Water management in ancient Alexandria, Egypt.
Comparison with Constantinople hydraulic system
S. Spanoudi, A. Golfinopoulos and I. Kalavrouziotis

ABSTRACT
The collection, evaluation and listing of all available data related to the supply, collection and disposal of water is a project of combining and recording all the data for infrastructure projects and their structure within the urban structure of Alexandria and the wider region, as it was discovered and studied to this day. The paper is a description of the most important storage structures for the waters of the Nile River and the rain. Composing data from previous descriptions, archaeological excavations and random discoveries during construction work created a database. This database currently has 144 tanks of 1 to 4 levels, from 6 m$^3$ to 2,500 m$^3$. In particular, they have identified 27 tanks on 1 level, 50 tanks on 2 levels, 49 tanks on 3 levels, 9 tanks on 4 levels and 9 tanks whose exact morphology is unknown to us. The examples of reservoir technologies and management practices given in this work may be of some importance to the sustainability of water resources for the present and the future. Reservoirs have been used to store both rainwater and spring and river water to meet the needs of seasonal variations. The tanks range from simple to large underground structures. Then, a comparison is made with the water management systems in the wider Mediterranean region and especially in Istanbul, where there is such infrastructure.

Key words | Alexandria, cisterns, Hippodamus system, rainwater management, tanks, water management

HIGHLIGHTS
- Topography and urban planning of Alexandria.
- The tanks (cisterns) of Alexandria and their construction features.
- The topography of the tanks and their placement on the city map.
- Type-morphology and capacity of the tanks.
- Evolution of the construction of reservoirs in the Mediterranean basin.

INTRODUCTION
The need for water as a vital element of human existence led the ancient world to incessant care for its better management. The provision of adequate and clean water and the operation of a complete sanitation network are undoubtedly the most essential applications of hydraulic technology and the basic infrastructure of the most organized cities. The provision of ancient civilizations to ensure adequate amounts of water for daily activities and to ensure the collection or removal of rainwater and dirty water are observed by almost all excavating missions and are reflected in written sources (Angelakis & Spyridakis 2010).

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Unlike the preceding civilization of Egypt, which was based on the exploitation of the abundant waters of the large Nile river, the city of Alexandria has been plagued by limited, often scarce and inadequate natural water resources (Butzer 1976).

The adoption of the design of Hippodamus during the Hellenistic era created residential renewal in the cities under construction, and it was, from the outset, fertile ground for the implementation of the most innovative hydraulic infrastructure of their time (Bacon 2012).

Since the founding of Alexandria, a coastal city in ancient Egypt, the use of facilities and infrastructure for groundwater exploitation and wastewater management has been studied and designed, and over time, as the city grew, management expanded their development and adaptation (Hairy 2009). The calculation of groundwater required an accurate knowledge of both the stony nature of the geological formations and their location, layout and ‘architecture’. The determination of hydrogeological structures allowed the Alexandrian engineers to determine the shape and dimensions of the aquifers. Their exploitation required complex techniques, as they were renewable water sources. The volume of exploitable water also had to be assessed in order to adapt the structures for water supply and wastewater accordingly (Hairy 2011a, 2011b).

Despite its location on the Egyptian coast, bathed in the waters of the Mediterranean and Lake Mareotidos, the city of Alexandria has always had a shortage of drinking water (Figure 1). The place that Alexander the Great chose for the founding of his city was a barren area, where there were only brackish wells. Various intelligent systems were implemented from the first days of the city’s founding: the supply of water from the Nile through the opening of a canal (Schedia, Centia), its distribution with a branched pipeline system and the storage of water in many underground tanks (Hairy 2016).

The ancient city of Alexandria, which has evolved into the most cosmopolitan and vibrant metropolis of the Mediterranean, is often referred to as the city of reservoirs (Empereur 2017).

The whole city was basically built on a level of sewerage and water supply infrastructure, which ran underground from the south to the north and ended at the sea. According to written sources, Ancient Alexandria was built over a network of water canals that operated under the city streets. The roads intersected in order to take advantage of the air currents coming from the sea to cool the city in a natural way, to keep the inhabitants healthy, and to give the city a bioclimatic character (Empereur 2009).

In recent decades, successive archaeological excavations in and around the city have uncovered, in the ruins of various buildings, public baths and pipes, sewer sections, ceramics and occasional indications for the use of covered sewer systems for rainwater and sewage. In addition, part of the internal sewer system of some modern homes was found to be directly connected to the...
ancient central sewer system. These archaeological finds will form the basis of this study.

Although several studies have traced and presented traces of water supply and water distribution systems in ancient Alexandria, there is still a lack of sufficient data on waste management and sewerage. This lack allows us to present an overview, rather than a fragmentary picture, of the complete and innovative management system mentioned in the historical sources (Ferro & Magli 2012). However, the indisputable fact is that most travelers and historians of ancient times describe, impressed, the number, size, complex operation (collection of river and rainwater) and the majestic construction of water storage tanks that existed in the city (Fraser 1972).

This study aims to highlight the infrastructure of ancient Alexandria, identifying the structure of sewerage systems and highlighting the importance of sewerage and water management systems as the basic principles on which the hygiene of the city’s inhabitants depends.

So wisdom in management seems to be the solution to the ever-growing global water resources problem rather than engineering development, as was previously suggested (Angelakis et al. 2012).

**Topography and urban planning of Alexandria**

The architect Deinocrates of Rhodes designed Alexandria, in the form of a rectangle (grid). It was an important city of the ancient world (Figure 2). For more than two thousand years, it was the largest city in Egypt and was its capital for almost half of this period. As an important trading position between Europe and Asia, it has benefited from the easy land connection between the Mediterranean and the Red Sea. On July 21, 365 AD, a tsunami caused by an earthquake centered in Crete struck Alexandria. Many historians and scholars estimate that the event contributed to the gradual decline of the state city, because in addition to the millions of victims among the population, much of its coastline sank in Mediterranean waters in addition to water in drinking water supply canals water becoming brackish (Decobert 1998; Hairy 2008a, 2008b).

After the tsunami of 365 AD, the Alexandrians depended exclusively on the reservoirs, as the groundwater became salty. There were smaller private and medium-sized or larger public tanks that served the city, as well as tanks intended for mosques and madrassas (Islamic seminaries) during the Islamic period. The construction of reservoirs was vital in Alexandria and so an advanced architecture was developed for them, with differences proportional to the different historical periods (Greek, Roman and Islamic) (Decobert 1998). These large underground reservoirs were developed in height on many levels with columns and dividing arches. Remains of the infrastructure of the byzantine period were used as building materials.

**The tanks (cisterns) of Alexandria and their construction features**

Drinking water was a valuable commodity in this barren area without natural sources of fresh water. The need for
storage led to the construction of buildings in the form of large, closed, watertight, compact tanks that maintained the freshness of the water. The first tanks in Alexandria date back to the Ptolemaic period. They are fed artificially or by collecting rainwater. They are located in places where access to water is difficult, in special facilities such as thermal baths or necropolises, or even in areas with craft activities.

Their shape varies depending on the time they were made. Thus, during the Ptolemaic period, the tanks were small, just dug into the rock and often adopted the so-called ‘bottle’ as a shape. The techniques were perfected in Roman times. At this time, the tanks are made of bricks connected with plaster and are watertight, covered with ceramic mortar (from fragments of tiles and bricks). They are small and adopt as a shape the so-called ‘tree’; that is, a set of decreasing volumes, which are connected to each other by vaulted passages. They gradually become larger and adopt a form known as ‘welded volumes’. At the end of antiquity, they had a roof and were powered by an aqueduct (Ahmed et al. 2020).

Overuse and artificial feeding of most tanks, however, led to network damage that affected water quality. In addition, the year 365 AD tsunami caused large amounts of salt water to invade the earth, destroying the city’s aquifer. The gradual sinking of part of the coast also put the freshwater network in contact with seawater (Angelakis 2014).

This is why the system was completely redesigned in the 5th century AD. New public tanks were created, larger in size, and a freer design was adopted. These reservoirs were filled with fresh water during the Nile flood season.

During the Arab conquest, this system of reservoirs was abandoned and reused only when Ahmed Ibn Toulon (835–884 AD) adopted the construction of multi-storey tanks that were fed either by the flood of the Nile River or from rainwater collection. They brought a sakieh pumping system and a compluvium (rainwater collection system), of which remains have been found on the roofs of many of them (Empereur 2002). Some were connected to each other by a network of underground pipelines (Hairy 2016).

The dimensions of the tanks are extremely variable and depend directly on their destination, from a few cubic meters for a private home to a medium and large capacity with several thousand liters for a public building such as the baths of Kom el-Dikka (Greco-Roman time). The bulky tanks were intended for public use. Mediums may have been suitable for feeding a neighborhood or a group of dwellings (Butzer 1976).

A characteristic type of architecture distinguished it. Their volumetric capacity could reach 2,500 m³. The excavations showed that they used special plaster in the masonry and the floor. The tanks were usually underground and covered with a roof to prevent external contamination.

These public structures were on one, two, three, or even four levels. The pumping holes were placed in the roof.

Their maintenance was carried out due to a drainage well, which provided access to the bottom of the tank, the depth of which could reach 13 m. With a semicircular shape, this well was usually placed around the perimeter of the building and often at one of the corners. The descent takes place through a staircase located on the walls of the well. This option allowed the tank to be cleaned before the annual filling, which was necessary to ensure good water quality (Guyard 2008).

The internal support system of this type of tank is based on a structural element with a square shape, whose average dimensions are 2.50 m × 2.50 m and height 3.50 m.

The unit consists of four columns, connected horizontally at the top by low arches. Multiplying this unit by length and height creates a bearing structure of a rectangular, light and open frame (Figure 3). The set is flexible enough to withstand the earthquakes that are common in this area. The roof loads are transmitted to the ground by the columns, while the arches transmit the thrusts sideways to the outer walls of the tank (Figure 4). The support structure is thus stabilized in its periphery by the walls. This architecture not only allows the construction of...
large volumes, but also the optimal storage of large volumes of water (Machinek 2009).

The topography of the tanks and their placement on the city map

The Alexandrian tanks mentioned here were identified based on information from four different sources (Figure 5):
(a) The ‘capture plan’: city surveys conducted between 1898 and 1905 by an English insurance company.
(b) The ‘SRG plan’: map of the cadaster of 1950 kept by the Royal Geographical Society.
(c) Data on tanks located at the Center d’Etudes Alexandrines (CE Alex) as part of the city’s tank inventory.
(d) Hydraulic data from the ‘Falaki plan’, a map of the city designed by astronomer Mahmud Bey El Falaki in 1865.

The information extracted from the first three sources was placed on the Falaki map. The data obtained from the Falaki plan were placed in the general plan of the two ports, the modern city, and the city of the Arabs, and were published in the huge project ‘Description of Egypt’, written by engineers of the Eastern army of Napoleon Bonaparte during his campaign in Egypt between 1798 and 1801 (Hairy 2009; Simony 2011).

Type-morphology and capacity of the tanks

Data on the morphology of the tanks, obtained from the drawings of the Kamil files, have been recorded in a database. This database currently has 144 tanks of 1 to 4 levels, from 6 m$^3$ to 2.500 m$^3$.

There are:
(a) 27 tanks on 1 level
(b) 50 tanks on 2 levels
(c) 49 tanks on 3 levels
(d) 9 tanks on 4 levels
and (e) 9 tanks whose exact morphology is unknown to us.

Examining the morphological data recorded, five more general types of tanks can be identified (Table 1). The issue of their dating remains unresolved.

Other reports mention that 500 tanks are known from the more than two thousand that existed. Sedimentation
tanks were probably used at that time as by Greeks centuries ago (Ahmed et al. 2020).

Some samples of the variety of cisterns are the following. The one in Figure 6 is the entrance of the large reservoir below the Greek Orthodox Church of the Annunciation, which today has been renovated and turned into a museum. It belongs in type III and consists of large tanks on one level with a vaulted roof supported by rectangular pillars. An extremely durable hydraulic plaster protects the masonry. Examples also include the Roman baths at Kom el-Dikka, and the reservoir at the southern end of the Serapion hill.

Another tank is the one that was discovered during the restoration and renovation work (Figure 7) of the fortress of Qait Bey, which now stands on the site of the ancient lighthouse of Alexandria at the edge of the Heptastadium.

This belongs to the type I category and is a typical example of infrastructure that provided drinking water to the supporters of the city’s defense during the siege (Figure 8).

As in Pompeii, it can be shown that the tanks that were connected to an urban network at a given time could then operate independently, after the supply canals were destroyed or filled, or vice versa could be reconnected when new mains were installed (De Feo et al. 2014).

Rainwater management

Especially in the city of Alexandria, the composition of all the data proves that there has always been care for the utilization of rainwater.

### Table 1: Tank type, number and capacity by type

<table>
<thead>
<tr>
<th>Tank type</th>
<th>Number of levels</th>
<th>Number of tanks</th>
<th>Estimated capacity in m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>1 level - 1 chamber</td>
<td>20</td>
<td>10-50</td>
</tr>
<tr>
<td>Type II</td>
<td>1 level till 3 chamber</td>
<td>7</td>
<td>50-200</td>
</tr>
<tr>
<td>Type III</td>
<td>1 level-many chambers</td>
<td>50</td>
<td>200-1000</td>
</tr>
<tr>
<td>Type IV</td>
<td>Informal layout</td>
<td>9</td>
<td>1500</td>
</tr>
<tr>
<td>Type V</td>
<td>3-4 levels</td>
<td>58</td>
<td>2000-2500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>144</strong></td>
<td><strong>131,050–165,000</strong></td>
</tr>
</tbody>
</table>

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**Figure 6** | The entrance of the reservoir below the Greek Orthodox Church of the Annunciation (Spanoudi 2021).

**Figure 7** | The reservoir of the Qait Bey fort during the works of restoration (Machinek 2020).
Excavations in the Terra Santa area have uncovered structures discovered in the six excavation areas that belong to a vast hydraulic network. Nine wells, a reservoir, a sakieh and several galleries have been found. The Terra Santa location features a wide range of urban plumbing fixtures, each structure meeting a well-defined function: collecting, designing, installing, storing or transporting water. The dating of the finds places them in the primary Hellenistic hydraulic network of Alexandria (Boulud 2015).

A small tank carved directly into the rock was discovered in area 6 of Terra Santa. It is a bell-shaped tank, accessible from the surface through a cylindrical hole and two closed longitudinal arms. Its walls are covered with hydraulic coating, ensuring complete waterproofing. The construction of 0.30 to 0.40 m depth, functioned as a rainwater collection basin. The shallow grooves observed along its walls facilitated the flow of rainwater to the reservoir. The large shaft, located 1 m from the east portico, is another possible source of power for the reservoir. The type of small tank provided a solution to the issue of water storage and supply of rainwater collection, while it also functioned as a sedimentation tank (Bengtsson 2017). The household tanks dug in the rock, in the shape of a bell or a bottle, with or without a neighboring pipeline, are common in the Hellenistic area of the Mediterranean. In Pergamon, Syracuse or Piraeus, for example, most houses of the Hellenistic period had a rainwater collection tank. The small capacity is a general characteristic of the Hellenistic period (Kollyropoulos et al. 2013). Then, the private indoor tanks were replaced by large collective tanks.

One of the most characteristic cases was the Complex of Serapio (Figures 9–11). There contained, among other structures, the Nilometer system, which also functioned as a rainwater collection tank (Rowe 1942).

In parts of the roof of some tanks in the Arab city, such as the El Gharaba and El Nabih reservoirs, grooves have been discovered connected to openings that ended inside the reservoir. A second addition is installed in the form of a pipe, at an incline that also ends at the tank (Guyard 2008; Hairy 2011a, 2011b).

We can therefore conclude that in the effort to utilize all available water during the period of the year when the quantities transported by the network of canals were small, the network also had infrastructure for the collection and storage of rainwater (Shafy et al. 2010).
Evolution of the construction of reservoirs in the Mediterranean basin

After the decline of the Roman empire, water systems underwent fundamental changes. The medieval cities of Western Europe, as well as castles and monasteries, had their own wells, fountains, faucets and reservoirs (Ceçen 1992). On the other hand, the eastern part of the empire maintained for a few centuries the relevant Roman construction tradition, which was applied mainly to the water supply system of Constantinople and other major centers of the eastern Mediterranean.

This tradition gradually diminished over the centuries, but some of the surviving techniques were incorporated into Arabic building practices and improved by the application of vaulted arches and other innovations of the time. Roman technology was applied to the water system of Constantinople (Bogdanović 2008). The reservoir of the Causein Istanbul, at least 36 cisterns were built (Lerner 1989).

The Basilica Cistern, or Yerebatan Sarayi in Turkish, was the largest known covered reservoir (140 m × 70 m and capable of holding 80,000 m³). During the empire’s thousand years of existence, its influence spread widely in North Africa and the Near East. Several Byzantine tanks were built in various parts of the Empire (Ciniç 2005).

DISCUSSION AND CONCLUSION

In the light of new discoveries and combined studies, however, the belief is beginning to form that Alexandria can be compared to Constantinople, which until now has been called ‘the city of tanks’. The number of 144 large tanks revealed so far is greater than the approximately 100 surviving in Istanbul. Although not comparable in size it is just as majestic. The largest tank discovered in Alexandria, El Nabih has a storage capacity of 2,500 m³. Continuation of the investigations will probably reveal the quantities of water stored for it compared to the approximately 1,000,000 m³ that could be collected in total in the cisterns of Istanbul (Ciniç 2003; Bogdanović 2008).

Another question that can be asked is that of their architectural structure. As described in detail in the work, in the large structures of Alexandria it has been used as a repeating building unit, a square defined by four columns connected by a dome. This unit is repeated and expanded, allowing the creation of large and stable building structures. In addition, the use of granite and marble columns, as a means of support, reduced maintenance costs and made the most of the reproduction of the basic, square architectural unit (Forchheimer & Strzygowski 1893).
This structure is considered the characteristic shape for the development and standardization of Byzantine architecture, both utilitarian and religious. The tanks of Constantinople were built with the same type after the 6th century AD during the period when it was the largest and most important city of the Byzantine Empire (Hakan 2020). However, the great reservoirs of Alexandria certainly began to be built after the 8th AD Century, during the Arab conquest of the city. At the time, it was now an insignificant provincial city of Egypt and the Arab world. What was it that pushed the Arab administration to build such expensive infrastructure and what was the standard?

The evolution of rainwater collection systems to increase water use efficiency and the ongoing effort to preserve the environment for sustainable development has been presented and discussed in this paper. It is believed that these early systems were used in the Mediterranean region to collect runoff from mountain slopes, open courtyards and roofs mainly for domestic purposes (Golfinopoulos et al. 2016).

Rainwater drainage storage facilities have been built throughout the Mediterranean and the Near East since the third millennium BC. Not only were the tanks used to store rainwater runoff, but also to store aqueduct water for seasonal fluctuations (Mays et al. 2013). Historical examples of reservoir technologies may still be relevant to today’s water engineering. Some of the conclusions drawn include:

(a) Throughout history, reservoirs have been an essential part of water technology for the survival and well-being of humans for the sustainability of water resources.

(b) A combination and balance of smaller scale measures (such as reservoirs for water collection systems) and large scale water projects (such as reservoirs for storing aqueduct flows) have been used by many ancient civilizations.

(c) Ancient reservoir water technologies should not be considered as historical objects, but as possible models for sustainable water technologies for the present and the future.

(d) Ancient water technologies, such as tanks, were characterized by simplicity, ease of operation and the requirement for complex controls, making them more sustainable (Mays 2010). However, the successful design and operation of some of them systems were huge achievements in engineering.

(e) Reservoirs have been used by ancient civilizations for the sustainability of water resources and have been used since, although their importance for today’s water supply purposes has somewhat disappeared in developed parts of the world, despite the fact that it has continued in many developing parts of the world (Mays 2013).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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