EVOLUTION OF RAINWATER HARVESTING AND USE IN CRETE, HELLAS THROUGH THE MILLENNIA

A. N. ANGELAKIS

National Agricultural Research Foundation (N.AG.RE.F.), Institute of Iraklion, 71307 Iraklion, and Hellenic Water Supply and Sewerage Systems Association, 41222 Larissa, Hellas, info@a-angelakis.gr

ABSTRACT

The low water availability in several region of southeaster Greece and particularly in several islands, such as Crete, resulted in the construction of various water reservoir types for collection and storage rainwater, since the beginning of very early habitation on it. Since then the technology of construction and use of several types cisterns (such as rectangular, square, and cylindrical-shaped, roofed and roofless, and uncoated or coated internally with impervious material) have been developed. In Minoan Era water cisterns were very well practiced as a basic technology for water supply in several settlements. Minoan water cistern technologies were further developed, mainly by enlargement of the scale of water systems, at subsequent stages of the Greek civilizations. New more advanced water cistern technologies were also invented there, with a peak in the Hellenistic period that follows Alexander the Great, during which they spread over a geographical area from Greece to the west (central and south Italy) and to the east (Egypt and probably eastern and southern of Egypt). The Romans, whose Empire replaced the Greek rule in most part of this area, and of course in Crete, inherited the cistern technologies and were further developed mainly by changing their application scale from small to large and implementing them to almost every large city. Characteristic paradigms of Minoan, Hellenistic, Roman, Byzantine, Venetian, Ottoman, and modern time cisterns are considered which justify the significance of that technology for water supply in areas with low water availability during the whole Cretan history.

Keywords: Ancient Crete; Aptera; Dreros; Hellenistic period; Minoan Crete; Roman period; Lato; Ottomans; Water cistern

1. PROLEGOMENA

Every settlement of the humankind basically depends on a sufficient water supply. This applies especially for arid and semi-arid climate conditions in the regions around the Mediterranean basin and especially in southeastern Greece, where water resources availability is extremely limited mainly during the summer. In this region rainwater harvesting was practiced in order to increase water availability since the early habitation. Rainwater is defined in this paper as atmospheric precipitation originating from impermeable surfaces, collecting and storing usually in artificial reservoirs, known as cisterns. This water is used for household purposes such as bathing or washing, washing dishes, laundering clothes, irrigation or other urban uses. Appropriately treated rainwater has the potential for use within dwellings, offices, housing estates, industry, horticulture, gardens etc. However the final use of the rainwater will dictate the level of treatment that it will require. Where such use does occur, it is essential that appropriate safeguards are taken to prevent cross contamination of potable water supplies, damage to internal fixtures and fittings or harm to the environment (Angelakis et al., 2012). The design and development of such water collecting systems is an emerging technology encouraged by the need for water conservation and water taxes. It can be of great value where water is scarce but in many circumstances it is still expensive and not necessarily beneficial to the
environment. It is essential that any applications, which are allowed, be properly controlled to prevent risks to public health (Angelakis et al., 2012).

There are examples of rainwater harvesting systems in many countries. Some are well installed and operated for centuries. Rainwater harvesting has been practiced in the island of Crete since the Minoan times, ca. 3,200-1,100 BC (Angelakis and Koutsoyiannis, 2003; Angelakis and Spyridakis, 2013). In Minoan Crete water cisterns were used for both harvesting rainwater and as reservoirs for storage spring water. In Minoan Phaestos, Chamaizi, and Myrtos- Pyrgos, in contrary to Knossos, Zakros, and other Minoan establishments the water supply system was dependent directly on precipitation: here, the rainwater was collected from the roofs and yards of buildings in cisterns. At Phaestos no wells or springs have been found. Special care was given to securing clean surfaces in order to maintain the purity of water and to hygienic of collecting water by: (a) cleaning the surfaces used for collecting the runoff water and (b) filtering in coarse sandy filters the water before it flew into the cisterns in order to maintain the purity of water. That water was mainly used for washing clothes and for other cleaning tasks (Angelakis and Spyridakis, 1996).

The scope of this paper is to present the main achievements in harvesting of rainwater in Crete, Greece chronologically including water supply technological principles and consumption by humans, extending from the earliest to the present. It is not an exhaustive presentation of what is known today about rainwater harvest, storage, treatment, and use water supply since the beginning of humans’ quest for water supply systems. Emphasis is given to the periods of great achievements.

2. RAINWATER COLLECTION (HARVESTING) SYSTEMS
From the early civilizations, people in arid and semi-arid regions have relied on collecting (harvesting) surface water from rainfalls and storing the water in cisterns. Not only were cisterns used to store rainfall runoff, they were also used to store spring water transported by aqueducts. Cisterns during the ancient times have ranged from construction of irregular shaped holes (tanks) dug out of sand and loose rock and then lined with plaster (stucco) to the construction of rather sophisticated structures (Gorokhovich et al., 2011).

Minoans were very well practices in water collection systems. They were developed remarkable technologies for collecting and transporting water to settlements. In Crete due to very dry summers rainfall collection was accomplished from both roofs of the buildings and larger court areas. Hydraulic structures associated with the rainfall collection were found in Knossos, Phaestos, Tylissos, Aghia Triadha, Chamaizi, Myrtos Pyrgos and Zakros. These hydraulic structures include large stone conduits with branches that were used to supply collected water to cisterns such as those found in Knossos. Terracotta pipes were also used to convey rainwater to cisterns. In Myrtos - Pyrgos the terracotta pipe of rectangular shape (Fig. 1a) supplied the nearby cistern system with stormwater collected from the rooftops (Cadogan, 1978). Also, alongside a stairway in Knossos is a small stepped channel consisting of a series of parabolic-shaped step chutes that was used to convey rainwater from terraces down to a sedimentation (desalting) basin. The same components of rainfall harvesting system, e. g. cistern, channel and sedimentation tank, also existed in other settlements (Angelakis and Spyridakis, 1996; Gorokhovich et al., 2011).

3. MINOAN ERA
In Minoan Crete the technology of surface and stormwater storage was highly developed. Water was conveyed into cisterns, a technique still practiced today in rural areas of the island. In fact, this practice has been widely used throughout the history of Crete. In
ancient Crete the technology of surface and rain water storage for water supply was very well developed and was continuously used up to modern times (Angelakis et al., 2012). The Minoan water cisterns were of cylindrical shape, constructed with stones under the soil surface, with a diameter ranging from 1.5 to 7.0 m and depth from 2.5 to 5.0 m. At least one layer of hydraulic plaster prevented water losses through the bottom and the walls.

In general, one of the earliest Minoan cisterns was found in the center of a house complex at Chamaizi dated from the 3rd to the 2nd millennium BC (Davars, 1976). Four others of the earliest structures which may be considered as large scale cisterns in Minoan Crete, were built in the first half of the 2nd millennium BC (the time of the first Minoan palaces) at Myrtos-Pyrgos (west of ancient Hierapytna), Archanes, Tylissos and Zakros (Cadogan, 2007). Similar technologies were used in the Phaestos and Malia palaces. Those cisterns were associated with small canals collecting surface water from rainfall and from mountain streams (Angelakis and Spyridakis, 2010).

In more details the cistern at Chamaize, a pre-palatial house complex, referred to the early-middle Minoan period in the closing years of the third and the dawning of the second millennium BC (Fig. 1b). It is a small scale cistern. Its rooms were clustered around a small open court with a deep circular rock-cut cistern 3.5 m deep and 1.5 m in diameter, lined with masonry in its upper part (Davaras, 1972). From the period of the Minoan palaces (middle-late Minoan period) four cisterns have been identified at Myrtos-Pyrgos, Archanes, Zakro. At Myrtos-Pyrgos two cisterns have been found, one on the top of the hill where the settlement lies and the other on its slop (Cadogan, 2007). The latter is the larger, with a diameter of 5.3 m and a depth of more than 3m. Both cisterns have a capacity of more than 80 m3 and date to the middle Minoan period (ca. 1,700 BC), a chronology which corresponds with the last phase of the existence of the First Minoan palaces which are also dated ca. 1,900-1,700 BC. Minoans have also developed special network systems for collecting the rainwater. These systems were mainly constructed from terracotta pipes, such as those shown in Figure 1a.

In the Zakros palace on the side of the Central Court, a circular cistern below the ground level was found (Platon, 1974). It is 7 m in diameter and has steps constructed for cleaning and drawing purposes. The cistern belongs to the late period (ca. 1,500 BC). A screen or parapet projected from the floor supports a row of at least five columns set in a circle. The area above the cistern was uncovered. This installation is unique in Minoan architecture (Angelakis and Spyridakis, 1996; Evans, 1921-1935). Their use as swimming pools or aquaria has been also proposed (Alexiou, 1964). Since the room must have had a ceremonial/administrative character as suggested by its layout, the cistern most likely performed a central role in this context as it constitutes the core feature of this particular space. Finally, it has been argued that it was used as a means of estimating the precipitation required for calculating the adequate share of agricultural products provided to the storage areas of the palace, in the manner of the Egyptian nilometers (Lyrinztis and Angelakis, 2006). Most likely, however, the cistern served multiple purposes, including recreational ones.
Two similar cisterns have been also found at Archanes-Tourkoyeitonia (Sakellarakis and Sapouna-Sakellarakis, 1997) and Zakro (Platon, 1974). Unlike the cisterns of Myrtos-Pyrgos, they belong to a later period that of the second palaces, which were built after the catastrophic earthquakes of ca. 1,700 BC, ruined the First palaces. Both are of a middle late period (ca. 1,500 BC) and of similar cylindrical shape, each with a diameter of about 5 m and depth of 2.5 m. They were built in limestone ashlar masonry and were probably roofed. Both have steps that facilitated their water supply. Another feature shared by them is the enclosure of the spring as the water came from the lower levels in a manner recalling the traditional Majahir cisterns found in Syria (Angelakis et al., 2012).

The rainwater was collected in cisterns from rooftops and open courts. Special care must have been given to secure clean surfaces in order to maintain the purity and quality of collected water by: (a) cleaning the surfaces used for collecting the runoff water and (b) by the use of other filtering devises or coarse sandy filters. The water collected in the cistern was primarily used in crafts (e.g. pottery, metallurgy), in domestic activities and in gardening irrigation (Angelakis and Spyridakis, 1996). It would have been used for drinking only in case of drought or siege.

4. USE OF HARVESTED WATER IN MINOAN CRETE
One of the salient characteristics of the Minoan civilization (ca. 3,200–1,100 BC) was the treatment devices used for water supply in palaces, cities, and villages from the beginning of the Bronze Age. It is truly amazing that the most common water quality modification technique for providing suitable domestic water supplies was known to Minoan engineers. A strange, oblong device with an opening in one of its ends, was used to treat domestic water according to Defner (Spanakis, 1981). The device was constructed in a similar manner and with the same material as the terracotta water pipes (Fig. 2). Spanakis (1981) theorized this device as a hydraulic filter which was probably connected to a water supply reservoir by a rope passing through its outside holds. Its operation relied on local, high speed, turbulent conditions in order to continuously clean the porous surface thus allowing the continuous flow of filtered water to the jar. For cleaning purposes after extensive solids accumulation, it was possible to release it from the pipe end by loosening the rope in the holes.

In addition to the terracotta filters, in some case cisterns were associated with small canals collecting water from rainfall and from mountain streams (Viiolet, 2003 and 2007).
It is therefore possible that cisterns in the Phaestos palace have been connected to the sandy filters.

![Minoan water ceramic filter](adapted from Spanakis, 1981).

**Figure 2.** Minoan water ceramic filter (adapted from Spanakis, 1981).

5. HISTORICAL TIMES

5.1. The Hellenistic period (ca. 323-67 BC)

In the castle areas of Classical and Hellenist Crete on the top of the hills there was neither spring nor a deep well. In order to guarantee the water supply for the inhabitants, especially in the case of a siege, cisterns had been constructed to collect rainwater during the rainy winter season. The Greeks improved the cisterns technology of Minoans by building not only circular of cross section shaped cisterns, but also of rectangular cross sections. Also, in rocky castle areas cisterns were hewn into rooks. A good example is the city of Polyrhrenia in the western Crete, which was built on top of a high hill (more than 400 m elevation); a location which offers excellent view to all the surrounding area (from Crete to the Libyan sea), flourished during the Classic times. It was a powerful political center and had two excellent harbors, Kissamos and Falasarna. They were mostly pear shaped. At least one layer of hydraulic plaster prevented water losses through the bottom and the walls. The estimated size of those cisterns is $10m^3$.

![Historical times carved cisterns](a at Hellenistic town Lato town and b at Roman Aptera town (with permission of A. N. Angelakis).

**Figure 3.** Historical times carved cisterns: (a) at Hellenistic town Lato town and (b) at Roman Aptera town (with permission of A. N. Angelakis).

In addition to the carved cistern, Myers et al. (1992) have reported build cisterns. One that one of the larger such cistern ever known in Hellenistic Crete is that in the Agora (city...
center) of the Hellenistic Lato. Its walls are coated internally with impervious plaster and built stairway on one side leads down to the bottom of the cistern. From the situation and the size of the cistern, we can only conclude that it was the public cistern of the city (Fig. 3a). The area of the cistern is of 27.56m² and its depth is of about 6m. It was originally covered above two Dorian colons. A similar cistern of dimensions 5x3x6 m³ exists in the agora of ancient Dreros, as well as in other cities of Crete. There are of about 15 smaller cisterns in Lato city.

5.2. The Roman period (ca. 67 BC-330 AD)
The Romans built 'mega water supply systems' including many magnificent structures. The advanced water and wastewater technologies developed in Minoan and Hellenistic Crete were expanded and improved during the Roman domination of the Greek world (Angelakis et al., 2012). The achievements of this era, which met the hygienic and functional requirements of ancient cities, were so advanced that they could only be compared to the modern urban water systems which developed in Europe and North America in the second half of the nineteenth century (Mays et al., 2007). However, it should be noted that hydraulic technologies, included water cisterns, which were developed in the Historical times were in principle similar to those developed earlier by the Minoans and Meceaneans (De Feo et al., 2012).

During the Roman period, a number of major hydraulic projects were undertaken in order to ensure fresh water and hygienic living conditions. In addition to aqueducts, several cisterns have been found in Dictynna, Lappa, Rhizenia, Elyro, and Aptera (Fig. 3b). The town of Aptera, located south of Souda bay, in Chania, is regarded as one of the most significant townships on the island during the Hellenistic and Roman periods. The most prominent constructions in terms of hydraulic and architecture are two marvelous cisterns, the public baths, and the thermae. There are two cisterns in the town; an L-shape cistern (3,050 m³) and a rectangular tri-aisle one (2,900 m³), both functionally connected to the nearby located bath-thermae of the town. The roofed-cisterns with a total water storage capacity of about 6,000 m³ were mainly used to supply water to thermae (Gikas et al., 2009). Thermae also have been found in other Roman towns, e.g. Kissamos, Lefki island and Hierapytna.

6. MEDIEVAL TIMES
After the fall of the Roman Empire, water supply and sewage systems experienced fundamental changes in Europe. Medieval cities, castles and monasteries had their own wells, fountains or cisterns (Juuti, & Vuorinen, 2007).

6.1. The Byzantine period (ca. 330-1,204 AD)
From 961 to 1,204 AD, Crete was part of the Byzantine Empire. 'Chandax' (present-day Iraklion) was the headquarters of the Duke of Crete. During this period, the technologies applied for water supply of the cities were more or less the same as those in the Arabic period. Water cisterns were the major water technologies developed in Crete during that period (Fig. 4a). At the end of the Byzantine period Crete fell into the hands of the Venetians.

6.2. The Venetian period (ca. 1,204-1,668 AD)
In Crete during the Venetian period many water cisterns and fountain houses were constructed in both the towns and the countryside. In several Venetian cities and villages (e.g. in the Pediada region), which were densely populated and rich in water, significant water supply systems, expressed mainly in water cisterns and fountain houses were constructed (Panagiotakis, 2006). In general, Venetians’ accomplishments in hydraulics are worth noting, such as the construction and operation of aqueducts, cisterns, wells, fountains, baths, toilets, and harbours. Many of these technologies were developed and used in the famous castles constructed during that period. Thus, several cisterns have
been found in Venetian Rethymnon, on the island of Gramboussa (Fig. 4b), and in Viannos Vigla castle. Also small cisterns have been located in several villages in the area of Vamos, Chania such as those in the villages of Gavalochori at the locations of wells and Agios Pavlos and Paleloni. Later evidences from the Venetian period suggest the existence of more than 500 cisterns in the city of Iraklion after ca. 1,500 AD (Spanakis, 1981). All those cisterns were collecting surface water from rainfall.

Figure 4. Medieval times water cisterns: (a) Cistern (of rectangular cross-section) in the Byzantine Monastery Areti in the eastern Crete and (b) Venetian water cistern at Grambousa in northwestern Crete (with permission of A. Angelakis).

7. MODERN TIMES

7.1 The Ottoman period (ca. 1,669-1,898 AD)
Water was connected to Islam, so that during the Ottoman period there was a water tap in all mosques. Hammam is a very old Ottoman institution and was established in all the regions of the Ottoman Empire. Following the very old Moslem tradition, water supply to hammams and fountains was the major hydraulic works developed during the Ottoman period. The most remarkable water systems of the Ottoman period served Constantinople (Istanbul). There are also cisterns from this period that were circular-shaped, domed or other located in several Mediterranean countries (Mays et al., 2012). These cisterns were constructed primarily in the 16th century in various places occupied by Ottomans. Some of these are still in use for livestock water supply. They originally served the Ottoman army at military logistic points.

7.2. Present Times
By the end of 19th and the beginning of 20th century, the independent Greek-state was established and the modern water technologies started to be developed, as in other parts of the world. They were based on the past technologies as well as on new ones such as deep wells, pumps, pipes, and so on. At that time the growth of populations required an increase in agriculture production. In addition, the steep terrain of the island highly increased the scale and the cost of the required hydraulic projects (Koutsoyiannis and Angelakis, 2004). Meanwhile, water supply of the urban areas was facing similar problems due to the population increase. Thus, collect, storage, and use of rainwater in several urban areas in Crete and especially in eastern Crete where in practice still the middle of the last century. The fundamental principles to capture, convey, and use rainwater in urban areas where similar of those developed in ancient times (Fig. 5).
Figure 5. Modern times water cisterns in the eastern Crete since the middle of the last century: (a) Private cistern outside a house and (b) Public cistern which was used for water supply of the village of Lakonia (with permission of A. Angelakis).

8. DISCUSSION AND CONCLUSIONS

The ancient Greek wisdom must put into practice by creating awareness, undertaking policy research and lobbying to bring about change in policy as required so that water management is decentralized and water availability increased. The evolution of rainwater harvesting system to increase water use efficiency and continuous effort to preserve the environment for sustainable development through the Hellenic civilizations has been presented and discussed in this paper. It is believed that these early systems were used in Mediterranean region to collect runoff from hillsides, open yards and roofs mainly for domestic purposes (Gould and Nissen-Peterson, 1999).

From the early civilizations people in arid and semi-arid regions have relied on harvesting surface water from rainfalls and storing the water in reservoirs known as cisterns. The storage of rainwater runoff has been constructed in the entire region around the Mediterranean and the Near East since the 3rd millennium BC. Not only were cisterns used to store rainfall runoff they were also used to store aqueduct water for seasonal variations. Cisterns during the ancient times have ranged from construction of irregular shaped holes (tanks) dug out of sand and loose rocks, and then lined with plaster (stucco) water proofing, to the construction of rather sophisticated structures such as those built first by the Minoans (Mays, 2007).

A brief historical development of rainwater harvesting by water cisterns in Crete from the Minoan Era to the present times has been presented. These unique structures have allowed humans to live in arid and semi-arid regions of Crete for over 5,000 years. These hydraulic structures are certainly evidence of the social, political, and economic conditions, and most likely the military conditions, of the various periods of human history of Crete.

It should be concluded that the first evidence of the use of water cisterns for water supply in Greek settlements lies in Minoan era. However, that technology was tremendously further developed through history, mainly by enlargement the scale of the projects, with a peak in the Hellenistic period. The achievements of Greeks in dealing with the cisterns and functional requirements of water collection and distribution systems can only be compared to modern urban water systems, re-established in Europe and North America from the second half of the 19th century AD (Angelakis and Koutsoyiannis, 2003) until present day. Thus, with a few exceptions, the basis for present day progress in technological development of water cisterns is clearly not a recent development, but an extension and refinement of the past. Traditional knowledge incorporates innovation in a
dynamic fashion, subject to the test of a long term, achieving local and environmental sustainability (Mays, 2007).

Ancient Cretans lived in harmony with nature and their environment; those that did not, failed. Local water supply sources were first used by the ancient Cretan of the Minoan Era. When these were exhausted, local and temporal transfers were instituted and the necessary hydraulic structures built such as water cisterns. In this context it is noteworthy that the Minoans knew all the necessary basic principles and physical parameters. Those basic Minoan hydraulic works were further improved by Greeks during the Classical and Hellenistic periods. The Romans and Venetians did not add much to the water cistern fundamental knowledge, however, the scale of application and of the apparatus used were highly affected during the Roman period.

The legacies and lessons on water supply evolution in Crete since the Minoan era are summarized as follows:

a) In water-short areas, development of cost-effective decentralized water supply management program based on harvesting and storage rain water in cisterns is a sustainable technology.

b) Ancient Cretan knowledge on water cisterns could play an important role for sustainable water supply and decrease of flood risks in the cities of the future.

c) The meaning of sustainability in modern times should be re-evaluated in light of ancient public works and water management practices.

d) Ancient Cretan (particularly Minoan) water technologies should be considered not just as historical artifacts but as potential models for sustainable water technologies.

e) Thus, the development of effective water supply management projects, in short-water areas could be based on historical knowledge.

REFERENCES


