

Article

Roman Aqueducts in Crete, Greece: Learning From the Past

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Abstract: The Romans were well aware of the strategic importance of Crete and tried, by any means possible, its final conquest. The island was under Roman rule over four centuries (*ca* 67 BC–330 AD). Under Roman rule, Crete witnessed a growth of its population and prosperity and an increase in its connectivity with other parts of the Empire. In addition, Gortys, Chersonisos, Elyros, Lyttos, Kissamos and other cities flourished under their rule. At that prosperous time, several luxurious infrastructures, such as hydraulic works, were developed. In this paper, we wish to examine the principles and the technical characteristics of major aqueducts built at that time. They constructed impressive hydro-works, such as aqueducts, by using the knowledge gained from earlier Greek civilizations in Minoan and Classical and Hellenistic times. However, they mainly increased the scale of applied technologies to support the increased population water demand. Water is a common need of humankind and several ancient civilizations developed simple but practical techniques, such as the aqueduct, especially during Roman times. We can gain from their experience and knowledge to develop a sustainable water supply, presently and in the future, both in developed and developing countries.

Keywords: Ancient civilizations; aqueducts; Chersonisos; Elyros; Falassarna; Fountana; Gavdos; Gortys; Kissamos; Syia; Lyttos; Minoa

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1. Prolegomena

Gortys is considered as one of the most important Roman cities in Crete (Figure 1). Epigraphic evidence demonstrates that Gortys was just as receptive to Roman influence as the poleis of Lyttos, Hierapytna and Knossos [1]. The four powerful cities of Knossos, Lyttos, Cydonia and Gortys returned to civil war as a method of exerting full authority. The Romans intervened with ambassadors in 184, 180 and 174 BC, but the island remained embroiled in war. Marcus Antonius Creticus attacked Crete in 71 BC and was repelled. However, in 66 BC, after three years (69–66 BC) of attempts by the Rome Consul Quintus, Caecilius Metellus, the island was completely conquered. Initially, the island was annexed to Cyrene and became a Roman province, until 298 AD, when it was separated and became an autonomous province [2]. Metellus earned the agnomen “Creticus” as an honor for his conquest and subjugation of Crete [3].

The so-called Law Code of Gortys from the mid-5th century BC includes 12 columns and more than 600 lines of text of 10 by 1.5 m [4]. The inscription was reused and incorporated into the Roman Odeon built under the reign of Trajan (98–117 AD). The Law code contains stipulations on judicial procedure, rape and adultery, marriage, property and inheritance rights. Other laws from 4th century Gortyn (among them the so-called Second Law Code of Gortyn) regulates restrictions for water extraction from the river Litheos to

fields and households and leading water to the land of neighbors [5,6]. Moreover, two inscriptions from Gortys instruct litigants on how to deal with conflicts and how to prevent damage caused by farmers leading drainage water into the neighboring field (ICret IV 73 A, ICret IV 52 A and 52 B, 1–6; this second law is from between *ca* 400–350 BC [6]). This issue was also the subject of a forensic speech by the Athenian politician and orator, Demosthenes, presumably from the middle of the *ca* 4th century BC.



Figure 1. View of Gortys (Photo of A. N. Angelakis).

Archaeological findings indicate the connection of the island with several areas of the Roman Empire [7]. In addition, three of the largest cities in Crete (i.e., Gortys, Hierapetra and Lyttos), from the 2nd century AD, merged with other Greek cities; the union was known as “Panhellenic”, founded during the reign of Emperor Hadrian [8]. Other significant cities in Crete were Aptera, Chersonisos, Elyros, Polyrrhenia, Kissamos, Knossos and Kydonia (present-day Chania). During this period, the Roman population in Crete rose to around 300,000 inhabitants and several luxurious infrastructures, such as theatres, temples, water supply pipes of networks, cisterns, aqueducts and baths were constructed [9,10],

The Roman aqueducts included a series of constructions, such as bridges, canals, tunnels and pipes, used to transfer and supply with freshwater populated areas, even at long distances; usually, surface waters were transferred to cities for drinking, agricultural and other purposes. Their design and construction is considered as fully sophisticated for that period, exceeding in many cases the preceding knowledge of earlier civilizations (e.g., Greeks and Egyptians) [11].

Roman aqueducts are also found in other places all over Greece, such as Athens (Hadrianean), Naxos, Nikopolis, Moria, Corinth and Rhodos. They generally operated using a free water surface flow. In Italy and elsewhere, the understanding of hydrostatics principles as well as other concepts relevant to water and air pressures (due to Archimedes, Hero of Alexandria and others [12]) allowed the construction of even inverted siphons to convey water across valleys in aqueducts at large scales, e.g., Pergamon. Finally, after the 2nd century BC local Greek authorities constructed aqueducts across pre-existing and older borders and boundaries between city-states [13].

The Roman aqueducts in Crete and elsewhere in Greece, apparently allowed ancient civilizations to cope with the various water requirements and challenges, e.g., water scarcity during drought seasons or periods. Thus, the present study aims: (a) to describe the technical characteristics of the major Roman aqueducts in Crete, based mainly on the information in the literature and in situ investigations; (b) to extract and highlight, whenever feasible, the basic ideas and principles governing these Roman aqueduct constructions. This information highlights the technological superiority of the infrastructures built at that time and the potential basic ideas and principles in water supply (i.e., large scale, profitably surface and cost-efficient aqueducts to prevent water loss and possible adverse impacts by climatic phenomena, such as drought). Such information may still be helpful

in addressing current or future challenges in water sector. Water demand and use has been a common need in human history and we still can learn from the ancient civilizations, especially the Romans' water management principles, in a sustainable manner.

2. Methodology

A comprehensive review of the main Roman aqueducts in Crete, Greece, was carried out in the present study to enhance our understanding of the ideas, means, technology and the possible benefits-consequences gained, where it is feasible, in water supply/irrigation and overall water management. Therefore, the available information in literature on the technical characteristics of the main Roman aqueducts in Crete and *in situ* observations are considered and properly elaborated and discussed based on the main objectives of the study. Such information can be valuable and even necessary in the context of the current and future problems and challenges in water technology and management. "Study the past, if you would divine the future" — Confucius (551–479 BC).

Specifically, this review, based on the objectives of the study, is organized as follows: Section 1 — Prolegomena introduces the theme and elements of the review and is followed by Section 2, which discusses the methodology used. Then, Section 3 deals with the physical settings in Crete to provide valid information of the climatic and hydrological conditions of the island throughout the different periods (from the iron period to the present day) as a means to connect and understand the cause and role of the Roman aqueducts in the island of Crete. In Section 4, where the major Roman aqueducts are described, emphasis is given on the available technical information, provided by records in literature, combined with exploring of the landscapes and surface investigation in many cases. Finally, in Section 5, the discussion and conclusions are included in which remarks and highlights are considered.

3. Physical Settings

The land area of the Region of Crete and that of the North and South Aegean cover areas of 8336 and 9104 km², respectively, which account for 6.36% and 6.95% of the total area of Greece, respectively. The permanent population of the Crete and North and South Aegean regions is 623,065 and 508,206 inhabitants, indicating an increase since the beginning of this century of 4.54% and 0.89%, respectively. The total population of Greece during the same period decreased by 1.34%. The population density of Crete and of the Aegean Islands is 74.74 and 55.82 inh./km², respectively [14]. Even if the population densities of both Crete and Aegean Islands are below the population density of Greece, both regions receive a large number of tourists, particularly during the summer months.

Regarding climatic and hydrological conditions, the early Cretans had to develop innovative technological means to capture, store and convey water even from long distances, as well as set legislation and institutions to manage water more effectively [15]. Naturally, the main technical and hydraulic operations associated with water resources development, were aqueducts and harvesting and storage rainwater constructions, followed by the development of sewer and drainage systems. Such operations have been practiced in varying forms since ca 3000 BC [16].

Thereafter, during the Iron period (ca 1300–600 BC) there was another cold and wet period. Then, during classical and Hellenistic times (ca 600–67 BC), the climate was rather warm and dry. During the Roman period (ca 67 BC–330 AD) a colder and more humid period prevailed. In addition, finally, a warm and dry climate prevailed during the Arab period and reached a peak of high temperatures and drought ca 800–1000 AD [17].

Recently, recorded measurements of precipitation (Figure 2), more than a century in Heraklion (black), Chania (blue) and Sitia (red)), shown in the diagram below, confirm the variability of precipitation in Crete, but not their reduction in the popular expressions of "climatologists" [18]. An example of incorrect estimation of climate changes is as follows: if, for example, we are considering the data of Figure 2 (measurements) of Iraklion,

one isolates them from 1964 to 2007 and makes future forecasts, an apparent reduction of atmospheric precipitation will be shown.

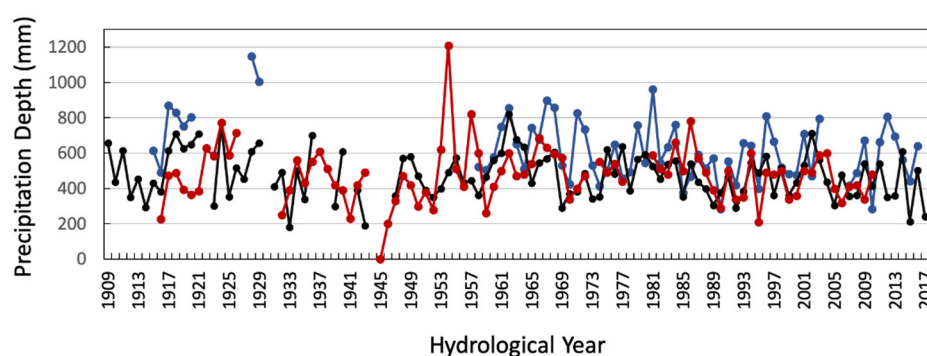


Figure 2. Measured precipitation rates in Chania (blue), Iraklion (black) and Setia (red) for one century (1909–2017) [14].

The precipitation in Crete is characterized by spatial and temporal variation, increasing in amount towards the western and north parts of the island [17]. The mean annual precipitation in the eastern part has been estimated at 675 mm/yr, while in western Crete, it is 1179 mm/yr, averaging 927 mm/yr for the island as a whole (Table 1). The spatial and temporal distribution of mean annual precipitation indicates a considerable correlation with altitude due to orographic effects [19]. The calculated mean vertical rate of change is 61 mm/100 m in altitude. Indicative of the precipitation variation along the terrain of Crete is an analysis of 40-year time-series measurements showing 440 mm/yr at the plain of Ierapetra (SE Crete) and over the 2000 mm/yr in the Askifou upland (NW Crete).

Table 1. Average annual values of the hydrologic circle of Crete ^a (average values in mm and in hm³) (adapted from [14]).

Hydrologic Conditions	u	Precipitation	Actual ET (57.50%)	Run-Off (15.00%)	Infiltration (27.50%)
Normal Year	mm	927			
	hm ³	7,727.47	4,443.30	1,159.12	2,125.05
Wet Year	mm	1244			
	hm ³	10,369.98	5,962.74	1,555.50	2,851.74
Dry year	mm	610			
	hm ³	5,084.96	2,923.85	762.75	1,398.36
Year 2017–2018	mm	480			
	hm ³	4,001.28	2,300.74	600.19	1,100.35

^a Data of 40 years from 90 Meteorological stations.

4. Major Roman Aqueducts in Crete

In general, aqueduct technology in the Mediterranean reached an apex in the Roman period (*ca* 100–330 AD), when hundreds of aqueducts were built in a time of great economic prosperity [20]; Roman aqueducts are also found in many locations of Europe, Africa and Asia [21]. Compared to Minoan, Etruscan and Hellenistic aqueducts, Roman aqueducts were arguably more typical with greater water capacity [21].

Hydro-technologies on the island of Crete were highly increased during the Roman times [22]. In principle, the technology of Roman aqueducts was very similar to that developed earlier during the Archaic, Classical and Hellenistic periods, but larger in size and capacity, capable of transporting greater water volumes at longer distances [22]. In the Roman period, aqueducts are found in several places on the island, e.g., Apollonia

(Agia Pelagia), Chersonesos, Gortys, Elyros, Diktyнна, Falasarna, Funtana (Scalani tunnel), Hierapytna, Ini (Arkadia), Kasteliana, Lappa, Lassea, Syia, Lyttos, Minoa (Marathi), Pachyammos, Tarra (Agia Roumeli) and Tholos (Kavousi) (Table 2). In addition, most of these major Roman aqueducts are shown in Figure 3.

Table 2. Characteristics of selected Roman aqueducts (adapted from [21–23]).

Aqueduct Name	Location	Period	Age of Construction	Length (km)	Flow Rate (m ³ ·d ⁻¹)
Axos	Axos, Rethymnon	-	-	-	-
Arkadia	Ini, Iraklion	-	-	-	-
Chersonisos	Chersonisos Heraklion	Roman	2 nd –6 th century AD	14.00	-
Elyros ^a	Rodovani, Chania	Roman	2 nd century AD	2.00	-
Fountana	Skalani, Heraklion	Roman, Egyptian	-	1.15	682.56
Hierapytna	Ierapetra	Roman	-	-	-
Syia ^b	Souyia, Chania	Roman	2 nd century AD	8.10	-
Falassarna ^c	Falasarna, Chania	-	2 nd century AD	1.40	-
Lefki (Koufonissi)	Island Lefki Island	Roman	-	-	-
Lassea	Kali Limenes, Heraklion	Roman	-	-	-
Gavdos Island ^d	Gavdos Island	Roman	2 nd century AD	1.10	-
Gortys ^e	South Heraklion	Roman	2 nd –6 th century AD	15.00	7,000
Lyttos ^f	Xidas, Heraklion	Roman	33 BC–14 AD	22.00	-
Minoa (Chania) ^g	Akrotiri, Chania	Roman	2 nd century AD	2.78	~ 250

Notes: ^a Section of clay pipes 0.25 m × 0.22 m and 0.13–0.18 m (int.) on the wall and underground, respectively. ^b Pipe section on the wall is 0.20 m × 0.28 m. ^c Pipe section on the wall is 0.26 m (with; height not preserved). ^d Pipe section on the wall is 0.20 m × 0.18 m. ^e Cross Section 0.50–0.60 × 0.9–1.0. ^f Stone made siphon. ^g Pipe section on the wall is 0.20 m.

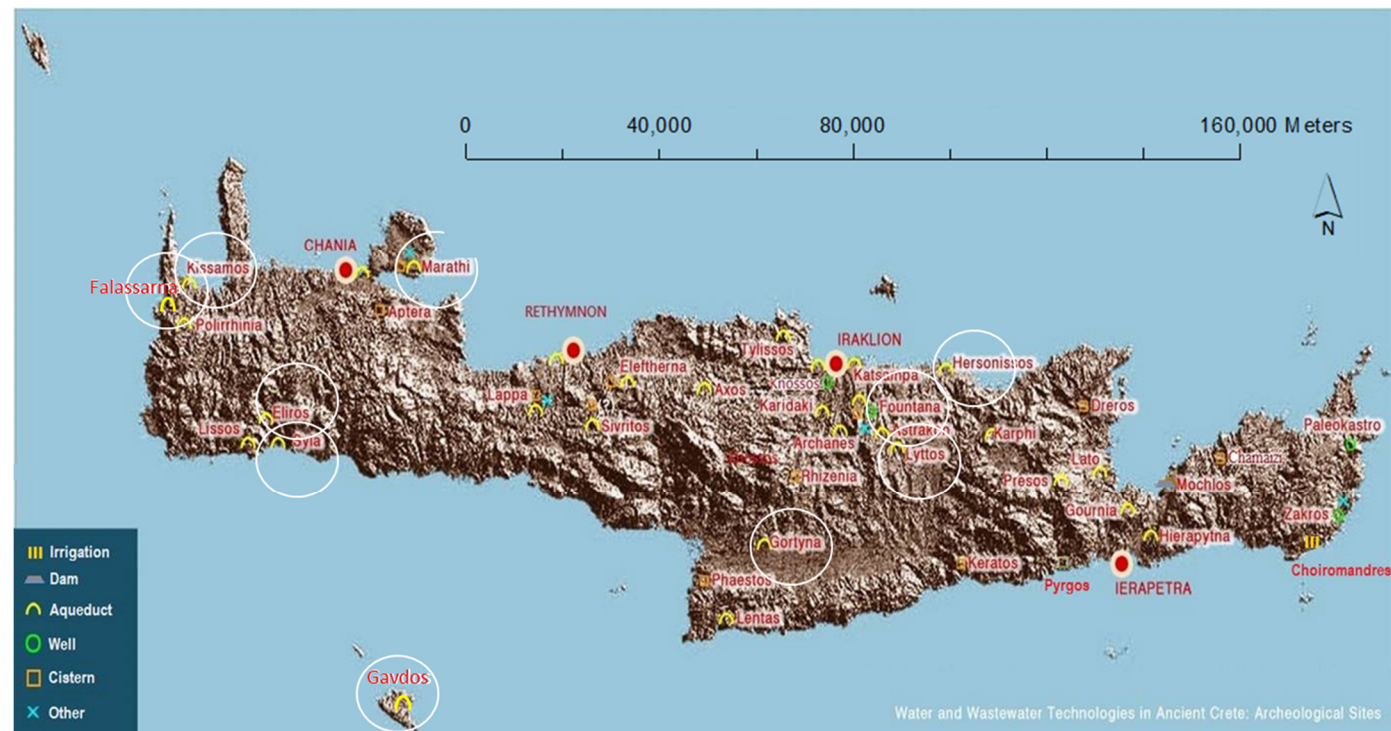


Figure 3. Geographical locations of the main aqueducts in the island of Crete, also including dams, wells, cisterns and irrigation channels. In circles are the locations of the aqueducts described in the study (provided by A.N. Angelakis).

Roman aqueducts were usually constructed as buried masonry canals with a rectangular inner profile and a semicircular vault (Figure 4). The larger channels were high enough to allow workers to cross. Structures like bridges (e.g., Gortys), inverted siphons (e.g., Lyttos) and tunnels (e.g., Fountana in Scalani) are standard applications in these constructions. Roman aqueducts in Crete were fed by one single water source and nearly all had a single target, i.e., water supply of urban areas. Further details about the aqueducts are given below.

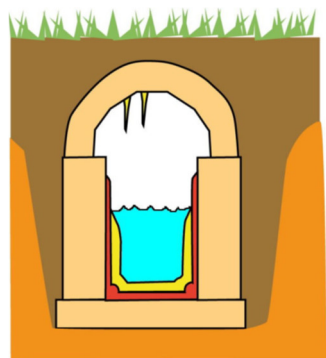


Figure 4. Typical cross-section of a Roman aqueduct channel. The channel is built of masonry and lies in an excavation in the soil. The inside is covered with a red waterproof cement (opus signinum—in red), with characteristic quarter rounds to seal the edges. Carbonate deposits (yellow) are common in some channels [21].

4.1. Lyttos

Lyttos, a prosperous Roman city despite its unfavorable location altitude [24], is known for an impressive Roman aqueduct of 22 km in length [15]. The water source was located on the west side of the Nissimos Plateau, a few kilometers south of the village of Krasi, at an altitude of over 600 m (Figure 5) [25]. The most visible ones can be seen between Kastamonitsa and Tichos. Notice that “tichos” in Greek means wall. It is a stone wall that in some places reaches 10 m in height (Figure 6a). At ground level, the wall is more than 2 m wide. Unfortunately, so far, no visible remains have been found until Lyttos. The presence of stone pipes is quite unique; unfortunately, most of them were used locally as a building material [25]. The one on Figure 6b, right with dimensions of 0.52 x 0.52 m² and 0.66 m long, was found in a garden of a villager of Kastamonitsa and had a bore of 21 cm in diameter without any sign of connection (no male or female side or rings) [25]. These stone pipes can serve as a conduit under pressure and have been used to build an inverted siphon on top of the wall (tichos) [26]. Aerial photographs overlaid [27] with remnants are shown in Figures 5 and 6, respectively.

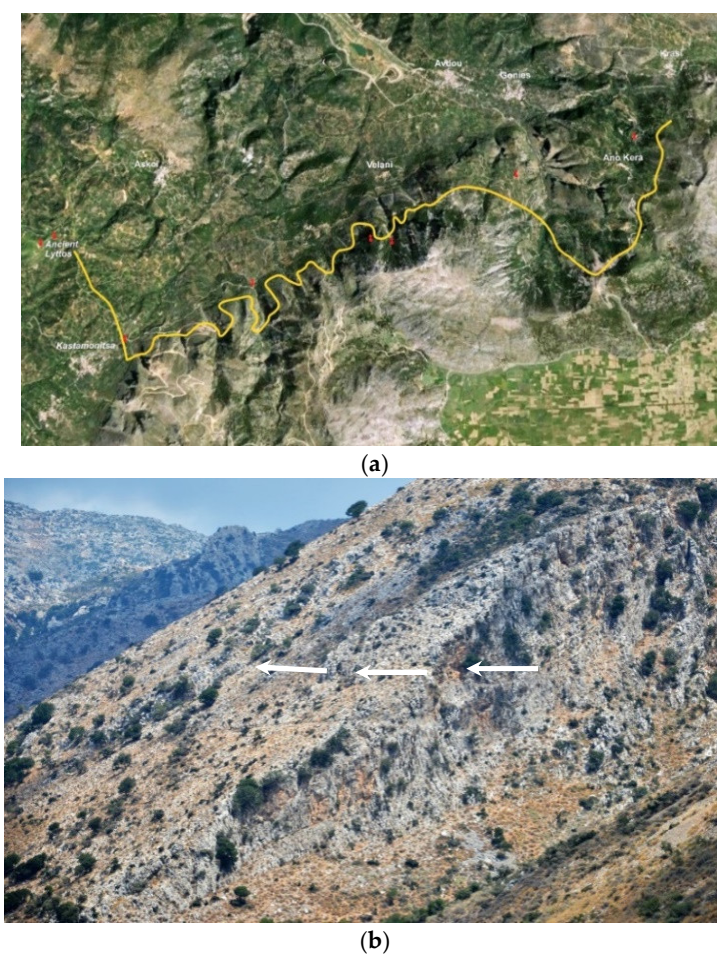


Figure 5. Lyttos aqueduct: (a) Aerial photograph overlaid with Oikononakis (after [27]) and (b) the pass of the aqueduct in the location of Petrokopoio (photo by A. N. Angelakis).



Figure 6. Remnants of Lyttos aqueduct: (a) of the aqueduct (known as tichos) [24] and (b) a stone used in the inverted siphon (photos by A. N. Angelakis).

4.2. Chersonisos

The aqueduct of Chersonisos, which brought water to city from mountain villages to the south, is thought to have been 14 km in length, while an underground reservoir has also been found, measuring 58 m in length, 22 m wide and 5.5 m deep [28]. This shows that Chersonisos had grown into quite a large city during Roman times, also indicated by other infrastructure findings [24]. A layout of the Chersonisos aqueduct is shown in Figure 7a. In addition, there is a large complex of tanks, the largest in Crete, measuring 55 m

$\times 18.50 \text{ m} \times 5.5 \text{ m}$ and a capacity of 5596.25 m, found only in areas outside Crete [24]. The aqueduct and reservoir residues are shown in Figure 7b and c, respectively.

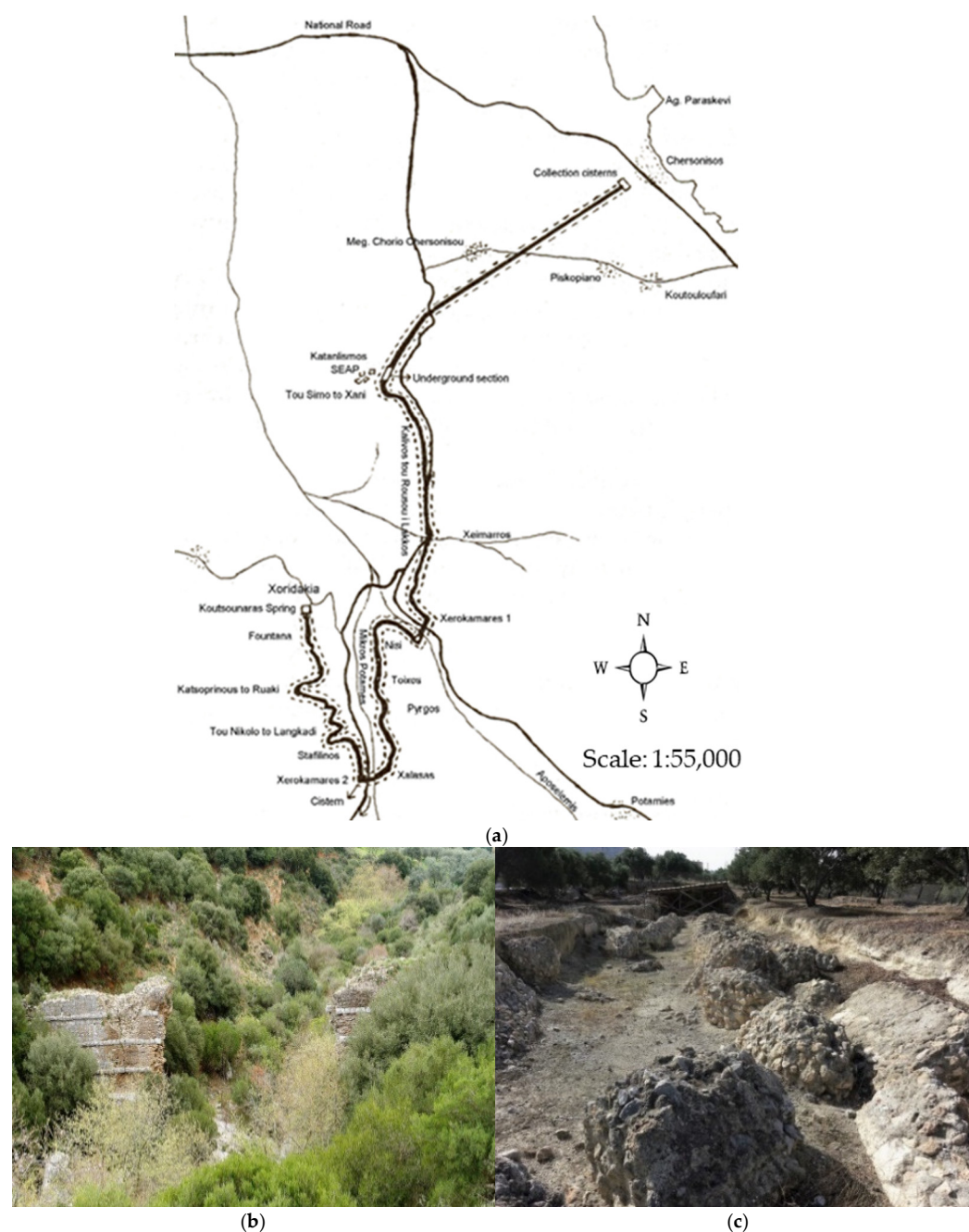


Figure 7. Chersonisos aqueduct: (a) the layout (scale: 1:55,000) [28], (b) remnants of a water bridge and (c) Cistern complex in Piskopiano (photos by A. N. Angelakis).

4.3. Gortys

The first indications suggest that the city was constructed originally during the Minoan era. The water of the city was provided by a large-scale aqueduct that extends from Zaros springs to the city of Gortys via the southern slope of Mount, Zaros, Panagia and Moroni to reach the acropolis of Gortys and the benefits to the capital Crete at that time are obvious (Figure 8a). Recent studies have provided a picture of the city's water supply system, dating to the Late Roman and Early Byzantine periods [29]. Water was transferred to the city from the springs of Zaros, ca 15 km away (Figure 8a). Before reaching the acrop-

olis, the aqueduct was divided into two branches of different dimensions. There is a man-hole near the acropolis for access to the subterranean channel. The inscription mentions an aqueduct built by a high priest of Koinon of Cretans. It is of rectangular section, constructed by trapezoidal bricks. Average dimensions of specus are: W 0.50 m and H 0.70 m. A large siphon with receiving tank is preserved, constructed near Lethaios River [30]. The aqueduct bridged the deep Metropolianos River and ended on the hillside above the Agora at Volakas. Thereafter, it was divided into a system of ceramic conduits supplying the different areas of the city [31]. The remnants of Gortys aqueduct and a Cistern in Praetorium are shown in Figure 8b and c, respectively.

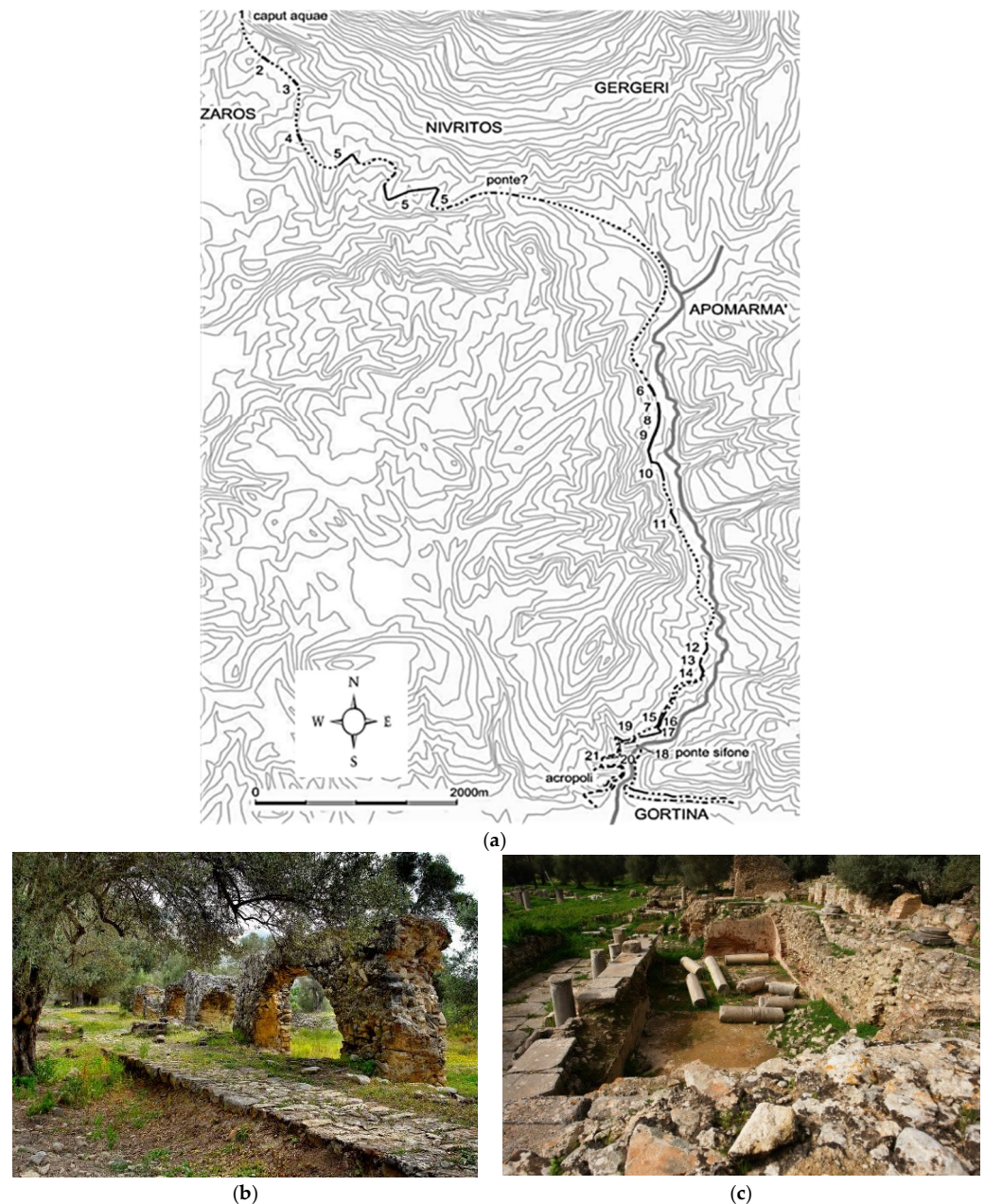


Figure 8. Gortys aqueduct: (a) the layout [32], (b) the remnants of it before reaching Praetorium and (c) Cistern in Praetorium (photos by A. N. Angelakis).

4.4. Fountana, Iraklion

During the Roman Period, the economic relations between Knossos and Iraklion city continued affecting the treacherous conditions of the two settlements. Thus, the water

supply of Iraklion was probably based on that of Knossos [33]. The water supply of Iraklion in the Roman period was based on wells and reservoirs, as in previous periods. However, the further increase of the population of the two residential complexes and their water supply needs could not be addressed from the spring Mavrokolympos, in which the water supply of Knossos was based since the Minoan Era. The Fountana aqueduct was probably built during the Roman period to bring water from the spring located in *Vathis* river [34]. It is 11 km long, starting from the spring of Fundana of $Q = 7.9$ L/s in 1867 [35]. There is evidence that the Fountana spring was originally used by the Romans [35]. However, the central part of the Fountana aqueduct was rebuilt during the Egyptian Period (ca 1830–1840) (Figure 9a). At that time (1839), the tunnel in Skalani was reconstructed with a cross-section of 1×2 m² and a length of 1150 m (Figure 9b). It should be one of the longer Roman tunnels in the Mediterranean region. The spring is located 5 km from Knossos, at an altitude of 220 m and the entire supply of good quality water is still used today for the water supply of the city of Iraklion [16]. In this period, the famous water bridge in Agia Irini, in Spilia area (6 km from Iraklion), was also constructed. Through the bridge construction, the Fundana aqueduct was connected with that of Morozini aqueduct, implemented during the Venetian period (ca 1204–1669), to improve the water supply of Iraklion city [36]. This aqueduct is still in use today, by having replaced the opened conduit with a PVC-pipe.

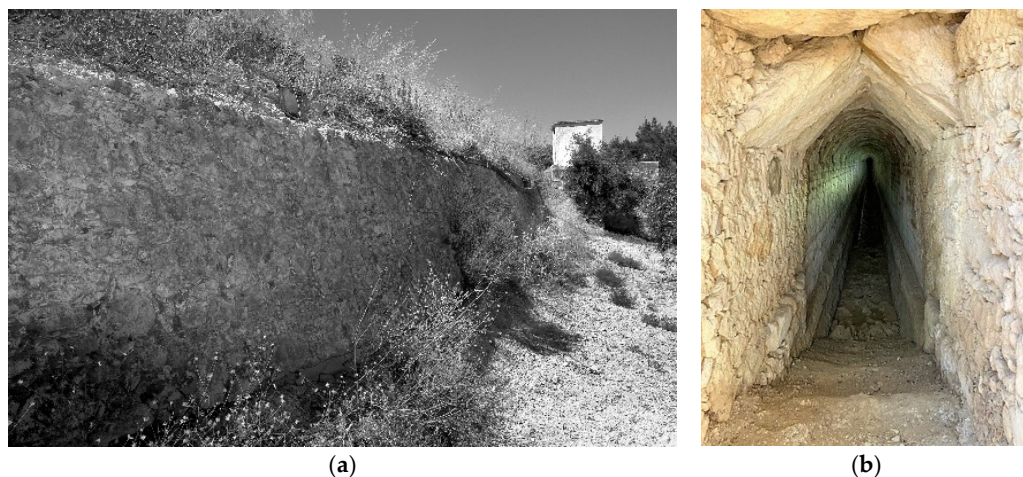


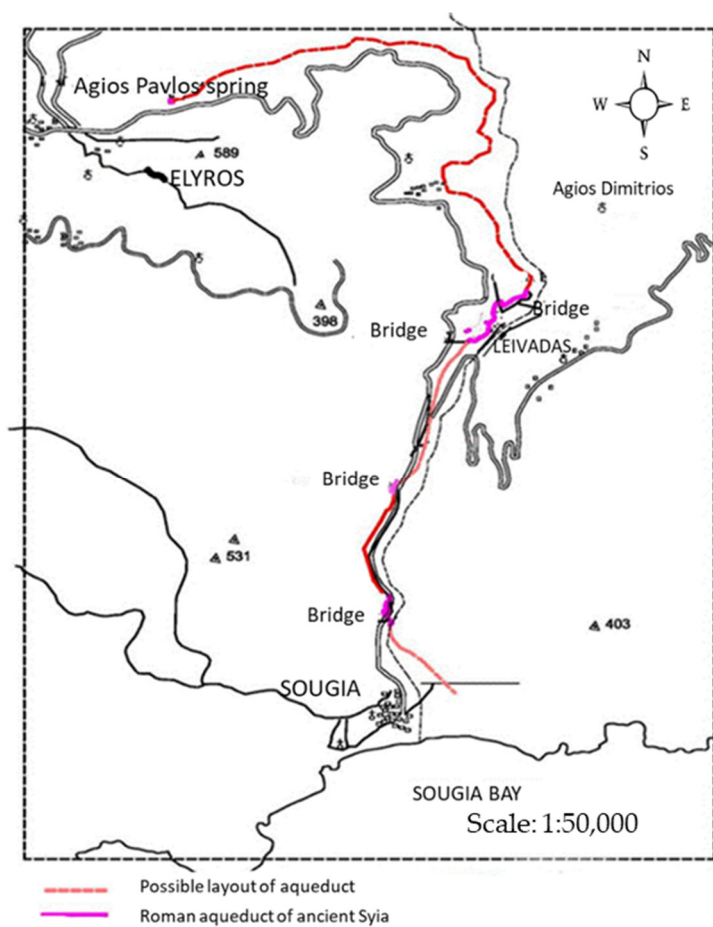
Figure 9. Fountana aqueduct: (a) remnant of it and (b) cross section of its tunnel (photos by A. N. Angelakis).

4.5. Syia

Ancient Syia (modern Sougia) lies on the southern coast of Selinon district (Figure 10a); Syia was Elyros port. On the eastern bank of torrent “Lakkos Zografou”, we can see extensive ruins of Roman buildings, as well as aqueduct remains [37]. There is sufficient evidence for this aqueduct on the way to Sougia, reaching at some parts at a height of 5 m (Figure 10b). It was probably fed by the spring located at Ayios Pavlos (Figure 10a). This source supplies Livada village with enough water today. It lies north to Kefala hill, where the acropolis of Elyros is located, at +500 m altitude. The first visible remains registered to lay near Moni village, 3326 m away from ancient Syia center, while their assumed continuation up to Ayios Pavlos source would be 4815 m long. Therefore, the aqueduct may have had a total length of around 8 km (remains 936 m long have been registered) (Figure 10a). The entire known part of the aqueduct is constructed as a conventional channel of natural flow on the wall. The pipe’s characteristic route follows the relief contours to maintain a small but steady slope. The wall is mostly made of coarse stones, with the outer part roughly processed.

Except for some sensitive areas regions, such as the ravine span, where the arch made of carefully cut stones is visible, the rest of the construction is designed to avoid high walls

or arches, while the average height of the wall is about 1.5–2 m. This explains the significant difference in length, which initially was around 4.1 km, later increased to 8 km in order to avoid steep slopes and high tall walls or arches. The location where the aqueduct forms a bridge over the river near Sougia was chosen so that the pipe could reach the city where the ground is favorable and the distance between the two banks is 70 m. The wall there is 5.50 m high. It follows a route difficult to explain today. Thus, while the relief explains crossing the stream 20 m in advance, the polygonal route increases its length by 44 m on a fairly high wall (5.5 m). It can only be assumed that the additive construction aimed to limit the stream speed before it entered the city (the slope of the channel was measured and found to be almost naught in this position).



(a)



(b)

Figure 10. The water pipe route in Syia (Sougia): (a) Map on background scale: 1:50,000 (Provided by Y. Christodoulakos on background of the Hellenic Military Geographical Service maps [38]) and (b) water channel on wall (photo by Y. Christodoulakos)

4.6. Minoa

Minoa, one of the two ports of Roman Aptera, is located at Marathi, on the northern coast of Suda bay of Chania Municipality (Figure 3) [39,40]. The aqueduct on a background scale of 1:5000 is shown in Figure 11a. Before the 2nd World War, excavations revealed a pier, cisterns and other roman buildings (Figure 11b). A spring with sufficient water in the summer rises near the deserted village Pervolitsa, a 2.36 km NE of the Roman ruins, at +99.10 m [41]. A fountain stands there with an underground reservoir and hydraulic plaster (Figure 11c).

Three wall sections are visible at St. Nikolas, south of Pervolitsa, 1.8 km away from the roman construction at +74.40 m. These sections are 4 m high and 26 m long in total, carefully situated on both sides of the stream [42]. There should be an arch to span the ravine so that the pipes route would not be disrupted. After repeated visits, a total length of the remains of 735 m was finally registered [42].

Regarding the stream span upstream, the wall bearing the water channel is visible to a length of 78 m. Downstream the span remains; the wall is partially preserved on the steep bank, carefully anchored to the rock. Following roughly the contour of 70 m on the foothill, a wall runs preserved to a length of at least 581 m. It is 60 cm wide and 0.80 m to 1.0 m high.

Drains of waste rainwater for wall protection are partly visible. The channel has a trapezoidal section measuring $0.20 \times 0.07 \text{ m}^2$ and 0.08–0.10 m high, with internal hydraulic plaster and an adequate bed slant to prevent sedimentation. We still can see mineral incrustation on several spots (Figure 11d).

The total registered length is 735 m, while the remaining undetected part should be 2,043 m long. Therefore, the total length is estimated 2,778 m and the horizontal distance between the stream and the buildings is 2,366 m. This was a “private” aqueduct, since it did not supply water to a city or village, but, instead, a villa consisting of baths, administration areas and perhaps vessel servicing. If feeding the villa and the port, could it be qualified as “private”? In addition, securing a smooth supply of water to the harbor facilities was a matter of great significance; therefore, the required decisions and supervision should be made and executed by the administration.

During restoration works of the Roman complex, carried out by the 25th Ephorate of Antiquities of Chania, Crete, in 2016, plenty of clay tubes aroused our interest. At first glance, it appeared as though these were unused water pipes, without any discernible

traces or remnants of plaster sealing the junctions, nor any mineral sediments from the water flow. In addition, the inner surface was unprocessed. Another characteristic of the “pipes” is their short length of 19 cm, including the adaptation piston. A significant difference in the diameter of the piston was noted; “male” with Φ 5–5.5 cm, “female” with Φ 8–9 cm. Therefore, the adjustment would lead to large gaps and waterproofing would be problematic. The widespread discovery of such tubes not in situ (besides those found in the new excavation trench of 2016 in “area Θ ”), is also mentioned in the excavation report of Theofanides [42]. Thus, we can assert that the reason behind the existence of so many tubes was their use in the manufacture of arches and vaults, necessary for the housing of vaulted bathtubs in the complex.

Additional examples for using similar tubes in the making of arches and domes are detected in various areas, both in antiquity and beyond. In northern Africa, during the second half of the 2nd century AD, pipes of 6 cm in diameter were used almost exclusively to construct arches and vaults. Lynne C. Lancaster indicates examples of the construction manner, as well as the different tubes used in each area. Consequently, the “shell technique” involving placing such interconnected tubes covered with plaster is imported from N. Africa during the 4th century AD to Rome and Ravenna [41].

The existence of an aqueduct corroborates the view that the Roman complex in Marathi was a productive administrative coastal center of strategic significance and authority. A sea-side “castrum” with the objective of defense and a communication sense in power. One of the two harbors of Roman Aptera was still thriving during the Roman rule [43].

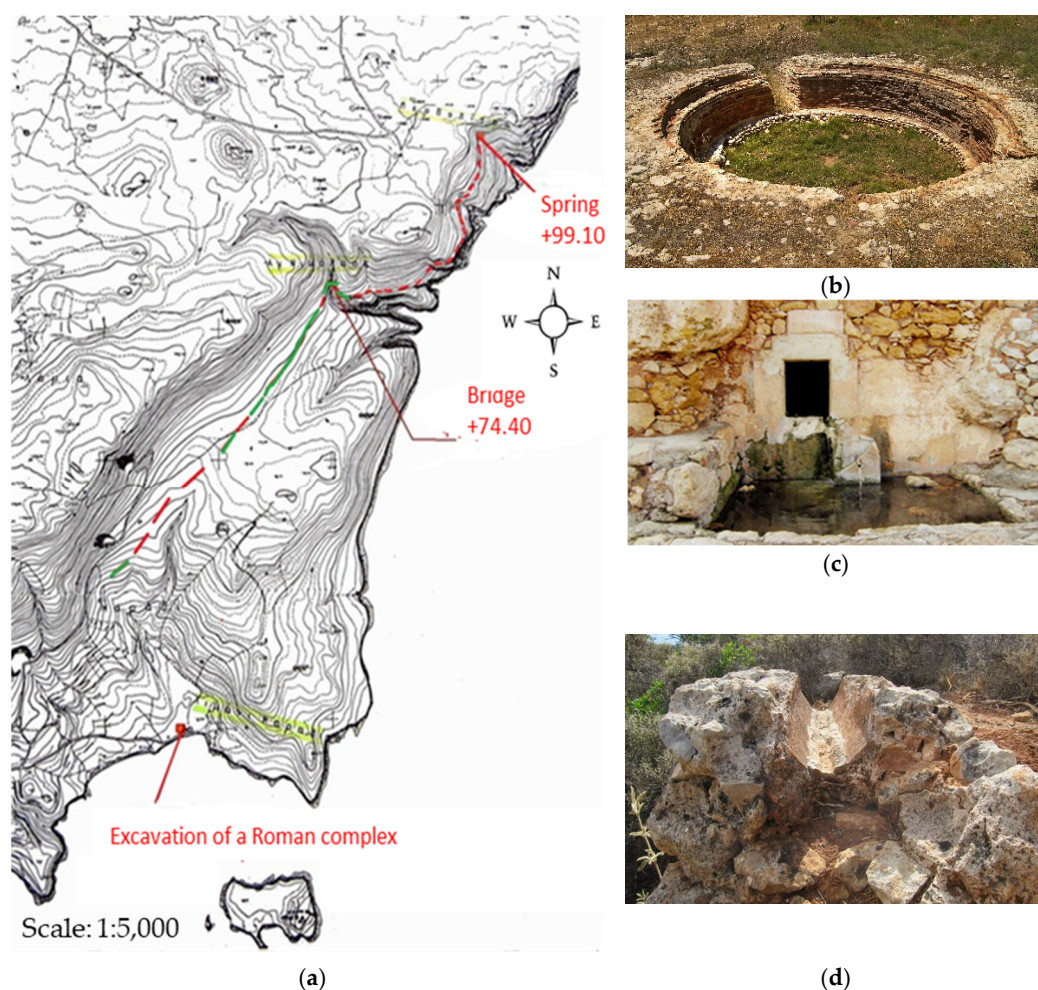


Figure 11. Minoa aqueduct: (a) The aqueduct on background scale 1:5000, preserved part in green (provided by Y. Christodoulakos on background of the Hellenic Military Geographical Service

maps [38]); (b) cistern at Marathi (photo taken by A. N. Angelakis); (c) source at Pervolitsa; and (d) cross section of the aqueduct (photos (c) and (d) taken by Y. Christodoulakos).

4.7. Falassarna

Ancient Falassarna, a city-state of Hellenistic dominion, is located in Kissamos Kissamos Municipality and is referred to as a pirates base of operations, according to archaeologist E. Hadjidaki. Later in the 4th century, the city minted its own coins. During the 1st century BC, Falassarna was destroyed by the Romans [44].

In the flatland 3 km south of the city, the remnants of an aqueduct wall are preserved. It is shown in Figure 12a. The wall is 229 m long and 0.50–2.5 m high and 0.75 m wide. It rests today among the tomato greenhouses, while part of it has been incorporated into a farmers storehouse (Figure 12b). The supporting wall of the pipe is orientated N–S, with the north part bent towards the sea. Its continuation is disrupted, however, by the rural road, while the southern end is poorly preserved until its traces are lost. The rectangular channel, 0.26 m wide, is visible in four spots on the wall, while its height is nowhere entirely preserved. The upper section must have been covered for water protection. An incrustation on the hydraulic mortar coating the channel is discernible, as well as the connection mortar of the wall. We can easily assert that it is a typical aqueduct of the Roman era; the wall is in *opus caementicium* and the pipe is coated with *opus signinum*.

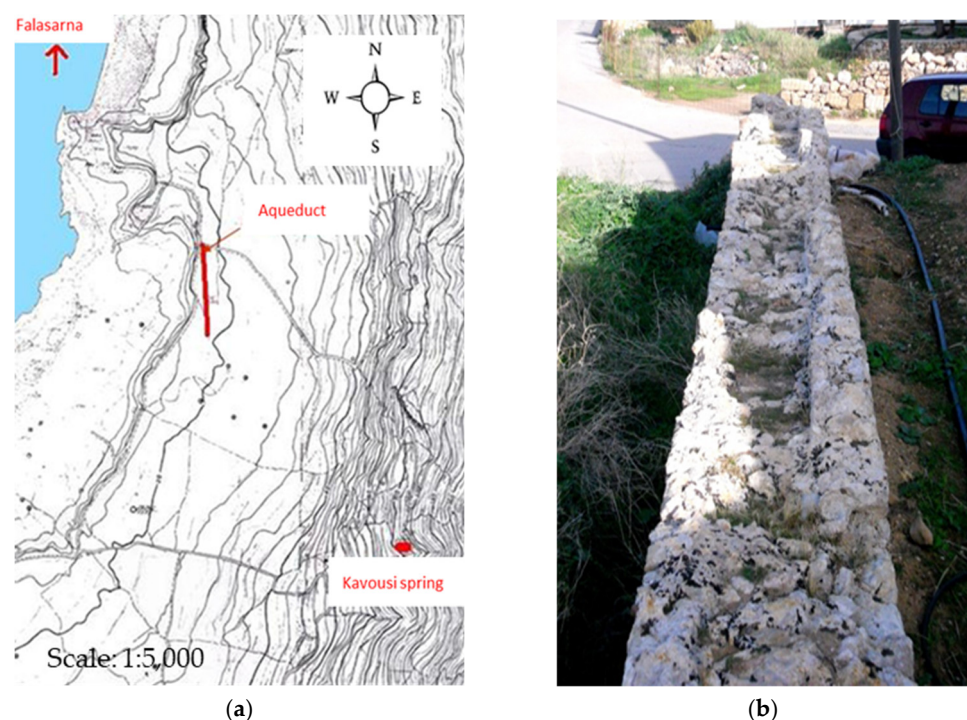


Figure 12. The aqueduct of ancient Falassarna: (a) Preserved part of aqueduct, background scale 1:5000 (provided by Y. Christodoulakos on background of the Hellenic Military Geographical Service maps [38]) and (b) channel remains (photo taken by Y. Christodoulakos).

The direction of the aqueduct is uncertain, as there is no extensive Roman settlement in the area. Even if it was directed towards Falassarna, which is difficult considering the level of the channel (+ 15.40 m according to Mrs. E. Hadjidaki, who excavates in the area), the city was destroyed by the Romans and never rebuilt. Thus, we must assume the water supply concerned important Roman estates of the area, whose remains have yet to be discovered (it is rare for such evidence to disappear).

Another question is the water source, which is assumed to originate in the area near “Kavoussi”, according to residents who saw traces of the pipes, as well as to our own observations of nearby sources that are still functioning. In this area, two sources have

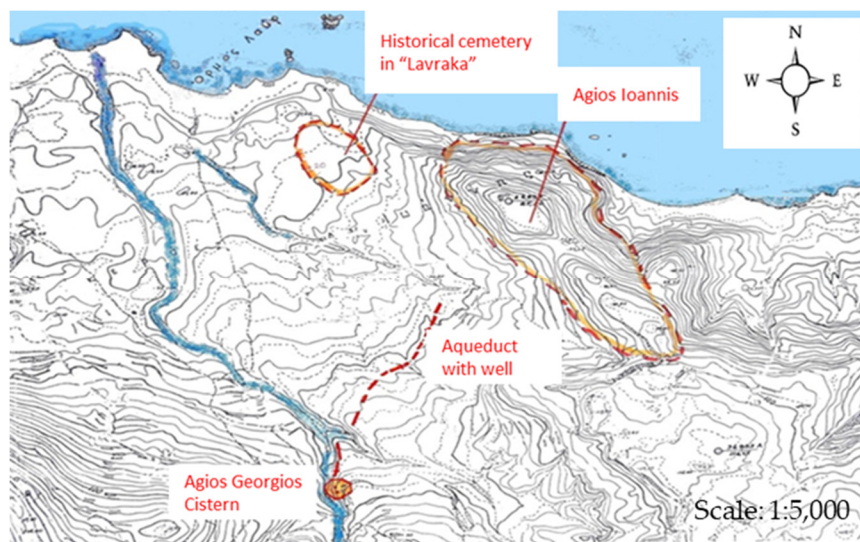
been identified that supply enough water to this day. One of them rises at the NE of the aqueduct, in the village of Kavoussi, at + 95.00 m altitude and 882 m horizontal distance from the sea. The other source is to the north, 1484 m in horizontal distance and +45.00 m altitude. Neither of them shows any ancient evidence, which is understandable considering the constant care and maintenance of the water supply (Figure 12). Either one could have supplied the aqueduct with water. However, given the difference in altitude, the second source is a more probable choice, even though it is significantly further away. This is because the second source would ensure a smoother slope of approximately 1.5%, while the first one had a much larger one of 6%.

A very careful etching is observed here [45], still under the Vitruvius limit for an adequate slant. The plain is nevertheless favorable for a smooth gradient and our evidence rather limited to fully evaluate the aqueduct construction [46].

4.8. Gavdos Island

Gavdos is a small island south of Sfakia Municipality (the location is shown in Figure 13a). During a survey conducted in 1990–1995 by the 25th Ephorate of Antiquities of Chania and the University of Crete (represented by archaeologist V. Drossinou and Y. Christodoulakos) it was found that a purely Roman aqueduct has been located on the island [47] (part of a water pipe 57 m long on a wall of 1 m average height). At the point of a route shift, a shaft is preserved, measuring 1.18 m × 0.50 m inside (Figure 12b). The wall 0.60 m wide bears a channel on top, 0.20 m wide, 0.18 m deep, plastered with *opus signinum* 1.50 cm thick. No covering to the channel has been found [48].

The shaft bed is a slab coated with mortar [49]; its walls are slightly sloped and coated with hydraulic mortar as well (Figure 13b). The construction is elaborate in order to prevent sedimentation of loose material as well as for easy cleaning. The aqueduct is set up close to the church of Ayios Georgios. One of the two springs on the island still rises here, the other one being at Korfos. In the river bed, the remains of a small tank (Figure 13c) are visible, measuring 3 × 1.70 m; it is connected to a wall bearing the channel. Its bed is coated with hydraulic mortar and walls are in *opus testaceum*. The tank rests on the rock whose erosion caused the superstructure to crumble. This tank should be considered as the *caput aquae*. In the same area, mainly south of this tank, channels or small tanks are cut into the rock, but their connection to the aqueduct is not ascertained because they have been repaired and altered through use. It is easy to assume that they may have served for water management. This aqueduct is important as no extensive settlement of the Roman times has yet been recovered, since the area has not been systematically excavated. At the Ai Yannis site (St. John)), ruins of different periods are visible, mainly those of historical times. The presence of an aqueduct suggests a settlement, if not a city, as it implies an organized society.



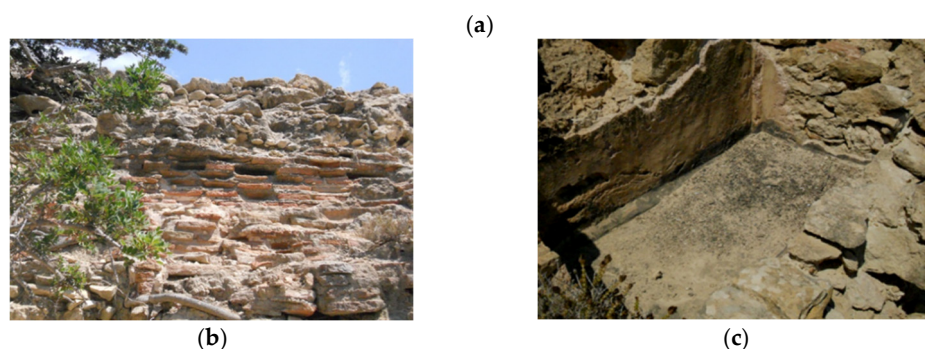


Figure 13. Roman aqueduct of the island of Gavdos: (a) Background scale 1:5000 (provided by Y. Christodoulakos on background of the Hellenic Military Geographical Service maps [38]), (b) the beginning and route of the aqueduct and (c) the cistern (photos taken by Y. Christodoulakos.).

The construction and quality of the material are not inferior to other Cretan aqueducts. *Opus signinum* and *opus testaceum* imply an “industrial” production of mudbricks widely used here. The aqueduct direction points to Ai Yannis, the most extended and significant site on Gavdos. It must have traversed a distance of at least 1 km to the NE side of the hill.

The aqueduct gradient has been measured on two spots where the bed is preserved: On the first, a slant difference of 21 cm to a length of 6.60 m has been measured. On the second spot, there is a slant of 27 cm to a length of 2.90 m; therefore, a gradient equal to 9.50% was measured. The gradient on both spots must be considered as high [50], especially the second one, but, concerning a small pipe length [51] (the average gradient of Rome aqueducts has been measured to about 2%, but some parts have a higher slant while others a much lower one: gradient rates from 60.7–0.20%), the error allowance is greater [50–52] (the slant on the bed we measured is perhaps a little differentiated, as the material is worn. The gradient is not steady throughout the whole length of the aqueduct, it can be partly quite different; the evidence available makes it difficult for us to reckon the average gradient.

Water capacity is difficult to reckon due to limited evidence, certain observations can still be made about water distribution. As *caput aquae* stands on a height of +50 m, it could only feed the lower foothill of Ai Yannis, since the highest hilltop measures +87.30 m. Thus, Roman ruins on the NW hillside could hardly be supplied by the aqueduct.

4.9. Elyros

Elyros was supplied with water through an aqueduct. In the first part of the aqueduct near the source, the water pipe was placed in a shallow pit and covered with stone slabs [22]. In the second part, clay pipes (tubuli) (Figure 14a), 13 cm in diameter, run partly underground and partly in a wall up to the tanks [22]. The water was stored in stone tanks (Figure 14b). The wall carrying the water channel is also shown Figure 14c.





(c)

Figure 14. Aqueduct of Elyros: (a) Remnants of the aqueduct; Junction of clay pipes and (b) cistern and (c) wall carrying the water channel (Photos taken by Y. Christodoulakos).

The ancient Elyros is located in Selinon district, close to modern Rodhovani, and it was built on Kephala hill, at +550 m a.s.l. A city-state with its own currency [53] is considered the most powerful one in the south-west Crete during the Hellenistic Period [54]. The city walls are visible on the northeast side of the hill. Ruins of a possible theater are also being preserved as well as Roman buildings and cisterns.

The source by Livada village [37] must have fed the aqueduct (it still provides enough water all year long). This is inferred by its altitude, which is good enough (+668.22 m), a reasonable distance of 2 km away from the ancient town and also by the direction of the preserved pipe stretches accidentally unearthed during digging works. These two pipe parts lie 13 m away from each other, where the open gravity pipe turned to a close one under pressure.

4.10. Water Supply of Kissamos

Ancient Kissamos, a city on the north coast of West Crete (Figure 15a), has long been identified in the alluvial plain framing Kissamos gulf “Myrtilos” during antiquity; In the 15th century, Buondelmonti described the ruins he observed [55,56]. In the 16th century, O. Belli described Kissamos as “Theater” [57]. Kissamos was first inhabited during the Minoan times. Hellenistic Kissamos had no currency of its own and no interference to major historical events, whose information is available by inscriptions. It must have been a small port city within the territory of Polyrrhenia, which it was administratively adhered to and also served as a harbor to this mighty city. On this same spot, another city has been plotted out following Hippodamus system; it was built in the 1st century AD. It was made available for systematic study by the excavation at the Health Center. Under the mosaic floors of the end of the 2nd century AD a ceramic workshop came to light. Its production, mainly amphorae and lamps of the “Cretan type”, is dated to this century [58]. During the Imperial era, the city expanded between two rivers (torrents today) on the east and west, from the low foothills on the south to the sea to the north.

Infrastructure work comprised water management. Built cisterns in courtyards or atria and wells for domestic use have been brought to light in several excavations. Moreover, small cisterns have been found, usually in public or private baths, connected to an aqueduct.

According to evidence so far, the sprig in the fountain to the SW of Zachariana village should be considered as the start to the aqueduct of Roman Kissamos: archaeological remains on this spot (most probably the caput aquae) are preserved. The aqueduct runs to a distance of 7.570 m up to Kissamos city. On the way, the water pipe has been located on top of a wall in Zachariana village area, as well as cistern parts in Konidiana.

Water came to town on two sides: to the SW, related to the aqueduct and to the south, from a non-identified source (just one underground cistern has been located at Ano

Kounoupitses area. There is also excavation evidence for this: at the Gymnasterion plot conduits and shafts came to light (Figure 15b), while to the south side, remains of a pillar row seem to have retained a water pipe. Another plot of land (“Niotaki” plot) contains conduits and shafts, but the most significant remains came out in a small plot (13 × 20 m): a system of pipes and two cisterns that covered it completely. One cistern measured 15.75 × 2.0 m × 2.21 m high to the beginning of the vault) (Figure 15c). The cisterns are in opus caementicium, the inner and outer front made of triangular bricks ($\frac{1}{4}$ of a plinth measuring 25.5 × 25.5 cm² and 4.5 cm thick) and plaster joint 1.5–2.2 cm (for the steady horizontal height of masonry to reach approximately the foot unity (1ft = 0.296 m), five layers of bricks were laid alternately with four layers of plaster: $4.5 \times 5 + 2.0 \times 4 = 0.30$ m). The inner surface of the bricks is plastered with strong hydraulic plaster 4 cm thick. On the outer side, bricks remained plain as usual, while there is no outer front for bricks in rock-cut areas. The floor is covered with hydraulic plaster.

South to the cistern, which is a rock-cut underground one, up to the beginning of the vault there is a complex of nine pipes. One of them fed the cisterns; the others joined a conduit following a different direction. There is a slight slant to the north, where the city center stands. All conduits are plastered inside, one is made of clay.

No oversize cisterns or any “water tower” have been located in Kissamos city. Not one of the seven known cisterns may be considered as a central cistern of public use. We have seen no arches or pillars supporting water pipes in town, while pipes that have come to light are stone-built or underground clay pipes.

As already noted, one of the most significant excavations in Roman Kissamos is the villa at the Health Center [59]. Water is of private use here, as a small bath complex adheres to the villa and is probably fed by the aqueduct. Parts of clay pipes have been found in the building.

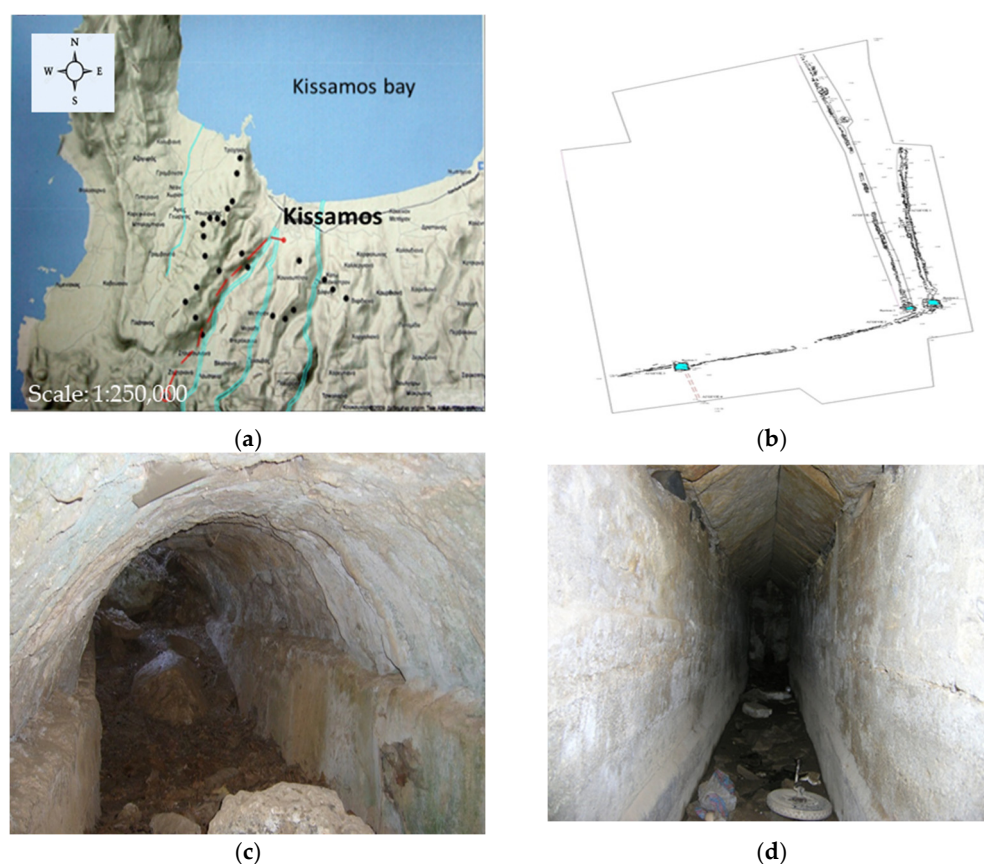


Figure 15. Water supply of Kissamos: (a) Hydrogeology map (scale 1:250,000) with registered springs (Emeric Program of the Institute of Mediterranean Studies, (gr. ITE) and Technology and Research Institute, (gr. IMΣ); (b) Water pipes and shafts at Gymnasterion plot; plan: archive of the

Eph. of Ant. of Chania (c) collection cistern (*caput aquae*), (photo by M. Skordou, archaeologist) and (d) Interior of conduit under a room (Photo taken by Y. Christodoulakos).

The most characteristic building for its use and water need is the “thermae” [60,61]. To evaluate the construction elements, the function of each room and especially water management (with the collaboration of the topographer Ch. Frangonikolaki, since we only had a schematic plan), we led the building out in detail. This building is one of the most impressive in size and structure excavated in Kissamos, mainly made in opus latericium, with extensive use of marble floors. In the middle of a room, under the floor, an incredibly elaborate and sizeable pipe (1.20 m high $\times$ 0.63 m wide) runs from N to S (Figure 15d). It has a triangle-shaped covering and solid hydraulic plastering. Going south outside the room, it is ramified to the west. It has not been thoroughly explored. For the everyday function of the thermae a significant quantity of water was needed, ensured only by means of an aqueduct or huge cisterns [62]. The water quantity needed for bath function was large and continual flow was necessary. If filling just the four piscinae of the baths, a quantity of 46 cubic m was necessary, supposing that water was changed once or twice per day for sanitary reasons, at least 80 cubic m was needed per day. According to excavation evidence in eight more plots, remains of baths have been located, except for the thermae, with equally important needs for water.

5. Discussion and Conclusions

The use of traditional knowledge does not directly apply techniques of the past, but instead, attempts “to understand the logic of this model of knowledge” [63]. Knowledge from tradition has allowed ancient societies to keep ecosystems in balance and to carry out world-renowned technical, artistic and architectural work [64]. Traditional knowledge can renew and adapt itself and dynamically incorporate innovation, subject to the long-term test, achieving local and environmental sustainability. An essential subject for sustainability in developing nations of the world is to research the traditional knowledge methods for water supply and irrigation [65]. Many of these techniques may prove more valuable over the conventional (more sophisticated) ones.

Our study describes and highlights the main characteristics of the significant Roman aqueducts on the island of Crete. It is about, in most cases, for large-scale technological constructions, which emerged along with other large-scale water projects and probably are due to climatic variability, i.e., warm and dry conditions, which occurred during the end of the Hellenistic period in Crete [18]; these technologies were highly increased and developed in almost all the Crete around by Romans. The main characteristics of these large-scale technologies, as we presented here, included complex or simplified constructions (i.e., aqueducts, cisterns, bridges and pipe networks) capable of transferring and delivering large quantities of water to populated areas, even from long distances, to satisfy water supply and requirements in agriculture or other uses. These large-scale Roman hydro-technologies, especially aqueducts for water supply and irrigation of cultivated fields, appear to be more practical, operational and cost-effective practices.

However, we should mention that the experience and knowledge about the building of urban aqueducts pre-existed in Greece from Meso-Minoan times (*ca* 2200–1500 BC); The knowledge from the Minoan Era was undoubtedly the basis for the development and evolution of the aqueducts in the later period and mainly during the Classical and Hellenistic and Roman periods [21]. During that time in the cities, fountains flourished; large baths and latrines were adopted, which led to a high need for water. However, Roman aqueducts were arguably more typical, larger and capable of transporting a greater water volume than their Minoan, Classical and Hellene predecessors. Some representative examples of Roman aqueducts are the Syia, Lyttos, Chersonisos, Kissamos, Fountana, Gavdos, Gortys, Elyros, Falassarna and Minoa (Marathi) in the eastern and western Crete, presented in this study. In the main country larger-scale Roman aqueducts were also found

in Korinthos (Stymfalida), Moria in Lesvos inland, Phobos inland, Patara, Epfesus, Demetrias and Athens (Hadrian). These aqueducts are considered cost-effective and some of them were used for a very long time. The Hadrian aqueduct in Athens never stopped supplying water, even after the collapse of the tunnel near the Agios Dimitrios church at Ampelokipi, where the water overran to the surface and was therefore considered as a spring. In the second half of the 19th century, it was cleaned and reused and remained the main water supply of Athens up to 1931, when the Marathon reservoir was completed [66].

On the ancient Greek territory of the Classical and Hellenistic times, the aqueduct construction involved tunnels (Athens, Samos, Megara, Syracuse, etc.). Greeks remained constant to the Middle East technique of carrying water by means of underground water plants following the topography, whereas Romans used to construct arches in order to span intense leaning slopes. Thus, tunnels were dug into the earth, sometimes very deep down, with an opening large enough for a man to stand and work ($2.00 \times 0.80 \text{ m}^2$). Pax Romana on the contrary, allowed aqueducts to stay on the ground, out of danger, while material standardization led to the construction of aqueducts of a large size and the transport of vast quantities of water at great distances, thus sparing time and work (this implies cost-efficient constructions). These same construction methods and material standardization were used pro-rata in Cretan aqueducts.

As far as the Crete area is concerned, some Hellenistic and Roman cities still exist; Iraklion, Kissamos (the Roman town lies under the modern one) and villages at Elyros and Syia sites. On Gavdos island several small and sparse settlements still exist. Evidently, aqueducts constituted a sustainable intervention to the environment, with no waste of natural resources; in addition, water springs are still preserved today. If the same water pipes were meticulously maintained today without any modern damage, they would still carry water! As mentioned above, the Roman Fontana aqueduct is still supplying water to Iraklion by replacing the opened conduit with a PVC-pipe. Indeed, there has been neither overexploitation of natural resources nor alienation of the morphological characteristics in cities under Roman rule in Crete and other parts of Greece. Most city-states of the Hellenistic period lost their political role during the Roman occupation and adhered to it mainly as an agrarian economy. The cultural traditions of the Hellenistic period, as well as language, have been preserved.

Archaeology offers—especially in Crete, Greece, where numerous well-preserved Roman water systems have been found—some precise illustrations of their aqueducts technique. These remains give a picture of the best available water technology in the Roman Empire, especially between the 2nd and the 4th century AD. The analysis of these remains, including the use of the actual knowledge of fluid mechanics, demonstrates that the Romans had an excellent engineering knowledge of aqueduct technology.

Today the meaning of sustainability should be reconsidered in the light of ancient public works and water management practices. Technological insights can extend the usable life of aqueducts [21]. By comparison, the use of small-scale infrastructures with that of large-scale ones, the operation, sustainability and resiliency are improved. However, even under high water availability, the principles and practices of sustainable water supply use of small-scale infrastructures should not be forgotten. Safety and security of water supply use under emergency situations, including turbulent periods, should be kept in mind in our designs of urban water aqueducts.

Taking into account the above, certain conclusions could be drawn and help in further reflection and systematic investigation:

1. Studying the aqueduct principles and hydraulics works from the Minoan, Greek and Roman civilizations, we realize, in some cases, the similarities between the old and modern practices since present technologies descend directly from those times of engineering. These works are characterized by simplicity, robustness of operation and absence of complicated controls.

2. For our modern times, the meaning of sustainability should be reevaluated in the light of Minoan, Greek and, especially, Roman aqueduct hydraulic works and water supply management practices.
3. The development of cost-effective and environmentally friendly water resources management technologies and practices, based on ancient civilizations' principles, can help vulnerable areas of the planet to cope with the water scarcity phenomena; technological developments should be based on sound engineering principles according to the "ancient model of knowledge".
4. Even small-scale infrastructures can be sustainable and resilient even under high water availability conditions.

Finally, water is a common need of humankind and several ancient civilizations developed simple but practical techniques, such as aqueducts, especially during Roman times. Their experience and knowledge can inspire and have an essential role for sustainable water supply, presently both in developed and developing countries. In Crete, at the present time, twenty surface aqueducts have been constructed and are operated (with a total volume of 280 hm³) and several others are under planning [14]. Over 50% of water consumption is based on these systems. Despite the recent advances in engineering and aqueduct technology, covering construction materials, control and monitoring and distribution systems and mechanisms, it is widely acknowledged that the core of the current technology is still based on the past technological achievements and that this will continue to be the case in the future.

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