

Review

## History of Water Cisterns: Legacies and Lessons

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**Abstract:** The use of water cisterns has been traced back to the Neolithic Age; this paper thus presents a brief historical development of water cisterns worldwide over the last 5500 years. This paper is not an exhaustive presentation of all that is known today about water cisterns, but rather provides some characteristic examples of cistern technology in a chronological manner extending from prehistoric times to the present. The examples of water cistern technologies and management practices given in this paper may have some importance for water resource sustainability for the present and future. Cisterns have been used to store both rainfall runoff water and aqueduct water originating in springs and streams for the purpose of meeting water needs through seasonal variations. Cisterns have ranged in construction from simple clay pots to large underground structures.

**Keywords:** ancient civilizations; Byzantine period; Classical period; Hellenistic period; Maya; Minoan Crete; Roman period; Ottomans; Venetian period; Xochicalco

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### 1. Prolegomena

The evolution of the use and major achievements of water cisterns is presented and discussed here with emphasis placed on the most significant technologies applied throughout the centuries. Valuable

insights into ancient water cistern technologies and management are provided, highlighting their characteristics of durability, environmental adaptability, and sustainability. A comparison of the water technological developments in several civilizations is undertaken. These technologies are the underpinning of modern achievements in water engineering, illustrating clearly that “the past is the key for the future”.

A historical development of water cisterns worldwide over the last 5500 years of human history is considered. A chronological order is followed with emphasis on the main civilizations. Rapid technological progress in the twentieth century created a disregard for past water technologies that were considered to be far behind the present ones, even though there are a number of unresolved problems related to water supply systems, especially cisterns. In the developing world, such problems have been intensified to an unprecedented degree.

The construction and use of cisterns can be traced back to the Neolithic Age, when waterproof lime plaster cisterns were built in the floors of houses in village locations of the Levant, such as Ramad and Lebwe [1]. The Levant is a geographical term that refers to a large area in Southwest Asia, south of the Taurus Mountains, bound by the Mediterranean Sea in the west, the Arabian Desert in the south, and Mesopotamia in the east. By the late fourth millennium BC, cisterns were essential elements of emerging water management techniques used in dry-land farming, such as at Jawa in northeastern Lebanon [2].

During biblical times (Old Testament) cisterns were not only used to store water, but were also used as underground chambers, hiding places for fugitives, burial places, and even as prison cells. The prophet Jeremiah was held as a prisoner in a muddy cistern that belonged to Malchaiah, the son of King Zedekiah (Jeremiah 38:6). Many ancient cisterns have been discovered in Jerusalem and the entire Land of Israel. At the site believed by some to be that of the biblical city of Ai (Khirbet et-Tell), a large cistern dating back to around 2500 BC was discovered that had a capacity of nearly 1700 m<sup>3</sup>. It was carved out of solid rock, lined with large stones, and sealed with clay to keep from leaking.

During historical times, the cisterns became the essential feature of a well-designed city. The increased number of people during the Roman era led to an increase in size and to the combination of cisterns with the impressive water conveyance constructions. During that period, these water technologies emerged to a certain degree, and reappeared later during the beginning of the industrial revolution.

The scope of this paper is not an exhaustive presentation of what is known today about water cisterns or their related technologies uses worldwide. Rather, some characteristic examples in selected fields are discussed that extend chronologically from prehistoric times to the present. The examples of water cistern technologies and management practices given in this paper—which are not widely known among engineers—may have some importance for improving current water engineering systems, as is discussed later in the paper.

## **2. Bronze Age**

On the island of Crete, the technology of surface water storage was highly developed since the late Neolithic period. A cistern at Azoria in the eastern part of Crete dates back to the Neolithic period [3]. Water was conveyed into the cistern, a technique still practiced today in rural areas of the island. In fact, this practice has been widely used throughout the history of Crete. On ancient Crete, the

technology of surface water storage for water supply was very well developed and used until modern times [4]. The Minoan water cisterns were of cylindrical shape, constructed with stones under the soil surface, with diameters ranging from 1.5 to 7.0 m and depths ranging from 2.5 to 5.0 m. At least one layer of hydraulic plaster prevented water losses through the bottom and the walls of the cisterns.

One of the earliest Minoan cisterns was found in the center of a house complex at Chamaizi, which dates from the third to the second millennium BC [5]. This is a pre-palatial house complex, built during the early-middle Minoan period in the closing years of the third and the beginning of the second millennium BC (Figure 1a). Rooms of the house 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 [6]. From the period of the Minoan palaces (middle-late Minoan period) four cisterns were identified at Myrtos–Pyrgos, Archanes, and Zakro (Table 1). At the Myrtos–Pyrgos site, two cisterns have been found: one on the top of the hill where the settlement lies, and the other on its slope [7]. The cistern on the slope (the larger of the two) has been excavated as shown in Figure 1c. This cistern has a diameter of 5.3 m and a depth of more than 3 m. The cisterns at Myrtos–Pyrgos each have a capacity of more than 80 m<sup>3</sup> and date back to the middle Minoan period (*ca.* 1700 BC). The chronology corresponds with the last phase of the existence of the first Minoan palaces which are also dated *ca.* 1900–1700 BC. Minoans developed special network systems (channels) for collecting the rainwater. These channels were mainly constructed from terracotta pipes, such as the one shown in Figure 1b. Similar technologies were used in the Phaistos and Malia palaces. Those cisterns were associated with small canals collecting surface water from rainfall and from mountain streams [8].

**Figure 1.** (a) Minoan water cistern at the house complex in the vicinity of Chamaizi, near the town of Sitia in the eastern Crete; (b) Minoan rainfall water collection system in Myrtos–Pyrgos near the city of Ierapetra (with permission of A. Angelakis); and (c) Excavated cistern at Myrtos–Pyrgos (photo copyright by L.W. Mays).



(a)

Figure 1. Cont.



Table 1. Minoan Cisterns (adapted from [9]).

Cistern's Name	Construction	Reconstruction	Type (water collecting)	Volume (m <sup>3</sup> )
Knossos (several)	Early Minoan		Spring water	na
Archanes	ca. 1500BC		Rainwater	50
Phaistos (several)	Early Minoan	Hellenistic	Rainwater	na
Tylissos	ca. 1330–1200 BC		Spring water	appox.100
Aghia Triadha	Middle Minoan		Control drainage water	20
Myrtos Pyrgos 1	ca. 1700 BC		Rainwater	66
Myrtos Pyrgos 2	ca. 1700 BC		Rainwater	22
Zakros	ca. 1500 BC		Rainwater	50
Chamaizi	Middle–Late Minoan		Rainwater	6.5

### 3. Archaic, Classical, and Hellenistic Periods

#### 3.1. Introduction

During the Hellenic era, the necessity of water supply and storage improved the construction, technological and hygienic aspects of the cisterns of the period both for public and domestic use. Because of the methodology of water acquisition (rainwater harvesting), most cisterns of that period were supplied by rainfall runoff, but there are several examples in which spring water was stored in the cisterns, such as at the sanctuary of Epidauros.

Inside the fortified settlements and sites of Classical and Hellenistic Crete, of the smaller Aegean islands and other semi-arid regions of the mainland, mainly on the acropolis, there were neither springs nor deep wells. In order to guarantee the water supply for the inhabitants, especially in the case of a siege, cisterns were constructed to collect rainwater during the rainy winter season. The Hellenistic people improved the cistern technology of the Minoans and Mycenaeans by building cisterns of not only circular cross-sectioning, but also with rectangular cross-sections (e.g., at Lato, Dreros, Santorini, Amorgos, and Delos). Also, in castle areas, cisterns were carved into rock, either entirely or partially, as on the island of Rho [10]. Several small-scale rainwater cisterns in residences have survived, such as those on Santorini, Delos, Aegina (Figure 2a,b), Amorgos, and Polyrrenia in the western region of Crete where they were carved into rock. These cisterns were mostly pear shaped and at least one layer

of hydraulic plaster was applied to prevent water loss through the bottom and the walls. The estimated capacity of those cisterns is 10 m<sup>3</sup>.

**Figure 2.** (a) Rural rainwater cisterns at Mpourdechtis area and (b) The main cistern at the Elanion sanctuary (possibly covered) Aegina, Greece [11] (with permission of G. Antoniou).



In addition to the small-scale cisterns, many larger ones were excavated in the rocky fortresses. Several examples preserve more regular and well-designed shapes, *i.e.*, the great rainwater cistern at the Theater of Delos [12]. Furthermore, in ancient Eleutherna, a cistern of about 1000 m<sup>3</sup> was constructed during that period. Other characteristic examples of rainwater cisterns of that period include a slab-covered cistern (Figure 3a,b) at the Sanctuary of Heraion at Loutraki, and the public open air rainwater cistern at the Hellenistic town of Orraon [13]. At Orraon, an enclosure ensured the purity of the collected water as well. Orraon was a small walled town, and, despite being located in the rainiest part of the Hellenistic mainland, the cistern was built on top of a rocky hill, as there was limited water resources inside its fortification. Therefore, rainwater collection was the most reasonable solution.

**Figure 3.** (a) The slab-covered cistern of the Sanctuary of Heraion at Loutraki Attika and (b) Open air public cistern at Orraon (modified by G. Antoniou).

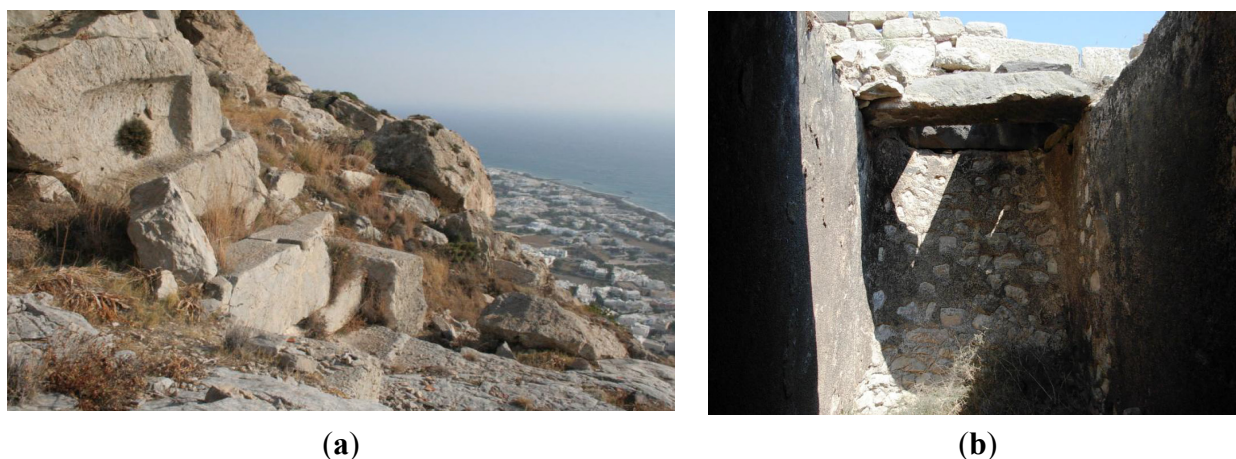




### 3.2. Exploitation of Rainwater in the Aegean Islands

On the island of Thera, otherwise known as Santorini, admirable achievements were accomplished in ancient times, including water supply by harvesting rainwater and/or spring water. As previously described, most of the Aegean islands, including Santorini, are characterized by low water availability. The inhabitants were thus forced to turn to rainwater and to develop extensive collection and storage systems (see Figure 4a,b) [13]. Rainwater was first collected from rainfall on the flat roofs of the buildings and subsequently channeled to the cisterns using drains and/or channels. The small to medium size of these cisterns on one hand, and their large number on the other (more than 55 have been discovered so far), is an indication that the water was collected more on a micro-scale, e.g., in proportion to the size of the building unit. Such a method was certainly anticipated because of the construction of the city on different successive levels, and the huge mechanism for the collection of water in its properly adjusted underground spaces [14].

**Figure 4.** Cisterns on Santorini: (a) Collection and storage rainwater on Santorini: Structure for the collection of a spring water and (b) Inner view of an ancient cistern [14].



It is important to note that the existence of a cistern has no relationship to the use of the building that was constructed above it; cisterns are found equally as often under private and public buildings, but also under temples and theaters. The quality of craftsmanship of these cisterns is admirable, a particular strong point being the quality of the plaster used for coating the interiors. The use of Thera soil as an ingredient of the plaster, with its high content in silicon oxide, gave the plaster a high degree of impermeability. It is not accidental that the cisterns which preserve their coating until today have maintained their capacity to store water [14].

Delos is another Aegean island with very low water availability since the beginning of its inhabitation, so that water supply has always been a problem. The solution was found in a mix of cisterns and wells. Smaller cisterns used to store rainwater are found frequently in residences. The central cistern is located in the front of the theater (see Figure 5). Rainwater fell on the cavea of the theater and was channeled into the slab-covered cistern (22.5 m long and 6 m wide) [12,13]. It was a public works project that supplied the town with water. The theater and the cistern date back to 300 BC, with remains of the cistern shown in Figure 5.

**Figure 5.** Central cistern on island of Delos (by G.P. Antoniou).



### 3.3. Cisterns on Hellenistic Crete

Dreros, a city-state of the Classical period, is located near modern Neapolis in the eastern region of Crete. Like the neighboring Lato, it was erected on a saddle between two peaks, on the slope of Mount Kadistos [5]. The archaic city had an agora (market place) about  $30 \times 40$  m in size, including some mouldering steps along the southern side, a retaining wall of the eighth century BC, and a large open cistern [13]. During this time, the cistern at Dreros was the largest known. Located in the agora, the cistern has a rectangular shape with dimensions of  $13.0 \times 5.5 \times 6.0$  m, and was used for water supply of the city. Davaras [5], however, reports that the depth of the cistern is 8 m. Another Hellenistic water cistern is the one at Lato, located in the eastern part of Crete (Figure 6a). The covered cistern was located in the central square of the town near the theater and has a rectangular shape with the dimensions of  $5.2 \times 5.3 \times 6.0$  m.

**Figure 6.** Hellenistic cisterns on Crete: (a) cistern in the town of Lato and (b) carved cistern in the town of Polyrrenia (with permission of A.N. Angelakis).



(a)



(b)

During the Classical and Hellenistic periods, castles were built on the top of hills where there were neither springs nor deep wells. In order to guarantee the water supply for the inhabitants, especially in



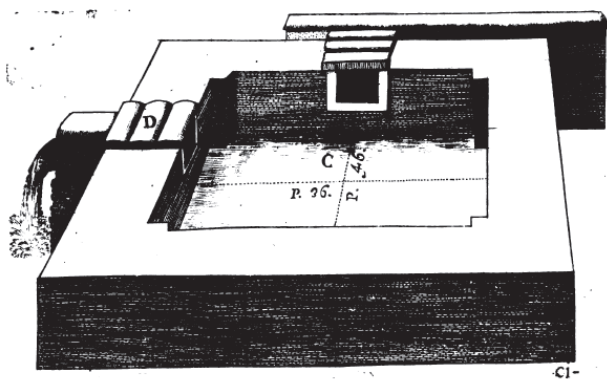
the case of a siege, cisterns were constructed to collect rainwater during the rainy winter season. During the Hellenistic period, cistern technology improved over that of the Minoans by building not only circular-shaped cisterns, but also rectangular-shaped cisterns. Also, in rocky castle areas, cisterns were carved into rocks. Good examples are the carved cisterns at Polyrrhenia in western part of Crete (Figure 6b), which was built on top of a high hill (more than 400 m elevation). The estimated size of those cisterns is  $10 \text{ m}^3$ . In addition to the carved cisterns, there were also constructed cisterns [15]. One of the largest of such cisterns from Hellenistic Crete was located in the agora of Hellenistic Lato. The walls were coated with impervious plaster and a stairway that leads down to the bottom of the cistern. This cistern was most likely the public cistern of the city. The area of the cistern is  $27.56 \text{ m}^2$  and the depth is about 6 m. It was originally a covered cistern with two Doric columns.

#### 4. Roman Period

##### 4.1. Introduction

The Romans made extensive use of cisterns and, therefore, only very few of the many that were built are discussed herein. Pompeii had an extensive water distribution system including both aqueduct water and well water. The roofs of houses collected rainwater that flowed through terracotta pipes down to cisterns where water was stored for domestic use. In Pompeii, the aqueduct and well water were contaminated by the volcano, requiring cisterns to be used for drinking water [16]. A drawing of a Roman cistern that was supplied by the Aqua Marcia near Villa Vignacce outside of Rome is shown in Figure 7a. Also an interior view of the three-aisled vaulted Roman cistern in the ancient town of Aptera, Chania (volume of about  $3000 \text{ m}^3$ ) is shown in Figure 7b. A comparison of Roman cisterns is shown in Figure 8: a small cistern in Ostica Antica in Figure 8a and a cistern below the Acropolis of Athens in Figure 8b. The Roman cistern at the base of the Acropolis of Athens, Greece had a domed roof supported by the columns. This cistern at the southern foothills of the Acropolis could have been supplied with rainwater collected either from the relevant slope or from the roof of the Odeon of Herodes Atticus, and the water probably was used for the supply of the Roman baths in the vicinity.

**Figure 7.** Roman cistern in the ancient town Aptera, Chania, Crete: (a) Drawing of cistern from Raffaele Fabretti [17] and (b) Interior view of the three-aisled vaulted cistern (of about  $3000 \text{ m}^3$ ).



(a)



(b)



**Figure 8.** Comparison of Roman cisterns: (a) Small cistern in Ostica Antica and (b) Much larger cistern below the Acropolis of Athens (photo copyright by L.W. Mays).



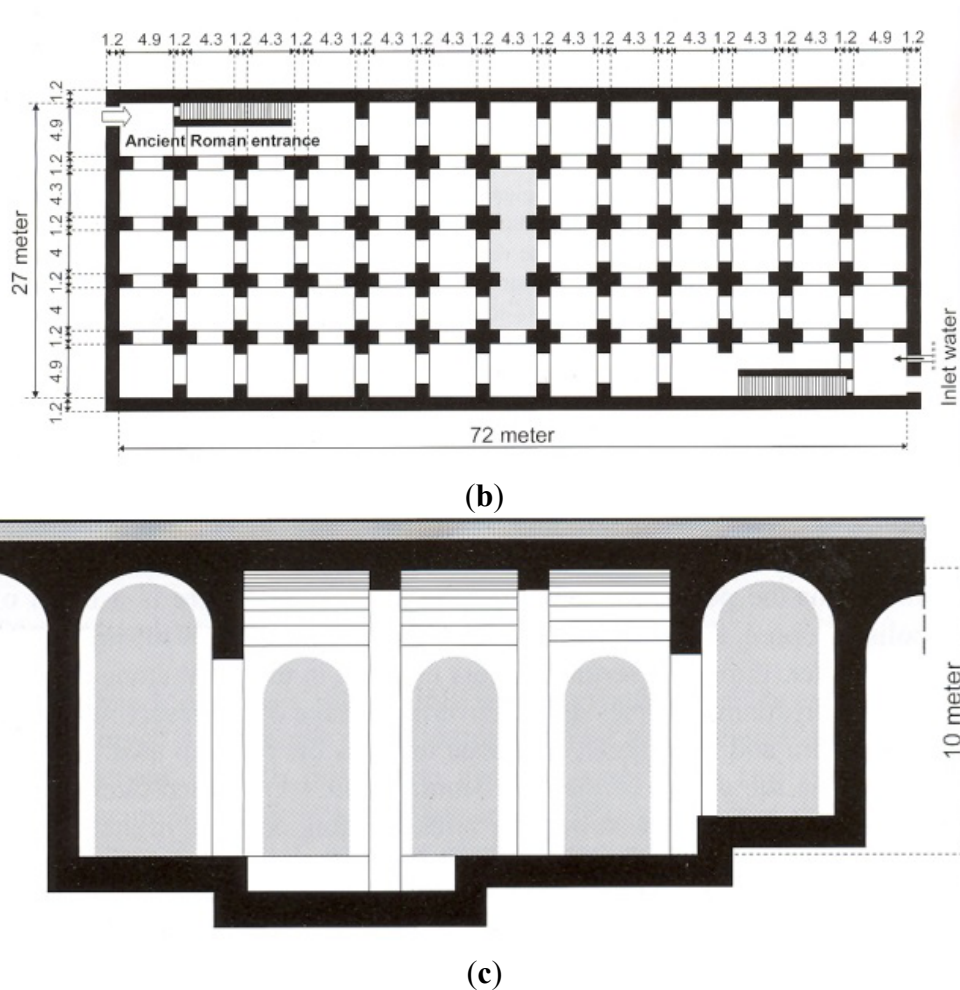
The Piscina Mirabilis (Figure 9) is one of the largest Roman cisterns (capacity of 12,600 m<sup>3</sup>). The cistern was supplied by water from the Augustan aqueduct, referred to as the Serino aqueduct, which was built from Serino to Miseno. The Serino aqueduct, which is 96 km long with seven branches, supplied many towns including Pompeii, Herculaneum, Acerra, Atella, Nola, among others. The total drop in elevation from the source, the Acquaro–Pelosi spring in Serino, to the Piscina Mirabilis is 366 m (0.38%). This large cistern is 72 m by 27 m in plan (as shown in Figure 9b,c) and is 15 m deep [18]. Large Roman cisterns were also built in Spain, southern Italy, Crete, Asia Minor, and North Africa, where the largest number can be found.

**Figure 9.** Piscina Mirabilis: (a) Photograph (copyright by L.W. Mays); (b) Plan view; and (c) Cross-section view [19].



(a)

Figure 9. Cont.



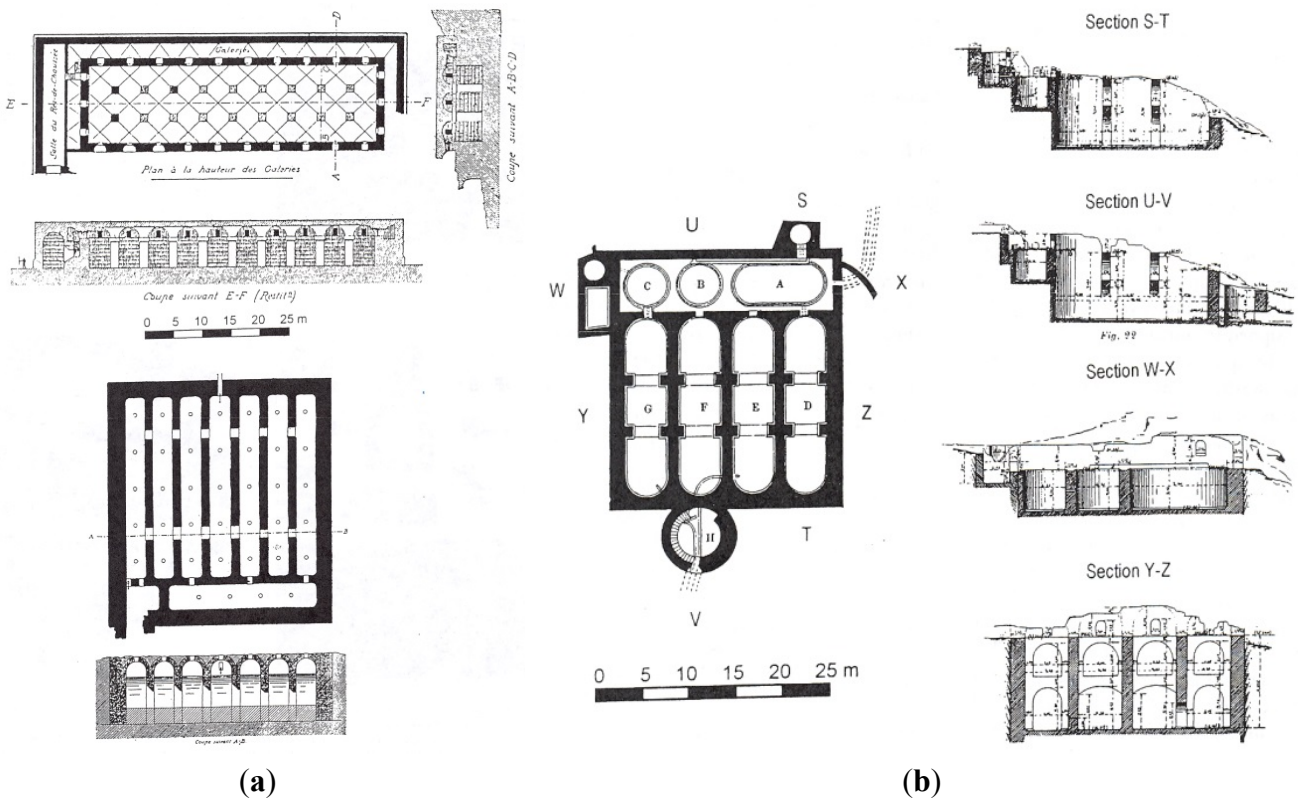
#### 4.2. Roman Cisterns in North Africa

Wilson [20] points out that in Roman North Africa, vast cistern complexes were used in conjunction with aqueducts. These cisterns had capacities that were often several thousand cubic meters, which were much larger than domestic cisterns. The large cisterns in North Africa were typically located where the aqueducts reached the edge of towns. Wilson [20] describes two types of common cistern complexes in North Africa, both of which were used at Uthina (see Figure 10a) in Oudna, Tunisia. Large cross-vaulted chambers, with a roof supported by piers, was one common type of cistern. A second common type of cistern complex includes several barrel-vaulted chambers with a transverse chamber set across them.

In the cisterns at Tuccabor and Djebel M'rabba in Tunisia, the transverse chamber was placed between the inlet and the parallel chambers; the chamber serves as a settling tank before water enters the storage chambers [20]. At Tugga, Thuburnica, Thapsus and Uthina, the transverse chamber is placed between the parallel chambers and the outlet, without a settling tank [20]. At Thuburnica and the Ain el-Hammam cisterns at Thugga, the entrance of the aqueduct channel runs along an internal wall of the cistern so that it distributes water to the cistern chambers. Cisterns at Dar Saniat at Carthage were constructed with three settling basins and two storage reservoirs, each bearing two compartments

with a total storage capacity of 2780 m<sup>3</sup> (see Figure 10b). Primary settling tank A (oval in shape) received water from the aqueduct and water entered.

**Figure 10.** Cisterns in North Africa: (a) plans and sections of the small (top) and large (bottom) cisterns at Uthina (Oudna, Tunisia) (after Babelon and Cagnat [21], text to f.XXVIII, Oudna) and (b) cisterns at Dar Saniat at Carthage (after Cagnat and Chapot, [22,23]. Both (a) and (b) as presented in [20]). Water also flowed from settling tank A into secondary circular settling tanks B and C before entering the second cistern chambers F and G. The water in F and G obviously would have been cleaner. A circular tap chamber (H in Figure 10b) received water through two lead pipes from D and E at floor level. It also received the higher quality water from G and F in a third lead pipe a meter higher than floor level.



Similar small cisterns had been constructed in numerous cities of the Roman Empire. During the times of Emperor Hadrian, a medium-sized cistern was built at the foothills of Lycabettus, outside the city of Athens (Figure 11) to store the water from an aqueduct and thus supply water to the new Roman neighborhood, situated at a level 70 m lower. It is remarkable that the water pressure found in this hypsometrical difference is a quite common water pressure in many modern water supply networks.

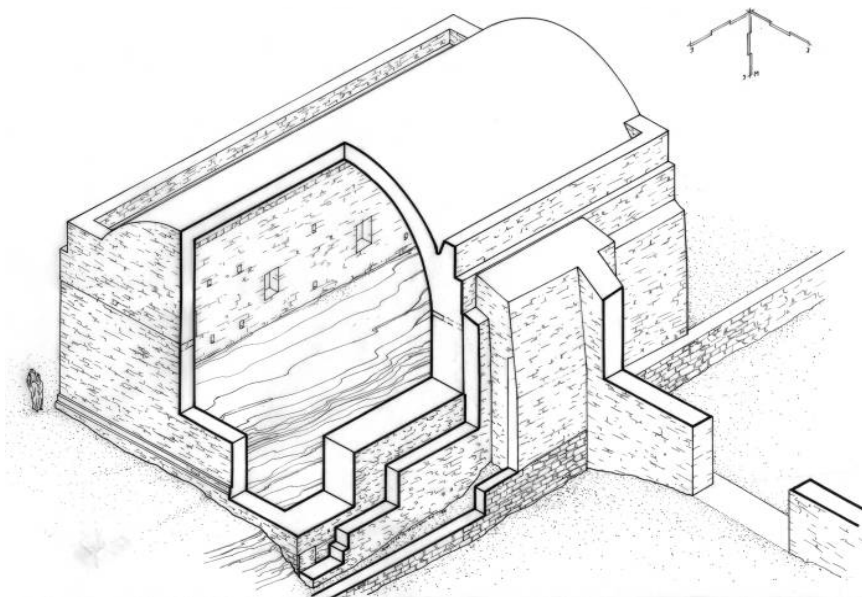
The habits and social customs of the ancient Romans, along with the needs of growing craftsmanship, resulted in an increased demand for water, either for bathing and toilet flushing or for the various workshops. These needs led to the construction of cisterns in places like Minoa on Amorgos (Figure 12), where previously the water demand was managed with small-scale rainwater collection and water reuse [24].



**Figure 11.** Cistern of Hadrian in Athens, as it was rebuilt after the original design in the 1880s (photo copyright by G.P. Antoniou).



**Figure 12.** Cistern at Minoa on Amorgos, built on the open space of the former agora. (Reconstruction by G.P. Antoniou).



## 5. Byzantine Period

The Byzantine Empire in the Byzantine period (*ca.* 330–1204 AD) and the Eastern Roman Empire are names used to describe the Roman Empire during the Middle Ages, with the capital in Constantinople (Istanbul). During the thousand-year existence of the empire, its influence spread widely into North Africa and the Near East.

After the decline of the Roman Empire, water supply systems experienced fundamental changes. Medieval cities in Western Europe, as well as castles and monasteries, had their own wells, fountains

or cisterns [25]. On the other hand, the eastern part of the empire retained for a few centuries the relevant Roman construction tradition, implemented mostly on the watering system of Constantinople and other major centers of the eastern Mediterranean. That tradition slowly diminished over the centuries, but some of the techniques that survived were incorporated into the Ottoman building practices, and were improved by the implementation of pointed arches and other innovations of that era. On the other hand, the more advanced technology of Western Europe, during the late Middle Ages, contributed to the cistern technology, incorporating knowledge of the Gothic arch dome construction. The surviving relevant Roman tradition was applied to the water system of Constantinople [26]. The system included aqueducts that supplied water to covered cisterns, but also open air cisterns that were supplied by rainwater, such as Xerokipion (“dry garden”) and the Aetius cistern [27,28]. In Constantinople, at least 36 cisterns were constructed [29]. A Byzantine cistern at the base of the Acropolis of Athens is shown in Figure 13.

**Figure 13.** Byzantine cistern at the base of the Acropolis of Athens (photo copyright by L.W. Mays).



The Basilica Cistern, or the Yerebatan Sarayı’ in Turkish, was the largest known covered cistern (140 m × 70 m and capable of holding 80,000 m<sup>3</sup>). This cistern, shown in Figure 14, is an underground cistern with 336 marble columns each standing 9 m high. The columns are arranged in 12 rows with 38 columns, spaced 4.9 m apart. The Basilica Cistern was built underneath the Stoa Basilica which was a large public square on the First Hill of Constantinople during the reign of Emperor Justinian I in the 6th century. Water was supplied to the cistern by an aqueduct from springs in Marmara in the Belgrade forest.

During the thousand-year existence of the empire, its influence spread widely into North Africa and the Near East. Several Byzantine cisterns were built in various places of Greece, e.g., Mistra, Leontari Arkadias (Figure 15), Monemvasia, Crete, and Athens (Figure 13), where several rainwater cisterns had been built on the Acropolis [30], as well as in smaller places such as the islands Amorgos and Megisti.

**Figure 14.** Basilica cistern of Constantinople (photo copyright by L.W. Mays).

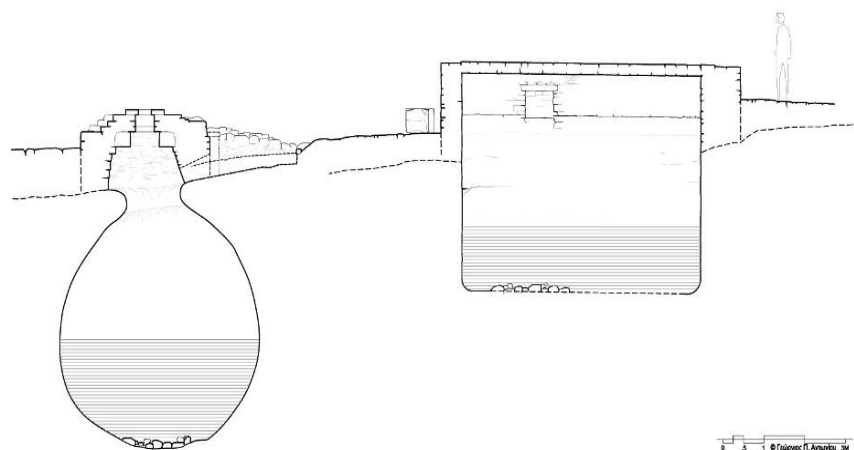


Rainwater cisterns were built not only as public facilities, but also as private ones in monasteries such as at Osios Loukas and Dafni [31,32], illustrated in Figure 16a,b, respectively. Also, cisterns were built next to or under churches, as well as in the residences of that era. The cisterns in the Byzantine town of Mystras [33] and of the arid Monemvasia [34] are quite characteristic. Additionally, the numerous rainwater cisterns found are basically the only remains of the collapsed houses at the castle of Leontari in Arkadia. The extensive use of domestic cisterns was typical during the last period of the Byzantine Empire since the state could not afford the construction of the necessary public ones, not only for financial reasons, but also due to the limited space of the regularly fortified towns.

**Figure 15.** (a) The great cistern at the Goulas of the castle at Leontari Arkadias and (b) Combined cross-section of the single-vaulted cistern in Ag. Anna on Amorgos dated to the Byzantine times [35] and the pear-shaped newer one (with permission of G.P. Antoniou).



(a)

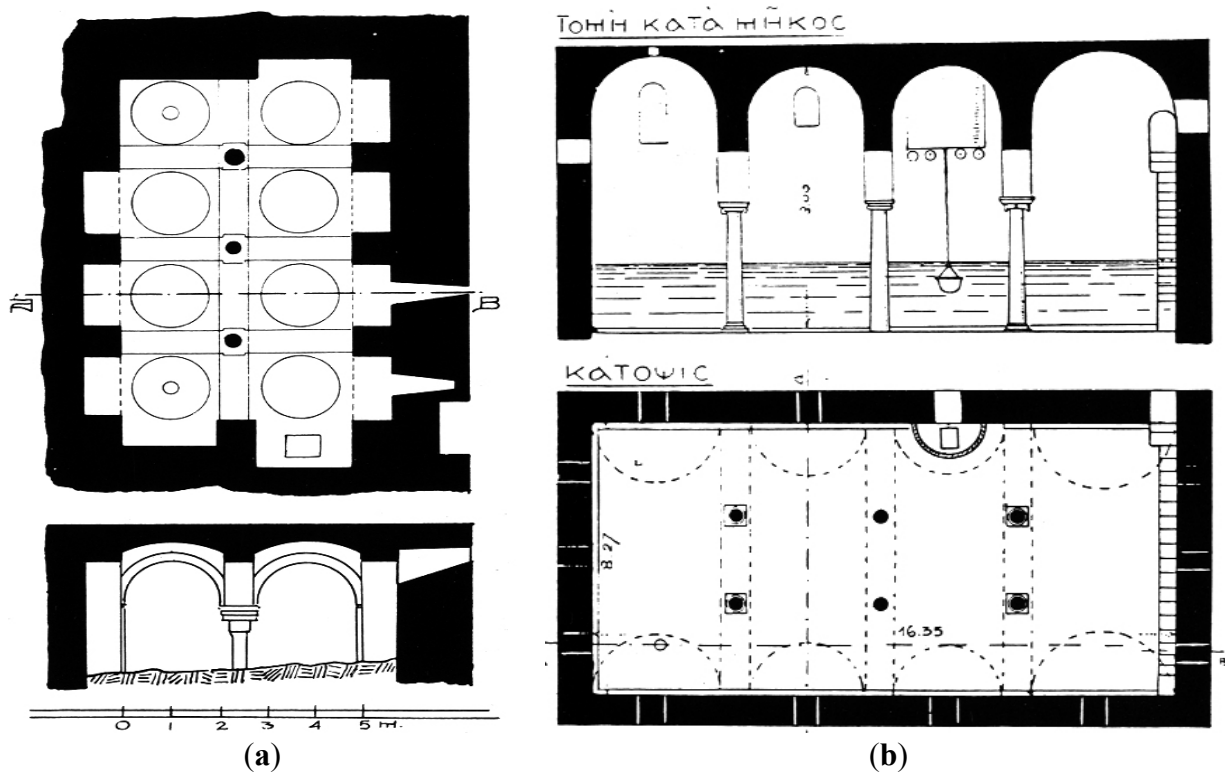


(b)

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**Figure 16.** Cisterns at monasteries: (a) cistern at Osios Loukas monastery in Boeotia, Greece [31] covered with lowered domes and (b) cistern at Ag. Apostoles monastery in Thessaloniki, Greece [31] covered with simple vaults.



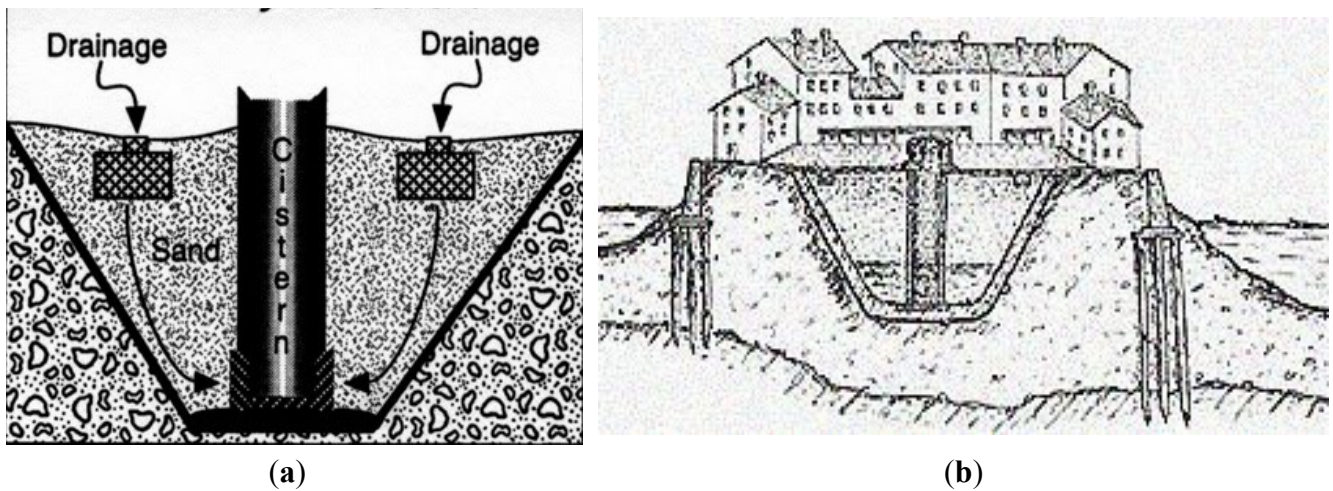
## 6. Venetian Period

One remarkable technique applied in Venice was the well-filtered cistern (Figure 17a,b), which spread around parts of Europe during the Venetian period (*ca.* 1204–1668). During the Venetian, Frankish and the Knights of St. John period in the eastern Mediterranean territories, rainwater harvesting and water storage were also improved by the implementation of advanced techniques of the new Western rulers of the region. The extensive and well-articulated runoff surfaces of the cisterns at Monemvasia (Figure 18a,b), dated to the post-Byzantine period, are characteristic examples. The double-vaulted rainwater cistern under the southern extension of Aghia Sofia Byzantine church at the same place (Figure 19a), follows a typical Byzantine tradition of cisterns under churches. The improved technological skills of that period permitted the erection of well-articulated cisterns even on remote islands such as Amorgos (Figure 19b). In addition, it is probable that the better financial capabilities of the Western states resulted in the construction of numerous public cisterns along with the domestic ones. Furthermore, the increase of workshops of various kinds during that period increased the need for water, and therefore, the construction of cisterns.

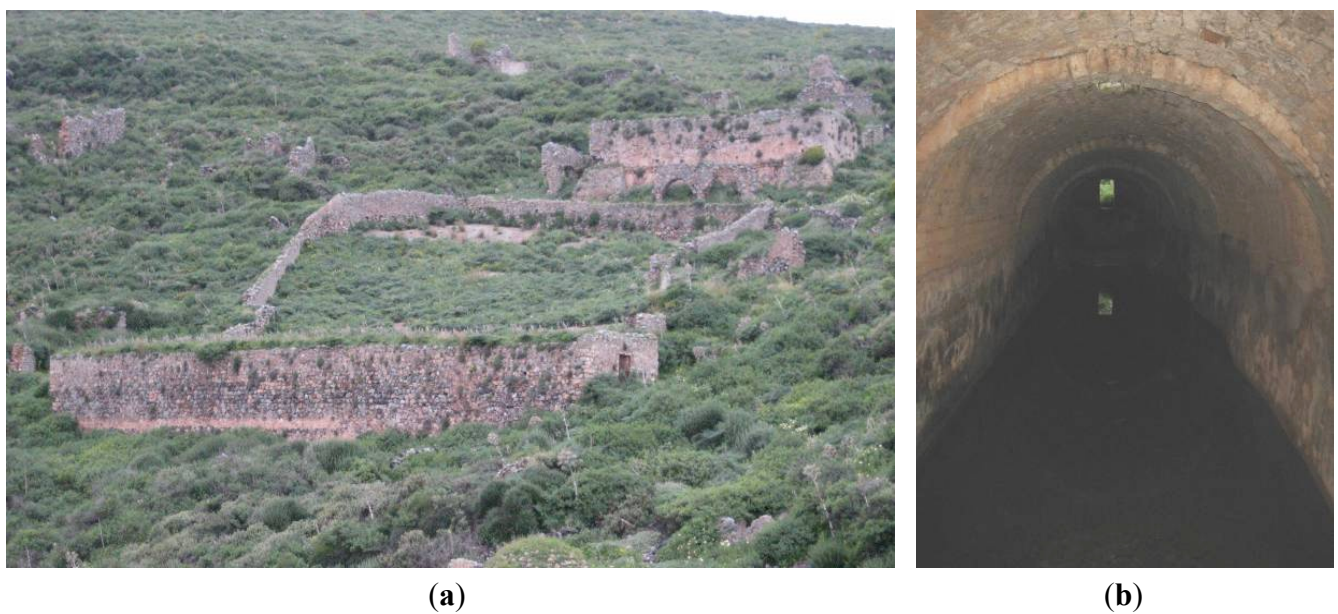
On Crete during the Venetian period, many water cisterns and fountain houses were constructed in both the towns and the countryside. In several Venetian cities and villages (e.g., in the Pediada region), which were densely populated and rich in water, significant water supply systems—expressed mainly in water cisterns and fountain houses—were constructed [36]. In general, the Venetian accomplishments in hydraulics are worth noting, such as the construction and operation of aqueducts, cisterns, wells,

fountains, baths, toilets, and harbors. 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, and in the Viannos Vigla castle. Also, small cisterns have been located in several villages in the area of Vamos, Chania, such as those in the village of Gavalochori, and those located with the wells at Agios Pavlos (Figure 19b) and Paleloni. Later evidences from the Venetian period suggest the existence of more than 500 cisterns in the city of Iraklion after *ca.* 1500 AD [37]. All those cisterns were collecting rainfall runoff.

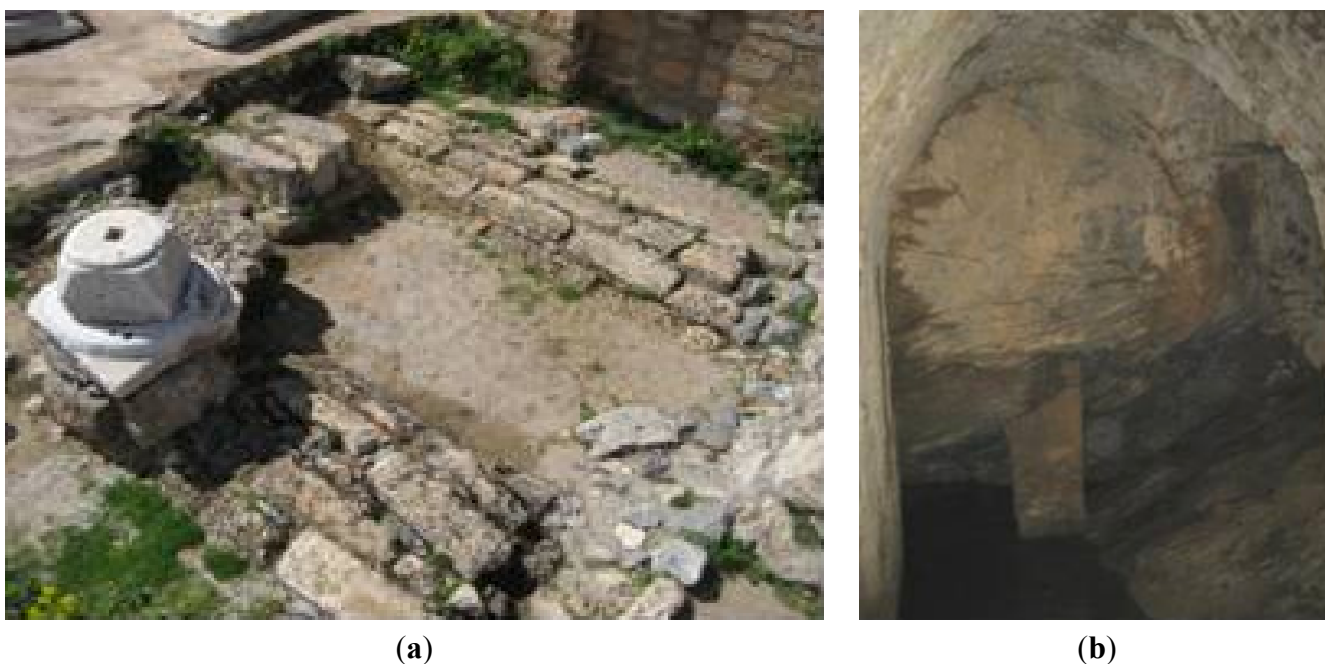
**Figure 17.** (a) Graphical section of the Venetian filtered cistern and (b) Schematic section of the implementation of the filtered cistern in a European fortified settlement.



**Figure 18.** Public rainwater cisterns at Monemvasia: (a) with runoff area and (b) the interior of the Katergo (with permission of G. P. Antoniou).



**Figure 19.** Cisterns of the Venetian period: (a) Double-domed cistern at Aghia Sofia at the upper town of Monemvasia and (b) Chora on Amorgos, the so-called Kato Lakkos (with permission of G. Antoniou).



## 7. Pre-Columbian Americas

### 7.1. Xochicalco (ca. 650–900 AD)

After the disintegration of Teotihuacan's empire in the 7th century AD, foreigners from the Gulf Coast lowlands and the Yucatan Peninsula appeared in central Mexico. Cacaxtla and Xochicalco, both of Mayan influence, are two regional centers that became important with the disappearance of Teotihuacan. Xochicalco ("in the place of the house of flowers"), was located on a hill top approximately 38 km from modern-day Cuernavaca, Mexico, and became one of the great Mesoamerican cities in the late classic period (ca. 650–900 AD). Despite the Mayan influences, the predominant style of architecture was that of Teotihuacan. There were no rivers or streams or wells to obtain water, so rainwater harvesting was the source of water. Rainwater was collected in the large plaza area and conveyed using drainage structures (see Figure 20a) and drainage ditches (Figure 20b) into cisterns such as the one shown in Figure 20c,d. From the cisterns, water was conveyed to other areas of the city using pipes as shown in Figure 20e. The collapse/abandonment of Xochicalco most likely resulted from drought, warfare, and internal political struggles.

### 7.2. Maya

The ancient Maya lived in a vast area covering parts of present-day Guatemala, Mexico, Belize, and the western areas of Honduras and El Salvador. Maya settled in the last millennium B.C. and their civilization flourished until around 870 AD. The environment that the Maya lived in was less fragile than that of the semi-arid lands where the Ancestral Puebloans and Hohokam lived. Tikal was one of the largest lowland Maya centers, located some 300 km north of present-day Guatemala City. The city



was located in a rainforest setting with a present-day average annual rainfall of 135 cm. Irrigated (hydraulic) agriculture did not result in the urbanism of Tikal. A number of artificial reservoirs were built in Tikal, which became more and more important as the population increased.

Another source was water that collected when soil was removed for house construction in depressions called *aguados*. The Maya also constructed cisterns called *chultans* in limestone rock under buildings and ceremonial plazas. The *chultans* were bottle-shaped underground cisterns that were dug in limestone bedrock and plastered with cement (see Figure 21). Drainage systems were developed to divert surface runoff from buildings and courtyards or plazas into the *chultans*. In the lowlands, the Maya typically used one or more of these methods for obtaining and storing water supplies [38].

**Figure 20.** Components of Xochicalco rainwater harvesting system: (a) drainage structure; (b) drainage channel; (c) cistern; (d) cistern; (e) terracota pipes. (photos copyright by L.W. Mays).



(a)



(b)



(c)



(d)



(e)

**Figure 21.** Entrance to Mayan chultan located in Tikal, Guatemala (photo copyright by L.W. Mays).



## 8. Ottoman Period

Water was so important to Islam that during the Ottoman period (*ca.* 1669–1898) there was a water tap in every mosque. Hamams, which are also referred to as Turkish baths, played an important role in the Ottoman culture and served as places of social gathering, ritual cleansing, and as architectural structures, institutes, *etc.* [39]. The cleansing of the body symbolizes the cleansing of the soul according to the Koran. The hamam 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 hamams and fountains was via major hydraulic works developed during the Ottoman period.

On the other hand, the role of cisterns in Istanbul decreased during the Ottoman period due to the centralized water systems, but continued in remote areas not served by the water systems. In this period, contrary to the rectangular plan of Byzantine cisterns, circular-type cisterns emerged in rural areas. A large number of these cisterns (Figure 22) have been found in southwest Anatolia, dating from the 16th century, and served military logistics purposes of the Ottoman army. They are about 7 m diameter structures, consisting of a domed roof with a height about one-third of the diameter on a superstructure 1 to 2 m high and a substructure a few meters in depth, with stairs descending to the bottom of the cistern. Many of these cisterns are still in use today for livestock water supply [40]. These cisterns were built on a superstructure 1 to 2 m high and a substructure a few meters in depth, with stairs that descended to the bottom of the cistern. Most of these cisterns are still used today for livestock water supply [41].

Koyuncu *et al.* [42] focused on nomad cisterns in Antalya, stating that around 110 cisterns have been located with the following construction: cisterns with wells, cistern wells with staircases, cisterns with gable roofs and vaulted/cupola cisterns. These cisterns were the products of nomad migration in the Antalya area. The cisterns were plastered on the outside with a khorasan mortar.

The fortifications built or reformed by the Ottomans in the 16th and 17th centuries were equipped with enough cisterns for the needs of the population living inside the enclosure. The castles of Lepanto



at the Corinthian Gulf in Greece and Niocastro or Navarino-Pylos in the Peloponnese are characteristic examples. At the second one, the cisterns were supplied by two aqueducts conveying the water from a spring in the vicinity, and another much further away [43].

**Figure 22.** Ottoman cistern located near Bodrum, Turkey (photo copyright by L.W. Mays).



Moreover, in locations where Hellenic inhabitants and the pre-existing traditions were strong, several cisterns following that tradition were constructed during the Ottoman period. Characteristic examples are the large cistern at the upper castle of Mytilene (Figure 23a) and the smaller one at Palaiokastro of Megisti (Figure 23b) with a possibly earlier origin.

**Figure 23.** (a) The great cistern at the upper castle of Mytilene was rebuilt over a pre-existing Roman or Byzantine one, and supplied the Ottoman fortress and its inhabitants; (b) Domed rainwater cistern at Palaiokastro at Megisti, partially hewn in the rock of the hill (with permission of G. Antoniou).



(a)



(b)



## 9. Modern Times: 19th and 20th Centuries

During the mid and late 19th century, distribution cisterns represented the technological efforts to fulfill the emerging needs of water supply, combined with the expanding freshwater networks. These networks demanded also an essential water pressure for the multi-story buildings. In that period, several cisterns were constructed on hilly spots of the cities to ensure not only the necessary quantity of the water, but also the tap pressure.

The early examples of that era implemented mostly historic technologies. The gradual application of reinforced concrete provided the most suitable technique and material for the cistern—or water tank—construction almost all over the world, establishing an international approach on that field. The façade of the cistern at Mount Lycabettus in Athens, built in the 1870s over the Roman one following exactly the same plan as shown in Figure 24a. The central aisle of one of the two late 19th-century storage and distribution cisterns at the city of Patras, Greece [44] is shown in Figure 24b.

**Figure 24.** Modern cisterns: (a) The façade of the cistern at Mount Lycabettus in Athens, built in the 1870s over the Roman one following exactly the same design and (b) The central aisle of one of the two late 19th-century storage and distribution cisterns in the city of Patras, Greece (with permission of G.P. Antoniou).



(a)



(b)

## 10. Conclusions: Lessons Learned

The wisdom of several ancient civilizations must be put into practice by creating awareness, undertaking policy research, and lobbying to bring about the necessary change in policy so that water management becomes decentralized and subsequently increases water availability. From the time of very early civilizations, people in arid and semi-arid regions have relied on harvesting rainfall runoff and storing the water in cisterns. The evolution of rainwater harvesting systems to increase water use efficiency and the continuous effort to preserve the environment for sustainable development has been presented and discussed in this paper. It is believed that these early systems were used in the Mediterranean region to collect runoff from hillsides, open yards and roofs mainly for domestic purposes [45].

The storage of rainfall runoff facilities have been constructed in the entire region around the Mediterranean and the Near East since the third millennium BC. Not only were cisterns used to store rainfall runoff, they were also used to store aqueduct water for seasonal variations. Cisterns throughout ancient times have ranged from constructions comprised of irregularly shaped holes (tanks) dug out of sand or loose rocks and then lined with plaster (stucco) water proofing, to the rather sophisticated structures such as those built on Crete by the Minoans [46].

The scope of this paper is not an exhaustive presentation of all knowledge of cisterns throughout history. Some characteristic cisterns during different periods have been presented chronologically extending through to modern times. The historical examples of cistern technologies given in this paper may even have importance for today's water engineering. Some lessons learned include:

- (a) Throughout history, cisterns have been an essential part of water supply technology for human survival and well-being to obtain water resource sustainability;
- (b) A combination and balance of smaller scale measures (such as cisterns for water harvesting systems) and the large-scale water supply projects (such as cisterns for storage of aqueduct flows) were used by many ancient civilizations;
- (c) The ancient water technologies of cisterns should be considered not as historical artifacts, but as potential models for sustainable water technologies for the present and the future;
- (d) Ancient water technologies such as cisterns were characterized by simplicity, ease of operation, and the requirement of no complex controls, making them more sustainable [47]. Nevertheless, the successful design and operation of some of these systems were massive achievements in engineering;
- (e) Cisterns were used by ancient civilizations for water resource sustainability and have been used ever since, though their importance to modern-day water supply purposes have vanished somewhat in developed parts of the world, despite having continued in many developing parts of the world [48];
- (f) The ancients considered water security as one of the critical aspects of the design and construction of their water supply systems. Water security is also a contemporary concern around the world, particularly from the viewpoint of adequate water supply, and, more recently, from the viewpoint of possible terrorist activity on water supply systems. Water supply security has been important throughout history and must continue to be in the future.

As the 21st century continues, increased freshwater resources will be required in many locations to meet increasing population needs and the uncertainties and consequences of climate change. Demographic changes are the most significant challenges to our present-day water and future challenges. What we can learn from the ancients, using traditional knowledge, could be a significant factor in solving our water needs, especially for developing parts of the world [47].

Finally, it should be noted that more than 2.6 billion people do not use improved sanitation, while 1.1 billion practice open defecation. There is therefore a vast need for sustainable and cost-effective water supply and sanitation facilities, particularly in cities of the developing world [49]. Applicability of selected ancient water supply management systems (e.g., storage of rainfall runoff facilities) for the contemporary developing world should be seriously considered.

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We dedicate this to the ancient ones who gave us so much knowledge.

## Conflicts of Interest

The authors declare no conflict of interest.

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