Use of cisterns during antiquity in the Mediterranean region for water resources sustainability

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ABSTRACT

From the early civilizations people in arid and semi-arid regions have relied on collecting or 'harvesting' surface water from rainfall and storing the water in human-made reservoirs or '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 to allow for seasonal variations in the supply. Cisterns during ancient times ranged from the construction of irregular shaped holes (tanks) dug out of sand and loose rock, and then lined with plaster (stucco) water proofing, to the construction of rather sophisticated structures such as those built by the Romans and Byzantines. The primary objective herein is to provide a review of the use of cisterns by ancient civilizations in the Mediterranean region, and to relate the use of these cisterns to water resources sustainability of the past and the present, outlining the lessons learned.

Key words | Byzantines, cisterns, Greeks, Minoans, Romans, water resources sustainability

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INTRODUCTION

'The centrality of freshwater in our lives cannot be overestimated. Water has been a major factor in the rise and fall of civilizations' (UN Secretary General Kofi Annan; United Nations 2003). Mays (2007) defined water resources sustainability as 'the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life.'

Cisterns were used by ancient civilizations for water resources sustainability, and have continued to be used since; however, their importance for modern day water supply purposes has somewhat vanished in developed parts of the world, but has continued in many developing parts of the world. The importance of cisterns, however, is becoming more and more recognized throughout the world as a traditional knowledge (Laureano 2001), another factor in water resources sustainability. Few publications have been directed at discussing cisterns during antiquity and their importance for human survival. A brief review of the use of cisterns by ancient civilizations is presented herein. This is not a complete and thorough review by any account but does include cisterns used as part of water harvesting systems and as storage of aqueduct water for seasonal variation of available water.

Cisterns have ranged from clay pots to very large underground structures. The Mycenaeans (in Mycenae in continental Greece by the end of the 13th century BC) built an underground cistern. This cistern was supplied by water from the Persia spring through a 200 m long buried conduit dug into the rock. A terracotta pipe is still visible at the roof of the cistern (Taylor 1983).

Even the grand aqueducts constructed by the Romans were not built to provide drinking water or to promote hygiene. Roman cities instead depended mainly upon cisterns or wells in individual houses for drinking water (Hodge 2002; Mays 2010; Angelakis *et al.* 2012).

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FIRST EFFORTS TO CONTROL WATER WITH CISTERNS AND REFERENCES IN THE BIBLE TO CISTERNS

Probably the first successful efforts to control water by humans were made in Mesopotamia and Egypt. The construction and use of cisterns has been traced back to the Neolithic Age when waterproof cisterns (lime plastered) were built in the floors of houses in villages in the Levant (Miller 1980) by the late 4th millennium BC. In Mari, in ancient Mesopotamia, a canal connected to the city from both ends and passed through the city. Servant women filled the 25 m^3 cistern of the palace with water supplied by the canal. Later on other cisterns were built in Mari and connected to an extended rainfall collection system. The ancients used a lime plaster to cover bedrock to prevent seepage and loss of water from the cisterns. The use of cisterns in ancient times ranged from storing rainwater in harvesting systems to storing water delivered by aqueducts originating in distant springs and streams. Rainwater harvesting systems include a catchment area for rainfall interception; a cistern for storage; a conveyance system to deliver the water from the catchment to the cistern; and a method to draw upon the storage for consumption. The catchment ranged from rooftop areas to courtyards and plazas.

The Bible refers to cisterns many times. One example is when Jeremiah, the prophet, proclaimed a scathing indictment against Israel and their idolatrous ways. He accused them of worshiping false gods which he compared to cisterns that could not hold water (broken cisterns). In *Jeremiah 2:13*, 'For my people have committed two evils; they have forsaken me the fountain of living waters, [and] hewed them out cisterns, broken cisterns, that can hold no water.' During Biblical times cisterns were also used as underground chambers, such as hiding places for fugitives, burial places, and even as prison cells. Jeremiah was held as a prisoner in a muddy cistern which belonged to Malchaiah, the son of King Zedekiah (*Jeremiah 38:6*), from where he was eventually hauled up with ropes. *Jeremiah 14* also gives us a description or definition of droughts.

Many ancient cisterns have been discovered throughout Jerusalem and the entire land of Israel. At the site believed by some to be that of ancient Ai of the Bible (Khirbet et-Tell), there was discovered a large cistern dating to around 2500 BC which could hold nearly 7,500 m^3 of water. It was carved out of solid rock, lined with large stones and sealed with clay to prevent leaking. Some sites contained over 50 cisterns (Tell en-Nasbeh). The Umm al-biyara (the mother of all cisterns) is at the ancient site of Edom, which became the Nabataean city of Petra.

MINOANS (CA. 3200–1200 BC)

The Minoan culture flourished during the Bronze Age in Crete. A systematic evolution of water management in ancient Greece began in Crete during the early Bronze Age, i.e. the Early Minoan period (ca. 3000–2150 BC, Myers *et al*. 1992). Wells, cisterns, water distribution, fountains, and even recreational functions existed. In prehistoric Crete rivers and springs provided people with water. Starting in the Early Minoan period II (ca. 2900–2300 BC), a variety of technologies such as wells, cisterns, and aqueducts were used. Also, the Minoan architecture included flat rooftops, light wells, and open courts which played an important role in the water management. The rooftops and open courts acted as catch basins to collect rainwater from which it flowed to storage areas or cisterns.

The Minoan settlements used cisterns about 1,000 years before the classical and Helenistic-Greek cities. Cisterns were used to supply (stored runoff from roof tops and court yards) water for the households through the dry summers of the Mediterranean. The two earliest large cisterns of Minoan Crete were built in the first half of the 2nd millennium BC, which was the time of the first Minoan palaces at Myrtos-Pyrgos (see Cadogan 2006). Figure 1(a) shows one of two cisterns at Myrtos-Pyrgos. These cisterns remain an unusual feature of the Minoan settlement, as the Myrtos River supplied water to the base of Pyrgos Hill. Both cisterns are circular with vertical walls and rounded bottoms. The walls and bottom are coated with white lime plaster 1–2 cm thick (Cadogan 2006). Similar round structures exist at Knossos, Mallia, and Phaistos, which have been called granaries, but according to Cadogan this is improbable because of their locations at the bottom of hills. It would have been difficult to prevent water from running into the

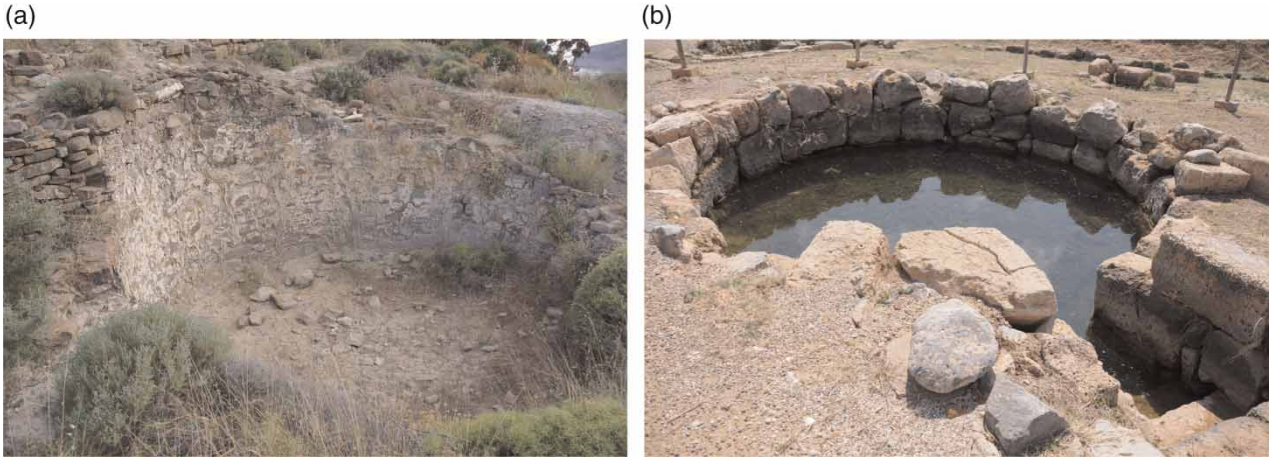

Figure 1 | Cisterns at (a) Myrtos-Pyrgos and (b) Kato Zakros (photo copyright by L.W. Mays).

round structures during a storm. Figure 1(b) shows a cistern at Kato Zakros.

Tylissos was one of the important cities in ancient Crete during the Minoan era, flourishing (ca. 2000–1100 BC) as a peripheral center dependent on Knossos. The water supply system to Tylissos included an aqueduct developed in the Minoan period that was constructed of closed pipes and curved stone channels. Secondary conduits were used to convey water to a settling tank constructed of stone (see Figure 2(a)), used to remove sediment and/or suspended sediments. Also note the hole in the lower part of the tank which enabled the tank to be drained for cleaning. Water then flowed from the settling tank to the main cistern for water storage. Steps, shown in Figure 2(b) were used to descend down to the various water levels.

The hill of Phaistos was settled for the first time at the end of the Neolithic period (4th millennium BC). Later in the early Bronze Age (during the Early Minoan period) the Minoans built above the ruins of the Neolithic houses. At the end of the prepalatial period Phaistos became very prosperous with the construction of the first palace (ca. 2000–1900 BC). The water supply system in the Palace of Phaistos, as well as in other cities and villages in Minoan Crete depended directly on rainfall, collected from

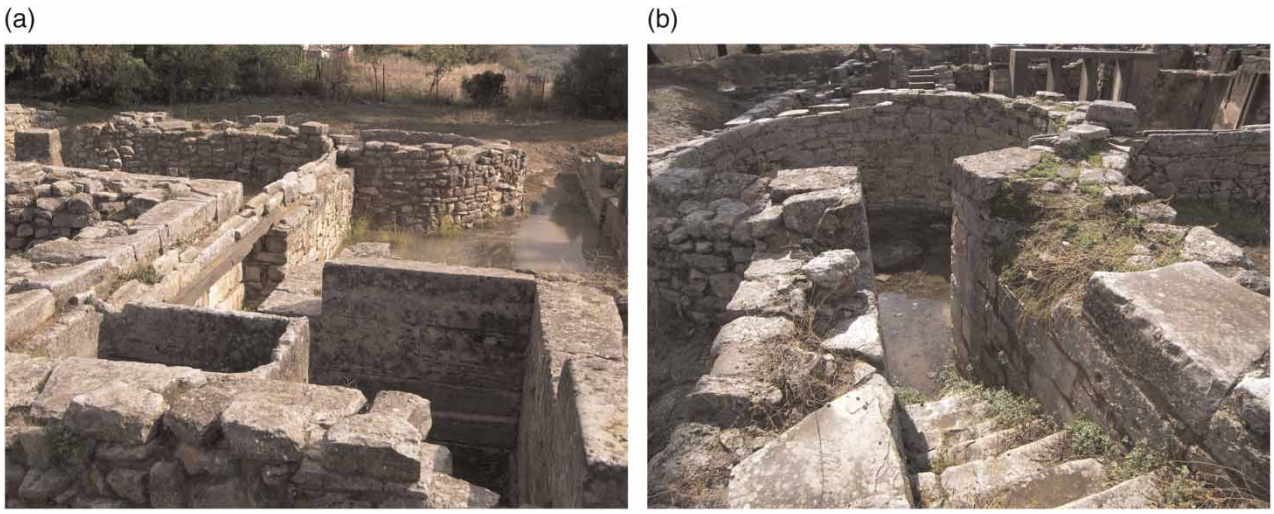

Figure 2 | Cistern in Tylissos, Crete. (a) Sedimentation tank in foreground with stone channel connecting to cistern. (b) Steps leading down to cistern (photo copyright by L.W. Mays).

roofs and courtyards and then directed to cisterns. The drainage systems were in some cases conveyed into terracotta vessels near light wells, which acted as water collectors.

GREEKS (CA. 750–146 BC)

During the archaic (ca. 750–480 BC) and the classical (ca. 480–323 BC) periods of the Greek civilization, cisterns were similar to those built by the Minoans. Most Greek houses had a cistern supplied by rainwater for purposes of bathing, cleaning, houseplants, domestic animals, and even for drinking during shortages of water. Most likely the water was of a quality of what we would today consider as sub-potable. Aristotle in his *Politics* (vii, 1330b) written in the 320s BC asserts that 'cities need cisterns for safety in war.' During this time a severe 25-year drought required the collection and saving of rainwater (Camp 1982). Also about this time cisterns were built in the Athenian Agora for the first time in centuries (Parsons 1943; Crouch 1993).

Most of the ancient Athenian Agora cisterns have been dated between the 4th and 1st century BC. These cisterns are believed to have had a secondary use when the natural supply of water was insufficient. Water from the wells would have been used for drinking, while the water stored in the cisterns would have been used for washing. Rainwater was stored in the cisterns after being collected from the surrounding roofs and drained into the eaves' gutter that drained into a canal at ground level that connected to a cistern. These cisterns had a diameter of approximately 3 m, and a flask-like shape, probably in order to avoid collapses of the rock formations. Frequently, two successive cisterns were connected through a channel, while the walls of the cistern and the channels were plastered with a mortar.

The city-state of Dreros during the Classical Greek period is located near Neapolis in eastern Crete in the district of Lassithi. Dreros was constructed on a saddle between two peaks on the slope of Mount Kadistos. A large rectangular cistern ($13 \times 5.5 \times 6\ m^3$) was constructed in the Agora for the purposes of water supply (Antoniou *et al.* 2006). According to Myers *et al.* (1992) this was the first and largest cistern ever known at that time. Figure 3 shows the cistern in the ancient Greek city of Dreros on Crete.

Figure 3 | Cistern in the classical Greek city of Dreros on Crete. Shown are the steps leading down to the bottom of the cistern located in the Agora. There is also another set of stairs leading down into the cistern (photo copyright by L.W. Mays).

The lack of adequate surface and groundwater from sources on the Greek islands, which are arid and semi-arid, resulted in the use of rainfall-runoff harvesting by the inhabitants. One of many examples is in Aegina where the uncovered cisterns were called Mpourdechtes. The construction of these cisterns consisted of a combination of masonry walls and curved parts of the natural rock beneath resulting in an irregular shaped cistern (Antoniou 2006). There are still surviving Mpourdechtes, made mostly of stone masonry, which are more regular in shape that have been dated to the Hellenistic period. Also there are many Mpourdechtes with irregular stone masonry constructed mostly of large stones, such as the small Mpourdechtis at Hellanio's Zeus sanctuary that is similar in construction to the Hellenistic impromptu fortification walls (Antoniou 2006).

During the Hellenistic period (ca. 323–146 BC) further developments were made by the Greeks in the construction and operation of cisterns, which most likely peaked during this period. Because of the lack of adequate water supplies on most Greek islands, cisterns were used. The water supply in several Greek cities was dependent entirely on rainfall which was collected from the roofs, yards and other open spaces. During this time the technology of cisterns progressed (Mays 2010).

ROMANS (CA. 3RD CENTURY BC–4TH CENTURY AD)

In 265 BC Rome's power extended only to northern Italy, and 120 years later it extended from Spain to eastern Asia and the Aegean Sea. During the Roman period larger scale hydraulic works (mainly water supply systems) characterized the advances in water technology. Roman engineers used the technologies of previous periods to their advantage and constructed advanced cisterns for their larger projects such as the Piscina Mirabilis (discussed below) for the Serino Aqueduct system (De Feo & Napoli 2006). The Romans made extensive use of cisterns, so that herein only a very few of the many that were built will be explored. In the Roman town of Pompeii, with the 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 as a result of the volcano, requiring cisterns to be used for drinking water (Crouch 1993).

Figures 4–8 show various Roman cisterns. Figure 4 shows the remains of a cistern built below the Acropolis in Athens. Figure 5 is a Roman cistern built in Iasos, Turkey. Figure 6 shows a rather unusual Roman cistern at Illici near modern day Elche, Spain, with a bottle shaped structure below the opening. Figure 7 shows the remains of a Roman cistern at Thera on Santorini.

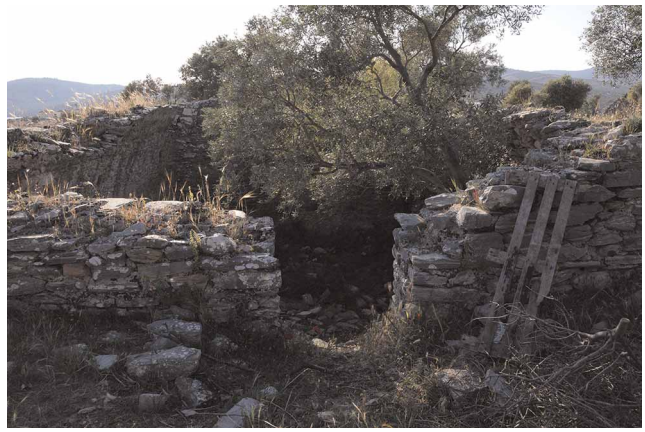

Figure 5 | Cistern at top of hill in Iasos, Turkey (photo copyright by L.W. Mays).

Figure 6 | Roman cistern in Ilici, Spain (photo by L.W. Mays).

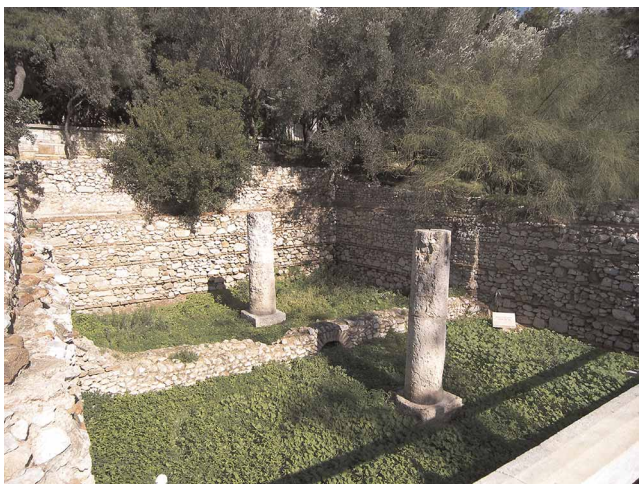

Figure 4 | Roman cistern below Athens Acropolis (photo copyright by L.W. Mays).

Figure 7 | Roman Cistern at Thera on Santorini (photo copyright by L.W. Mays).

The Romans also built very large cisterns. The Piscina Mirabilis (Figure 8) is one of the largest Roman cisterns (capacity of 12,600 m^3 of water) (De Feo *et al*. 2010). The cistern was supplied by water from the Augustan aqueduct, the Serino aqueduct that was built from Serino to Miseno. The Serino aqueduct, 96 km long with seven branches, supplied many towns including Pompeii, Herculaneum, Acerra, Atella, Nola, and 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 and is 15 m deep (according to Hodge (2002)).

Other large Roman cisterns have been found in Spain, southern Italy, Crete, Asia Minor, with the largest number in North Africa. Wilson (2001) points out that in Roman North Africa vast cistern complexes were used in conjunction with the aqueducts. These cisterns had capacities that were often several thousand m^3, that were much larger than the domestic cisterns. These cisterns in North Africa were typically located where the aqueducts reached the edge of towns. Wilson (2001) describes two types of common cistern complexes in North Africa, both of which were used at Uthina in Oudna, Tunisia. Large cross-vaulted chambers, with a roof supported by piers, is one type of cistern. A second common type of cistern complex includes several barrel-vaulted chambers with a transverse (connecting) 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 and the chamber served as a settling tank before water entered the storage chambers (Wilson 2001). At Tugga, Thuburnica, Thapsus and Uthina the transverse chamber was placed between the parallel chambers and the outlet, with no settling (Wilson 2001). 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 in Carthage were constructed with three settling basins and two storage reservoirs, each having two compartments with a total storage capacity of 2,780 m^3.

Cisterns may have also been used as a means to store water for fighting fires. Fahlbusch (2012) argues that the big cistern at the acropolis of Pergamum may have been used for this purpose. This cistern, 4.55 m in diameter and 6.20 m in depth, with a different type of construction, differs in comparison to the normal rainwater cistern of the time. This large cistern at Pergamum was built of mortared ashlars and did not have a stone ceiling which may indicate a different use. One question has been whether the cistern was built in the Hellenistic or the Roman era, with Fahlbusch (2012) stating that it was surely built in Roman times.

Figure 8 | Piscina Mirabilis (copyright by L.W. Mays).

TERMESSOS (CA. 4TH CENTURY BC–5TH CENTURY AD)

Termessos (originally an ancient Pisidian city possibly dating back before the 14th century BC) is located about 53 km northwest of Antalya, Turkey, in a valley on the steep slopes of the Gulluk in the Taurus Mountains at an elevation of over 1,000 m. What is known of the history of Termessos begins when Alexander the Great surrounded the city in 333 BC, but failed to conquer. The people of Termessos were the Solyms, not Greeks, and spoke a language referred to as Solymish. The area has no rainfall from the beginning of April to the end of October. Because of the lack of rainfall and the inability to transport water as a result of the steep topography, the people of Termessos made extensive use of collecting rainfall runoff for storage in cisterns and even constructed a dam (Kurkcu 2012). During the Hellenistic period the city adopted the Greek culture and language and other advances occurred during the Roman times. Termessos went through a gradual decline

and was finally abandoned in the 5th century AD. Two of several cistern locations at Termessos are illustrated in Figure 9. These cisterns certainly show influences of both Greek and Roman construction.

NABATAEANS (CA. 300 BC–300 AD)

Rainwater harvesting was used extensively in Petra by the Nabataeans (ca. 300 BC–300 AD). In Petra this meant using the technology in elevated places and on bare sandstone walls with many innovations. The Nabataeans used various types of cisterns that they carved out of the rock and waterproofed using chalk. These cisterns ranged from small pools in the highlands to catch runoff, to rectangular shaped cisterns at the bottom of the natural dips. Small pools were carved out of the highland and evolved into bell-shaped cisterns. These large cisterns are similar to large rooms carved out of vertical walls into which complex canals and pipe networks flow (Laureano 2001). What is so unique is that the Nabataeans used every slope and surface as a means to harvest rainfall and stored every water source from a few drops to large floods. This is why Strabo, the 1st century geographer, described Petra as ornamented with fountains and basins (Laureano 2001).

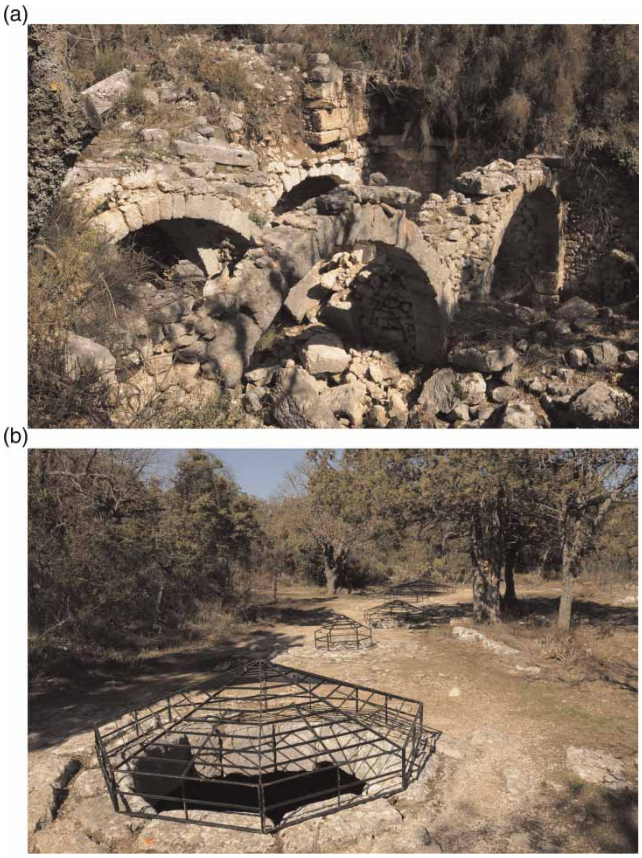

Figure 9 | (a) Remains of cistern in Termessos (photo copyright by L.W. Mays). (b) Shows five inlets for cisterns at Termessos for which there are actually three different cistern chambers (photo copyright by L.W. Mays).

Khottara make use of traces of moisture and night condensation of fog and dew by harvesting the condensation (humidity) by causing it to drip into tanks, cisterns, or channels that catch the water on the walls and convey it to pools. These structures provide water all year round. At the other extreme, one cistern called Bir Huweimel at the bottom of Ras as-Slimane, actually traps flood water using a large room (depth of 9 m) excavated in the riverbed. Flood water is diverted to water intakes and decanting basins to fill the large cistern where the water is stored. A staircase is used to enter the cistern and water is drawn from the cistern through a well shaft.

BYZANTINES (CA. 330–1204 AD)

The Byzantine Empire and 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 during the Middle Ages. Figure 10 shows a Byzantine cistern at the base of the acropolis in Athens, which is a covered cistern.

Both open-air (uncovered) and covered cisterns were built during this time period. One of the earliest cisterns was built in the 4th century AD in Modestus (Mango 1995). The cistern was built from 363 to 369 AD and measured approximately 154 m × 90 m in ground plan and was most likely uncovered. Covered cisterns were more numerous than open-air cisterns. At least around seventy of them existed in Constantinople, though not all of them have been verified by archeological evidence.

During the Byzantine times in Constantinople at least 36 cisterns were constructed (Lerner 1989). The Basilica Cistern, or in Turkish the Yerebatan Sarayi', was the largest

Figure 10 | Byzantine cistern at the base of the acropolis in Athens (photo copyright by L.W. Mays).

(140 m × 70 m and capable of holding 80,000 m^3) known covered cistern, probably completed in the early 6th century. This cistern, shown in Figure 11, is an underground cistern located in Sultanahmet, having 336 marble columns each 9 m high. The columns are arranged in 12 rows each with 28 columns, spaced 4.9 m apart. The cistern was built underneath the Stoa Basilica which is 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, which is west of the city. When the water was drained from the cistern two of the 336 columns were discovered to rest on ancient carved heads of Medusa. Other Byzantine cisterns located in Sultanahmet include the Binbirdirek Cistern, or Cistern of Philoxenos, and the Theodosius Cistern.

The most important open cisterns received water predominantly from the Belgrade forest west of the city. Aqueducts were used to convey water to the city and the cisterns were also located on the hills of Constantinople. The architecture of cisterns during the 4th to the 6th centuries provides an understanding of the standardization of architecture during that time period. The building materials were different as compared to the Roman construction of cisterns. Constantinopolitan cisterns were built with brick instead of the Roman concrete vaults, and marble columns instead of Roman brick and cement piers (Yavuzturk & Ozyalavac 2012).

OTTOMANS (CA. 1299–1922 AD)

During the 16th century AD of the Ottoman period in Turkey a different type of cistern (see Figure 12) emerged in rural areas, particularly in southwest Anatolia. These cisterns were built for military logistic purposes for the Ottoman Army. These circular shaped cisterns are about 7 m in diameter, with a domed roof of a height about one third of the diameter. The cistern was built on a superstructure 1–2 m

Figure 11 | Basilica cistern of Constantinople in Istanbul, Turkey (photo copyright by Susi. K. Mays).

Figure 12 | Ottoman cistern built for military purposes of the Ottoman Army, located near Bodrum, Turkey (photo copyright by L.W. Mays).

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 for livestock water supply (Ozis 1982).

Koyuncu *et al.* (2012) 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 plaster khorasan mortar.

LESSONS LEARNED AND WATER RESOURCES SUSTAINABILITY

A brief review of some of the types of cisterns used during antiquity has been presented in order to illustrate the progression of advances and to relate how humans have used this technology to advance water resources sustainability. These unique structures have allowed humans to live in arid and semi-arid regions of the world for well 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. The overall goal of water resources management must be water resources sustainability, as evidenced by the ancients. Because water impacts so many aspects of our existence, there are many facets that must be considered in water resources sustainability (see Mays 2007). Some lessons learned include the following:

- A combination and balance of smaller scale measures (such as cisterns for water harvesting systems) and large-scale water supply projects (such as cisterns for storage of aqueduct flows) were used by many ancient civilizations such as the Minoans, Greeks, Romans, Byzantines, and Ottomans.
- 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. A key factor in sustaining traditional water management systems depends on placing a premium on such methods which have proven to be successful, especially in arid and semi-arid lands.
- Ancient water technologies such as cisterns were characterized by simplicity, easy operation, and requiring no complex controls, making them more sustainable. However the successful design and operation of some of these systems were massive achievements, even by modern day standards. Keeping in mind that the fundamental concepts of the conservation of mass, energy and momentum did not exist, these systems were built and provided for water resources sustainability.
- The ancients considered water security as one of the critical aspects of the design and construction of their water supply systems. Water security is a modern day concern around the world, particularly from the viewpoint of adequate water supply, and now from the viewpoint of possible terrorist activity targeting water supply systems which can debilitate such systems. Water supply security has been important throughout history and must continue to be in the future.
- The looming present day water crisis in many parts of the world must be faced using traditional knowledge and techniques inherited from the past, in addition to our present day technological capabilities, for more sustainable ways of dealing with water scarcity, particularly in developing parts of the world. The use of cisterns as a part of rainwater harvesting systems can be implemented today, particularly in many developing parts of the world where this technology is lacking to strive for water resources sustainability.
- Many ancient water infrastructure projects were built in a piecemeal fashion over many years such as Rome (over 500 years, funded with the spoils of war and heavy taxes on conquered countries), but were not maintained after the wars ended. The government did not account for the expense to the future generations, a lesson being learned by many modern day nations.

As a concluding remark, the ancients lived more in harmony with nature and the environment as opposed to our modern day society. As water systems are very dynamic, especially in arid and semi-arid lands, traditional methodologies such as cisterns have proven to be very effective in both the past and the present, and should be part of our future. Our generation is not sustainable in that we are ignoring future generations, creating problems for them such as our contributions to climate change and our

continual greed for more. We need to learn from the ancients, they have spoken. Will we listen?

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