

# A very brief history of hydraulic technology during antiquity

Larry W. Mays

Received: 7 May 2008 / Accepted: 20 August 2008 / Published online: 25 September 2008  
© Springer Science+Business Media B.V. 2008

**Abstract** Hydraulic technology began during antiquity long before the great works of such investigators such as Leonardo da Vinci (1452–1519), Galileo Galilei (1564–1642), Evangelista Torricelli (1608–1647), Blaise Pascal (1623–1662), Isaac Newton (1642–1727), Daniel Bernoulli (1700–1782), and Leonhard Euler (1707–1783). The history of hydraulic technology even began long before Archimedes (287–212 BC). It is amazing to see what was accomplished in the application of hydraulic technology during antiquity, millenniums before the development of the concepts of conservation of mass, energy, and momentum used in present-day hydraulic design. The first developments of hydraulic technology occurred with the development of irrigation for agriculture, followed by the development of urban centers. A brief history is given of the development of hydraulic technology during antiquity.

**Keywords** History · Hydraulics · Antiquity

## 1 Hydraulic technology for irrigation

### 1.1 The Egyptians and the Mesopotamians

About 6,000–7,000 years ago, farming villages of the Near East and Middle East became urban centers. During the Neolithic age (ca. 5700–2800 BC), the first successful efforts to control the flow of water were driven by agricultural needs (irrigation) and were implemented in Mesopotamia and Egypt. Being one of the most predictable rivers in the world, the Nile River flood is seldom sudden or abrupt and is timely, in contrast to the floods of the Tigris and Euphrates Rivers. Ideally the Nile would rise to bank-full stage by mid-August in southern Egypt, with the northern most basins being flooded 4–6 weeks later. In contrast the Tigris and Euphrates floods occurred in April or May, which was too early for the fall planting because the summers were too hot. Also the ancient Mesopotamian valley lacked good drainage and

---

L. W. Mays (✉)  
Department of Civil and Environmental Engineering, Arizona State University, Tempe,  
AZ 85287-5306, USA  
e-mail: lwmay@aol.com

experienced many floods. The consequence was that the ancient Mesopotamians had to build canals to divert water from the rivers, to develop their canal irrigated agriculture. Sedimentation in many of the canals was such a critical problem that it was easier to abandon these canals and build new ones. The large scale diversion of water by humans probably had its origin in ancient Mesopotamia.

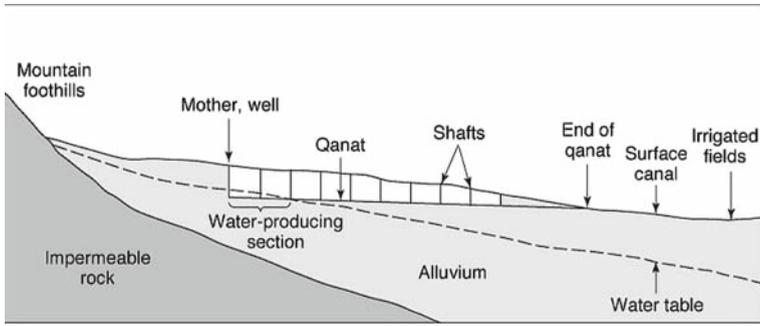
Other hydraulic technologies of the Mesopotamians included water tunnels, horse or donkey-powered chain lifts, and at least one major irrigation diversion dam. The ancient diversion dam, the Nimrud Dam, was built across the Tigris River, about 180 km upstream from Bagdad [2]. The river water was diverted through the Nahrawan Canal to irrigate an area extending over 100 km to the present town of Baquba. At Baquba this canal joined with the Diyala River to supplement its discharge for the 200 km reach of the Diyala in the ancient course from Baquba to the Tigris River at the modern day city of Kut [2]. The ancient diversion dam and the canal not only irrigated the desert area but also transferred water from one river to another.

The Egyptians built the first large-scale dam, the Sadd-el-Kafara dam (Dam of the Pagans), around 2650 BC according to Henning Fahlbusch (personal communication) from his dating studies. Dimensions of the dam were 14 m in height and 113 m in crest length with a 0.5 million m<sup>3</sup> storage capacity [30]. This dam was the first attempt at storing water on a large scale [11,26]. Possibly older dams include the Jawa reservoir in Jordan and diversion dams on the Kasakh River in the southern part of the former Soviet Union. However these structures were much smaller than the Sadd-el-Kafara dam allowing us to refer to this dam as the world's oldest large-scale dam [7,11,30].

## 1.2 Artificial basin irrigation and lift irrigation

Artificial basin irrigation, established in Egypt by the first Dynasty (ca. 3100 BC), included deliberate flooding and draining using sluice gates and contained water by longitudinal and transverse dikes. This form consisted of a network of earthen banks, some parallel to the river and some perpendicular to the river that formed basins of various sizes. Floodwaters were diverted into the basins where the water was allowed to saturate the soil with the remaining water drained off to a down-gradient basin or to a canal. After the draining process was completed in a basin, crops were planted. Basins were supplied with water by feeder canals. The bed level of the feeder canal was midway between low Nile and ground level with a natural downstream slope less than the slope of the Nile. Dikes (levees) separated the basins with controls (masonry regulators) on the earthen embankments to control the flow of water into the basin. The basins were very level as a result of the water laden alluvium that deposited in the basins. During years of low flow in the Nile, basins were drained into the next downstream basin instead of back to the river.

The first devices for lifting water from a source such as a well or a river or a canal were simple devices that made use of human strength. The *shaduf* had a bag and rope attached to the one end of a wooded arm or beam with a counter balance at the other end of the arm. The beam rotates around an axis so that the person operating the *shaduf* pulls down the bag into the water, then lifts the bag with water, and then drops the water from the bag. The *shaduf* was known in Mesopotamia as early as the time of Sargon of Akkad (ca. 2300 BC). According to the legend about the origin of Sargon, he was supposed to have been abandoned by his mother as a baby into a canal (*naru*) and to have been taken up by a man with a bag of water from this canal. Also there is a *shaduf* represented on a cylindrical seal from Mesopotamia dated by 2200 BC [32]. This technology appeared later in Egypt, with the technology well under way during the 18th Dynasty (ca. 1570 BC) and was effective by Roman times [3].



**Fig. 1** Qanat

Introduction of the *saqiya* (or waterwheel) during the early Ptolemaic times revolutionized lift irrigation. This device consists of a row of pots attached to the rim of a revolving wheel. The pots when dipped into an irrigation canal fill with water and are then lifted on the wheel to a height the diameter of the wheel (usually 3–6 m). The wheels were turned by oxens. The waterwheel (*saqiya*) enabled the reclamation of the Fayum depression, which had formed a lake and allowed the storage of high floods since the Middle Kingdom. The spread of the *saqiya* during the Ptolemaic and Roman times led to the introduction of summer crops as well as flood crops.

### 1.3 Persians and the qanats

The qanat is a collection and conveyance system for groundwater that was developed in Persia. A qanat, illustrated in Fig. 1 consists 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 [16]. The longest (71 km with 2,115 vertical shafts) and oldest (over 3,000 years) is to the ancient city of Zarch. Qanat comes from the Semitic word meaning “to dig” [24]. Presently there are about 33,000 operational qanats in Iran [16].

From 550–331 BC Persian rule extended from the Indus to the Nile, during which time qanat technology spread. As this technology transferred to other civilizations, it was known by different names: karez (Afghanistan and Pakistan), kanerjing (China), falaj (United Arab Emirates), and foggara and fughara (North Africa). Qanats were constructed to the west of Persia from Mesopotamia to the Mediterranean and southward into parts of Egypt. Qanats were also constructed to the east of Persia in Afghanistan, in the Silk Route oases settlements of central Asia and to Chinese Turkistan. The Persians introduced qanats to Egypt around 500 BC.

## 2 Hydraulic technology for early urban centers

### 2.1 Beginning of bringing of water to urban centers

The sources of water for urban centers during early civilizations [Bronze Age (4000–1100 BC)] included canals connected to rivers, rainwater harvesting systems, wells, aqueducts,

and underground cisterns. In ancient Mesopotamia, during the Bronze Age, urban centers of the Sumer (Sumerian) and Akkad (Akkadian) (third millennium BC) 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 [32]. Servant women filled the 25 m<sup>3</sup> 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 Syria), a Sumerian settlement in the middle Euphrates valley in the middle of the IVth millennium BC [32]. Mohenjo-Daro was a major urban center of the Indus Civilization during the early Bronze Age, located about 400 km north of Karachi, Pakistan. This was a planned city built around 2450 BC and serviced by at least 700 wells [15]. In the third millennium BC time period the Indus civilization had bathrooms in houses and sewers in streets. The Mesopotamians were not far behind [1].

## 2.2 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 BC). 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 BC), a variety of technologies such as wells, cisterns, and aqueducts were used [4]. 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 75,000–125,000 m<sup>2</sup> 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 [12] 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 (60–75 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 Fig. 2a. 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 [12, p. 219]. Figure 2b shows a drainage channel and Fig. 3c shows a rainfall harvesting system made of carved stone that collected water from the roof and directed it to a cistern. Unfortunately, around 1450 BC the Minoan palace was destroyed.



**Fig. 2** Water components in Knossos. (a) Pipes made of terracotta. (b) Drainage channel. (c) Carved stone elements of rainfall harvesting system collecting water falling from roof (photos copyright by L.W. Mays)



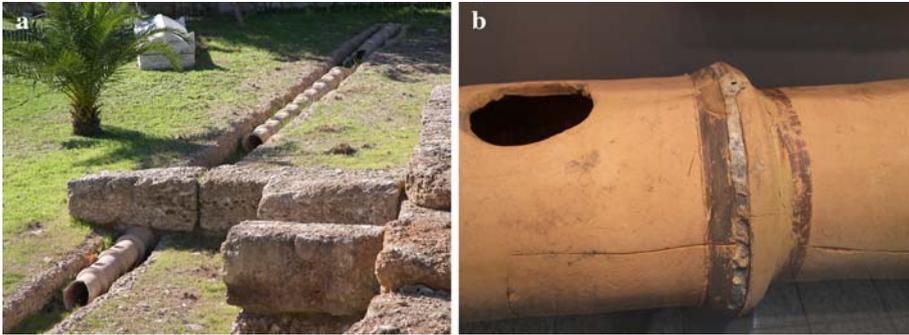
**Fig. 3** Water system in Tyliisos, Crete. (a) Aqueduct bringing water from springs. (b) Sedimentation tank in foreground with stone channel connecting to cistern. (c) Steps leading down to cistern (photos copyright by L.W. Mays)

The Minoan and Mycenaean settlements used rainfall collection and cisterns a 1,000 years before the classical and Hellenistic-Greek cities. Cisterns were used to supply water (store runoff from roof tops and court yards) for the households through the dry summers of the Mediterranean. Tyliisos was one of the important cities in Ancient Crete during the Minoan era, flourishing (2000–1100 BC) as a peripheral center dependent on Knossos. The water supply system to Tyliisos included an aqueduct developed in the Minoan period that was constructed of closed pipes and curved stone channels (Fig. 3a). Secondary conduits were used to convey water to a sediment tank constructed of stone (see Fig. 3b), 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 Fig. 3c were used to descend down to the various water levels.

### 2.3 Greeks

In the archaic and the classical periods of the Greek civilization, aqueducts, cisterns, and wells were similar to those built by the Minoans and Mycenaean. However, the scientific and engineering progress during those stages enabled the construction of more sophisticated structures. One of the most famous is the tunnel of Eupalinos (530 BC) on Samos Island, the first deep tunnel in history that was dug from two openings with the two lines of construction meeting near the middle. The construction of this tunnel, which served the water supply of Samos, was made possible by the progress in geometry and geodesy that was necessary to implement two independent lines of construction that would meet [17]. There are several other known aqueducts in Greek cities as water supply was regarded as an essential and necessary infrastructure of any city [5]. For safety reasons, aqueducts were always subterranean, either tunnels or trenches. At the entrance of the city, aqueducts would branch in the city and would feed cisterns and public fountains in central locations. Along in the bottom of trenches or tunnels of aqueducts, pipes usually from terracotta were laid, allowing for protection. One, two or more pipes in parallel were used depending upon the flow to be conveyed. The terracotta pipe segments (20–25 cm in diameter) fit into each other and allow access for cleaning and maintenance by elliptical openings (Fig. 4) that were covered by terracotta covers. This is one indication of the awareness that the Greeks had for hygienic conditions. The Peisistratanean aqueduct, constructed in Athens during the end of the sixth century BC, shown in Fig. 4 illustrates the pipe segments. Many wells and later cisterns were needed for the water supply system.

Later, during the Hellenistic period, further developments were made by Greeks in hydraulics, such as in the construction and operation of aqueducts, cisterns, wells, harbors, water



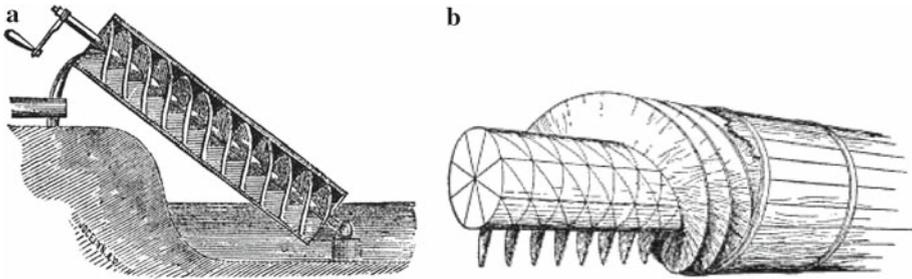
**Fig. 4** Peisistratenean aqueduct (a) Terracotta pipe segments. (b) Elliptical pipe opening for cleaning purposes and shows the leaded pipe joint (photos copyright by L.W. Mays)

supply systems, baths, toilets, and sewerage and drainage systems. During that period the political and economic situation changed leading to much more architectural development and urban beautification, of which aqueducts played a major role. The progress in science during the Hellenistic period provided a new technical expertise. Hellenistic aqueducts usually used pipes, as compared to the Roman masonry conduit. Furthermore, following the classical Greek tradition, the aqueducts continued to be subterranean for security reasons (not to be exposed to aliens, e.g. in case of war) but also for the safety of the construction during earthquakes which are frequent in the area. This again contrasts the Hellenistic technology with the later Roman technology, whose apparent characteristic was the use of the arches and aqueduct bridges.

Greek aqueducts generally operated by free surface flow. However, during the Hellenistic period, the scientific progress in understanding hydrostatics and water and air pressure (due to Archimedes, Hero of Alexandria and others; [18]) allowed the construction of inverted siphons at large scales (lengths of kilometers, hydraulic heads of hundreds of meters). Hellenistic engineers constructed inverted siphons to convey water across valleys in aqueducts of several cities including Ephesus, Methymna, Magnesia, Philadelphia, both Antiochias, Blandros, Patara, Smyrna, Prymnessos, Tralleis, Trapezopolis, Apameia, Akmonia, Laodikeia and Pergamon. These siphons initially were constructed of terracotta or stone pipes (square stone blocks to which a hole was carved). The need for higher pressures led to the use of metal pipes, specifically made from lead. Thus, one of the aqueducts of Pergamon includes an inverted siphon, constructed of lead pipes, over 3 km in length with a maximum pressure head of about 180 m [8, 10].

#### 2.4 Greek hydraulic technology of devices

The late-classical/Hellenistic city of Priene on the Anatolian west coast of present day Turkey had a main drainage canal with an unusual masonry outlet structure that allowed self-cleaning of the drainage outlet. This outlet structure contained a doubly curvilinear, contracting rectangular cross-section flow passageway that allowed drainage water to flow through the perimeter wall of the city. Hydraulic analysis by [28] showed that the internal shape of the structure causes the flow to create multiple circulatory mixing flows that agitated and entrained debris in the outflow stream, self-cleaning the outlet and preventing clogging. Once again we see that the Greeks possessed a high level of awareness about the hygienic conditions needed for health.



**Fig. 5** Illustrations of the Archimedes Screw. (a) Chambers Encyclopedia, J.B. Lippincott Company, Philadelphia, 1875. (b) Morgan [25]

Archimedes (287–212 BC), who has been considered by many as the greatest mathematician during antiquity, was the founder of hydrostatics and introduced the principle of buoyancy. He lived in Syracuse, located on Sicily. The foundation of hydraulics after Archimedes led to the invention of several hydraulic devices with applications ranging from the lifting of water to musical instruments. Archimedes’s helix or water screw (Fig. 5) is the first device characterized as a pump by modern standards. The invention of the water screw is linked to the study of the spiral, on which Archimedes wrote the treatise, *On Spirals* in 225 BC. The water screw consists of a cylinder with a continuous screw that extends the length of the cylinder forming a spiral chamber. To operate the device the lower end is placed in the water and the screw is turned with the handle (Fig. 5a) raising the water to the higher elevation. The hydrostatic principles that Archimedes developed have proven to be the most enduring achievements of Greek mechanics.

The force pump, a water lifting device, was invented by Ctesibius of Alexandria (ca. 385–222 BC), who also invented other instruments like the hydraulic clock and the *hydraulis* which is a hydraulic musical instrument. Vitruvius, the Roman author of *De Architectura*, was the only ancient author to attribute the invention of the force pump to Ctesibius of Alexandria by calling the device—*Ctesibica machina* (x, 7, 1) and by the comment in (x, 7, 4) *nec tamen haec sola ratio Ctesibii fertur exquisita* (and this is not the only choice device of Ctesibius current) [27]. The force pump is described in a later section on Roman hydraulic devices.

### 3 Romans

Romans were more pragmatic than their Greek predecessors in the manner that they planned and constructed the water supply systems [10]. They built what can be called mega water supply systems including many magnificent structures. Sources of water for the Greeks were predominantly groundwater as they avoided surface water because of hygienic reasons. The magnificent aqueducts built by the Romans were supplied by either surface water or groundwater. Water sources for the Roman systems included not only springs but reservoirs that were developed by building dams. One of the Roman systems that I classify as a mega system was at ancient *Augusta Emerita*, at present day Merida, Spain. This system included two reservoirs, now known as the Cornalvo dam and the Proserpina dam. The Proserpina dam is an earthen dam, approximately 427 m long and 12 m high, shown in Fig. 6a. The Cornalvo dam is an earthen dam, approximately 194 m long and 20 m high with an 8 m dam crest



**Fig. 6** Roman dams near Merida, Spain. (a) Proserpina dam. (b) Cornalvo dam showing the intake structure (photos copyright by L.W. Mays)



**Fig. 7** Aqueduct bridge of Ferreras (known as Puento del Diablo (devil's bridge) near Tarragona, Spain built during the first Century BC. Aqueduct bridge is 217 m long and 27 m high. (a) Bridge consists of two tiers of arches with diameters of 5.9 m (20 Roman feet) with a 15 cm variation and a distance between centers of piers of 7.95 feet (26 Roman feet). (b) The *specus* has a modern day width of 2.5 Roman feet (photos copyright by L.W. Mays)

width, shown in Fig. 6b. Both of these dams are still used in the present day, obviously with modifications over the years. Dams were built in many regions of the Roman Empire [31].

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. Figure 7 shows the Roman aqueduct bridge, near Tarragona (Tarraco), Spain, which was part of the Francoli Aqueduct to Tarraco. The Romans used siphons throughout the empire, and were especially numerous in Gaul, but relatively rare in Rome [13]. The siphons included a header tank for transitioning the open channel flow of the aqueduct into one or more pipes, the bends called *geniculus*, the *venter* bridge to support the pipes in the valley, and the transition of pipe flow to open channel flow using a receiving tank. Figure 8 shows the ramp, which had nine lead pipes, and the header tank. 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.



**Fig. 8** Siphon of aqueduct of Gier, Beaunant, France near Lyon (Ancient Lugdunum). (a) This reconstruction shows ramp with header tank on the top and the nine lead pipes of the siphon [23]. (b) Ramp of the siphon near Chaponost (photo copyright L. W. Mays). (c) The *venter* bridge of the siphon near Beaumont (Courtesy Henning Falhbusch)

To properly discuss Roman water supply we must be aware of the treatises of Vitruvius, *De Architectura* [25], and Sextus Julius Frontinus, *De aquaeductu urbis Romae* (translation 1973). The following quote from Vitruvius describes how the aqueduct *castellum* worked (as presented in [6]). “When it (the water) has reached the city, build a reservoir with a distribution tank in three compartments connected with reservoir to receive the water, and let the reservoir have three pipes, one for each of the connecting tanks, so that when the water runs over from the tanks at the ends, it may run into the one between them.” Frontinus was a retired army officer who, in AD 97 took over as the director of the Roman Metropolitan Waterworks. He declared the Roman aqueduct as the real mark of civilized living.

### 3.1 Urban water distribution

Pompeii (located on the Bay of Naples, south-southeast of Mt. Vesuvius in Italy) had a water supply system that is representative Roman urban water distribution systems. Sources of water for Pompeii included wells, cisterns and other reservoirs, and the Serino aqueduct. This aqueduct received water from springs at Serino, near Avellino, and then was routed via Sarno around the north side of Mt. Vesuvius to serve Naples and two large cisterns of Cento Camerelle (Baiae) and the Piscina Mirabilis (Misenum). From Sarno a branch aqueduct was routed to Pompeii terminating at the *castellum* at Porta Vesuvii, shown in Fig. 9. According to Richardson [29, p. 51] there were no springs within the city of Pompeii. The water table was tapped within Pompeii using wells as deep as 38 m below the surface [19, pp. 546–557].

Two approaches to laying out the pipe network were followed: (a) using a main pipe from the secondary *castellum* with smaller branch pipes attached to serve individual customers,



**Fig. 9** *Castellum divisorium* in Pompeii. (a) Building housing the *castellum*. (b–d) Three gated channels of the *castellum* used to control flow to geographical areas of Pompeii (photos copyright by L.W. Mays)



**Fig. 10** Components of water distribution system in Pompeii. (a) Water tower (secondary *castella*) with a storage tank was mounted on top of the tower. Lead pipes were used for the flow of water to and from the tank and were placed in the vertical recessed portion on the tower. The exiting pipes (*calices*) branched off to supply various customers and public fountains. (b) Lead pipe and joint found along the street. (c) Junction box. (photos copyright by L.W. Mays)

and (b) not using main pipes but using individual pipes laid from the secondary *castellum* to the individual customer, which was the normal Roman practice (Hodge 2002). Pompeii's water distribution system consisted of pipes along the main streets connecting the main *castellum* at Porta Vesuvii (Fig. 9a) to the various water towers (secondary *castella*) (Fig. 10a), from which smaller pipes (Fig. 10b) were placed under the sidewalks and streets and served the various customers. Not all customers had individual lines from a secondary *castellum* but instead received their supply from taps into the system at their locations.

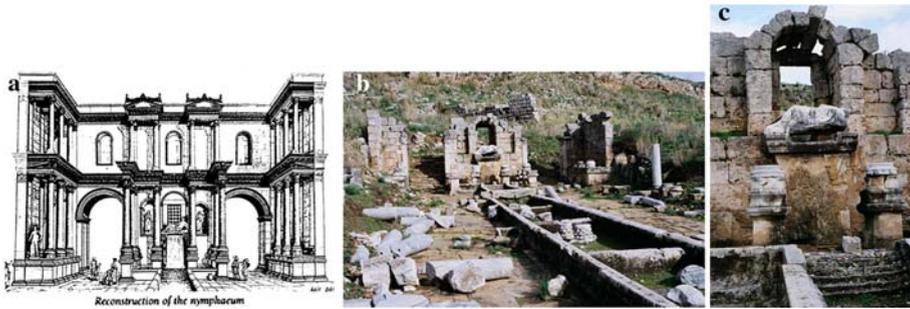
The fountains had an overflow weir so that the water would flow onto the streets and then into the drainage system. Terracotta pipes were not used in the water distribution system in Pompeii [14]. Lead pipes (Fig. 10b,c) in Pompeii are of the same construction and appearance as found in other Roman cities. The water taps found in Pompeii were also similar to those found in other Roman cities. Only a small number of houses had a water pipe that supplied a private bath or basins in the kitchen, in the toilet, or in the garden. Overflows were drained into cisterns for rainwater.

### 3.2 Cisterns

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. Cisterns were used extensively for storing water from rainfall collection and from aqueducts. One example of a cistern (Fig. 11a) is at the Roman



**Fig. 11** Cisterns (a) Cistern in Illici, Spain. (b) Cistern below Acropolis in Athens (photos copyright by L.W. Mays)



**Fig. 12** Perge, Turkey. (a) Two story monumental fountain where water overflowed into a canal that divided the colonnaded street. Covered canal delivered water to a pool behind the façade. Water from the pool flowed through an opening just below the reclining statue of the river god Cestrus. (b) Fountain and the canal downstream which divided the colonnaded street. (c) *Close-up* view of fountain showing Cestrus (photos copyright by L.W. Mays)

city of Ilici (La Alcudia de Elche) near present day Elchi, Spain. Figure 11b 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 down to cisterns where water was stored for domestic use. The Piscina Mirabilis, near Naples, Italy, is one of the largest Roman cisterns (capacity of 12,600 m<sup>3</sup> 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 × 27m in plan and is 15 m deep (Hodge 2002).

In Roman North Africa vast cistern complexes were used in conjunction with the aqueducts [34]. These cisterns had capacities that were often several thousand m<sup>3</sup>, that were much larger than the domestic cisterns. They were typically located where the aqueducts reached the edge of towns. 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 chamber set across them.

### 3.3 Fountains

Above the public fountains in Pompeii are briefly discussed. Now we briefly discuss the more monumental fountains (*nymphaeum*) and use as an example the Roman fountain found in Perge, approximately 20 km east of the present day city of Antalya, Turkey. Figure 12 illustrates the magnificent fountain that was built in Perge. There are many other examples of fountains and baths throughout the Roman Empire.

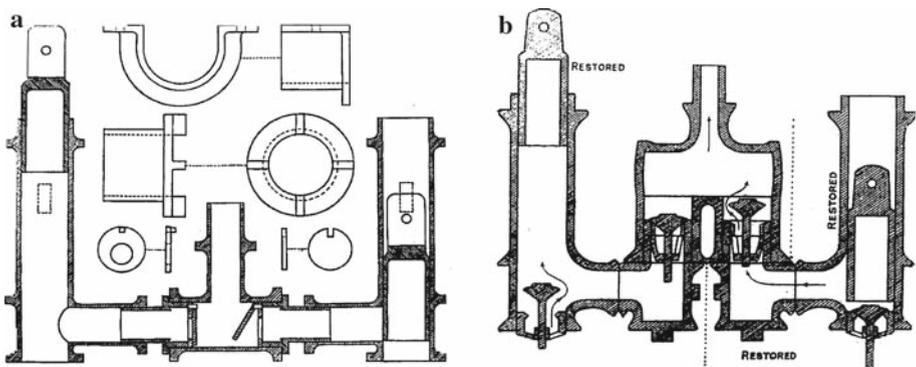
## 4 The Roman mega hydraulic projects

The Romans built what can be called mega water supply systems including many magnificent structures. Four of the magnificent mega water systems that were not described herein

include: the water system of aqueducts and dams to Merida, Spain (ancient *Augusta Emerita*), the system of aqueducts with various structures to Lyon, France (ancient *Lugdunum*); the system of aqueducts to Rome, and the aqueduct of Nimes (ancient *Nemausus*). There are many others that include the components of the Roman systems. See Hodge (1992) and [20,22], among many other references for details of these systems. The Romans did not add to science like the Greeks: however, they contributed tremendously to the advancement of engineering. They also invented new technologies such as the Roman concrete (*opus caementitium*) which allowed the construction of long canals, very large bridges and long tunnels in soft rock [10]. The Greeks lacked the technology of the Roman concrete which was needed for the mega projects.

## 5 Roman hydraulic devices

The force pump, a water lifting device, was invented by Ctesibius of Alexandria (ca. 270 BC) as mentioned previously. Roman force pumps were more technically complex than other ancient water lifting devices [33]. Two cylinders mounted vertically were connected near their bases by a horizontal pipe with a single upright delivery pipe at the center of the pipe (see Fig. 13). Bronze flap valves (intake valves) were hinged at the bottom of each cylinder so they would open inwardly into the cylinder. A bronze piston was placed inside each cylinder so that when it was lifted (the up stroke) from the base of the cylinder, water entered through the flap valve and filled the cylinder. When the piston was forced downward (down stroke) water entered the transverse pipe connecting the two cylinders as the intake valve at the base of the cylinder closed. The upright delivery pipe had a one-way flap valve at its base which kept water moving in the vertical direction. The pistons in the two cylinders were moved by means of a connecting rod attached to opposite ends of a single lever. This allowed the pistons to work reciprocally so that when one piston was down the other was up. Figure 13a shows the type of force pump described above. The force pump in Fig. 13b was constructed using beveled spindle valves instead of flap valves. Water was discharged from the force pump through a pipe or nozzle.



**Fig. 13** Reconstruction of force pumps found at Bolsena, Italy (as presented in [27]). (a) F. Davis, Note on a Roman Force Pump Found at Bolsena, *Archaeologia* 5, 1896. (b) H.B. Walters, A Guide to the Exhibition Illustrating Greek and Roman Life, 3rd edn. London: British Museum, 1929

## 6 Conclusions

The development of hydraulic technology has been traced, beginning with its infancy in the development of irrigated agriculture and water supply for urban centers. We have looked at some of the major advances that occurred in hydraulic technology during antiquity (before the end of the Roman Empire), long before the development of the laws of conservation used in modern day design of hydraulic structures. Considering the hydraulic structures that were built by the ancients, they had a remarkable observation of nature and were able to draw conclusions from their observations [9]. During antiquity the achievements of hydraulic technology was related to efforts to reduce labor and costs, rather than concepts related to conservation and the environment.

A comparison of the achievements in hydraulic technology during antiquity with the contemporary practices is an excellent example and motivation for the environmental and conservation issues of our present time [21]. Some of the ancient technologies discussed are still being used successfully for present day rural communities in Africa, India, Iran, Jordan and others. Also water problems exist in many parts of the world that could be solved by using ancient or traditional methods. Have we really listened to the ancients? One example to point out is the overuse and misuse of technologies such as irrigation canals by the ancients which led to salinization of agricultural fields and the consequential effects such as the migration of people in search of new lands. The drying of the Aral Sea in present times is one example of our not listening [21]. There are many others. As stated by Mariena Mondelli Montandon in *The Water Atlas* by Pietro Laureano, “Often the farmers, who are ‘the salt of the earth’ have simply forgotten the methods used by their ancestors. They have been blinded by the philosophy of ‘having it all and all at once’ that Western people have unfortunately spread around the world.”

## References

1. Adams R (1981) *Heartland of cities: surveys of ancient settlements and land use on the central floodplain of the Euphrates*. University of Chicago Press, Chicago
2. Butler SS (1960) Irrigation systems of the Tigris and Euphrates valleys. *J Irrigation Drainage Div. Proceedings of ASCE*, vol 86, No. IR 4, pp 59–79, December
3. Butzer KW (1976) *Hydraulic civilization in Egypt: a study in cultural ecology*. The University of Chicago Press, Chicago
4. Cadogan G (2006) Water management in Minoan Crete, Greece: the two cisterns of one Middle Bronze Age Settlement. In: Angelakis AD, Koutsoyiannis D (eds) *Proceedings of 1st IWA international symposium water and wastewater technologies in ancient civilizations*, national agricultural research foundation, Iraklio, held 28–30 October 2006, pp 447–456
5. Crouch DP (1993) *Water Management in Ancient Greek Cities*. Oxford University Press, New York
6. Evans HB (1994) *Water Distribution in Ancient Rome: the evidence of Frontius*. University of Michigan Press, Ann Arbor
7. Fahlbusch H (1996) Ancient dams in Egypt, *Transactions of the 16th Congress on Irrigation and Drainage*, vol 1G, New Delhi
8. Fahlbusch H (2000) Water in human life: technical innovations in hydraulic engineering in the Last 5,000 years. *ICID J* 49(4):1–10
9. Fahlbusch H (2004) Men of dikes and canals. In: *Men of dikes and canal: the archaeology of water in the Middle East*, (Hans-Dieter Bienert and Jutta Haser, eds), pp 1–16, International Symposium held at Petra, Wadi Musa (H.K. of Jordan), 15–20 June 1999, Verlag Marie Leidorf GmbH, Rahden/Westf, pp 1–16
10. Fahlbusch H (2006) Water engineering and management in the classic civilizations, *Proceedings, La Ingenieria Y La Gestion Del Agua a Traves de Los Tiempos*, held at the Universidad de Alicante, Spain, with the Universidad Politecnica de Valencia, Spain

11. Garbrecht G (1985) Sadd-el-Kafara: the world's oldest large dam, *Water power and dam construction*, pp 71–76, July
12. Graham JW (1987) *The Palaces of Crete*. Princeton University Press, Princeton
13. Hodge AT (2002) *Roman aqueducts and water supply*. Gerald Duckworth & Co., Ltd, London
14. Jansen GCM (2001) Water pipe systems in the houses of Pompeii. Water use and hydraulics in the Roman City. In: Koloski-Ostrow AO (ed) *Archaeological Institute of America, Colloquia and Conference Papers*, No. 3, Kendall/Hunt Publishing Company, Dubuque
15. Jansen M (1989) Water supply and sewage disposal at Mohenjo-Daro, *World Archaeology*, vol 21, No. 21, *The Archaeology of Public Health*, pp 177–192
16. Javan M, Hassanli AM, Shahrokhnia MA (2006) The ancient qanats of Iran. In: Angelakis AD, Koutsoyiannis D (eds) *Proceedings 1st IWA international symposium water and wastewater technologies in ancient civilizations*, national agricultural research foundation, Iraklio, held 28–30 October 2006, pp 531–534
17. Koutsoyiannis D, Zarkadoulas N, Angelakis AN, Tchobanoglous G (2008) Urban water management in Ancient Greece: legacies and lessons. *ASCE, J Water Resour Plann Manage*, 134(1):45–54
18. Koutsoyiannis D, Mamassis N, Tegos A (2007b) Logical and illogical exegeses of hydrometeorological phenomena in ancient Greece. *Water science and technology: water supply*, vol 7, No. 1. IWA Publishing, London
19. Maiuri A (1931) Pompeii Pozzi e Condotture d'Acqua and "Scoperta di Grandi Conditture in Piomb dell'Acqueducto Urbano". *Notizie degli Scavi di Antichita*, 7
20. Mays LW (2002) Urban water infrastructure: a historical perspective. In: *Mays LW Urban water supply handbook*. McGraw-Hill, New York
21. Mays LW (2006) Water sustainability: parallels of past civilizations and the present. In: *Mays LW Water resources sustainability*. McGraw-Hill, New York
22. Mays LW, Koutsoyiannis D, Angelakis AN (2007) A brief history of urban water distribution, water science and technology: water supply, vol 7, No. 1, pp 1–12. IWA Publishing, London
23. de Montauzan G (1908) *Les Aqueducs Antiques des Lyon*, Paris
24. Moosavi SAA (2006) Qanat invention puzzle. In: Angelakis AD, Koutsoyiannis D (eds) *Proceedings 1st IWA International Symposium Water and Wastewater Technologies in Ancient Civilizations*, National Agricultural Research Foundation, Iraklio, held 28–30 October 2006, pp 535–540
25. Morgan MH (1914) *Vitruvius. The ten books on architecture*, Cambridge
26. Murray GW (1955) Water from the desert: some ancient Egyptian achievements. *Geogr J* 121:171–187
27. Oleson JP (1984) Greek and Roman mechanical water-lifting devices: the history of a technology. University of Toronto Press, Toronto
28. Ortloff CR, Crouch DP (1998) Hydraulic analysis of a self-cleaning drainage outlet at the Hellenistic City of Priene. *J Archaeol Sci* 25:1211–1220
29. Richardson LJr (1988) *Pompeii: an architectural history*. John Hopkins University Press, Baltimore
30. Schnitter NJ (1988) A history of dams, the useful pyramids. A. A. Balkema, Rotterdam
31. Smith N (1971) *A history of dams*. Peter Davies, London
32. Viollet P-L (2006) Water Management in the Early Bronze Age Civilization Proceedings, *La Ingenieria Y La Gestion Del Agua a Traves de Los Tiempos*, held at the Universidad de Alicante, Spain, with the Universidad Politecnica de Valencia, Spain
33. Wikander O (ed) (2000) *Handbook of ancient water technology*, vol 2, Koninklijke NV, Brill, Leiden
34. Wilson A (2001) Urban water storage, distribution, and usage. In: Koloski-Ostrow AO (ed) *Water use and hydraulics in the Roman City*. Kendall/Hunt Publishing Company, Dubuque