Representing the operation and evolution of ancient Piraeus' water supply system

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Abstract

The newly excavated urban water supply system of the city of ancient Piraeus provides an excellent opportunity for the study and evaluation of the issues of sustainability, adaptability, simplicity and environmental protection, which are of main concern in modern engineering design. Well-digging in the area of Pireaus dates back to the city' founding during the Classical period. However scarcity of ground waters led to the development of water harvesting techniques, mainly construction of cisterns for the collection of rain water and to the gradual increase of their capacity in order to avoid overflows. Changes to land plot areas and the increase in water demand during the Hellenistic period affected the operation of cisterns and triggered a variety of subterranean constructions that expanded the existing capacity. During the Roman period, the city's water needs for domestic and public use skyrocketed beyond the supply capacity of the water resources of the Piraeus' peninsula. On account of this, an aqueduct which transferred water from outside the peninsula was constructed in the 2nd century AD, while cisterns and wells gradually were abandoned.

The present paper examines the operation of ancient Piraeus' urban water supply system and its evolution across nine centuries by studying the operation and evolution of cisterns through a combination of excavation finds (from the Ephorate of Antiquities of Piraeus and the Islands) and hydrologic techniques. Water consumption during several historical periods and the available water resources of the peninsula were quantified and a hydrologic model was developed to simulate the daily operation of the cisterns over an 82-year period. Various circumstances were examined by running numerous scenarios for the: (a) magnitude of collecting area, (b) annual water demand, and (c) capacity of the cisterns. For each scenario, the reliability of the hydrosystem for supplying residences with water was estimated, followed by a calculation of overflow-deficit volumes. Simulation results were then correlated with specific socio-economic characteristics of the corresponding historical periods.

Keywords Cisterns, Rain water harvesting, Simulation, Ancient Piraeus, Sustainability, Adaptation

1. Introduction

Reliable water supply is of major concern in modern societies. In the beginning of 21th century more than 10% of global population lacked a basic drinking water service (WHO 2000), despite several large scale water supply projects having been constructed around the world. With the situation worsening due to overpopulation and contamination of water resources, the concepts of sustainability, adaptability and environmental protection become central in the design of modern hydrosystems. Thus, it is of great benefit to modern engineers to evaluate the aforementioned concepts in projects of the past, in order to be more effectively implemented in the future. With water supply being a diachronic problem, there are several large scale ancient hydrosystems that (a) operated for several centuries, (b) adapted diachronically to new requirements arising from changing economic, social and political conditions and (c) were environmentally friendly.

Although large-scale hydraulic works were not uncommon in ancient civilizations, private installations (wells, rain water harvesting cisterns) were also used for water supply by the majority of the population of the ancient world. These structures serve as examples of the concepts of simplicity and self-sufficiency for the modern world. These small-scale water structures were used all over the world since the dawn of human civilization, as they (a) were simple to build and operate, (b) ensured the independence of water supply, (c) were convenient and not costly, as the water was collected close to the place of consumption and (d) ensured the safety of water supply, especially in times of war. On this last point it is worth referencing a relevant passage from Aristotle: "*…and* [the city] *must possess if possible a plentiful natural supply of pools and springs, but failing this, a mode has been invented of supplying water by means of constructing an abundance of large reservoirs for rainwater, so that a supply may never fail the citizens when they are debarred from their territory by war*" (Politics, III, I330b). This passage suggests that, despite the construction of aqueducts which usually transported water from long distances, ancient cities also adopted rain water harvesting techniques, as they ensured independence and safety of water supply.

In modern times, given the stress of water resources in several areas of the world, rainwater harvesting is widely promoted as a standalone or supportive solution or to major water supply systems. This ancient technology exhibits great advantages even today, mainly: (a) decentralized deployment (autonomy in water supply), (b) low construction and preservation costs and (c) negligible environmental impact. Also, it serves as the only viable water-supply solution in cases of isolated communities not supported by large-scale hydraulic works, where the local aquifer is poor or degraded.

Archeological investigation of ancient hydraulic works reveals their technical characteristics and widens our knowledge about robustness of materials and resilience of constructions. Additionally, historical research provides important information, related to hydrosystems' operation and water management practices. Archeological finds and historical texts could be exploited through engineering methods to study the performance of ancient water supply systems. Specifically, using simulation techniques, the operation and management of ancient hydrosystems is reconstructed and evaluated for various circumstances. Hydrological regime, technical characteristics of hydraulic works and water demand patterns are some of the conditions that are accessed through simulation. The methodology permits the quantification of systems' performance and the evaluation of engineering solutions of the past. Having the opportunity to evaluate the operation and the evolution of specific ancient hydraulic works over long time periods provided important lessons to modern engineers. Furthermore, the quantification of water resources and demand of ancient civilizations adds some important pieces to the puzzle of human history. In particular, estimation of consumed water quantities facilitates archeological and historical research, especially in evaluating speculations about population and living standards of ancient communities. Finally, the consideration of water management in the scale of ancient households raises awareness amongst the general public about rational water use and environmental protection.

The newly discovered water supply system of ancient Piraeus provides an excellent opportunity to study and evaluate the aforementioned issues of sustainability, adaptability, simplicity and environmental protection. The supply system was based on residence-scale rain water harvesting systems that gradually prevailed as the main technology of water supply and were ultimately unified to a city-scale hydrosystem. The system was operated from the foundation of the ancient city of Piraeus (5th century BC) until its decline (4th century AD). During its long history, the city's hydrosystem was continuously adapting to urban evolution and the increase in water needs.

Until 2004, several excavations had revealed around 384 underground residential water supply structures in ancient Piraeus. From 2012 to 2015, rescue excavations were conducted by the Ephorate of Antiquities of Piraeus and the Islands, as part of the construction of the Athens Metro (project "Extension of Line 3: Haidari-Piraeus part"). The excavations revealed parts of the urban grid of ancient Piraeus and, among other finds, 130 underground structures (deep and shallow wells, cisterns, and tunnels) related to the evolution of the water system through almost nine centuries.

The main aim of this paper is to study the water supply system of the ancient city of Piraeus by combining (a) recent excavation finds, (b) ancient literary sources and (c) hydrologic techniques for representing the operation and evolution of the system. An initial review of the historical background is followed by a presentation of the excavated water structures of various eras. Also, specific conversions of initial cisterns to more composite structures (in order to be adapted in new water needs) are examined. Next, the water consumption and the available water resources of Piraeus' peninsula are estimated for various historic periods using a hydrologic model to simulate the daily operation of the cisterns. Several cases are investigated, considering various combinations of technical characteristics and water demand patterns. More specifically the examined scenarios are related to the: (a) magnitude of the rain water collecting areas, (b) water demand and (c) cisterns' capacity. For each scenario, overflow and deficit volumes are estimated and the reliability of the hydrosystem in supplying the residents with water is calculated. Finally, based on the simulation results, an attempt is made to draw connections between the evolution of hydraulic works and engineering practices and the sociologic, economic and political characteristics of the changing societies.

2. Historical background

During the early 5th century BC, Piraeus was an obscure citadel due to lack of fresh water resources and its rough and rocky terrain which precluded cultivation. Athenians (after prevailing at the Naval Battle of Salamis in 480 BC against the Persians) realized that they had to fortify the peninsula and protect the three natural harbors (Kantharos, Zea and Mounychia), in order to develop maritime and trade activities and a powerful fleet. So, they constructed a fortification wall around the Piraeus peninsula, with a perimeter of about 11 km, and two walls (Long Walls) running from the city of Athens to the ports at Phaleron and Piraeus. These walls ensured a fortified connection between Athens and the Piraeus harbors in case of siege. Athenians founded a new city in the Piraeus peninsula that supported their maritime activities (Garland 1987). In Figure 1a the general position of Athens-Piraeus area is presented and in Figure 1b the two city-limits, the harbors and the fortifications of the 5th century, are depicted according to Cox (1876).

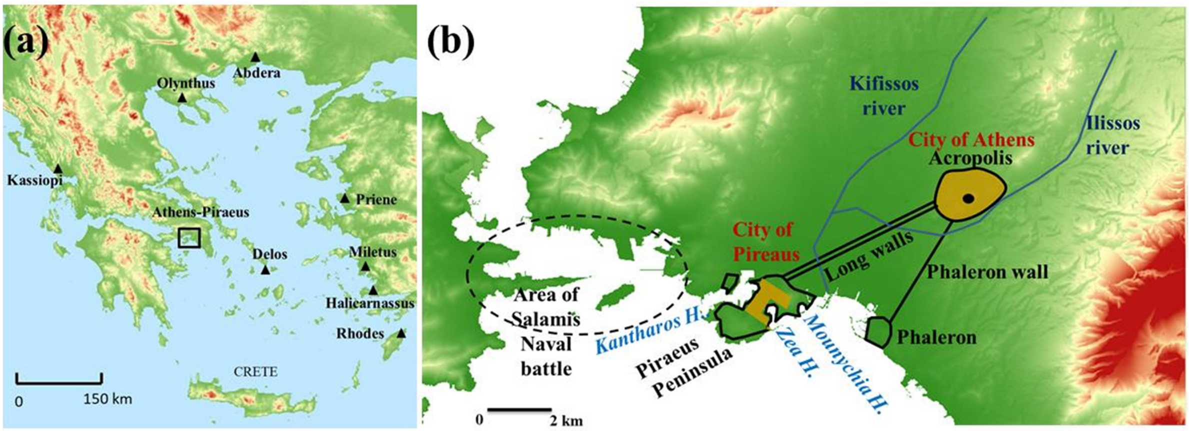


Figure 1. (a) General position of Athens-Piraeus area (box) and cities with Hippodamian grid (triangles), (b) Map of Athens and Piraeus city-limits, Piraeus harbors and fortifications during the 5th century BC (source: Cox 1876)

The city of Piraeus was built according to "modern" (for the era) urban planning, conducted by Hippodamus of Miletus, who probably arrived in Athens in the second half of the 5th century BC. The Hippodamian urban plan was known as "Hippodamian nemesis", a Greek word that means "divine justice". The name was used to describe a plan that incorporated the equality of citizens under Athenian democracy, which was reflected in the equal areas of land plots and the rational allocation of common uses (baths, shrines, market). The Hippodamian urban plan was based on the design of parallel streets which intersect at right angles to create perfectly aligned building blocks divided into plots of equal area (Shipley, 2005). The few main arteries crossed the city lengthwise. Several cities were built according to Hippodamian plan, such as Miletus, Olynthus, Rhodes, Priene, Kassiopi, Abdera, Halicarnassus and Delos (Figure 1a). In the case of Piraeus, the building blocks had dimensions of about 45x41 m and each block consisted of eight house plots arranged in two rows of four. Each plot had an area of about 230 m². Groups of 5x7 blocks constituted districts. The roads that separated the blocks and the districts had an average width of 5.2 and 8.2 m respectively. Also, there were central road axes (with a width of about 15 m) that defined key areas of the city, such as the trade port, the dockyard, the market, and the city entrances (Burns 1976; Hoepfner 1999; Shipley 2005; Steinhauer 2012). It is worth noting that a different Hippodamian grid was adopted in ancient OlynthusWhere building blocks measured approximately 88.5x34.8 m, and each block consisted of 10 house plots arranged in two rows of five. Each plot had an area of about 300 m² (Stillwell 2017).

The peninsula had no streams or springs with permantent flow, so from its founding the city's residents dug wells in order to find water, a common practice in Attica. The prevailing geological formation in the area is marl (belonging to the Pliocene period of Neogene), which has limited capability to store and provide water. Also, it must be emphasized that the Piraeus peninsula is hydrogeologically independent and the aquifers are not connected to the neighboring areas (Chiotis 2019). As the aquifer of the Piraeus peninsula was poor in ground water, rain water harvesting techniques were very soon developed. First, cisterns for collecting rain water were constructed at the end of the 5th century BC. As the climate of the area is semi-arid with a distinct wet and dry season, these earliest cisterns were emptied during summer months, where rainfall was negligible. On the other hand cisterns were filled during rainy winters and the excess water overflowed to streets. In order to reduce losses of valuable water, larger cisterns were either constructed or the existing ones expanded, thus achieving an increase in the water storage capacity.

From the 3rd century BC onwards, the changing attitudes in the Hellenistic world and the transition from a collective to an individual perception of life were reflected in the city planning of Piraeus. The city was a flourishing commercial and shipbuilding center, and as a consequence, the differences in financial status led over time to an abandonment of the dwellings' uniformity. From the outset of the Hellenistic period, there was a clear trend for construction of luxurious residences, which resulted from the combination of more than one house plots: two or four adjacent plots were combined to afford space for a bigger house (Westgate 2000; Westgate 2001; Steinhauer 2012).

In 86 BC, after a long siege, Sulla destroyed Piraeus. The city was deserted and habitation was limited to the area around the temple of Zeus Soter and the harbor, which continued its operation and contribution to the economy of the city (Grigoropoulos 2016). At the end of the 1st century BC, sanctuaries were repaired and the port and public buildings restored. Also a bath installation located in a small cave between Zea and Mounychia harbors, was renovated. That cave was of great importance to residents as it housed a shrine dedicated to the local hero Serangos.

During 2nd century AD Piraeus was revived. Wealthy Roman villas were built with peristyle atrium using the foundations of classical houses, and public baths and fountains were constructed. The city was strongly affected by the invasion of Heruli in 267 AD and was gradually deserted and abandoned after the invasion of the Goths in 396 AD.

3. Water supply structures

3.1 Rain water harvesting in antiquity

The collection and use of rainwater from roofs and other surfaces of dwellings is an ancient technique, which is still popular in areas with limited water resources. The construction and use of cisterns is traced back to the Neolithic age, as they were essential elements of the houses in the Levant territory (Mays et al. 2013). In most cases the cisterns were fed by rain water as suggested by Vitruvius (De Architectura, 8, 6.14) and recent researchers (Sazakli et al. 2007; Mays 2010; Van Liefferinge 2013; Klingborg and Finné 2018). In ancient Greece rain water harvesting was rare during the Archaic period, but gradually became more popular and it was one of the primary water sources during Classical and Hellenistic periods. Also in the same period several cisterns were constructed inside the fortified sites of Aegean islands and other arid regions of the mainland Greece, in order to guarantee the water supply, especially in the case of a siege (Mays et al. 2013). Cisterns had a wide variety of shapes but most of them were shallow conical, well-shaped conical or bell-shaped. The last type was more common and was characterized by a long narrow neck which gradually expanded to a shape of a bell. Typically the cisterns were constructed below the ground and the majority was coated with hydraulic mortar in order to be waterproof. In many cases, two or more cisterns were connected by tunnels, forming a cistern system. In ancient Greece, cisterns were used in all types of constructions, such as residences, public buildings, sanctuaries and forts. Four hundred and ten (410) cisterns from 49 sites in Greece, which are dated from 600 to 50 BC, have been recorded by Klingborg (2017).

The vast majority of cisterns had capacity between 10-30 m^3 but in some cases it could be extremely large. Such examples are the cistern in Kameiros (Rhodes) that has a capacity of 600 m^3 (Klingborg 2017), in Eleutherna (Crete) with capacity of 1000 m^3 (Mays et al. 2013) and two cisterns in Aptera (Crete) with capacities 2900 and 3050 m^3 (Gorokhovich et. al. 2012). In ancient Olynthus, which was also built according to Hippodamian grid (with house plot areas 25% higher than Piraeus), several houses were equipped with rain water collecting systems and cisterns, which had capacities between 23-26 m^3 (Crouch 1993). Most cisterns were between 3 and 6 m deep but in some cases the depth could reach 13 m. In order to increase the capacity two or more cisterns could be connected by tunnels or blind tunnels were constructed to expand the volume of a single cistern. Various features were used to enhance the functionality and the maintenance of the system, such as climbing holes, staircases, bottom depressions, separation walls, and overflow conduits (Klingborg 2017). Extensive use of rainwater harvesting techniques has been confirmed at the Aegean island of Delos. Because of the dry climate and the overpopulation of the island through centuries, rainwater cisterns have been found in several residences. The most impressive system has been constructed in the Hellenistic theater. Rainwater fell on the cavea and the orchestra (with a total area of about 5000 m^2) was channeled to a slab-covered cistern (22.5 m long, 6 m wide and 3 m deep) that was located in the front of the theater (Mays et al 2013). The number of cisterns constructed in Greece declined significantly at the end of the Hellenistic period. Also, in Athens the cisterns that were destroyed after the invasion of Sulla were not replaced by new ones, but rather by wells (Klingborg and Finné 2018). Cisterns were no longer attractive in areas where the transportation of water by constructing aqueducts was possible.

3.2 Water structures in Piraeus excavations

Several water structures within the limits of the ancient city of Piraeus are referred by Eickstedt (1991) and are reported in the Archaiologikon Deltion (Archaeological Bulletin). Most of them were found in excavations on the construction of private buildings and public works.

In the framework of the construction of the Athens Metro (project "Extension of Line 3: Haidari-Piraeus”) archaeological investigations were conducted by the Ephorate of Antiquities of Piraeus and the Islands. The construction sites of five Metro stations and four shafts were explored. The total area of archeological investigations was approximately 25000 m^2 and rescue excavations were carried out in a total area of 7000 m^2, (Chrysoulaki et al., 2017).

The rescue excavations in Municipal Theater area lasted about 33 months (2012-2015) and revealed about 130 underground structures, which are related to the evolution of the water system for almost nine centuries. Also parts of the Hippodamian urban grid of ancient Piraeus were discovered.

In Figure 2 the area of excavations in Municipal Theater and the position of the various water structures, are presented. The findings include deep and shallow wells, cisterns, connecting and blind tunnels and also a 95 m section of an aqueduct.

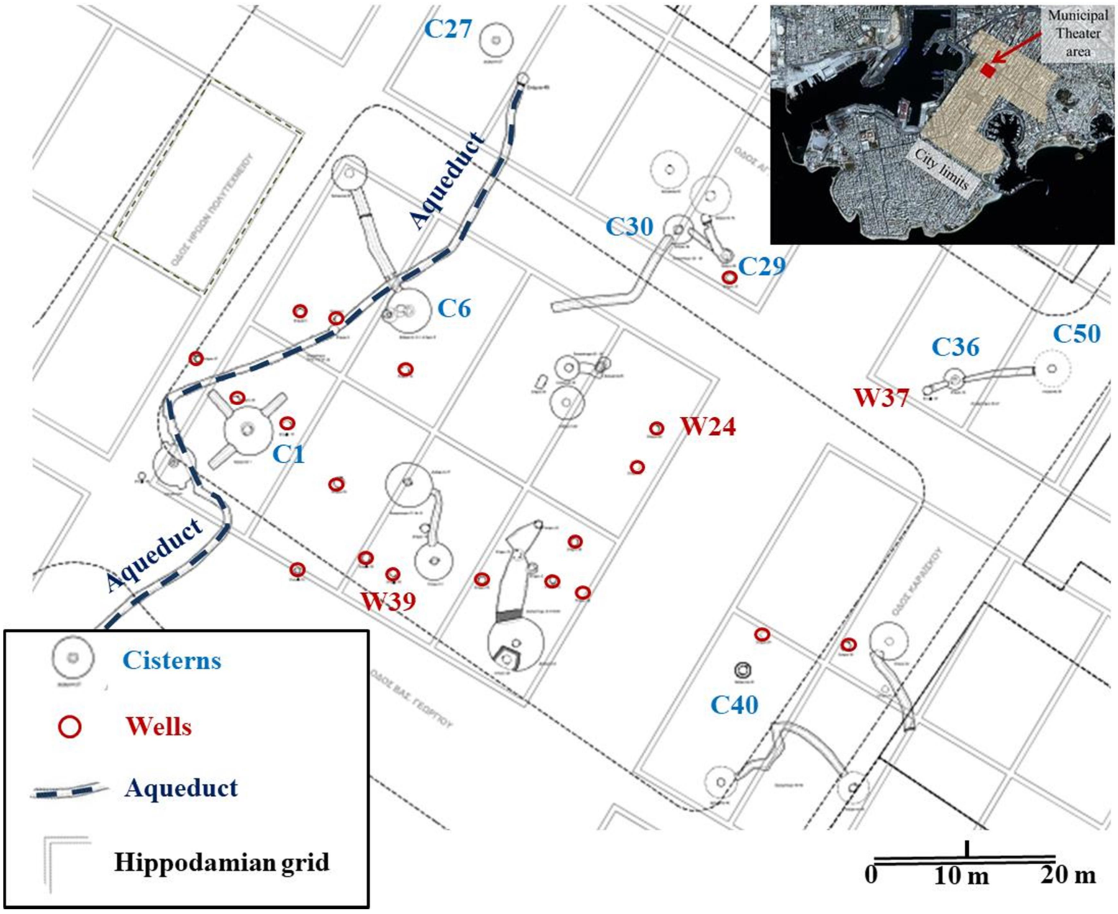


Figure 2. Area of excavations and position of water structures in Municipal Theater. Cisterns C1-C6-C27-C29-C30-C36- C40-C50 and wells W24-W37-W39 are commented later in this text.

The excavations revealed several wells since the city's construction phase in the late 5th century BC. Aquifer investigation and exploitation by digging wells was a prehistoric practice in Attica, as the geology favored ground water storage (Camp 1977; Chiotis and Chioti 2012; Stroszeck 2017). The construction of several wells was not completed, so they were used as deposits. The wells have a typical diameter of 0.8 m and rectangular cavities carved in the walls in two facing rows spaced at 0.50 m as steps for vertical access (Figure 3). The aquifer, which the wells drew water from, appears today to be at an absolute altitude of 3 m above sea level. The wells have a depth up to 18 m from the surface of the modern city, with their bottoms ranging from 1.42 m to 4.95 m below sea level. During excavations, samples of water in wells were tested for several quality parameters. The analysis showed that, according to modern standards, the water was appropriate for use. The salinity values were below the limits of potable water and there were not indications for sea water intrusion to the aquifer.

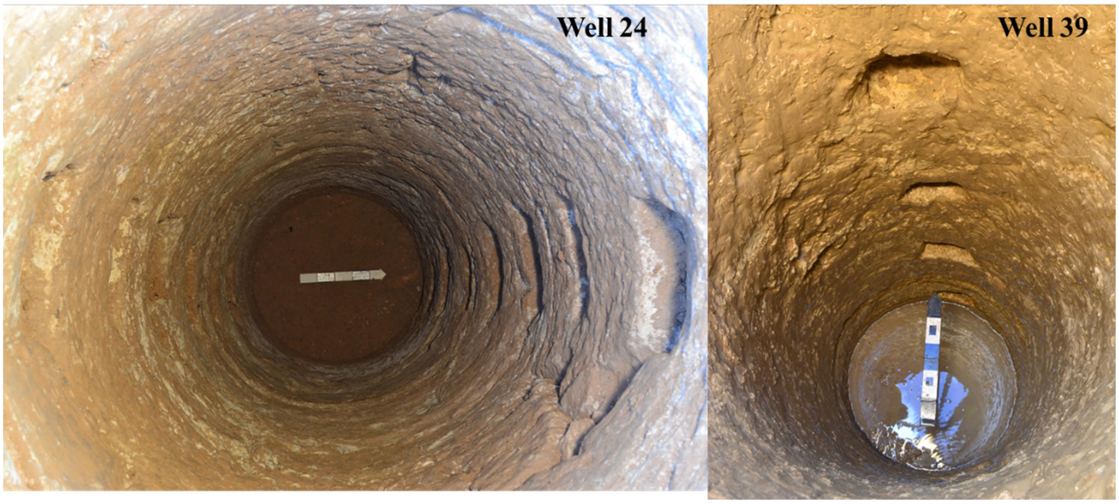


Figure 3. Wells 24 and 39 from excavations in Municipal Theater area (photos by authors)

Constant use of limited ground waters combined with population growth, leading to increased drinking water needs, resulted in overexploitation of aquifers. As a consequence, rain water harvesting techniques were applied to ensure sufficient water supply. Thus, the houses with their yards served as water collectors and various structures (cisterns, draining pipes, roof slope) were built to collect rain water (Camp 1977; Klingborg 2017).

The excavations in the Municipal Theater area revealed 35 subterranean cisterns. Their shape and size exhibit three main typologies: (a) small shallow conical cisterns with diameter up to 1.60 m, (b) conical well-shaped cisterns with diameter up to 1.60 m and depth 6-8 m, and (c) bell-shaped cisterns with diameter from 2.80 m to 6.14 m and neck at least 2-3 m deep. Cross sections of the aforementioned typologies are presented in Figure 4.

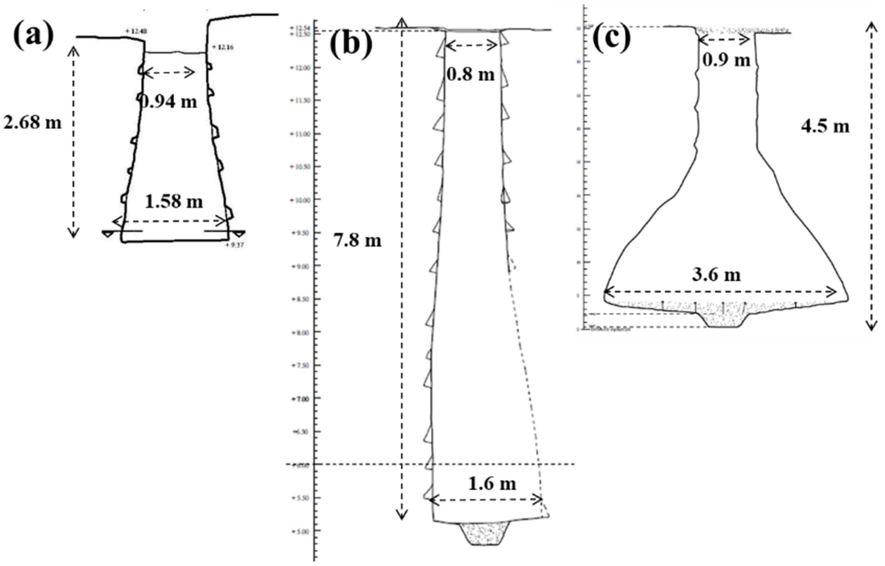


Figure 4. Cross sections of cisterns of various typologies in Municipal Theater area: (a) cistern 40 – small shallow conical, (b) cistern 6 – conical well shape, (c) cistern 27 – bell-shaped (drawings by authors)

Cisterns were carved into natural rock and most of them were coated with hydraulic mortar. At the bottom's center was a pit for collecting the sinking materials that existed in the stored water, but also for the management of the bucket used for lifting. Cisterns were first constructed at the end of the 5th century BC, and from the early beginning, a constant effort for capacity expansion was observed. In many cases, bell-shaped cisterns could not be expanded due to static equilibrium issues. In other cases, the surface was inadequate for an extra mouth. Thus, the capacity was increased by digging tunnels that connected the cisterns, or they were blind. The tunnels were coated with hydraulic mortar of similar composition to that of the cisterns. In Figure 5, an example of increasing capacity by digging blind tunnels is presented. Cistern 1 in Municipal Theater area had an initial capacity of 67 m^3 that was increased by about 21% by digging three symmetrical tunnels.

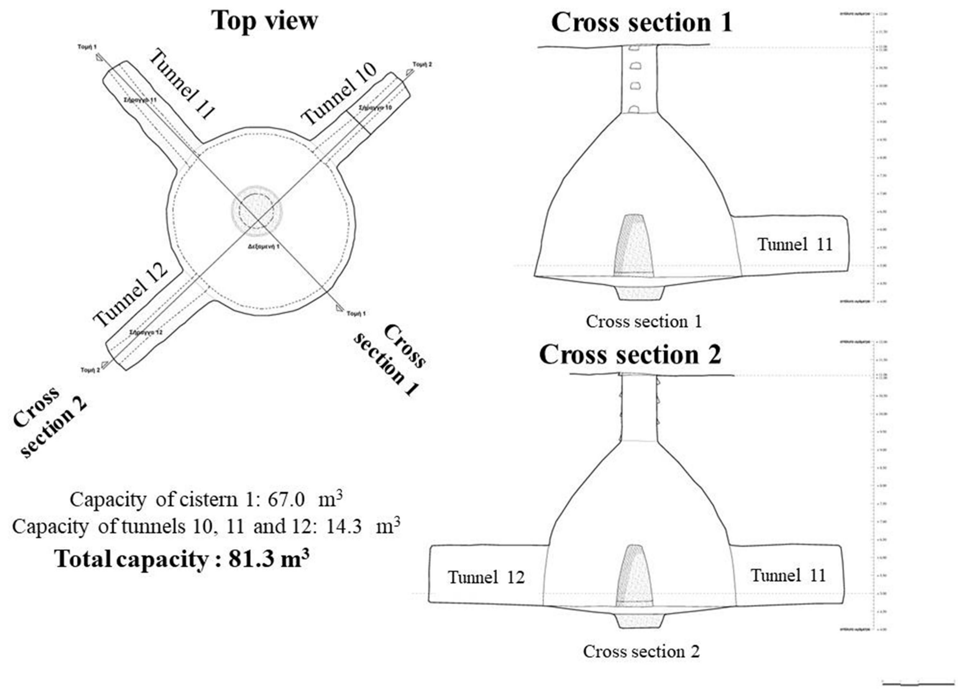
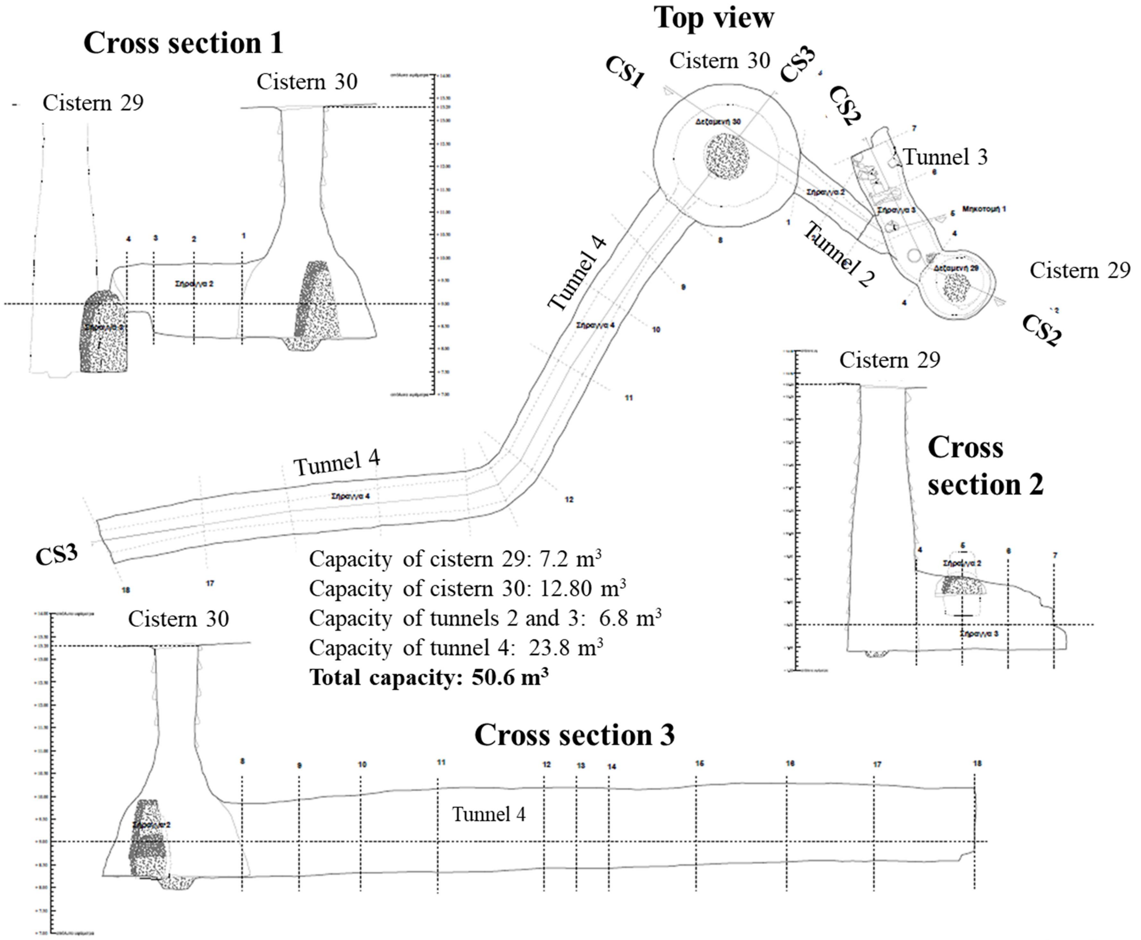


Figure 5. Top view, cross sections and capacity calculations of Cistern 1 in Municipal Theater area (drawings by authors)

During the Hellenistic period, luxurious houses were built that resulted from the unification of more than one former house plots. Increasing collecting areas of new residences and growing water needs caused the construction of new subterranean structures. These works improved the management of existing systems under new property areas but at the same time expanded the water storage capacity. Archaeological evidence reveals that Hellenistic residences and later Roman villas had autonomous systems of two, three or four cisterns and wells. In Figure 6, an example of increasing capacity by joining cisterns in Municipal theater area is presented. Cistern 30 had an initial capacity of 12.8 m^3 that was increased by digging tunnel 4 that had almost double the capacity (23.8 m^3). Cistern 29 with an initial capacity of 7.2 m^3 was increased by digging tunnel 3. The two systems were connected with tunnel 2, achieving a total capacity of 50.6 m^3.



Capacity of cistern 29: 7.2 m^3
Capacity of cistern 30: 12.80 m^3
Capacity of tunnels 2 and 3: 6.8 m^3
Capacity of tunnel 4: 23.8 m^3
Total capacity: 50.6 m^3

Figure 6. Top view and cross sections of Cisterns 29-30 complex in Municipal Theater area (drawings by authors)

More sophisticated, in technical terms, was the combined operation of cisterns and wells. Very often the cisterns were linked directly to wells, through which water was collected via an alternative source other than rain. On the other hand, cisterns could overflow into wells in order to prevent houses from flooding and to store the overflows of rainy period by enriching the poor-in-water aquifer. In Figure 7, an example of combined well and cistern operation is presented. Cisterns 36 and 50 in Municipal Theater area were connected through tunnel 9 and the system overflowed to well 37. At the end of the Hellenistic period till the early Roman period, the vast majority of rain water collecting systems were gradually abandoned and used as deposits. This is probably related to the city's rebuilding phase after its destruction by Sulla in 86 BC.

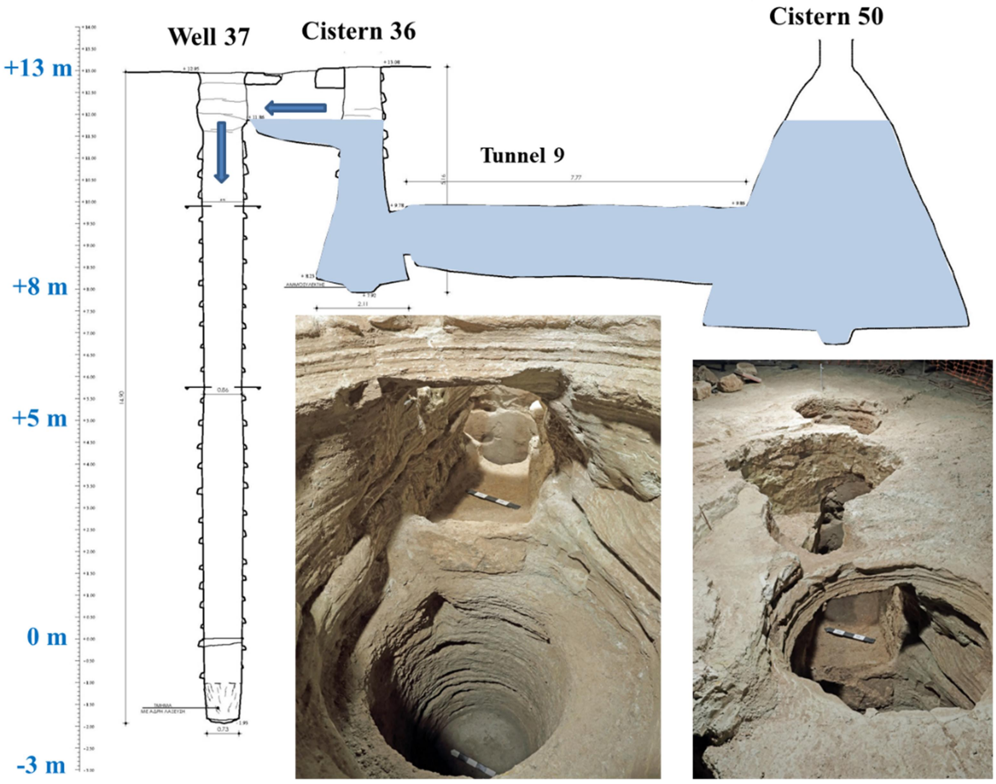


Figure 7. Example of combined well and cistern management (cisterns 36 and 50, well 37) in Municipal Theater area (drawings and photos by authors)

An aqueduct, which transferred water from outside the peninsula, was constructed in the 2nd century AD. It possibly was not designed to cover the needs of private residences, as in Roman houses the wells and the cisterns were still in use (Eickstedt 1991; Tsaravopoulos 1993; Grigoropoulos 2005; Steinhauer 2012;). However, the construction of the aqueduct shows that there were increased needs for water that the usual sources could not meet. It is obvious that the main purpose of the aqueduct was to provide the necessary water for the operation of public and private baths. A large thermae (bath) complex was constructed in the 4th century AD, near the route of the aqueduct, at Kolokotroni Street (Steinhauer 1988; Hodge 1992; Fagan 1999). The baths, as principal areas for public and social activity, were considered one of the greatest symbols of the Roman way of life. Therefore, the aqueducts, together with other major technical works, contributed to the Romanization of the cities (Aryamontri 2009; Laurence 2009; Furness 2010; Rizakis 2014; Rogers 2018).

The existence of an aqueduct is always considered probable by scholars and is depicted in maps as crossing the Piraeus peninsula from north to south (Curtius et al. 1904; Judeich 1905). It has been supposed to have entered the city through the Long Walls (Ziller 1877; Grigoropoulos 2005). Constructions resembling an aqueduct were first identified in 1992 at Iroon Polytechniou Street (Steinhauer 2012). At the same axis, at St. Constantine Square, a section of the same aqueduct of about 95 m in length was revealed in recent excavations in Municipal Theater area. Besides the central tunnel-conduit, three vertical access shafts and two earlier cisterns that were also used as wells for the same purpose were discovered. The tunnel has a trapezoidal section with a slight decrease upwards and has an average width of 0.85 m and height of 1.80 m. The walls are not coated like the tunnels connecting the cisterns and the vertical walls at regular intervals bear carved shallow niches for placing lamps (Figure 8). The path is not straight, as it is bent in three cases (in one case for almost 90 degrees) to circumvent already known underground structures that were in use. The distances between the three entrances of the wells are 26, 33 and 34 m respectively. The tunnel drilling began from each well towards both set of opposite directions.

The construction of the tunnel exhibits similarities with the Hadrianic aqueduct of Athens that was built during 2th century AD. That was a large scale hydrosystem that collected and transported water from the nearby mountains to the city of Athens. The hydrosystem included: (a) a 20 km tunnel, (b) about 500 access shafts and (c) at least three lateral aqueducts that enriched the main tunnel along its route with surface and spring water from several areas. The main tunnel was constructed using the technique of successive vertical shafts, which were dug every 40 m on average. Vertical shafts were dug first and then they were connected at their bottom by tunnel sections driven upstream. The carved underground tunnel (coated or uncoated) has an average section of 0.50 m wide and 1.20 m high; however, the height can locally reach 2 m or even more.

Unlike Hadrianic aqueduct, the operation of the aqueduct in Piraeus seems to have been interrupted, as the access shafts were revealed filled with dump material. The abandonment of such a major public project can only be attributed to a large-scale disaster, natural or man-made. The historical event that could be related to the end of its use is the invasion of the Goths in 397 AD.

Figure 8. Excavated aqueduct in Municipal Theater area (photos by authors)

4. Water consumption and resourses

4.1 Water consumtion

There are several estimations in the literature of the water needs in ancient societies. According to Mays et al. (2012), the water consumption of primitive communities is estimated at 10-20 litres per capita per day (L/cap/d) or 3.6-7.2 cubic meters per capita per year (m^3/cap/y). Especially for the city of Jerusalem in 1000 BC, water consumption was assesed at 20 L/cap/d.

Usefull information about ground water resourses management and water consuption in the beginning of 6th century BC is given by Plutarch: "*Since the area is not sufficiently supplied with water, either from continuous flow rivers, or lakes or rich springs, but most people used artificial wells, Solon made a law, that, where there was a public well within a hippicon, that is, four stadia [710 m], all should use that; but when it was farther off,* *they should try and procure water of their own; and if they had dug ten fathoms [18.3 m] deep and could find no water, they had liberty to fetch a hydria (pitcher) of six choae* ***[20 L] twice a day*** *from their neighbours; for he thought it prudent to make provision against need, but not to supply laziness"* (Solon, 23). From this passage we can conclude that in 6th century BC, a minimum requirement of 40 L/d per household was considered as plausible (Koutsoyiannis and Mamassis 2018).

According to Frontinus (De Aquae ductu Urbis Romae, 78), the total water consumption in Rome during the 1st century AD was 14018 quinariae (1 quinariae is about 41.5 m^3/d), i.e. about 580.000 m^3/d. A quarter (25%) of this quantity was consumed by the Caesars installations and 45% by luxury villas. Five hundred and ninety-one (591) cisterns (each served about 900 residents) distributed the water to the districts of the middle and lower class at about 1335 quinariae (55400 m^3/d), so a mean water consumption of about 100 L/cap/d is estimated. Also, another 110000 m^3/d were used in public baths and fountains, a quantity that corresponds to about 200 L/cap/d.

In several European cities in the 19th century, water consumption was less than 20 L/cap/d. According to Hodge (2000), water consumption was about 14.1 L/cap/d in each of Paris and London in 1823 and 16.6 L/cap/d in Liverpool in 1835.

In the beginning of the 21st century, 20 L/cap/d was considered the minimum amount of water required by each person. This quantity must be provided for domestic hygiene purposes from a source located within 1 km of the person's dwelling (WHO /UNICEF, 2000). This requirement was fulfilled for 82% of the global population in the year 2000. According to Gleick (1986), at least 50 L/cap/d are required to meet human needs, namely 5 L/cap/d for drinking, 10 L/cap/d for food preparation, 15 L/cap/d for bathing, and 20 L/cap/d for sanitation. Today, there are several countries where the average water consumption is less than 10 L/cap/d (Chad, Congo, Somalia). On the other hand, in other countries it is more than 500/L/cap/d (Australia, United States, Canada). In contemporary Athens, the domestic water consumption is about 300 L/cap/d, a quantity that includes losses.

In order to estimate the water needs of an ancient city, a gross estimation of the population is necessary. There are several studies in the literature that relate the area of ancient cities with the total population, considering the population density in persons per hectare (p/ha). Frankfort (1950) alleges that the cities of ancient Messopotapian had 300-500 p/ha. Using the text of Diodorus Siculus (17.52.6), which refers to the population of Alexandria in Egypt (established by Alexander the Great), a density of 326 p/ha is calculated. Storey (2015) calculates a population density of about 166 p/ha for Pompeii and 317 p/ha for Ostia. For the cities of medieval Europe, densities of 100-500 p/ha (Mols 1955) and 100-200 p/ha (Russel 1958) are proposed. Today, the population density of the 50 densest cities of the world is estimated to be in the range of 177-461 p/ha.

The population of Athens during the Classical period has been estimated by Travlos (1960) to be about 36000. As the walls of Athens enclose 215 hectares (120 of which were used for housing), a population density of about 170 p/ha is calculated. According to Morris (2005), the population of Athens around 430 BC was between 35000 and 40000, and Piraeus probably had at least another 25000 people. Also, Garland (1987) estimates that the population of Piraeus exceeded 30000. As the Hippodamian grid of Piraeus is almost known, the area of the city has been calculated to be about 1 km^2. Considering the previous estimations for the population of Piraeus, the density is estimated at about 250-300 p/ha, a value that is plaussible.

A common way to calculate the population of a city (with a known number of dwellings) is to estimate the members per household. There are few references in the literature on that method, but Robinson and Graham (1938) estimates that in ancient Olynthus, there were six to eight members per household, excluding slaves. As house plots in ancient Olynthus were 25% larger than in ancient Piraeus, a value of 5 persons per residence could be assumed. Based on this hypothesis and considering that ancient Piraeus had 4000 dwellings, the city in full expansion could host about 20000 people (200 p/ha). This number must be increased by about 25% to factor in visitors and the operation of the harbor.

Considering a minimum water consumption of about 20 L/cap/d, the annual water volume of the city is estimated at about 180000 m^3. As there are evidences that the city never deployed to the whole area of the Hippodamian grid, this quantity must be decreased. During the Roman period, the population was less but the water needs were many times higher. According to Frontinus figures, which were presented earlier in this chapter, the water consumption of the middle class in Rome was estimated to be about 300 L/cap/d, a quantity that included public uses. Considering that estimation, even for a small Roman city with 5000 residents, the water needs are estimated to be more than 500000 m^3.

4.2 Water resources

Water resources of the Piraeus peninsula were limited because of the dry climate and the low capability of the local aquifer to provide water. The mean annual precipitation is about 370 mm and as the peninsula has an area of 4.4 km^2 the average annual rain water volume received is estimated to be about 1.6 million m^3. Given the hydrogeology of the area and assuming a percolation coefficient of 5%, the annual feeding of aquifers is grossly estimated at about 80000 m^3.

As ground waters were limited, rainwater harvesting could provide greater supply of water. For example, the mean rainfall water volume that fell in a typical residence of the Classical period (considering a collecting area of 200 m^2) was about 74 m^3 per year. It was not possible to collect all of this water volume because of losses (evaporation, overflow). The percentage of water that could be harvested (runoff coefficient) depended on several technical and climatologic factors. In the literature, various runoff coefficients have been proposed in rain water harvesting systems such as 70% (Connelly and Wilson 2002), 80% (Farreny et al. 2011), 85% in a humid climate with heavy rains (Thomas and Martinson 2007).

Considering the dry climate of the Mediterranean and adopting a runoff coefficient of about 70%, the rain volume that could be collected in a typical residence of the Classical period was about 52 m^3 per year (142 L/d). On a city scale, the 4000 residences could harvest about 204000 m^3 per year, a quantity 2.5 times higher than the annual potential ground water.

As 60% of the annual precipitation fell in a four-month period (October to January), it was necessity for the cisterns to store water during wet periods in order to use it in dry periods. As the water capacity of a cistern increased, the overflow during rainy winters decreased, and the amount of the harvested water that was finally exploited also increased. It must be emphasized that even for cisterns with large capacities it was not possible to avoid overflows during wet periods, so only a fraction of the harvested rain water eventually got to be exploited. Generally, the capacity of a cistern depended on the following factors:

- The potential rain water yield. This is the maximum water quantity that can be collected, assuming unlimited storage capacity. This quantity is related to climatic conditions (precipitation, evaporation) and the area of the collecting surface.
- The precipitation regime of the area. In case of finite storage capacity, if precipitation occurred in a few intense events, the capacity of the cistern must be large. On the contrary, in areas where rainfall occurred in more frequent events, the required capacity was small.
- The water demand of the residents. The water needs are related to the social and cultural characteristics of each historical period. Also, the required water is dependent to the season as water needs increase during summer.
- The required probability of failure to cover the water demand. The percentage of the days that the water needs are not satisfied and the number of consecutive days with failure, are considered.

5. Operation of cisterns

In order to simulate the operation of cisterns, a hydrologic model was developed. Initially the daily potential rain water yield was calculated, using time series of precipitation measurements and potential evaporation estimations. Next, synthetic time series of daily water demand were generated with the intention to preserve (a) certain water consumption seasonal patterns and (b) a predefined mean annual water demand volume, which was chosen considering the demographic and sociologic characteristics of a specific era. Finally, the technical characteristics (collecting area, capacity of the cistern) of a specific system were defined and the daily time series of water balance processes (overflow, deficit, cistern's storage) were calculated. The performance of the hydrosystem was quantified by estimating the following indicators: (a) percentage of days that water demand was not satisfied, (b) mean annual rain water volume that was not exploited (overflow), (c) mean annual water deficit to fully satisfy the requested demand (deficit), (d) number of consecutive days with water deficit. The long time period of the simulation (82 years) permitted the inspection of the system under extreme conditions, such as prolonged droughts, floods, dry summers and periods with high water consumption. Considering various combinations, of water demand patterns and systems' technical characteristics, numerous cases were simulated in order to: (a) evaluate the operation of cisterns in various conditions, (b) interpret the operation of specific (discovered in excavations) water structure complexes and (c) assess the performance of Piraeus' hydrosystem during various historical eras.

The main processes and parameters of the model and the scheme of calculations are presented in Figure 9.

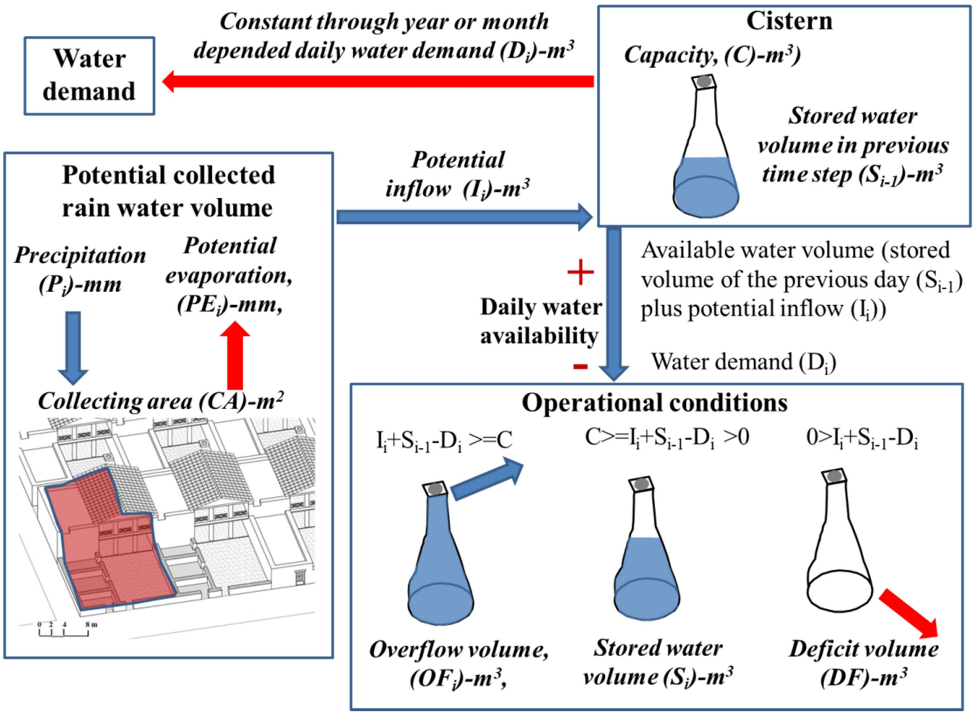


Figure 9. Main processes and parameters of hydrologic simulation

The collecting area (CA-m^2), the annual water withdrawal volume, and the storage capacity (C-m^3) of the cistern are the parameters of the model. For each daily time step *i*, the precipitation (P_i–mm) and potential evaporation (PE_i–mm) were considered, and the potential inflow to the cistern (I_i) was calculated according to equation (1).

$$I_i = \max\{(P_i - PE_i) * CA/1000, 0\} \qquad (1)$$

The daily water demand (D_i-m^3) was estimated by disaggregating the annual water withdrawal volume, considering constant or month-dependent distribution throughout the year. Adjustment in the water withdrawal during stressed periods was no considered.

The system dynamics are described by the following equations.

$$S_i = \begin{cases} \min\{I_i+S_{i-1}-D_i, C\} & \text{for } I_i+S_{i-1}-D_i > 0 \\ \max\{I_i+S_{i-1}-D_i, 0\} & \text{for } I_i+S_{i-1}-D_i <= 0 \end{cases} \qquad (2)$$

$$DF_i = \min\{I_i+S_{i-1}-D_i, 0\} \qquad (3)$$

$$OF_i = \max\{I_i+S_{i-1}-D_i-C, 0\} \qquad (4)$$

For each day *i*, the stored (S_i-m^3), deficit (DF_i-m^3) and overflow (OF_i-m^3) water volumes were calculated using equations (2), (3) and (4) respectively.

From the equations, the daily availability of water can be calculated by subtracting the water demand (D_i) from the available water volume. The latter is the stored water volume of the previous day (S_{i-1}) plus the potential inflow (I_i). If available water volume is negative, there is deficit, and if it is higher than the cistern's capacity, there is surplus.

The operation of the hydrosystem on a daily basis was simulated using precipitation and meteorological data measured at the Thissio Station of National Observatory of Athens for an 82-year period (1927-2009). Meteorological data (temperature, wind velocity, relative humidity, solar radiation) were used for the calculation of potential evaporation on a daily basis. According to several paleo-climatic reconstructions in Eastern Mediterranean, the climate of Greece was warmer and drier during Classical and Hellenistic periods and then returned to colder and moister conditions during the Roman period (Markonis 2016, pp. 119-120). As the time accuracy of these estimations is more than a century, the exact climate of the era remains uncertain but is reasonable to assume that the rainfall pattern (wet winters and dry summers) was similar. We consider that practically the climate variation does not affect the analysis and the data for a 82 year period is sufficient to simulate the operations of cisterns in various climatic conditions (extended wet or dry periods).

Statistical analysis was performed, and the mean annual precipitation and potential evaporation were found to be 367 mm and 1619 mm respectively. From the output of the daily model, the mean annual potential inflow to the cistern was found to be 255 mm (255 litres of water per m^2 of collecting area). Also, the calculated value of the mean annual losses was 112 mm (31% of the precipitation). The simulations results show that about 60% of the annual water volume was often harvested during three winter months (December-February). Daily potential inflow was greater than 18.9 mm in 1% and zero in 86.5% of the days.

The operation of a cistern was simulated according to equations (2), (3) and (4). Several scenarios were examined regarding the collecting area, the annual water demand volume, and the cistern capacity. For each scenario we estimated: (a) the daily overflow and deficit volumes, (b) the probability of failure to meet the daily water demand, and (c) the number of consecutive days with water deficit. Some of the results of simulation for various scenarios are summarized in Table 1, where for a various cistern capacities and annual water demands, the overflow volume and probability of failure to meet the daily demand are calculated. The cistern capacities, the annual water demands and the overflow volumes are expressed as a percentage of the potential annual rain water inflow.

Table 1. Overflow volume and probability of failure to meet the daily demand for various cistern capacities and annual water demands. (The cases that are discussed in the text are marked and highlighted gray).

Cistern capacity (% of the potential inflow)	**Annual water demand (% of the potential inflow)**			**Annual water demand (% of the potential inflow)**		
	50%	**75%**	**100%**	**50%**	**75%**	**100%**
	Overflow volume (% of the potential inflow)			**Probability of failure to meet the daily demand (%)**		
20	55.4	45.2$^{\text{Case1}}$	37.5	10.9	25.6$^{\text{Case1}}$	35.3
30	50.5$^{\text{Case 6}}$	36.7$^{\text{Case7}}$	29.2	1.4$^{\text{Case6}}$	15.5 $^{\text{Case7}}$	27.9
40	49.9	30.7$^{\text{Case2}}$	21.8	0.2$^{\text{Case3}}$	7.9$^{\text{Case2}}$	21.3
50	49.6	27.4	16.0	0.0	3.6	15.9
60	49.5	26.1	12.4	0.0	2.0$^{\text{Case 9}}$	12.4
70	49.4	25.5	10.3	0.0	1.3	10.4
80	49.3	25.0	9.0	0.0	0.9$^{\text{Case4}}$	9.2
90	49.2	24.6	8.1	0.0	0.5	8.4
100	49.0	24.3	7.4$^{\text{Case8}}$	0.0	0.2	7.9$^{\text{Case8}}$
120	48.8	23.9	6.3	0.0	0.0	7.1
140	48.5	23.7	5.5	0.0	0.0	6.6
160	48.3	23.4	5.0	0.0	0.0	6.3
180	48.1	23.2	4.5	0.0	0.0	6.0
200	47.8	23.0	4.1$^{\text{Case5}}$	0.0	0.0	5.8$^{\text{Case5}}$

Using Table 1, we can evaluate the performance of the system for various scenarios. For example, a house with a collecting area of 100 m^2 has a mean potential inflow volume of 25.5 m^3/y. Consider the Case 1 in Table 1 where the capacity of the cistern is 20% of the potential inflow (5.1 m^3) and the annual water demand is 75% of the potential inflow (19.1 m^3/y-52.5 L/d). In Case 1, the annual overflow volume is estimated at 45.2% of the potential inflow volume (about 11.5 m^3) and the probability of failure to meet the daily demand is 25.6%.

Consider the Case 2 in Table 1 where the same house has a cistern with double the capacity of the cistern in Case 1 (10.2 m^3; 40% of the potential inflow) and the water demand is the same as in Case 1, that is 19.1 m^3/y (75% of the potential inflow). The annual overflow volume now is decreased to 30.7% of the potential inflow volume (7.8 m^3/y) and the probability of failure to 7.9%.

From Table 1, we can conclude that in order to meet water demands that correspond to 50% and 75% of the potential inflow volume with low probability of failure (less than 1%), cisterns with capacities that correspond to about 40% and 80% respectively of the potential inflow volume are needed (Cases 3 and 4 in Table 1). According to the simulation results, even in cases where water management keeps the probability of failure low, there still exist long periods of empty cisterns, especially during dry periods. Finally, the total exploitation of the potential annual water inflow is not possible even for a huge cistern with double the usual capacity (Case 5 in Table 1). In that case, the overflows remain significant (more than 4% of the potential inflow) and the probability of failure higher than 5%.

Following the history of the city, we can examine the way changes in water demand and the area of the properties influenced the evolution of the system of cisterns through the centuries. An example of that development is given in Figure 10. Initially (during 5th century BC) small cisterns were constructed (Figure 10a) but in the next centuries the volume of cisterns was increased (Figure 10b). Later on, former separate cisterns were connected, in order to expand the total volume of the system (Figure 10c).

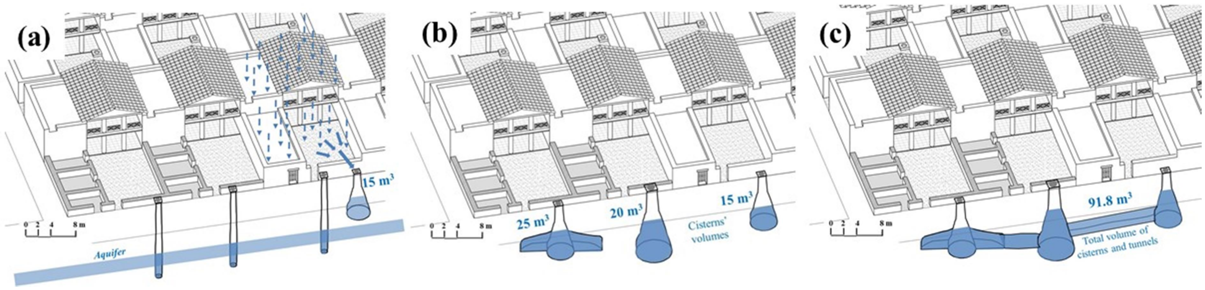


Figure 10. Temporal evolution of cistern volume (drawings by authors)

Consider a house during the Classical period, with a collecting area of 200 m^2 and a cistern capacity of 15.3 m^3, which was located in the Piraeus peninsula (Figure 10a). According to the hydrological model, the potential rain water inflow is about 51 m^3 per year and the specific cistern volume corresponds to 30% of the potential inflow. A mean daily demand of 70 litres (25.5 m^3/y) corresponds to 50% of the potential inflow (Case 6 in Table 1) and has a probability of failure of 1.4%. In that case, the annual overflow volume is found to be 50.5% of the potential inflow (25.8 m^3). Also, a mean daily demand of 105 litres (38.2 m^3/y) corresponds to 75% of the potential inflow (Case 7 in Table 1) and has a probability of failure of about 15.5%. The annual overflow volume in that case is about 36.7% of the potential inflow, that is 18.7 m^3/y.

During the late Classical and early Hellenistic periods, larger cisterns were gradually constructed or, alternatively, the capacity of the existing was increased in order to decrease the overflows and increase the water withdrawal. In Figure 10b, cisterns with capacities of 20 and 25 m^3 for the same house plot (collecting area of about 200 m^2) are presented. Operating these cisterns, a demand of 83 and 90 litres per day respectively could be satisfied with a probability of failure less than 1%. To satisfy higher demands with lower probability of failure, larger cistern capacities must be used, but the overflows still remain significant. As a consequence, it is not possible to fully satisfy a demand of 140 L/d (100% of the potential inflow volume) even for a cistern with a capacity of 51 m^3 (100% of the potential inflow). In this scenario (Case 8 in Table 1), the overflows are estimated at about 3.8 m^3/y (7.4% of the potential inflow) and the probability of failure at 7.9%.

During the late Hellenistic and Roman periods house plots and in consequence collecting areas were increased. Former separate cisterns were unified by digging subterranean tunnels to achieve an expansion of the total water capacity. In Figure 10c, such an expansion of the system is presented. Three former house plots were united to form a total collecting area of about 600 m^2. The three existing cisterns (with total volume of 60 m^3) were unified with tunnels and the total capacity of the system was increased to about 91.8 m^3. The storage capacity corresponds to 60% of the annual potential inflow, which is found to be 153 m^3. A mean daily demand of 315 litres (115 m^3/y) corresponds to 75% of the annual potential inflow (Case 9 in Table 1) and has a 2% probability of failure to be satisfied.

6. Conclusions

From the foundation of the city of Piraeus (middle 5th century BC), the first residents attempted to exploit groundwater for water supply by digging wells, a very common and ancient practice in the Attica region. Unfortunately, the capacity of the local aquifer was limited and, also, there were no torrents or permanent springs in the peninsula. As a consequence, rainwater harvesting techniques were considered, and around the end of the 5th century BC, the first cisterns for rainwater collection were constructed.

The rainwater exploitation could meet the water demand of the Classical period but the rainfall regime of Piraeus required large cistern capacities. Analysis showed that a residence of that period (considering a collecting area of about 200 m^2), with a cistern of capacity 15 m^3, could exploit 25.5 m^3/y (70 L/d) with a 99% reliability. Using a larger cistern, e.g. 25 m^3, the quantity of water that could be exploited with the same reliability (99%) increased to 90 L/d. For that, there was a continuous effort for the expansion of the capacities of the cisterns.

Considering plausible assumptions about water requirements (10-20 L/cap/d) and household members (5-6 residents per house plot), it is obvious that the rainwater harvesting could marginally meet the water demand of a family. As there were long summer periods when cisterns were empty, the exploitation of ground waters using wells was necessary. The analysis revealed that combined rainwater harvesting and groundwater exploitation could satisfy the typical water demands of the Classical and early Hellenistic periods, with high reliability.

During the late Hellenistic and Roman periods, there were changes to the property area and water needs. The subterranean water structures were continuously changed with the main purposes of: (a) adapting to new properties, (b) increasing water storage capacity of the system, and (c) favoring the combined operation of cisterns and wells. The increased water needs required better exploitation of rainwater by decreasing the overflows during winter, or by even using them for aquifer recharge. For this purpose, various techniques were used, including the: (a) construction of blind tunnels, (b) connection of cisterns by digging tunnels, and (c) channeling of cistern overflows to wells. Analysis showed that a residence of that period (considering a collecting area of about 600 m^2), with a storage system of capacity 92 m^3, could exploit about 300 L/d with 99% reliability.

The water consumption of the Roman period is estimated at more than 400 litres per household per day, but Roman cities had huge water demands for public uses (baths, fountains, etc.). It is evident that during this period, the local water resources of Piraeus were insufficient and could not meet the typical water needs even of a small Roman city. The use of additional sources, such as transportation of water from outside of Piraeus peninsula, was necessary. This task was achieved in the 2nd century AD, with the construction of an aqueduct that entered the city, probably through the Long Walls. However, the details of this aqueduct have yet to be uncovered. From this era until the city's abandonment (4th century AD), the existing water structures (cisterns, wells) became gradually dilapidated.

Overall, in the light of archaeological findings on this site, it is clear that the residents of Piraeus transformed a naturally dry area into a city of comfortable and hygienic living conditions. To achieve this goal, they throughout ages constructed various hydraulic works (wells, cisterns, tunnels, aqueduct), distributed all over the area, to form a kind of hydrosystem. This practice indicates good understanding of natural processes, advanced technology, and wise water management.

The ancient Piraeus' hydrosystem incorporates the concepts of simplicity, environmental protection, sustainability and adaptability, which concern modern societies. The water structures were simple to build and operate, as the water was collected close to the place that was consumed. Their construction and maintenance had low cost and also negligible environmental impacts, as they were underground. The sustainability of the water structures arises from the fact that they were operating during several centuries but also from the diachronic implementation of the technique. Finally, the simulation of the hydrosystem reveals its adaptability to new requirements, which were arising from changing conditions though centuries.

Although the cisterns were gradually abandoned, especially at the uninhabited areas outside the reduced limits of the Roman Piraeus, their importance has never been forgotten. This ancient sustainable water technology was available everywhere and, in every scale, providing independence in water supply. It is not a coincidence that rain water harvesting techniques were implemented in the Mediterranean basin for several centuries, especially in isolated (in terms of water resources) areas (forts, small islands). Today, as the water resources are stressed due to overpopulation and contamination, this ancient technique is widely proposed as a sustainable and environmental-friendly practice that could assist the water supply of various installations.

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