK, sa) Water Network at Western Crete

The Organization named OADYK (Organization for the Development of Western Crete, now OAK, sa) was founded in 1979 by the Ministry of Coordination, as the first Greek developmental organization with the aim to contribute to the water supply of Crete. The project “Optimal Utilization of the Water Resources of Western Crete” aimed at the utilization of the underground and ground water resources of western Crete. The initial design was divided into two phases and six areas starting at the western coast of Kasteli and ending at Rethymnon providing drinking and irrigation water using a closed, under pressure network. The initial project, approved by the Ministry of Public Works, included the main water network (of 103 km), the secondary distribution network, and the exploitation of springs and water drillings. The French Organization GERSAR was contracted as an advisor in the design of the network. The first two phases were financed by the European Investment Bank, and National and European funds. Today, the network includes 430 km of main and secondary water networks, 22 pump stations and 25 water sources in western Crete. Crete’s current major aqueducts are shown in Table 5.

**Table 5.** Aqueducts in modern times (Adapted from Voudouris et al. [9]).

Name	Location	Period	Length (km)	Flow Rate (m <sup>3</sup> ·Day <sup>−1</sup> )	References
Potamon Dam	Amari, Rethymnon	2005–2008	Main water network: 15.8 Secondary water networks: 3.9	48,000	OAK, sa. Study with title: “Exploitation of Potamon dam”
Aposelemis dam	Iraklion	2012–2015	30.00	85,000	[44]
Aposelemis dam	Agios Nikolaos	2012–2015	37.00	25,000	[44]
Aposelemis dam	TBM tunnel canyon Rosa	2012–today	3.50	1.728 × 10 <sup>6</sup> For 10 days of flooding per year	OAK, sa. Hydrological Study of the Project, 2010.
Valsamiotis dam	Vatolakos, Chania	2005–2015	3.52	40,000	OAK, sa. Study with title: “Valsamioti dam”

### 6.2.2. The Municipal Aqueduct of St. Ioannis (Water Supply for City of Chania)

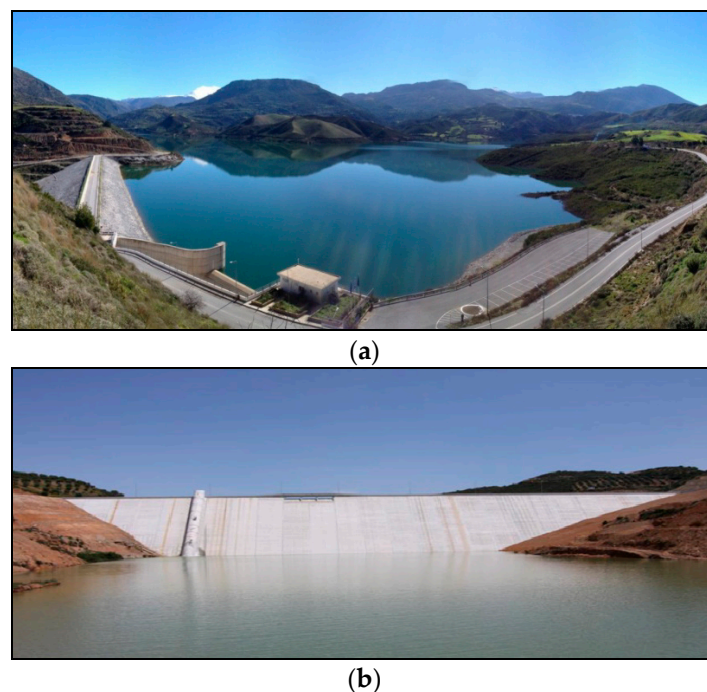
The project began in 1900 with the construction of a central tank with water distribution network in the old town and the small, for this period, extending walls. The construction of the imposing stone building of Tank of St. Ioannis (Figure 6), which stands up on a little hill district of St. Ioannis of Chania, started in 1913 and was completed in 1927. It has a storage volume of 3600 m<sup>3</sup> and is divided into two sections of 1800 m<sup>3</sup> in order to more easily carry out cleaning and maintenance of the installations of the tank, without affecting the water supply in the city. It is located at an altitude 59 m and it supplies water by gravity the low zone of the city of Chania. The tank, until 1936, was supplied with water from sources of Boutounaria region, and since 1937 was supplied with water from the springs of Agia. Today, the water tank of Agia has been removed and the water sources through iron pipes (diameter 350, 700 and 800 mm) feeds the three new tanks built at an altitude of 102 m in the Vandes area, from where a natural flow feeds the reservoir of St. Ioannis [45].



**Figure 6.** The municipal aqueduct of St. Ioannis in Chania: (a) Central tank; and (b) part of distribution water network.

### 6.2.3. Potamon Aqueduct

The Potamon dam (Figure 7a) was constructed in 2008 by the OAK, sa in the Prefecture of Rethymnon, Crete, Greece. It is an earth dam with a height of 55 m and its reservoirs' capacity is 22.5 million m<sup>3</sup>. The projects' aim is the irrigation of 1500 ha in the Rethymnon Plain area and the water supply of the city of Rethymnon. The constructed water networks (Figure 8) consist of 15.77 km of main networks and 3.9 km of distribution irrigation networks. The project is designed to irrigate an area of 2400 ha of the plain Rethymno and to support the water supply of the city of Rethymno. To this direction OAK, sa elaborates the expansion of the mains, the distribution and the irrigation networks in the area.



**Figure 7.** New dams: (a) Potamon (built in 2008); and (b) Valsamoti (built in 2014).

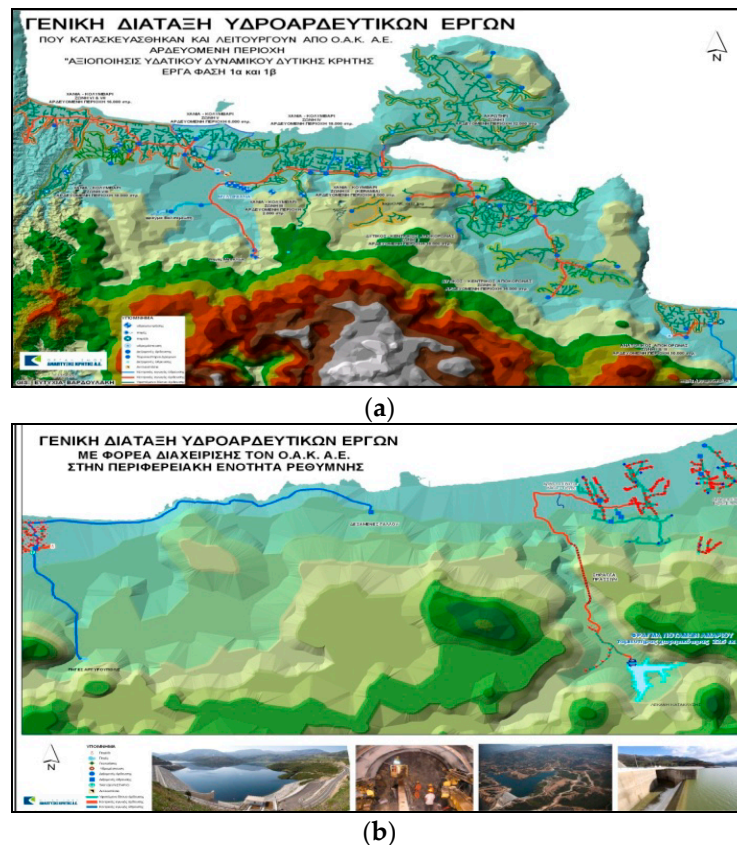


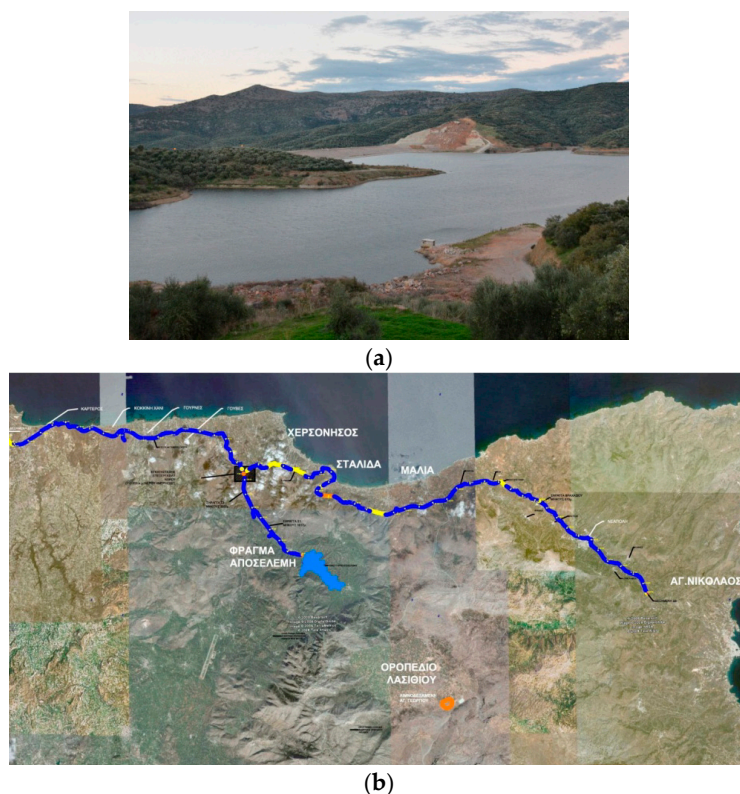
Figure 8. OAK, sa's water works network in the Prefectures of: (a) Chania; and (b) Rethymnon.

#### 6.2.4. Valsamioti Aqueduct

The Valsamoti dam in the area of Chania, Crete (Figure 7b) with capacity of 6 million m<sup>3</sup> of water, supplements the irrigation needs for the Chania Plain area. The dam began operation in March 2014. The connecting water pipeline, with a total length of 3.52 km, connects the reservoir of the dam to the main pipeline Agia–Mylonianon–Meskla. The pipeline supplies the reservoir with water from the springs of Meskla and irrigation water networks from savings banks and sources.

#### 6.2.5. Aposelemis Aqueduct

Recently, following the implementation of the Aposelemis dam (27.3 million m<sup>3</sup> usable volume) in the area of Iraklion (Figure 9a), Crete, two major aqueducts were constructed, for water supply of Iraklion and Agios Nickolaos cities providing drinking water to 264,000 residents and 125,000 hotel guests: one towards the east (Agios Nickolaos, 30 km) and another one in the west (Iraklion, 32.50 km) (Figure 9b). In addition, Aposelemis dam is connected with the water treatment plant with a third shorter aqueduct (3.64 km), which consists of two tunnels (2.05 + 1.59 km). In addition, the aqueduct of Agios Nickolaos includes a small tunnel (cistern) 0.60 km in length. Finally, the project includes a tunnel, at present (2016) under construction with a double shield Tunnel Boring Machine (TBM), of 3.5 km in length, 5 m in diameter and 15% slope, containing the 1.8 m pipe. It will divert floods from the Lasithi high plateau, today lost in sinkholes, to the Aposelemis reservoir.



**Figure 9.** The Aposelemi dam: (a) general view and (b) Water Supply Network Iraklion–Chersonisos–Agios Nickolaos–Malia–Elounda–Neapolis..

## 7. Energy Exploitation of Water Infrastructures and Networks

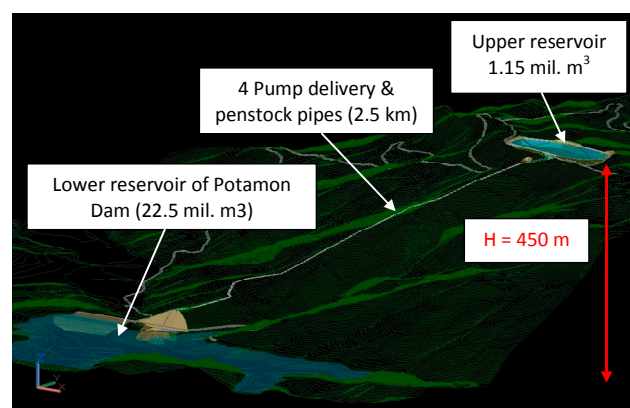
The Island of Crete has the advantage of high potential for Renewable Energy Sources (RES) projects development [13]. One of the policy strategies of OAK, sa is to reduce the cost of electricity, by utilizing its infrastructure (the dams and the water networks), to develop and implement renewable energy projects in order to reduce the energy costs by producing energy and taking advantage of “net metering” as a result of the implementation of Article 14a of Greek law 3468/2006. To this direction, the following projects of OAK, sa are presented.

### 7.1. Energy Exploitation of the Potamon Dam Hybrid Power Station (HPS) 50 MW

The use of wind–hydro hybrid power stations (pumped storage systems) for power production in isolated grids, such as the Island of Crete, appears to be the best solution for maximizing the wind energy penetration, minimizing electricity production cost and overcoming the problems of renewable energy penetration limits to the grid [46–49].

The project consists of a Pump Storage Hybrid Power Station (HPS) (Figure 10) with a guaranteed power of 50 MW. The renewable energy sources consists of two wind farms with a total installed capacity of 89 MW and a water turbine production unit consisting of three reversible fixed speed units with a production power of 50 MW and pumping power of 108 MW. The lower reservoir is the reservoir of the dam, while the upper reservoir with a capacity of 1.15 million m<sup>3</sup> is located in the area named Gargani in the municipality of Rethymno, with a height difference of 450 m and a distance of 2.5 km. The HPS will produce 227 GWh hydro-energy annually delivered to the isolated electrical grid of Crete. The hybrid pump station will contribute greatly in the further integration of renewable energy resource in Crete and in the stabilization of the electrical network, since the electricity generation is guaranteed. Reductions in pollution from existing conventional Public Power Corporation power plants in Crete are significant [14,15].





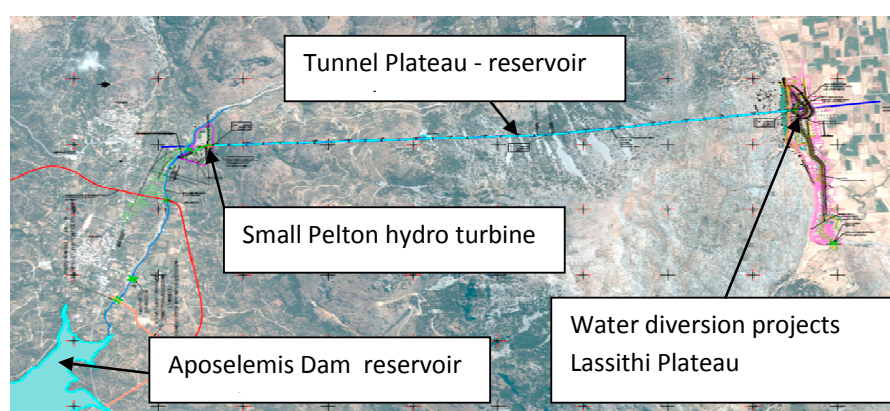
**Figure 10.** Schematic representation of Hybrid Power Station (HPS) in Potamon Dam.

### 7.2. Small Hydro Turbine in the Pipe Connecting the Aposelemis Dam with Lassithi Plateau

The Lassithi Plateau, is located in the north-central part of the island and it covers an area of 129.2 km<sup>2</sup>. The average slope is about 13%. The plateau is drained by the torrent of Chavga and ends in the sinkholes of Chonos and Vidiani, at elevation of 800 m a.s.l. Water that infiltrates the Chonos sinkhole discharges through the springs of Agios Georgios and recharges the streamflow of the Aposelemis River. The karst aquifers of the area are hydraulically connected with the sea, while these karst systems are drained by a significant number of springs discharging brackish fresh water [50].

The analytical project includes the construction of (Figure 11):

- Projects for the water diversion from Lassithi Plateau (to isolate the water sinks of Chonos area and leading the flood water to the tunnel to enhance the reservoir dam Aposelemis).
- Projects of the Tunnel (drilling and construction of a tunnel with total length in horizontal projection 3425.50 m). A tunnel boring machine (TBM) was used and a steel pipe of 1.8 m diameter was placed in this (Figure 12).
- The longitudinal gradient is about 15%, the height difference between the plateau and the Aposelemis dam reservoir is 515 m and the internal diameter of pipe is 4.35 m.
- Projects for the destruction of penstock energy, electromechanical facilities.
- Water pipe to lead the water from the energy destruction point to the Aposelemis reservoir.

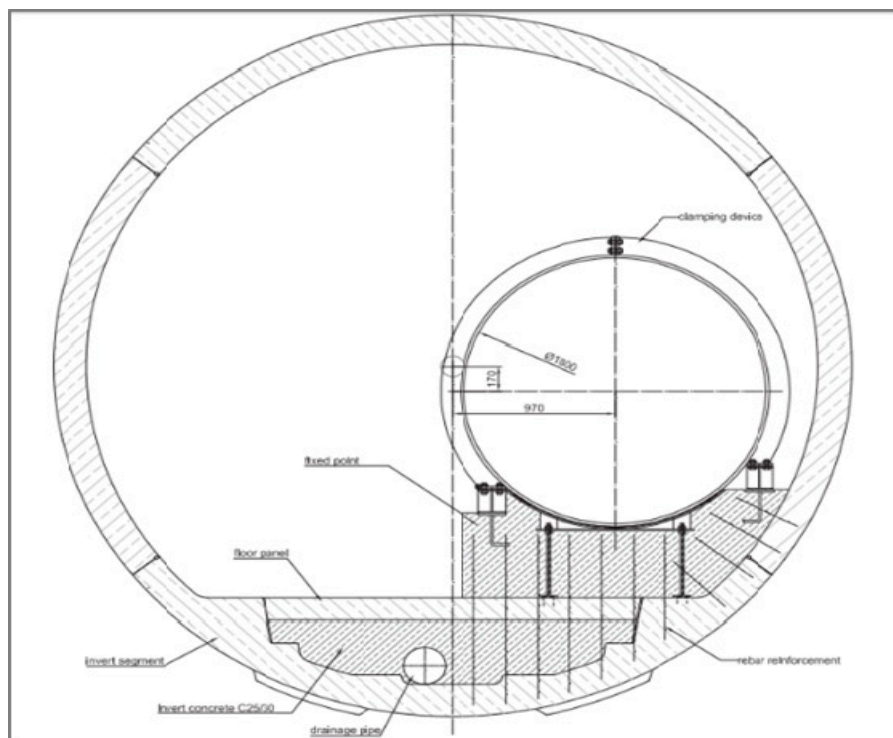


**Figure 11.** Panoramic view of the project.





(a)



(b)

**Figure 12.** Tunnels: (a) Aposelemis tunnel; and (b) tunnel–pipeline section.

The concept of the project is to replace the energy destruction equipment at the end of the pipe with a small hydro turbine for energy production.

Based on the simulation and feasibility study results of the project, the optimal scenario is: Pelton hydro turbine with power 0.5 MW and nominal flow rate  $1 \text{ m}^3/\text{s}$ . The annual produced energy is 6277.85 MWh/year. The initial cost of the project has been estimated to be around 2,550,000 € and the operational cost 51,000 €/year. The annual revenues are estimated at 547,116.62 €/year and the Net Present Value (for 25 years project lifetime) equal to 4,442,240.18 € (payback time: 7 years).

### 7.3. Hydropower Installation in Water Pipelines

In the main irrigation network of OAK, sa (western Crete), there are points with the required technical characteristics (such as height difference, water speed and pressure, pipeline diameter, and being located close to a pumping station for the direct supply of electricity) for hydro turbine installation and energy production. A centrifugal pump can be used as a water turbine (pump as a

turbine (PAT)) by reversing the flow to it, and the discharge port used as the inlet. The use of this kind of pump is common in small hydroelectric systems with medium hydraulic heights and relatively constant values of annual water flow rates. Studies show that with the installation of three PATs of 14 kW each, with nominal flow rate 3800 m<sup>3</sup>/h, 114,800 kWh/year can be produced.

## 8. Conclusions

The climatic and hydrologic conditions in the eastern Mediterranean, and especially in Crete, have been characterized by high variability, both spatially and temporally, through the long history of the island. This had a clear impact on the water availability and thus on the human responses. Rainwater harvesting systems, which increase water use efficiency and preserve the environment for sustainable development through the Cretan civilizations are presented and discussed in this article. The early Minoan water supply systems in Crete were based on aqueduct technologies. These unique hydraulic structures have allowed humans to live in arid coastal areas (e.g., Malia, Mochlos and Gournia). These technologies were mostly developed in Crete in the middle and late Minoan periods when warm and arid conditions were beginning, and were influenced by the social, political, and economic conditions of the various periods of human history of Crete [17]. The development of the hydrotechnologies, whenever the social conditions allowed, can be considered as one of these responses. Looking back at the long history of human inhabitation in the island, one can clearly outline some principles on which past water technologies were based; notably, they are the very same that are used in many applications of the present [16].

In the present article, the evolution of the aqueduct technology in the Island of Crete in Greece, through the centuries, from early Minoan civilization to the modern times, was reviewed and presented. The combination of the climate, the relief and the geological features, along with the cultural development in Crete since the Minoan era, resulted in the development of various and innovative water management techniques that constitute the bases of modern water techniques and systems including aqueducts (e.g., Knossos, Malia, Tylissos and Mochlos). These technologies were continued and improved during the Classical, Hellenistic and Roman periods and at the same time spread to other towns on the mainland and islands. Typical examples are the aqueducts and cisterns and other water supply plants in Polyrrhenia, Eleuthera, Gortys, Kissamos, Elyros, Falassarna, Chersonisos, Ierapytna, Lyttos, and Minoa (Marathi) [42].

Nowadays, the water management in Crete is performed by 11 Municipal Water Supply and Sewerage Companies (DEYA), 38 Local Agriculture Authorities and the OAK, sa, which is the core manager of the large water projects and is the main water supplier of the cities of Chania, Rethymnon, Iraklio, Chersonisos and Agios Nickolaos [12]. OAK, sa is responsible for operation, maintenance, administration, management, and use of water resources in Crete; the systematic monitoring and recording of the source levels, dams, reservoirs and underground aquifers; the monitoring of water quality; input–output in the plants; and for the improvements and interventions in necessary cases for the proper and efficient operation of the system [15].

Although Crete, as a water district, has surplus water resources compared to other Greek water regions, their proper use is hampered by the unequal distribution of the annual volume of precipitation, both geographically (western Crete receives 25% more annual rainfall than eastern Crete) and morphologically (i.e., mountains and lowlands). However, the uneven distribution of water demand in time, which also increases during the dry season (irrigation period, increased water demand for water during the tourist season, etc.) is another factor that requires the urgent need for immediate planning towards efficient water plants and integrated management and distribution of water sources and projects.

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