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Biennale del Restauro Architettonico e Urbano (BRAU4, Athens/Piraeus)

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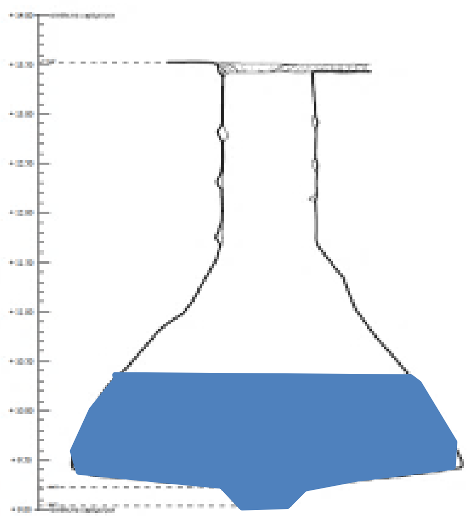
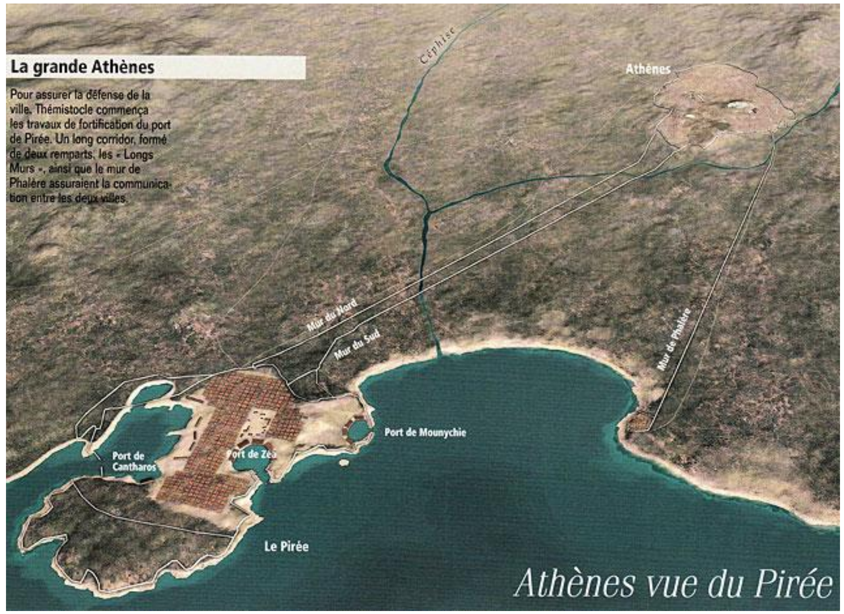
Hellenic Maritime Museum of Piraeus

Reconstructing the water supply conditions of the Ancient Piraeus





Demetris Koutsoyiannis & Nikos Mamassis
School of Civil Engineering, National Technical University of Athens, Greece

Presentation available online: http://itia.ntua.gr/1833/

Photos and designs: Courtesy of the Ephorate of Antiquities of West Attica, Piraeus and Islands

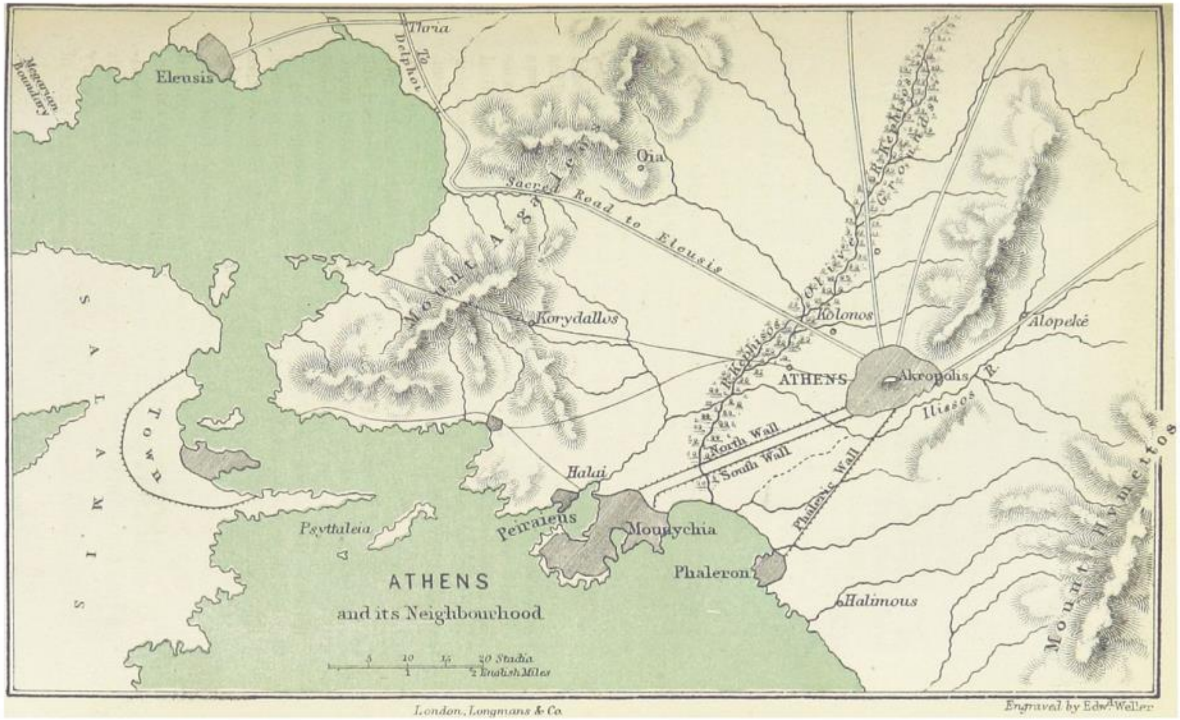
Inhabitance of Ancient Piraeus

During the 5th century BC, the Athenians decided to fortify Piraeus and construct a safe port for war and commercial vessels. The three natural harbours gave the city the opportunity to develop a powerful fleet and a wealthy trade. Athenians built:

(a) A port equipped with dockyards and other naval facilities.

(b) A residential area according to the urban plan by Hippodamus of Miletus; it comprised 500 building blocks, each measuring 47×41 m^2 and consisted of 8 residences (of about 240 m^2) in two rows of 4; groups of 5×7 blocks constituted districts.

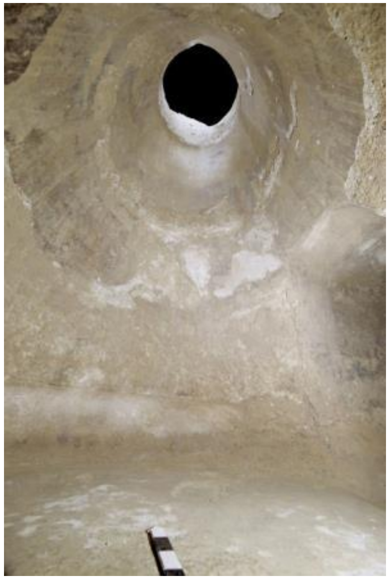
(c) A fortification wall around the Piraeus peninsula with a perimeter of about 11 km and the famous Long Walls (Μακρά Τείχη, 6 km each) providing a secure connection of Athens and Piraeus during times of siege.



Source: Cox (1876, p. 303).

Water supply works excavated

Underground structures for water supply of the houses of the ancient Piraeus are revealed from several rescue excavations. Until 2004 about 384 structures had been found. Recently, the excavations from the Ephorate of West Attica, Piraeus and the Islands, during the construction of Athens Metro (Line 3), revealed 112 new structures: 40 wells and shafts, 35 cisterns, 32 tunnels and 5 shallow wells.



- The most common structure is a **bell-shaped cistern** from 2 to 6 m in diameter, carved into bedrock and coated with hydraulic mortar. In many cases clusters of 2-4 cisterns and wells were formed through connections by tunnels.
- Also there are several **wells with a typical diameter of 0.80 m**. The wells exploit an aquifer which today has a water table at 3 m a.m.s.l. The wells have a depth up to 18 m (measured from the level of the modern city), reaching at 1.4 m – 5 m below sea level.
- Finally a section of about 95 m in length of **an aqueduct** was revealed. This includes, beside the central tunnel-conduit, 3 entrance wells and 2 earlier cisterns that were also used as wells for the same purpose. The duct has an average width of 0.85 m and height of 1.80 m. The walls are not coated.

Estimation of water needs

Ancient communities (Mays et al., 2012)

The water consumption of ancient communities which did not have water source nearby is estimated to about **10-20 L/d per capita**.

Water consumption in Jerusalem at 10th century BC is estimated to about **20 L/d per capita**.

Ancient Athens (Plutarch “Solon”)

Solon (640-558 BC) included in his famous legislation water management regulations:

“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 (4 furlongs, 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 litres) twice a day*** *from their neighbours”*

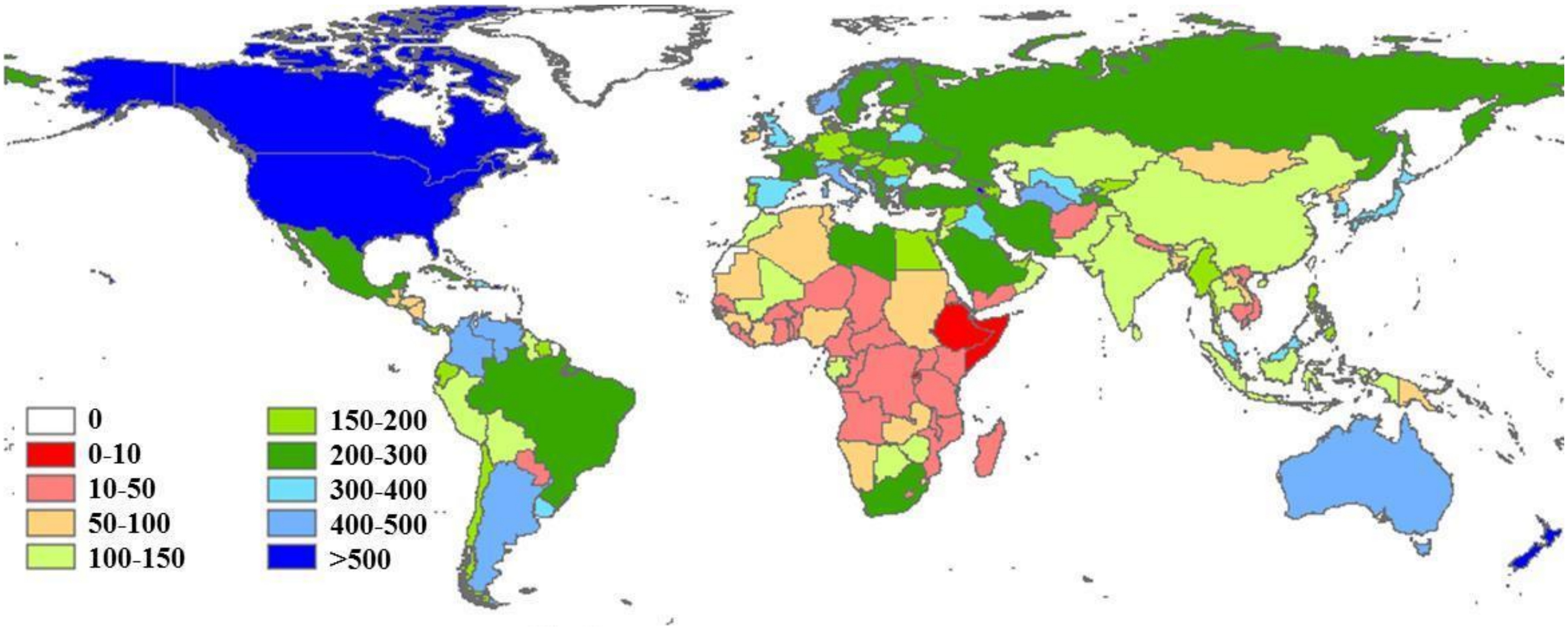
A minimum water need of about **40 L/d per household**, during 6th century BC.

Roman period (Sextus Julius Frontinus “De Aquaeductu Urbis Romae”)

The analysis of data from the book by Frontinus (40-103 AD) shows that:

- water needs, for domestic use, in the suburbs of lower and middle class, are estimated to about **85 L/d per capita**.
- the access to public water consumption installations (baths, fountains, naval battles in stadiums), corresponds to an additional water quantity that could reach **200 L/d per capita**.

Domestic water consumption in 2010 (L/d per capita)



The modern "target" for "reasonable access to water" is set to **20 L/d per capita at a distance of less than 1 km**.

This is too low as a target; yet 18% of the world population (~1 billion) do not meet it (Howard & Bartram, 2003; WHO and UNICEF, 2000).

Even if the target were achieved, again it would indicate regression if compared to what the ancients had achieved.

Domestic and urban water needs (rough estimates)

Mean domestic water consumption

According to the previous data the following figures for the mean domestic water consumption per capita in Piraeus could be hypothesized:

- **20 L/d** during Classical period
- **30 L/d** during Hellenistic period (a small increase)
- **60 L/d** during Roman period

Total water consumption of the city

- The residential area of Piraeus was partitioned in **500 building blocks** and each block was consisted of **8 residences**. Also an estimate of about 5 persons per residence during Classical and Hellenistic periods is plausible.
- In full development, the city must have had **20 000 residents plus 5000 visitors** related to the harbour activity.
- The mean annual total consumption of the city during the Classical and Hellenistic periods is estimated to about **180 000 - 240 000 m^3**.
- The mean annual total consumption of the city during the Roman period for domestic use is estimated to **540 000 m^3**. This quantity must be multiplied by 2 – 3 to include public water uses such as baths, fountains etc.

Water resources of Ancient Piraeus (rough estimates)

Area of peninsula 4.4 km^2 | **Area of ancient city 1.0 km^2**

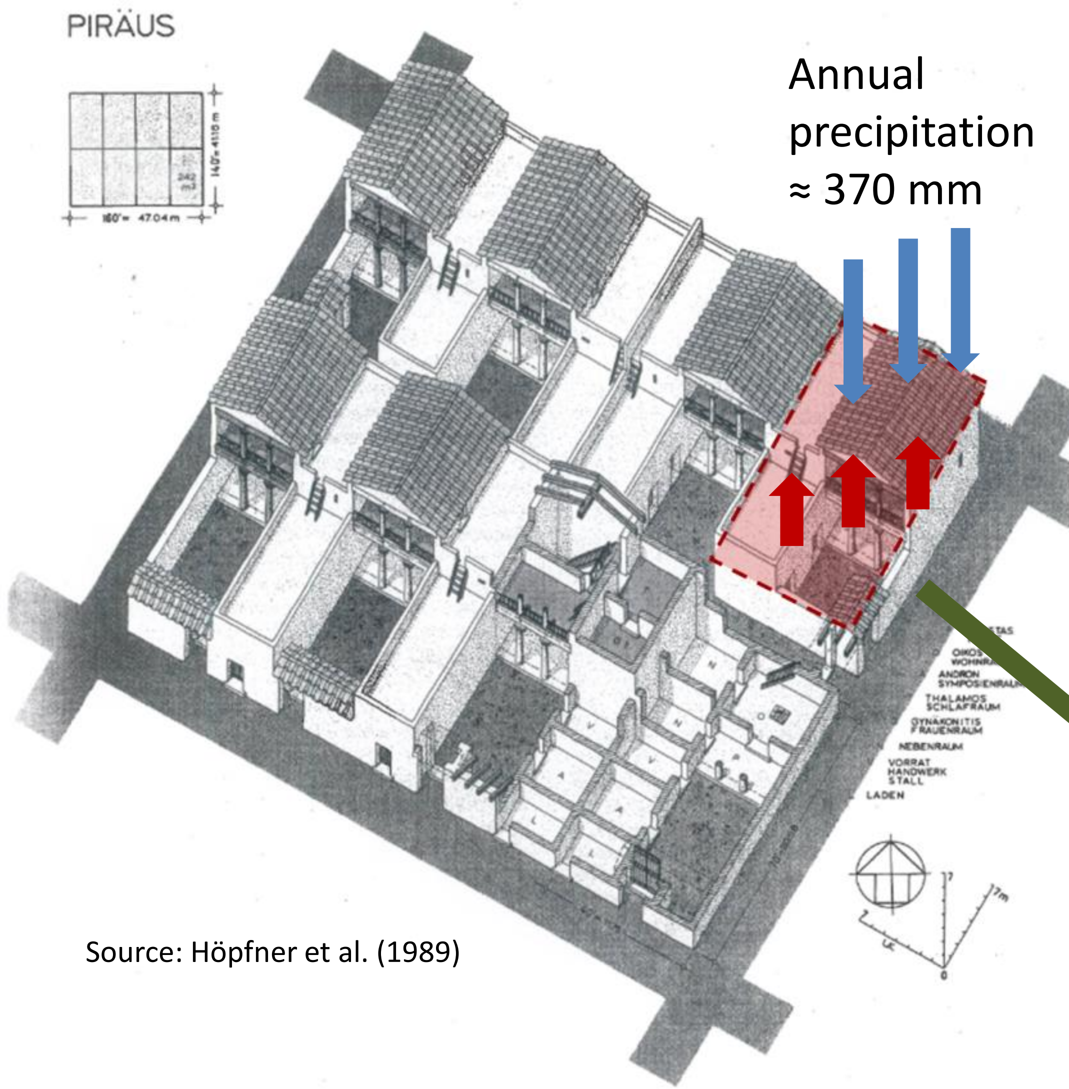
Mean annual precipitation ≈ 370 mm, Mean annual potential evaporation ≈ 1600 mm

- The mean annual precipitation volume at Piraeus peninsula (area **4.4 km^2**) is estimated to about **1.6 hm^3**.
- Using a simple hydrological model in daily time step the mean annual water inflow in urban surface was estimated 255 mm (runoff coefficient 70%). That means an annual potential water yield of 255 L/m^2 of collecting area.
- The potential collection of rainwater of a **residence** (area 200 m^2) is about **50 m^3** per year. The same quantity for the **total** urban territory (area 1.0 km^2) is about **250 000 m^3** per year.
- Considering the hydrogeology of the peninsula the mean annual **recharge of the aquifer** is estimated to **80 000 m^3**.

Residential rain water exploitation

Residence area: 242.0 m² (11.76 × 20.58 m²)

Block area: 1936.2 m² (41.16 × 47.04 m²)



Source: Höpfner et al. (1989)

Annual precipitation ≈ 370 mm

Rough estimation of annual potential withdrawal from a residence

Collecting area ≈ 200 m²

Evaporation losses ≈ 30 % of precipitation

Potential yield of a residence ≈ 50 m³/year ≈ 140 L/d

Simulation of a residence system (maximum demand)

Inputs

(a) Collecting area, (b) Cistern volume, (c) daily time series of precipitation, evaporation, and water demand

Outputs

Daily time series of spills, deficits and water consumption

Example (82 hydrological years)

Mean annual precipitation: **366.7 mm**

Mean annual loss: **111.2 mm**

Collecting area: **200 m^2**

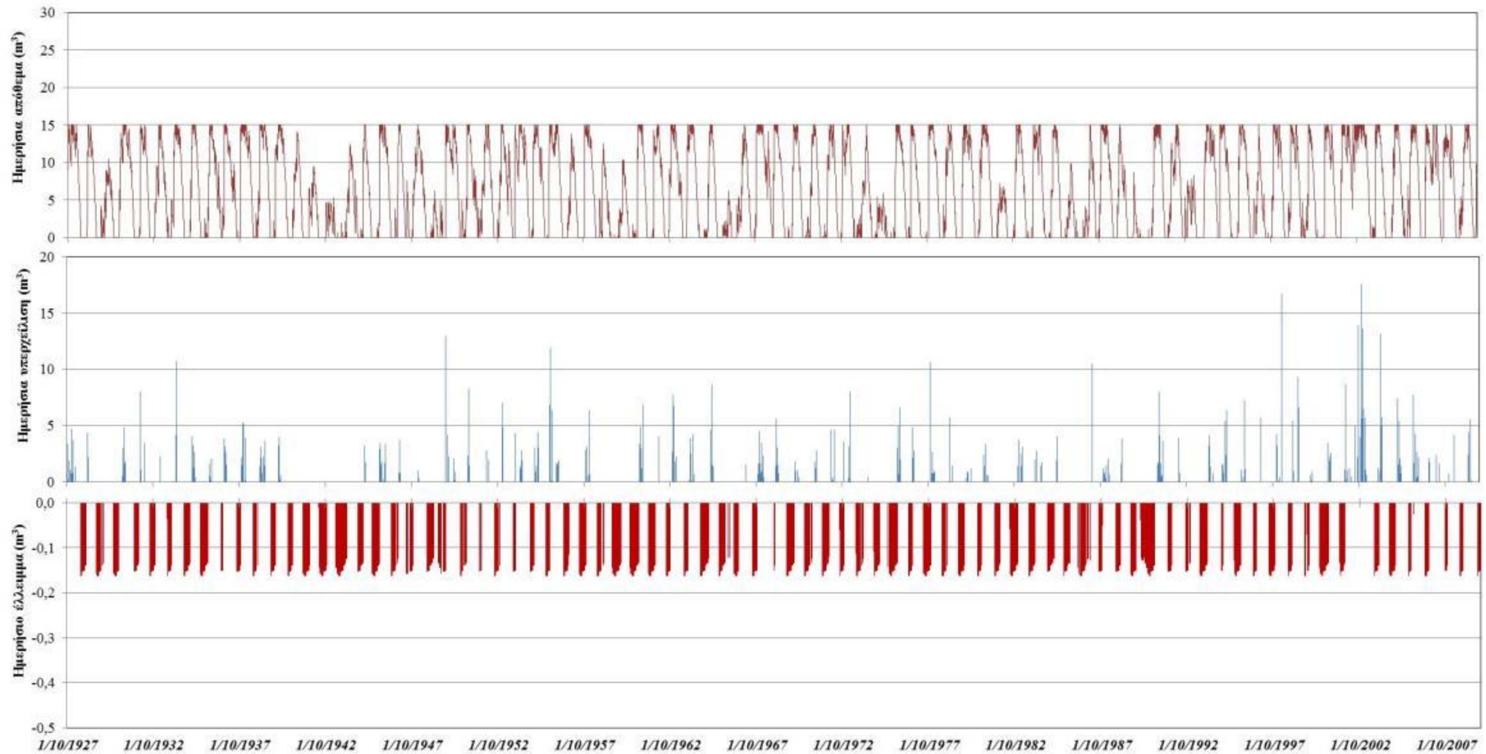
Cistern volume: **15 m^3**

Mean daily demand: **0.14 m^3**

Daily storage (m^3)

Daily spill (m^3)

Daily deficit (m^3)



Percentage of days with:
Spill: 2.2%
Deficit: 27.9%

31% of the spill volume occurs during the 0.16% of the days

Mean annual volumes:
Inflow = demand: 51.1 m^3
Spill: 15.2 m^3 /year

How large cistern?

The cistern volume depends on the following factors:

- **The potential rain water yield**. That is the maximum water quantity that can be collected and consumed, assuming unlimited storage capacity. This quantity is related to climatic conditions (precipitation, evaporation) and the area of collecting surface.

- **The precipitation regime of the area**. In case of finite storage capacity, if precipitation occurs in few intense events, the volume of the cistern must be large. On the contrary, in areas that rainfall occurs in more frequent events, the required volume is small.

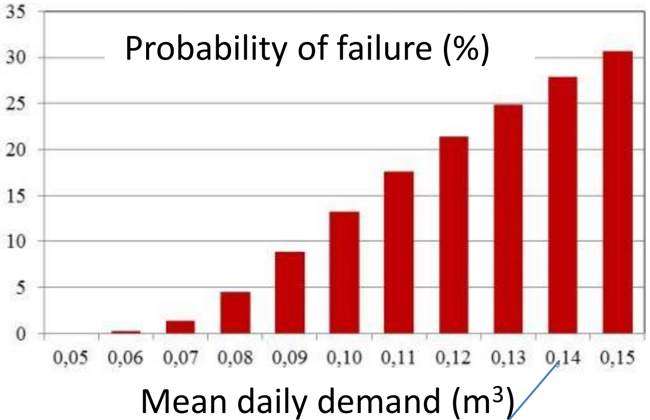
- **The water demand of the residents**. The water needs are related to the social and cultural characteristics of each historical period.

- **The probability of failure in providing the requested water demand**. It is expressed by the percentage of the days that the water needs cannot be satisfied by the cistern storage.

How large cistern? (contd.)

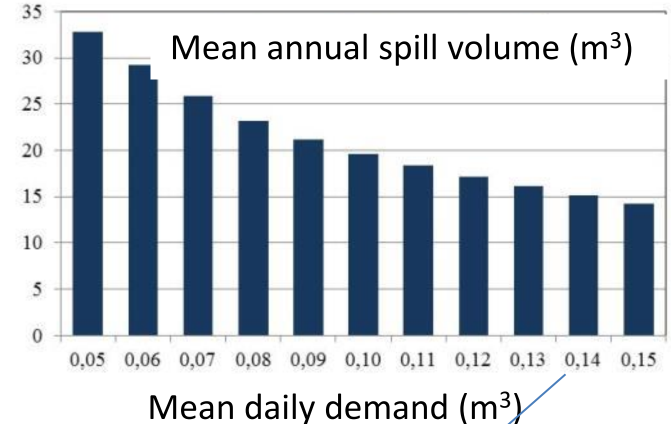
Collecting area: **200 m²** Cistern volume: **15 m³** Mean annual inflow: **51.1 m³ (≈ 0.14 m³/d)**

Demand varying from **0.05 to 0.15 m³/d**

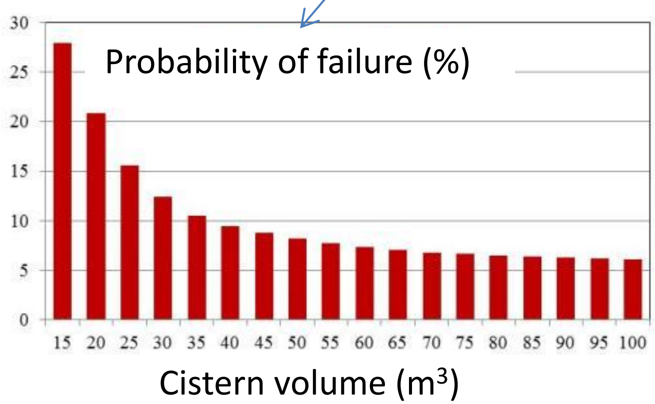


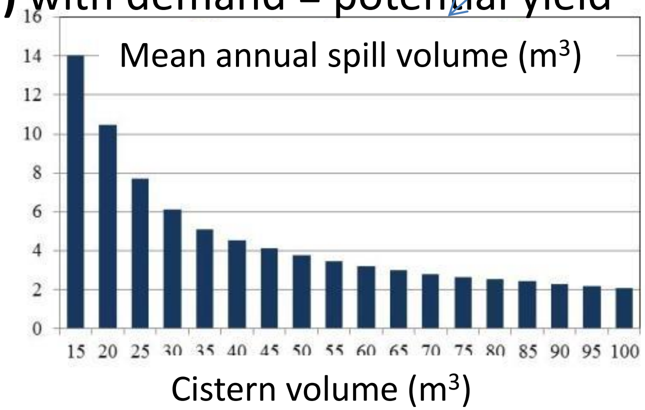
Results

- For demand greater than 90 L/d, the probability of failure (to cover demand) is greater than 10%.
- For demand greater 140 L/d (=potential yield), the probability of failure (to cover demand) is greater than 25%.
- The spill volume is always high (more than 30% of potential yield)



Effect of increased cistern volume **(up to 100 m³)** with demand = potential yield





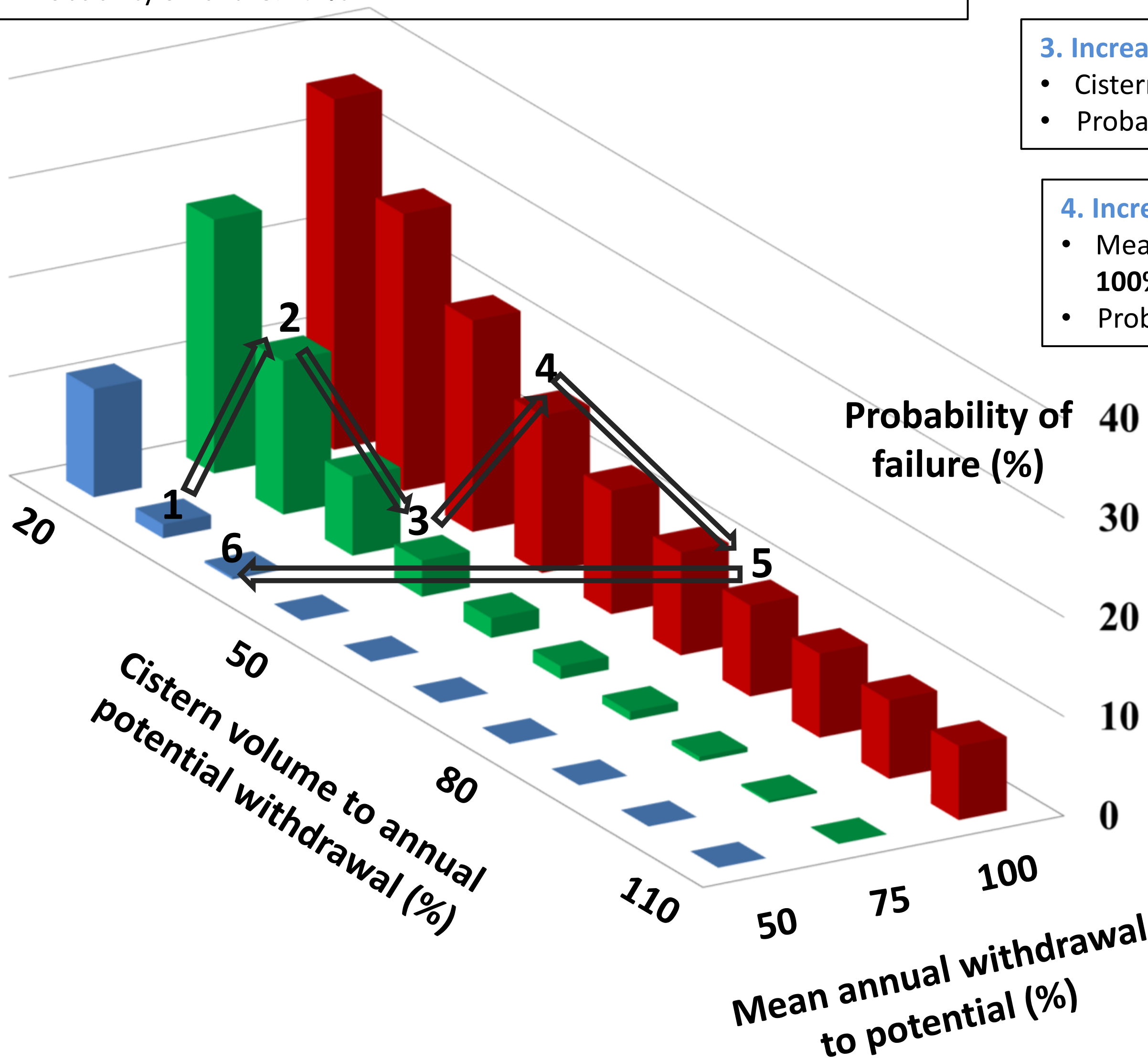
Results

- For cistern volume 40 m³, the probability of failure (to cover demand) is less than 10%; the spill volume is about the 8% of annual potential yield.
- Further increase of cistern volume does not lead to substantial decrease of the probability of failure.
- It is not possible to avoid spills even for cistern volume greater than 100 m³.

Relationship of cistern volume – water withdrawal – probability of failure

1 . Initial situation

- Collecting area: **200 m²**
- Mean annual inflow volume: **51 m³**
- Cistern volume: **15 m³ – 30%** of annual inflow volume
- Mean annual withdrawal: **25.5 m³ - 70 L/d – 50%** of inflow volume
- Probability of failure: **1.4%**



2. Increase of withdrawal → decrease of reliability

- Mean annual withdrawal volume: **38.3 m³ – 105 L/d – 75%** of inflow volume
- Probability of failure: **15.5%**

3. Increase of cistern volume → increase of reliability

- Cistern volume: **25 m³ – 50%** of inflow volume
- Probability of failure: **3.6%**

4. Increase of withdrawal → decrease of reliability

- Mean annual withdrawal volume: **51 m³ – 140 L/d – 100%** of inflow volume
- Probability of failure: **15.9%**

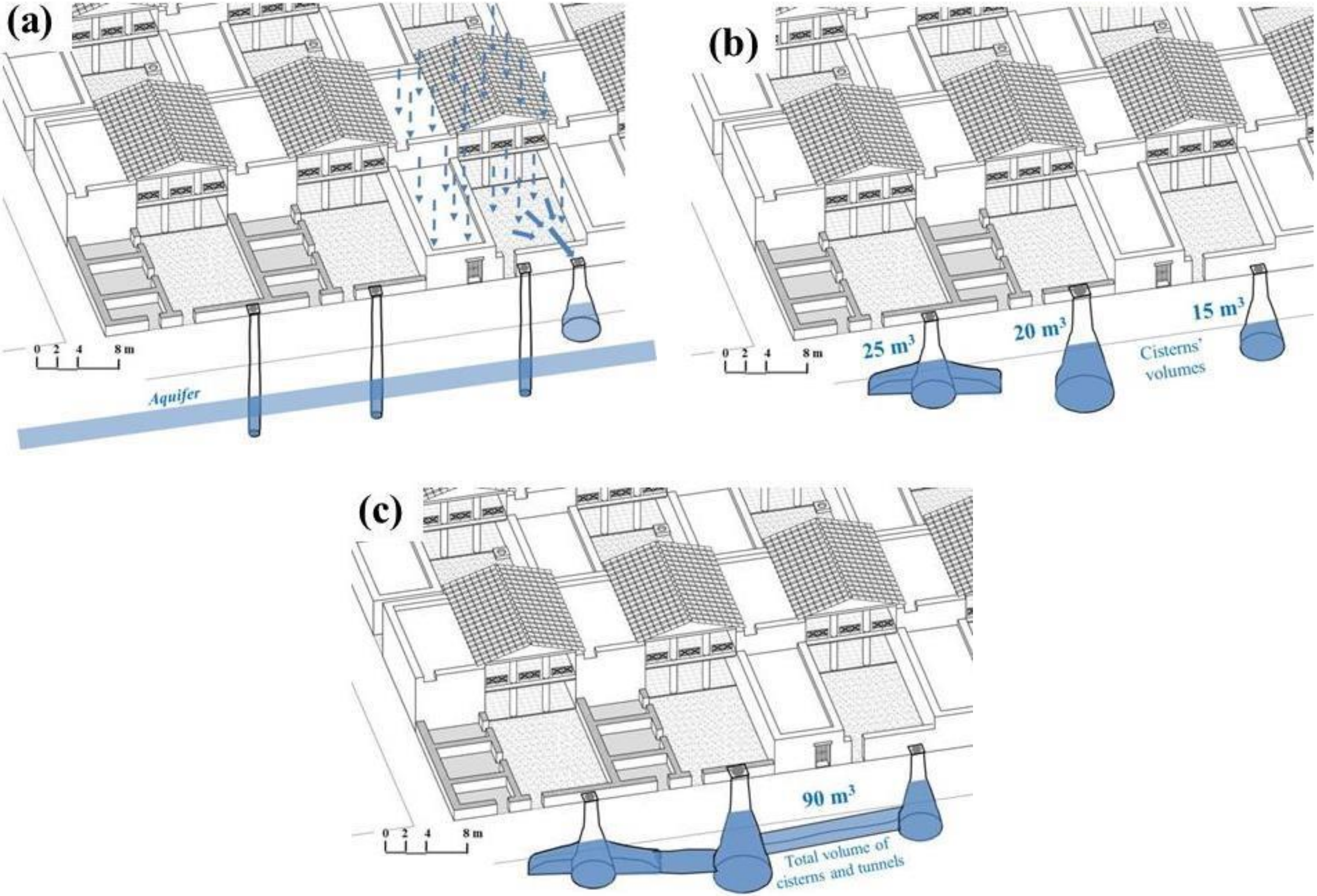
5. Increase of cistern volume → increase of reliability

- Cistern volume: **40 m³ – 80%** of inflow volume
- Probability of failure: **9%**
- Exploitation percentage: **92%**

6. Increase of collecting area → increase of reliability

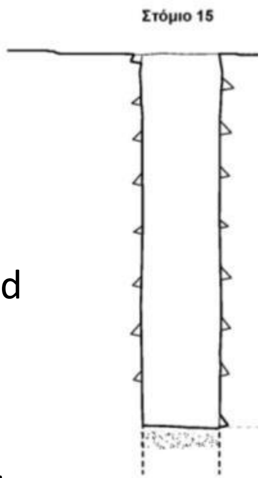
- Collecting area: **400 m²**
- Mean annual inflow volume: **102 m³**
- Cistern volume: **40 m³ – 40%** of inflow volume
- Mean annual withdrawal volume: **51 m³ – 140 L/d – 50%** of inflow volume
- Probability of failure < **1%**

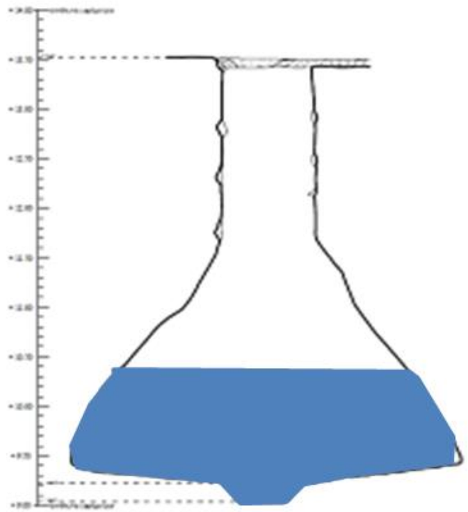
Temporal evolution of cistern volume

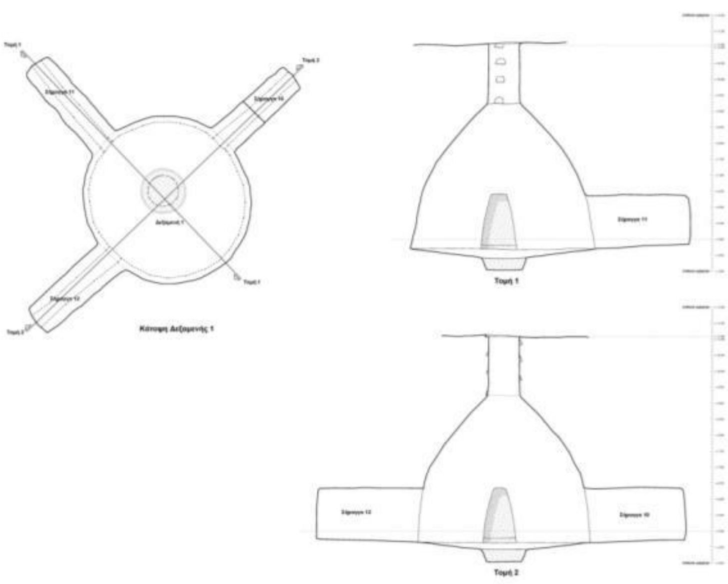


Reconstructing the water supply conditions of the Ancient Piraeus

- From the foundation of the city (mid 5th century BC) the residents dug **wells** (a very common practice in Attica region). Soon (end of 5th century BC) they realized the limited ability of the local aquifer and constructed the first **cisterns** for collecting **rainwater**.
- The potential rainwater exploitation could cover to a significant degree the water needs in the Classical period but the rainfall regime of Piraeus required significant storage volume.
- The potential rainwater yield at Piraeus is estimated to about to **0.25 m^3 per year and m^2** of collecting area. This corresponds to a potential inflow volume of **50 m^3** per year for a **residence of the Classical period** (collecting area of about **200 m^2**). Analysis shows that for withdrawing **25 m^3** per year (50% of inflow) with high reliability (about **99%**), a cistern volume of about **15 m^3** (30% of annual inflow volume) is required.
- Classical and Hellenistic periods are marked by a continuous effort for **cistern volume expansion**. The increased water needs required better exploitation of rainwater by decreasing the spills during winter, or even using them for aquifer recharge. For this purpose various techniques were used, including the construction of blind tunnels, connection tunnels between cisterns and connection of cistern spills to wells.

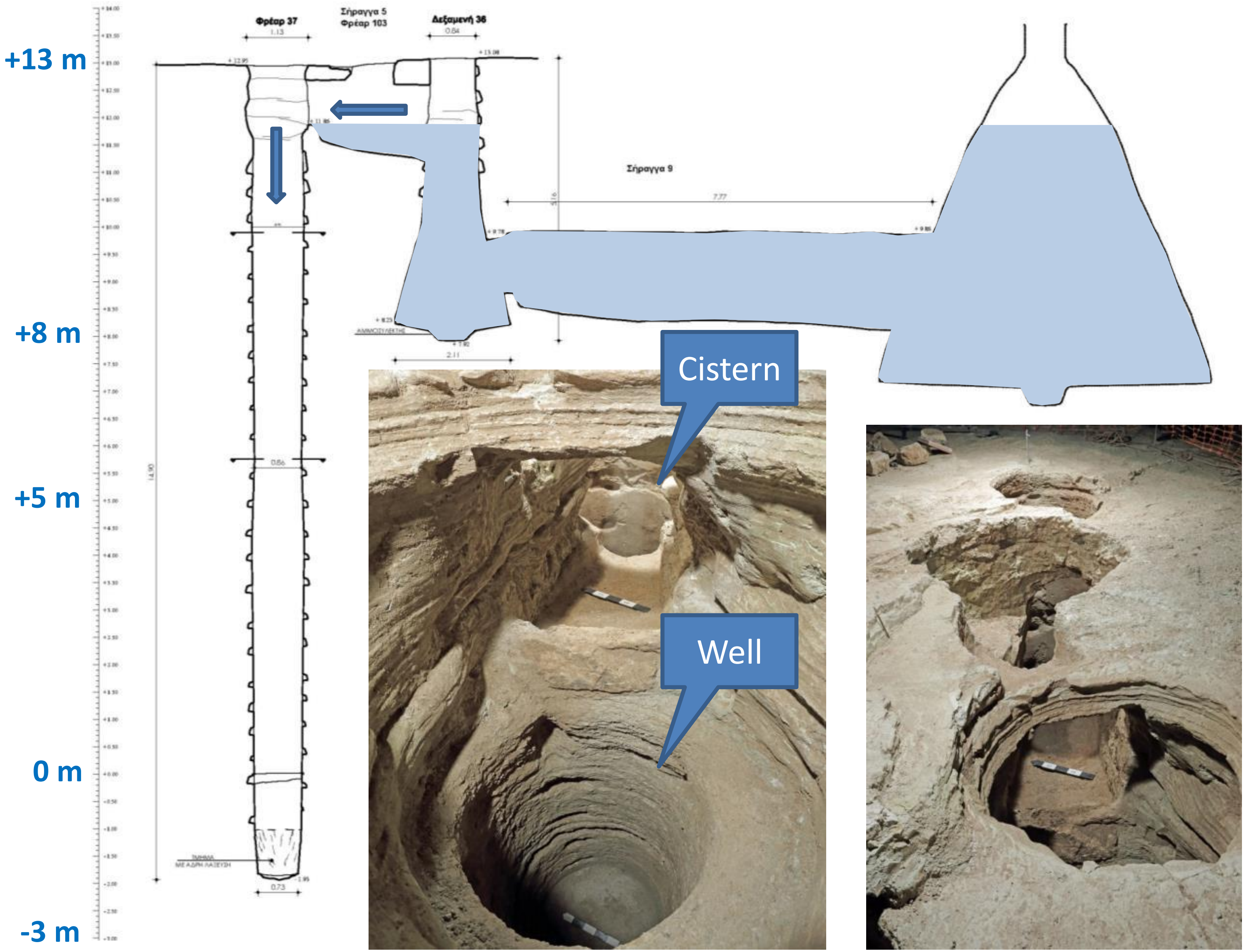




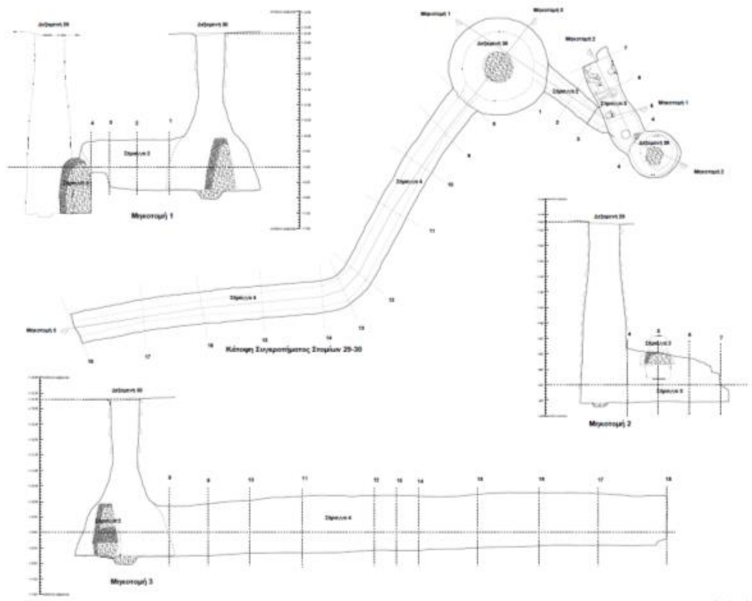


Combined management of surface and ground water

Storing cistern spills to wells and aquifer recharge



Reconstructing the water supply conditions of the Ancient Piraeus (contd.)



- During the Hellenistic and Roman periods, the changes to the property regime and the residence areas triggered a variety of subterranean constructions that expanded the existing system. The interventions also favoured the combined operation of cisterns and wells.
- During the Roman period, the increased water consumption mainly for public installations motivated the construction of an aqueduct that transported water from areas outside the Piraeus peninsula. However, the details of this aqueduct have yet to be uncovered.
- Overall, in the light of archaeological findings on this site, we see that, during the Classical period the citizens of Pireaus progressed far transforming a naturally dry area into a city with comfortable and hygienic living.
- This transformation indicates good understanding of natural processes, advanced technology and wise management.

Acknowledgments

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