ANCIENT URBAN WATER SUPPLY SYSTEMS IN ARID AND SEMI-ARID REGIONS

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ABSTRACT

Many civilizations, which were great centers of power and culture, were built in locations that could not support the populations that developed. Throughout history, arid and semi-arid lands seem to have produced more people than they could sustain. From the early civilizations people in arid and semi-arid regions have relied on collecting or "harvesting" surface water from rainfall runoff and storing the water in human-made reservoirs or "cisterns." Not only were cisterns used to store rainfall runoff they were also used to store water supplied by aqueducts for seasonal variations. The primary objective herein is to provide a brief survey of some of the water supply systems and their components used in antiquity in arid and semi-arid regions of the world. Can some of this traditional knowledge be used for water sustainability in the future?

Key words: water supply, ancient water systems, arid and semi-arid regions

1. BEGINING OF WATER FOR CITIES – ANCIENT MESOPOTAMIA

In ancient Mesopotamia, every city of the Sumer and Akkud had a canal(s) connected to the Euphrates River or a major stream for both navigation and water supply for daily uses. In Mari a canal connected to the city from both ends and passed through the city (Viollet, 2006). Servant women filled the $25m^3$ 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. Terracotta pipes were used in Habuba Kebira (in modern Turkey), a Sumerian settlement in the middle Euphrates valley in the middle of the IV the millennium B.C. (Viollet, 2006). In the 3rd millennium B.C. time period the Indus civilization had bathrooms in houses and sewers in streets. The Mesopotamians were not far behind (Adams, 1981). In the 2nd millennium B.C. the Minoan civilization on Crete had running water and flushing latrines (Evans, 1964). The Minoan and Mycenaean settlements used cisterns a 1000 years before the classical and Helenistic-Greek cities. Cisterns were used to supply (store runoff from roof tops) water for the households through the dry summers of the Mediterranean.

2. MINOANS

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. 3500 – 2150 B.C., 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 the Early Minoan period II (ca. 2900 – 2300 B.C.), a variety of technologies such as wells, cisterns, and aqueducts were used. Also the Minoan architecture included flat rooftops, light wells, and open courts 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.

During the Neopalatial period, ca. 1700-1400 BC, Knossos was at the height of its splendor. The city extended an area of 75,000 to $125,000m^2$ and had an estimated population in the order of tens of thousands of inhabitants. The water supply system at Knossos was most interesting; however, as Graham (1987) points out the sources and methods of supplying water are only partially understood. There were wells and an advanced system of rainfall collection for water supply. Terracotta pipe conduits (60 to 75 cm flanged to fit into one another and cemented at the joints) were used within the palace for rainfall

collection and/or water distribution as shown in Figure1. Possibly the piping system was pressurized. A water distribution system also makes possible the existence of an aqueduct. An aqueduct made of terracotta pipe could have crossed a bridge on a small stream south of the palace which carried water from a perennial spring on the Gypsadhes hill (Graham, p 219, 1987). Unfortunately, around 1450 BC the Mycenean palace was destroyed by an earthquake and fire, as were all the palatial cities of Crete.

The Minoan and Mycenaean settlements used cisterns a 1000 years before the classical and Helenistic-Greek cities. Cisterns were used to supply (store 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 wee built in the first half of the IInd millennium B.C., which was the time of the first Minoan palaces at Myrtos-Pyrgos (Cadogan, 2006). These cisterns remain an unusual attribute of the Minoan settlement, as the Myrtos River has been able to supply water to the base of the Pyrgos hill. Both cisterns are circular with vertical walls and rounded bottom. The walls and bottom are coated with white lime plaster 1 to 2 cm thick (Cadogan, 2006). Similar round structures exist at Knossos, Mallia, and Phaistos, which have been called granaries, but according to Cadogan improbable because the locations at the bottom of hills. It would have been difficult to prevent water from running into the round structures during a storm.

The hill of Phaistos was settled for the first time at the end of the Neoloithic period (4th million B.C.). 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 c. 2000/1900 B.C. 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 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 (Shaw, 1973).

Tylissos was one of the important cities in Ancient Crete during the Minoan era, flourishing (2,000 – 1100 B.C.) 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 sediment tank constructed of stone (see Figure 1(a)), used to remove sediment and/or suspended sediments. Also note the hole on the lower part of the tank to drain the tank for cleaning. Water then flowed from the sedimentation tank to the main cistern for water storage. Steps, shown in Figure 1(b) were used to descend down to the various water levels.

(a) (b)

Figure 1. Cistern system in Tylissos, Crete. (a) Sedimentation tank in foreground with stone channel connecting to cistern. (b) Steps leading down to cistern. (photos copyright by L.W. Mays)

3. PERSIA AND THE QANATS

A qanat is a water supply system consisting of an underground tunnel which uses gravity to convey water from the water table (or springs) at higher elevations to the surface of lower lands. Qanats also have a series of vertical shafts that were used for excavation of the tunnel and provided air circulation and lighting. The oldest qanats have been found in the northern part of Iran and date back to around 3,000 years ago when the Arians settled in present day Iran (Javan, et. al., 2006). The longest (71 km with 2115 vertical shafts) and oldest (over 3,000 years) is to the ancient city of Zarch Qanat comes from the Semitic word meaning "to dig" (Moosavi, 2006). Presently there are about 33,000 operational qanats in Iran (Javan, et al, 2006).

4. GREEKS

The Mycenaeans (in Mycenae on continental Greece by the end of the 13th century B.C.) built an underground cistern. This cistern was supplied water from the Perseia spring through a 200 m long buried conduit dug into the rock. A terracotta pipe is still visible at the roof of the cistern (Taylour, 1983). From the viewpoint of water supply in ancient Greece there are two periods before the Helenistic period, the archaic period and the classical period, during which time nothing was built in comparison with the grandiose of the Roman aqueducts. In the archaic and classical periods, Greek cities typically had a spring at the center from which it grew, without any aqueducts, at least in comparison to what the Romans built. The aqueducts built during the archaic and classical periods were similar. Terracotta pipelines probably were the usual method of conveying water during the classical Greece period. These terracotta pipes (20 to 25 cm in diameter) fit into each other. Cities were served by fountains in a central location receiving water either from a local source or a by conduit made of terracota pipes. Pipes were laid along in the bottom of trenches or tunnels, allowing for both protection and access. Two or more pipes in parallel were used depending upon the flow to be conveyed.

The Helenistic people did not have the Roman's engineering skill especially in the use of the arch and the building of aqueduct bridges. Greek and Helenistic aqueducts generally followed the contours, without using any major engineering structures. The one exception was the use of the siphon, which is the method used by the Helenistics to convey water across valleys. Locations of siphons included Ephesus, Methumna, Laodicea, Pergamon and many others, and because of difficulties in dating, these may be early Roman or Helenistic. These siphons obviously provided models for the later Roman work. Helenistic pipelines were built of stone or terracota whereas the Romans used lead pipes.

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 as subpotable. Aristotle in his *Politics* (vii, 1330b) written in the 320's B.C. 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). Figure 2 shows the cistern in the ancient Greek city of Dreros on Crete. This rectangular shaped cistern had dimensions of 13x5.5x6 m^3 (Antoniou, et al., 2006).

During the classical age, the time between the Archaic and the Roman epoch, the political situation was characterized in the Greek world (mainly Greece and Asia Minor) by wars among the various cities, the Persian wars, and the power struggle among Alexander the Greats successors after his death. The Roman Empire, west of the region of the Greek world, slowly grew to become the strongest power in the Mediterranean region after the defeat of Carthage in 146 B.C. Then step by step they conquered the entire Greek world. The political conditions influenced the development of water installation, primarily for water supply systems, as sufficient water supply was the backbone of every city. Pergamon (Pergamum), a city near the western coast of Turkey and founded at the beginning of the 3rd century B.C., had a water supply system that was included nearly all the components of a Greek water supply system. The city development began from a castle on the acropolis. No springs or deep wells existed, so cisterns were constructed to collect rainfall during the winter season. These cisterns were dug into the

rock and were mostly pear shaped with at least one layer of hydraulic plaster that prevented water loss. The cisterns varied in size from 10 to 90 m3 and possibly supplied up to 7900 people (Garbrecht, 2000). To prevent contamination of the water the mouth of the cistern was covered to keep out dust and debris, and to prevent light from entering avoiding the growth of bacteria and algae. The Attalos aqueduct was the first pipeline (buried, made of fired clay, and 13 cm inner diameter) in Pergamon, and was constructed, probably in the middle or 2nd half of the 3rd century B.C, bringing water from a spring in the mountains north of Pergamon (Fahlbusch, 2006). This aqueduct included an inverted siphon.

5. ROMANS

The Romans built what can be called mega water supply systems including many magnificent structures. Water flowed by gravity through enclosed conduits (*specus* or *rivus*), which typically were underground, from the source to a terminus or distribution tank (*castellum*). Above ground aqueducts were built on a raised embankment (*substructio*) or on an arcade or bridge. Settling tanks (*piscinae*) were located along the aqueducts to remove sediments and foreign matter. Secondary lines (*vamus*) were built at some locations along the aqueduct to supply additional water. Also subsidiary or branch lines (*ramus*) were used. At distribution points water was delivered through pipes (*fistulae*) made of tile or lead. These pipes were connected to the *castellum* by a fitting or nozzle (*calix*). These pipes were placed below ground level along major streets. See Hodge (2002), Mays (2006a) or Mays, et al.(2007) for more details.

(a) (b)

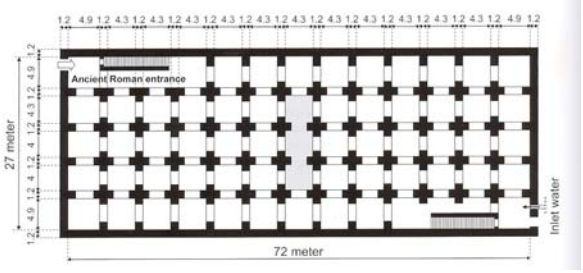
Figure 2. Central cistern in the classical Greek city of Dreros on Crete. (a) Agora (market place 30x40 m^2) with cistern below clump of trees. (b) Steps leading down to bottom of cistern
(photo copyright by L.W. Mays)

The Romans made extensive use of cisterns, so that herein I will only be able to explore a very few of the many that were built. Figure 3 shows a Roman cistern at the base of the Acropolis in Athens, Greece. 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 (Figure 4) 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 (Crouch, 1993).

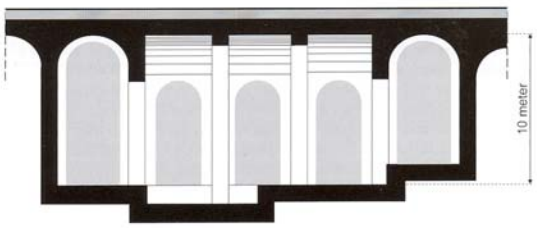
The Piscina Mirabilis (Figure 5) is one of the largest Roman cisterns (capacity of 12,600 m^3 of water). The cistern was supplied by water from the Augustan aqueduct, the Serino aqueduct that was built from Serino to Miseno. The Serino aqueduct, 96 km long with seven branches, supplied many towns including Pompeii, Herculaneum, Acerra, Atella, Nola, and others. The total elevation 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 5a) and is 15 m deep (according to Hodge, 2002).

Figure 3. Roman cistern below Athens Acropolis
(photo copyright by L.W. Mays)

Figure 4. Terracota pipes found in homes
in Pompei, Italy (photo copyright by L.W. Mays)



(a) Plan view.



(b) Cross-section view

Figure 5. Piscina Mirabilis in Miseneum (Italy)

Large Roman cisterns have been found in Spain, southern Italy, Crete, Asia Minor, and North Africa, having the largest number. Figure 6 shows a cistern in the Roman city of Ilici near modern day Elche, Spain. Figure 7 shows another cistern in the Roman city of Lucentum set on Mount Tossal, or Tossal de Manises (38 meters above the sea) in modern day Alicante, Spain.

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

Figure 7. Roman cistern in Lucentum
(photo by L.W. Mays)

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, Tunsia. 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 chamber set across them.

In the cisterns at Tuccabor and Djebel M'rabba in Tunsia, the transverse chamber was placed between the inlet and the parallel chambers and the chamber serves as a settling tank before water enters the storage chambers (Wilson, 2001). At Tugga, Thuburnica, Thapsus and Uthina the transverse chamber is 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 at Carthage were constructed with three settling basins and two storage reservoirs each of two compartments with a total storage capacity of 2,780 m^3 (see Figure 9). Primary settling tank A (oval in shape) received water from the aqueduct and water entered the two–chamber cistern (D and E). 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 9) 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.

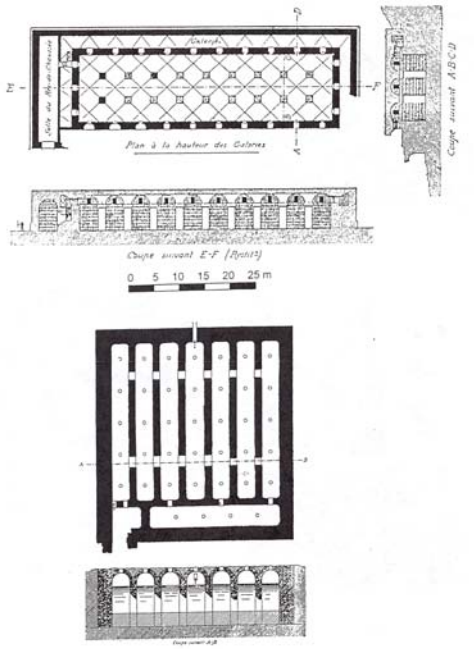


Figure 8. Plans and sections of the small (top) and large (bottom) cisterns at Uthina (Oudna, Tunsia) (after Babelon and Cagnat 1893, text to f.XXVIII, Oudna; as presented in Wilson (2001))

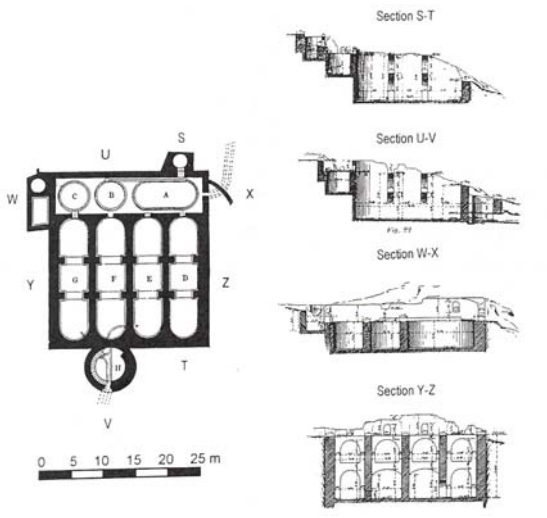


Figure 9. Cisterns at Dar Saniat at Carthage (after Cagnat and Chapot, 1916, 1:89, fig. 43, and Renault, 1912, 478-9, as presented in Wilson (2001)).

The story of cisterns continues to the magnificent cisterns built by the Byzantines. These include one of the largest and most magnificent cisterns of all, the Yerebatan Saryi or Basilica Cistern in Istanbul, Turkey. Other great cisterns and even cistern systems were built. In Aden, Yemen, built on the cone of a huge extinct volcano, tunnels and channels were built to transport water to a series of 50 large open air cisterns. Even today the use of cisterns remains a very important aspect of water supply in many parts of the world.

6. FUTURE

Can some of this traditional knowledge of water supply from the ancients be used to solve our future water sustainability issues? I think so; please refer to Mays (2006b).

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