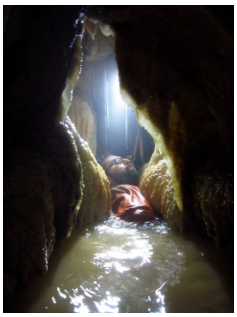
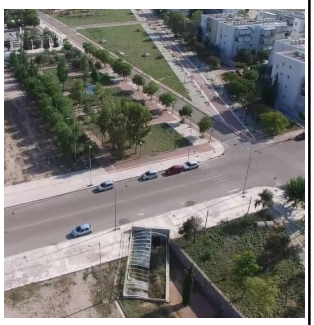
SWEDISH INSTITUTE at ATHENS

Lecture organized by Swedish Institute at Athens
29/10/2019

Exploring the operation of Athens' Hadrianic aqueduct

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Main topics




Presentation of ancient Hadrianic hydrosystem

- Water supply of Athens from Classical to Roman period
- Operation of Hadrianic hydrosystem
- Construction of the tunnel (hydraulics)
- Water resources (ground and surface water potential)
- Water management (transportation, reservoir, cistern)
- Water consumption of Roman city
- Specific issues (Kifissos, Peisistratean vs Hadrianic)
- Synopsis of the Hadrianic hydrosystem

Enhancement and promotion of ancient engineering heritage

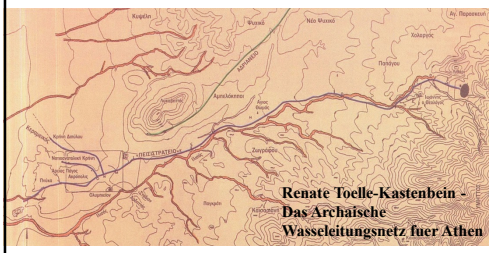
- Cooperation
- Information system
- Exploration-inspection of the aqueduct
- Dissemination actions
- Water use
- Scientific research

Athens' water supply before Romans

From the early beginning of the Athenian state, water scarcity caused institutional and technological advances, in order to ensure the supply of the city with fresh water.

Peisistratean aqueduct

The first major hydraulic project in Athens was Peisistratean aqueduct constructed at the end of 6th century BC. The aqueduct with a length of **about 8 km**, was carved as a tunnel at depth reaching 14 m and conveyed water from Hymettus area

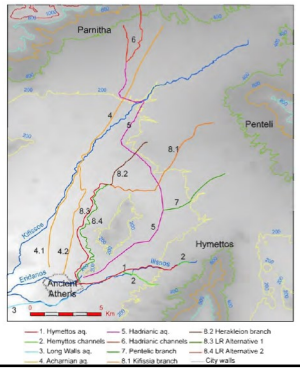


Other aqueducts

Several aqueducts were constructed during Classical and Hellenistic periods forming a network of waterways that provided with water the flourishing city of Athens (Chiotis and Chioti 2012)

Peisistratean aqueduct	Late 6th c. BC	Tunnel & wells	Na
Peisistratean pipeline	Late 6th c. BC	Terracotta pipes in trench	1.5+
Kimonian pipeline	2nd quarter of 5th c. BC	Terracotta pipes in trench	3.0+
Hymettos aqueduct	Early 4th c. BC (estimated)	Tunnel & wells	6.5
Acharnian aqueduct (4.2)	Early 4th c. BC	Elliptical terracotta tubes in trench	19.5
Hadrianic aqueduct	125–140 AD	Tunnel & wells	19.8
Late Roman	Middle of 5th c. AD	Built channel	21

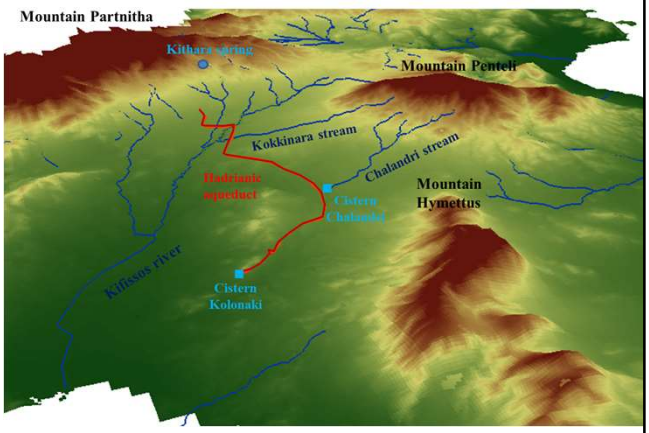
na: not available



Water supply of Roman Athens

To satisfy the increased water needs of Athens during Roman period the water resources of surrounding mountains were exploited. For that during the 2th century AD a large scale hydrosystem was constructed that included several hydraulic works and in particular:

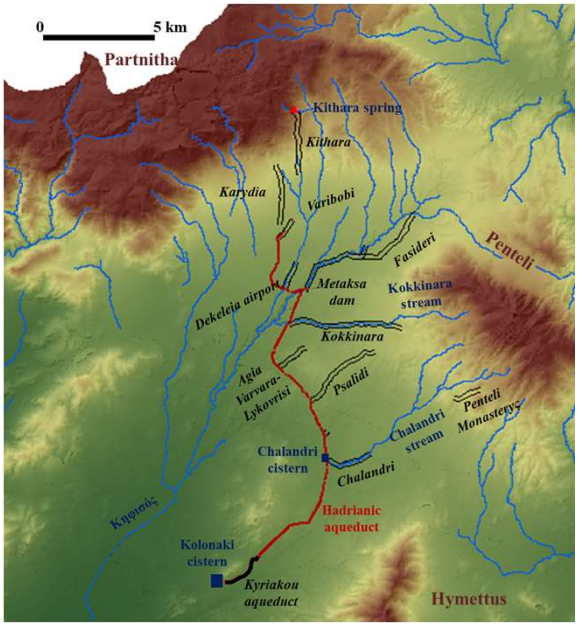
- a 20 km tunnel and about 500 wells that collected underground water, mainly from the Parnitha mountain but also from other sites along its course. ***It differs totally from other water transportation projects of that era, as it was constructed entirely subterranean.***
- lateral aqueducts that enriched the main tunnel in its beginning but also along its route transporting surface and spring water from other areas



- Kolonaki reservoit at Lycabetus hill and a piping system for water distribution to the city
- Other smaller works such as Chalandri cistern that was operated as desilter

Water supply of Roman Athens

Lateral aqueducts

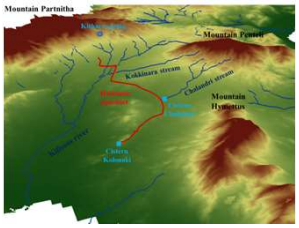


- Kithara and Karydia aqueducts were part of the initial hydrosystem and they transported Parnitha's spring water to the entrance of the tunnel.
- Kokkinara and Chalandri aqueducts it is possible to be constructed in the same period to transport surface and spring water from Penteli
- The other aqueducts have been constructed during modern times

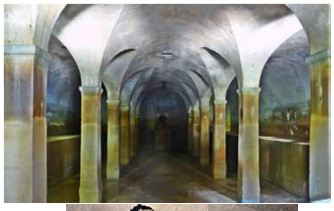
Hadrianic aqueduct is a paradigm of ***resilience and sustainability***, as it was used almost continuously, during its long history. It was repaired in the end of the 19th century and supported Athens' water supply ***until 1976***. Even today it carries significant quantities of water.

Operation of the hydrosystem

Water recourses-Hadrianic and lateral aqueducts



Water management-hydraulics, reservoir, cistern



Water consumption of Roman city

Issues that must be researched

What was?

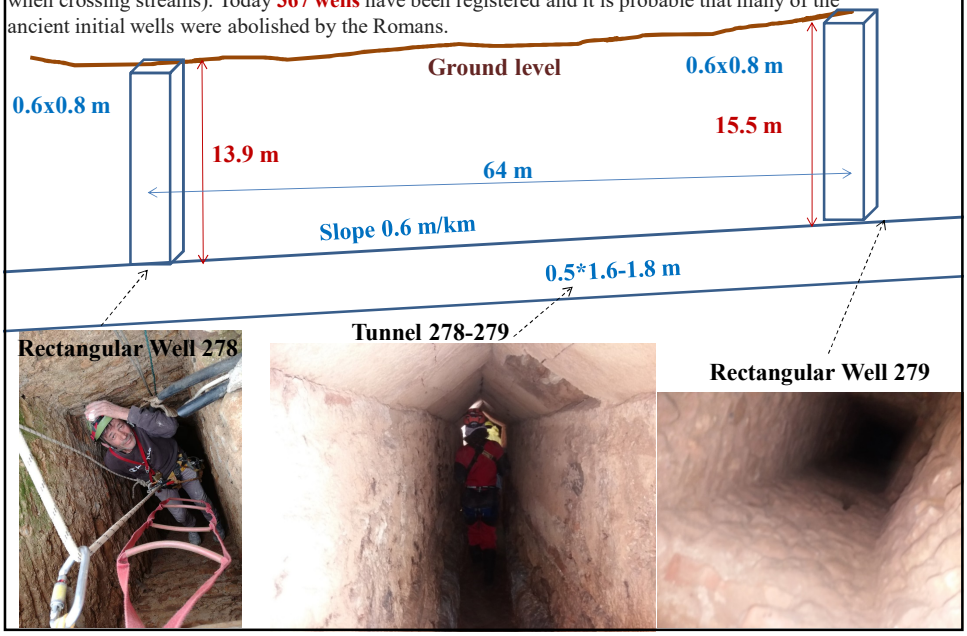
- the potential of surface and ground water
- the interaction between tunnel and ground water

- the hydraulic operation of the aqueduct
- the operation of Kolonaki reservoir?
- the operation of Chalandri Cistern

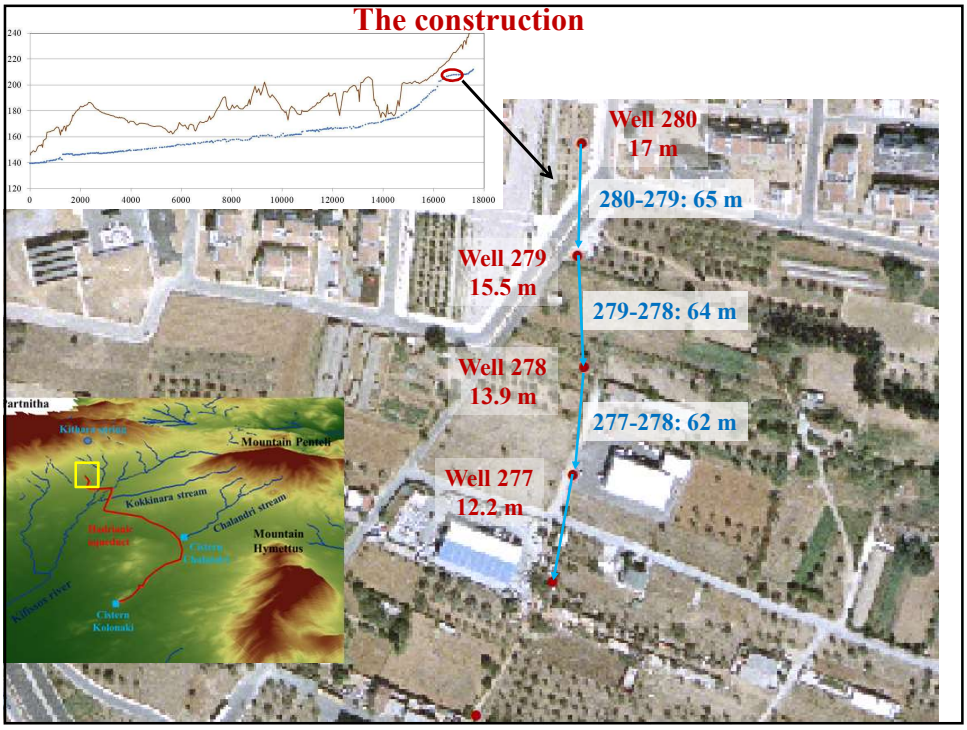
- the water demand of the Roman city
- storage capacity of cisterns in the city

The construction

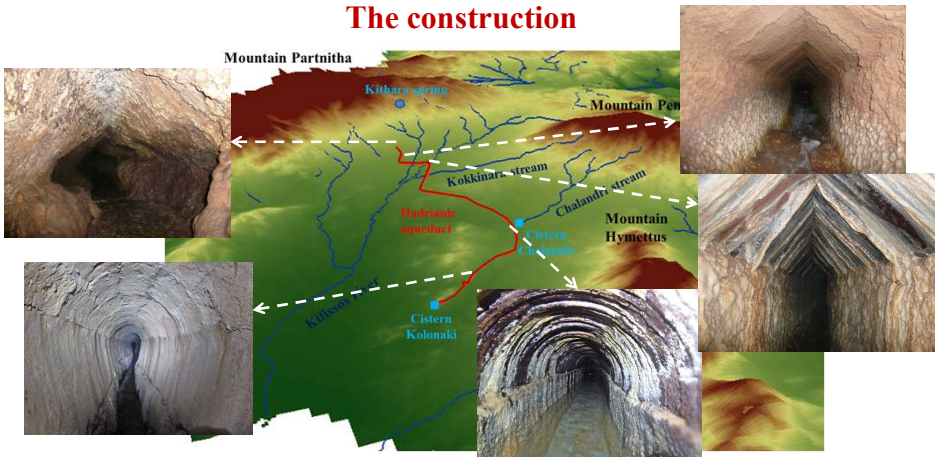
The tunnel was constructed using the technique of successive wells, which were dug every **40 m** on average. The minimum distance is 35-37 m but in many areas the distance is much longer (eg when crossing streams). Today **367 wells** have been registered and it is probable that many of the ancient initial wells were abolished by the Romans.



The construction



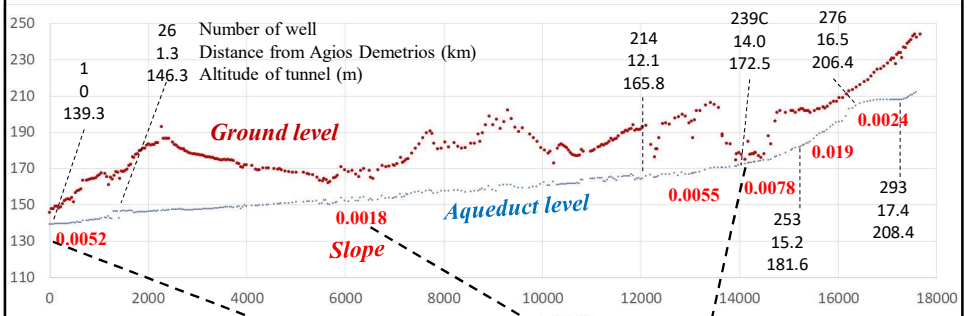
The construction

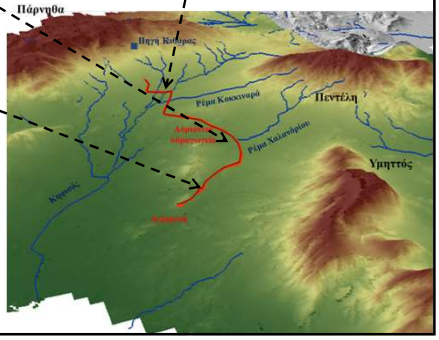


- The carved underground tunnel (coated or uncoated) has an average section of **0.50 m wide and 1.20 m high**; however, the height can locally reach 2 m or even more.
- Artificial roof support consists usually of prefabricated terracotta pieces, either of orthogonal plates or of curved bricks. Some impressive construction details are (a) collecting water from the walls, the mounting of the roof, and (b) the flow rate control through local level depression or small shaft incurvation.

The construction

Profile of the aqueduct from Olympic village to Agios Demetrios



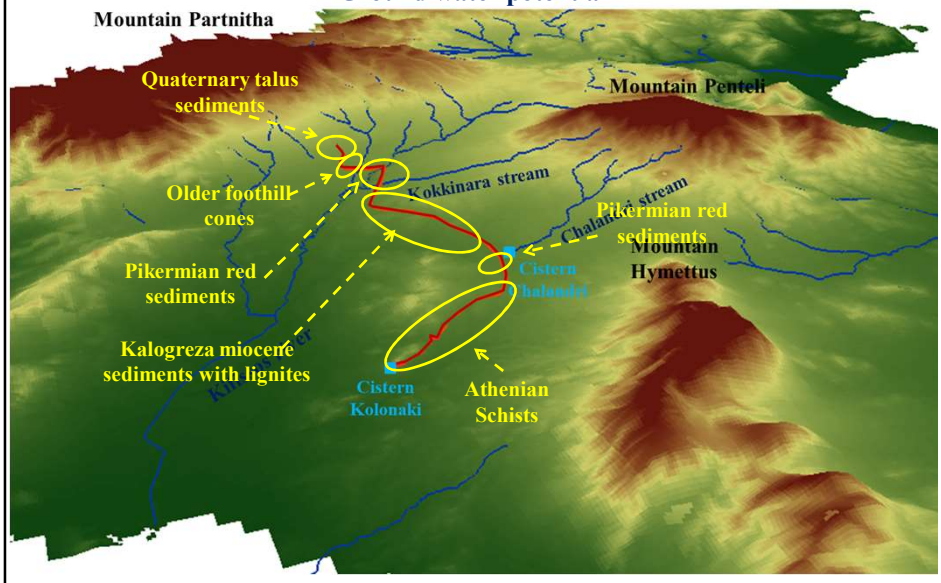


It is noted that 316 wells are depicted along the tunnel in older sections, with the following depths:

- 21 wells (6.7%) are shallower than 10 m,
- 118 (37.3%) range between 10 m and 20 m,
- 113 (35.8%) between 20 m and 30 m, and
- 64 wells (20.2%) are deeper than 30 m, with the deepest one being **41.4 m**.

Water recourses

Ground water potential

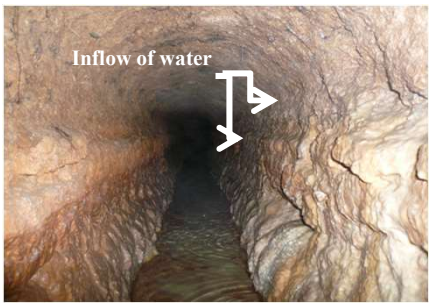


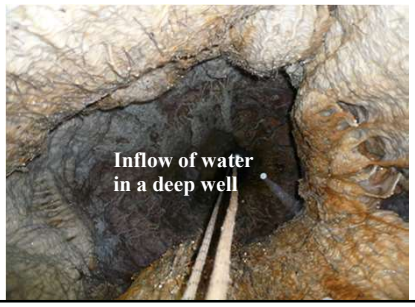
- ***Chiotis, E.D. and Chioti, L.E. 2012.*** Water supply of Athens in antiquity. In *Evolution of Water Supply Through the Millennia*, eds. A.N. Angelakis, L.W. Mays, D. Koutsoyiannis, and N. Mamassis, IWA Publishing, London, pp. 407–442.
- ***Chiotis, E.D. and Marinos, P.G. 2012.*** Geological aspects on the sustainability of ancient aqueducts of Athens, Bulletin of the Geological Society of Greece, 46:16–38, http://www.geosociety.gr/images/news_files/EGE_XLVI/2_CHIOTIS_p16-38.pdf.

Water recourses

Ground water potential

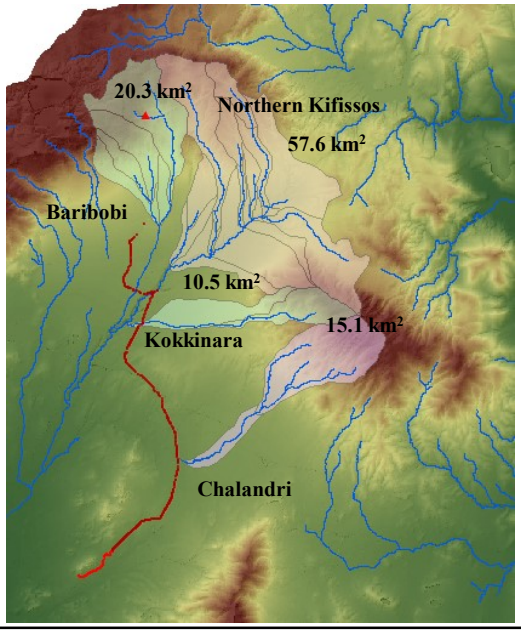
The continuous infiltration of groundwater flowing from the wells and the tunnel walls is presently obvious.
It is locally associated with incrustation of calcite, particularly in the roofed sections of loose sediments.





Water recourses

Water basins potential



Initial gross estimations

Basin	Surface Water (hm^3/y)	Ground Water (hm^3/y)
Baribobi	1.8-2	0.8-2
N. Kifissos	5.1-5.8	2.2-6.2
Kokkinaras	0.9-1.1	0.4-1.1
Chalandri	1.4-1.5	0.6-1.6

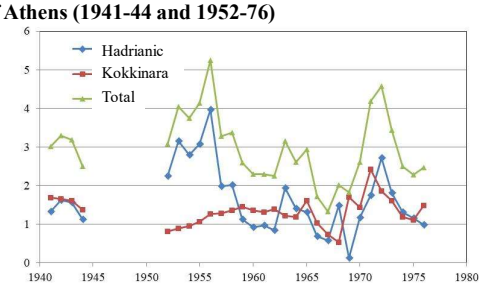
More detailed modelling is needed

Water recourses

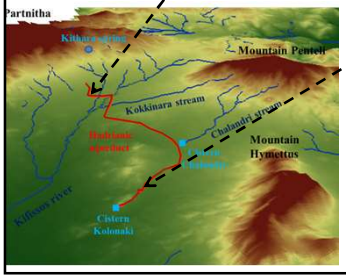
Measurements and estimations of the water potential

Annual withdrawals (hm^3) from Hadrianic and Kokkinara aqueducts for water supply of Athens (1941-44 and 1952-76)

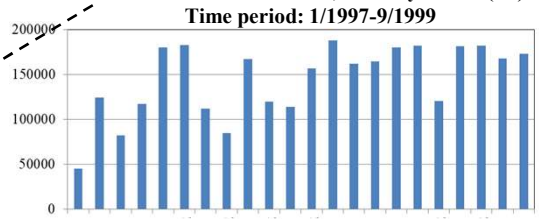
Mean annual discharge of Hadrianic:
1.6 hm^3/y - **4470 m^3/d** - 186 m^3/hr - 52 l/s
Maximum annual discharge of Hadrianic:
4.0 hm^3/y -**10890 m^3/d** - 453 m^3/hr-126 l/s
Maximum annual discharge of both aqueducts:
5.2 hm^3/y - **14379 m^3/d** -599 m^3/hr - 166 l/s



The discharge at well 275 was measured 86 l/s-7440 m^3/d (11/2013)



Measurements in well 18^A, monthly values (m^3)
Time period: 1/1997-9/1999

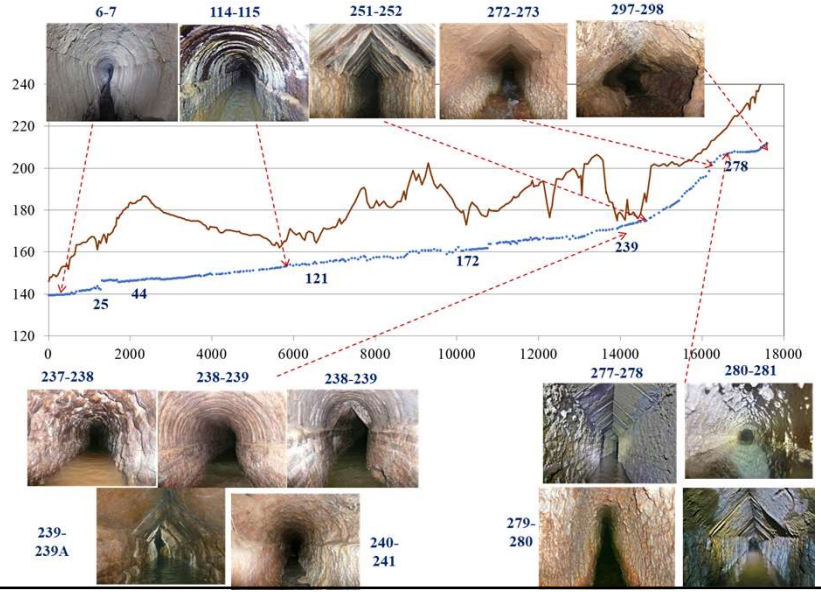


Mean daily discharge: **4733 m^3/d** - 55 l/s
Estimated annual water volume: 1.7 hm3

Water management

Transportation-velocities

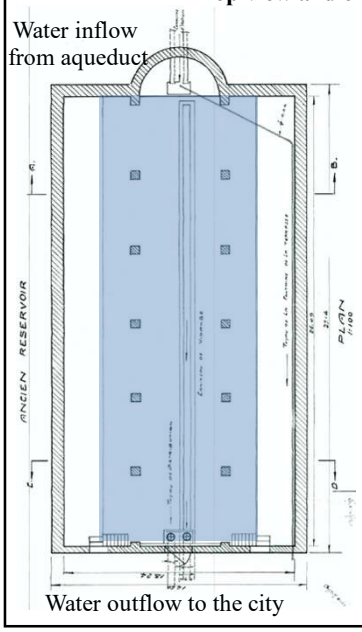
According to hydraulic analysis the water needed **8-9 hours** (depending on the discharge) to be transported from the start of the tunnel to Kolonaki reservoir

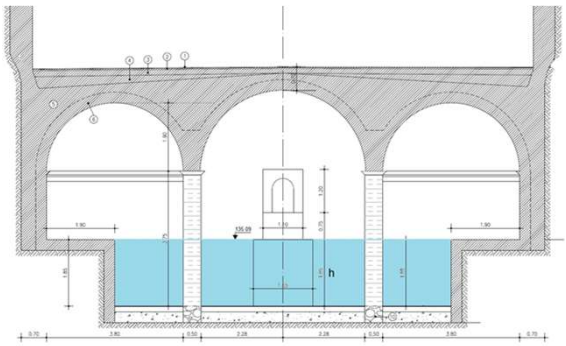


Water management

Hadrianic reservoir at Kolonaki

Top view and cross section of reconstructed reservoir





Source of drawings : ULEN, 1934

Capacity of reconstructed reservoir**:**
26.09 m*9.36 m*1,85 m=452 m^3

Water management

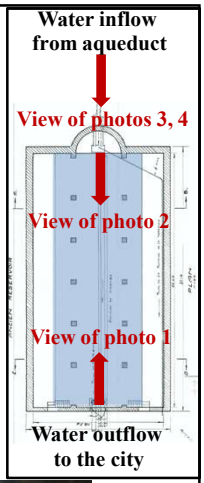
Hadrianic reservoir at Kolonaki

Photo 1

Photo 3

Photo 2

Photo 4



Water management

Hadrianic reservoir at Kolonaki

Capacity of reconstructed reservoir	**26.09 m*9.36 m*1,85 m=452 m^3**	**ULEN drawings, 1934**
	26.20 m*9,35 m*1.9 m=465 m^3	**Leigh, 1998**
Capacity of ancient reservoir	24.5 m*10.1 m*1.8 m=445 m^3	**Labegue, 1871**

Capacity of water pipes that fed the city

- Outflow of water using a lead pipe with diameter = 0.18 m (Leigh, 1998- Ziller, 1877)
- Different opinion: Kordelas, 1879: Two elliptical pipes with unknown diameter

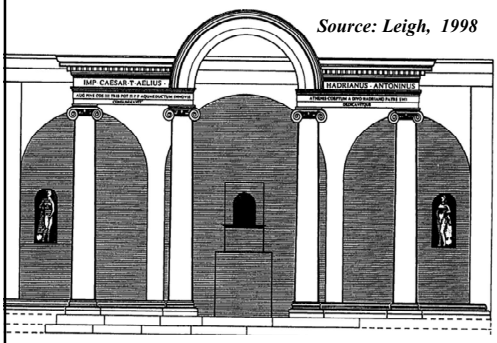
Area of circular pipe (d = 0.18 m): $A = \pi d^2/4 = 0.025$ m^2
Estimation of one circular pipes discharge:
$Q' = \mu (2 g h)^{0.5} A =$ **0.105 m^3/s** (μ=0.7).
It is equivalent to 9070 m^3/d

Area of elliptical pipe (α = 0.18 m και β= 0.12 m): $A = \pi \alpha \beta/4 = 0.017$ m^2
Estimation of two elliptical pipes discharge:
$Q' = \mu (2 g h)^{0.5} A =$ **0.14 m^3/s** (μ=0.7).
It is equivalent to 12100 m^3/d

Water management

Hadrianic reservoir at Kolonaki

Entrance of ancient reservoir

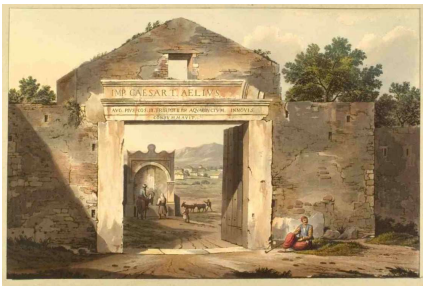


Source: Leigh, 1998

Fragment of the inscription is located to National Garden of Athens

The inscription

IMP CAESAR T AELIVS (HADRIANVS ANTONINVS)
AVG PIVS COS III TRIB POT II PP AQVAEDVCTVM IN NOVIS
(ATHENIS COEPTVM A DIVO HADRIANO PATRE SVO)
CONSVMMAVIT (DEDICAVITQVE)



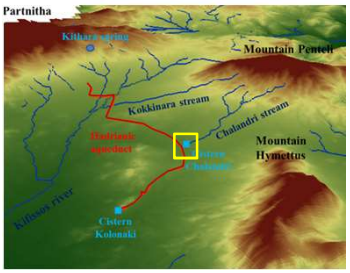
Fragment of the inscription was used in the eastern gate of Athens that was constructed during 18th century by the Ottomans, (water color painting by E. Dodwell)

Water management

Chalandri cistern

Chalandri stream transported surface and spring waters from Pendeli mountains to enrich Hadrianic aqueduct. A small aqueduct collects Chalandri waters and feeds a small cistern that is a desilter. From cistern a small tunnel leads the overflowed water to well 102 and to Hadrianic aqueduct that at this point passes 12 m below the stream.

Diameter 2.5 m, Depth: 2 m, Volume 12 m³



Water inflow from Chalandri stream

Water outflow to Hadrianic aqueduct (Well 102)

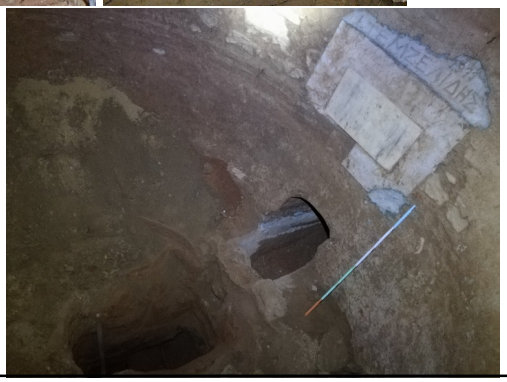
Water overflow to Hadrianic aqueduct (Well 102)

Water management

Chalandri cistern

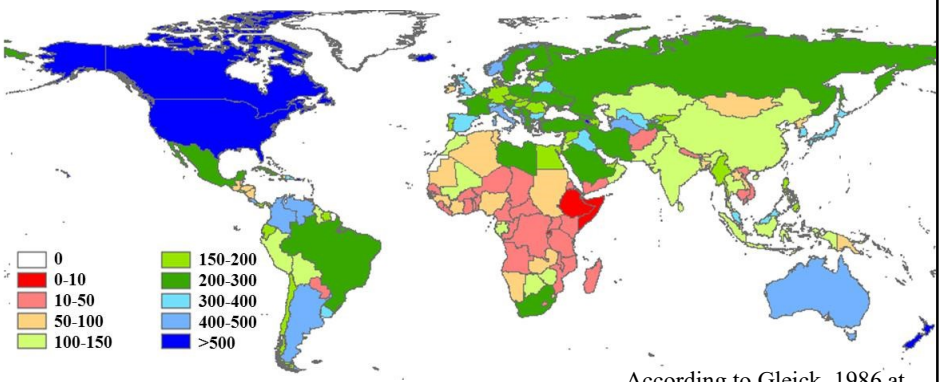
Exploration of tunnels

Excavation of cistern



Water consumption

Domestic use in year 2010 (liters per capita per day)



At the beginning of 21th century the quantity of **20 l/c/d** for domestic hygiene purposes from a source located within **1 km** of a person's dwelling is considered as the **minimum amount of water that a person can survive** (WHO /UNICEF, 2000). This requirement was fulfilled for the **82%** of the global population in year **2000**.

According to Gleick, 1986 at least **50 l/c/d** are required to meet human needs, namely:
5 l/c/d for drinking,
10 l/c/d for food preparation,
15 l/c/d for bathing and
20 l/c/d for sanitation

In the **contemporary city of Athens** the domestic water consumption is about **300 l/c/d** a quantity that include losses

Water consumption

Water needs in Ancient world

According to Mays et al., 2012, the water consumption in ancient communities that had no direct access to water resource was estimated to **10-20 l/cap/d** and especially for the city of Jerusalem in 1000 BC was estimated to **20 l/cap/d**

A ***minimum requirement of 40 l/d per household*** results from the legislation of Solon, in the beginning of the 6th century BC (Koutsoyiannis and Mamassis, 2018).

"*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,*

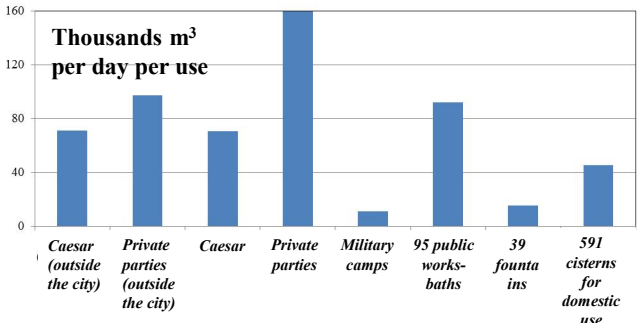
- *where there was a public well within a hippicon, that is, four stadia [710 m], all should use that;*
- *but when it was farther off, they should try and procure water of their own;*
- *and if they had dug ten fathoms [18.3 m] deep and could find no water, they had liberty to fetch a hydria (pitcher) 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."

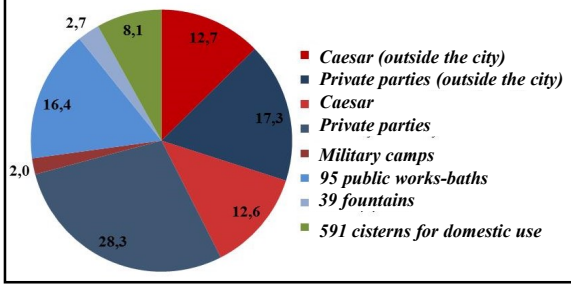
Source: Plutarch, Solon, 23. Translation by John Dryden (http://classics.mit.edu/Plutarch/solon.html) after adaptation.

Water consumption

Estimation of water consumption in Ancient Rome



Percentage per use



- Total water consumption was estimated to *14,018 quinariae* ***(about 550,000 m3)*** per day.
- 25% used by Caesar and 45% to upper class residences. With these quantities, hundreds of thousands of slaves were also fed.
- The 591 middle- and lower-class water cisterns served approximately 900 residents each, a **population of 530,000.** So domestic consumption in these neighborhoods is estimated **to 85 l/cap/d.**
- In addition, they also had access to public water consumption (baths, fountains, battleships) which corresponds to **another 200 l/cap/d**

Sextus Iulius Frontinus, *De Aquaeductu Urbis Romae*, On the water management of the city of Rome. Translated by R. H. Rodgers, The University of Vermont

Water consumption

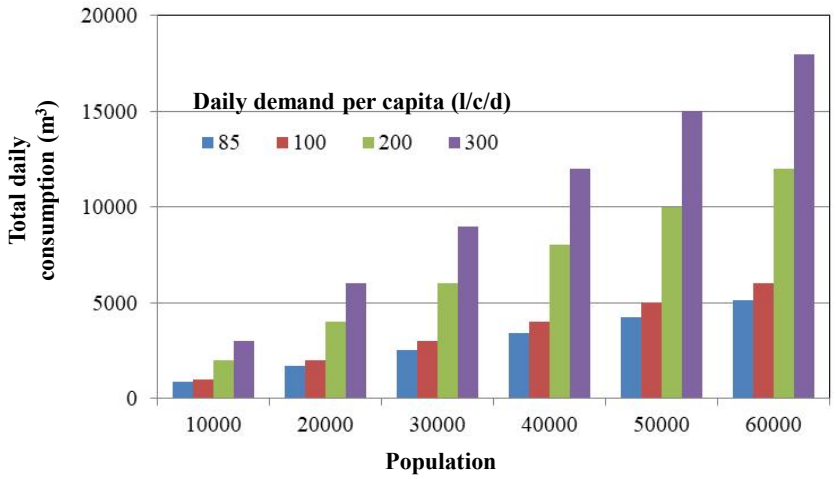
Estimation of population

Several estimations can be found in the literature, that relate the area of the city with population in **persons per hectare**. Indicative are:

- Ancient Mesopotamia ***300-500 p/ha*** (Frankfort, 1950);
- Alexandria ***326 p/ha***, Diodorus Siculus (17.52.6);
- Pompey ***100-150 p/ha***
- European cities 14-19^{ου} century ***100-500 p/ha***, Mols, 1955;
- Medieval Europe ***100-200 p/ha***, Russell, 1958;
- According to Hippodameian system in Piraeus a block of 8 residences in Hellenistic period with total 40 dwellers has an area of 0.2 ha. That gives a population density of ***200 p/ha.***

Water consumption

Total daily water consumption (m^3) for various scenarios of population and daily demand per capita



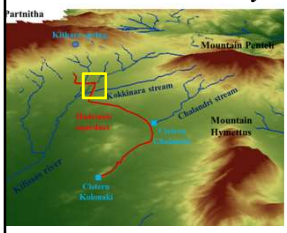
The water recourses are sufficient to cover water consumption even in scenarios with high values of population and water demand

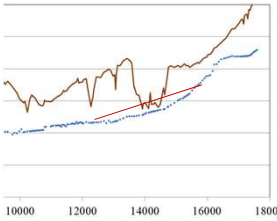
Specific issues

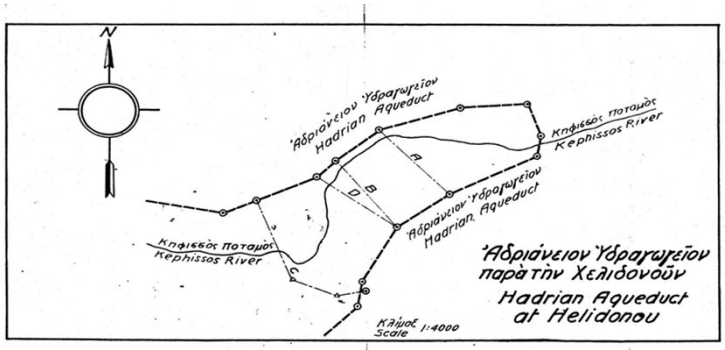
Kifissos passage

The tunnel pass successfully below Kifissos River and other streams

Why Romans didn't construct water bridges?







Specific issues

Did Romans follow the Greek way?

Peisistratean versus Hadrianic

Peisistratean
Construction period: 6th-4th century BC
Draining tunnel
Fed also from Hymettus springs and lateral aqueducts
Length: 8 km
Maximum depth: 14 m
Sustainable operation (irrigation of National Garden 1875-present)

Hadrianic
Construction period: 2th century AD
Draining tunnel
Fed also from Parnitha springs and lateral aqueducts
Length: 20 km
Maximum depth: 41 m
Sustainable operation (Modern Athens water supply 1870-1976)

Specific issues

Did Romans follow the Greek way?

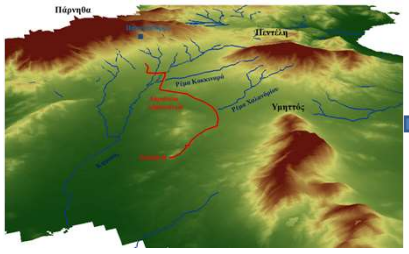
Peisistratean versus Hadrianic

Synopsis

Water recourses
More than 10.000 m³/d

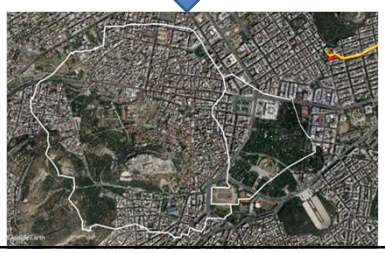
Operational figures

Reservoir capacity
450 m³



*The limited reservoir capacity (could store the inflows of **1-2 hours**) proves that it was regulatory (**Castellum divisorium**). The hydraulic operation of the system was similar to that of a spring that has been "transferred" to Lycabettus hill*

Capacity of pipe that transferred the water to the city: 9.000-12.000 m³/d



Water consumption of the city
5.000-10.000 m³/d

Synopsis

Issues that must be emphasized

- The contribution of the aqueduct to the city of Athens is **diachronic** and reflects a timeless value of the ancient hydraulic works. Exploiting the technology and materials of its age, it was used as the main source of Athens' water supply, about1800 years after its construction.
- Ancient Greek hydraulic constructions were mostly **underground** in contrast to later Roman ones. In case of Hadrianic **Roman engineers exploited the local experience.** Ancient subterranean hydraulic works all over the world are characterized by **endurance and sustainability**, as be preserved better and in many cases have a long-term operation. In contrast surface aqueducts of the same age have been already destroyed.
- At the time of its construction, the Hadrianic Aqueduct was capable of delivering water quantities that today meet the water needs **of a modern city of about 50.000 inhabitants**. The reservoir was able to store the inflow of only 1-2 hours, so the water probably was stored in the city's smaller cisterns and numerous baths, or ran abundantly in Nymphaea. Consequently, the operation of the hydrosystem skyrocketed the **living standards** in Roman Athens.
- Today the water of the aqueduct is equivalent to about **1% of the water demand** of modern city of Athens. Although the exploitation of water is not a priority for the water supply company, the insistence of the aqueduct to carry water proves the **sustainability** of the structure.
- The enhancement and promotion of Hadrianic hydrosystem is an **obligation** of the modern city of Athens and a **tribute** to ancient Greco-Roman water technology

Enhancement and Promotion

Cooperation of several stakeholders

Today Hadrian's aqueduct is **concurrently**

- an ancient monument,
- a withdrawn (but still available) water resource and
- a resilient and sustainable large-scale hydraulic system, that it worth to be studied for educational and research purposes.

During the last period, several actions were done to exhibit this unique hydraulic work to experts and to the public. Among them, the systematic exploration of the aqueduct, the web database development and the hydrological - hydraulic simulation of the hydrosystem, must be mentioned. For these actions, an interdisciplinary cooperation was established among the following stakeholders:

- The Water Supply and Sewage Company of Athens EYDAP SA
- three Ephorates of Antiquities (West Attica, East Attica and City of Athens)
- the National Technical University of Athens.

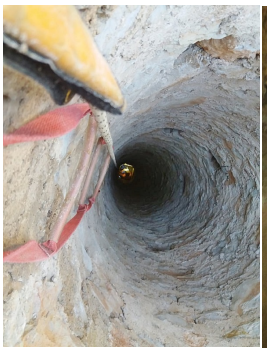
The next steps that have been scheduled include the:

- restoration and maintenance works in specific parts of the aqueduct,
- exploitation of water for public use and
- promotion of the project and providing accessibility to specific sites of the tunnel.

Enhancement and Promotion

Exploration of the aqueduct

The underground explorations are carried out from members of "**Urban Speleology** research team". They have been trained in the Training Programs of **Hellenic Speleological Society (ESE)** and follow all required security measures, methods and equipment.

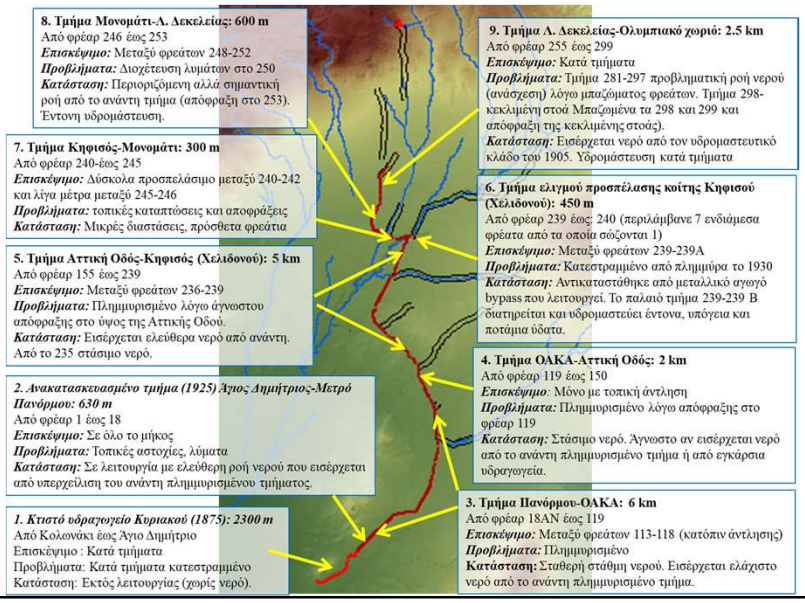


The visitor of the tunnel comes into direct contact with the project and the method of its construction.

Enhancement and Promotion

Inspection of the aqueduct

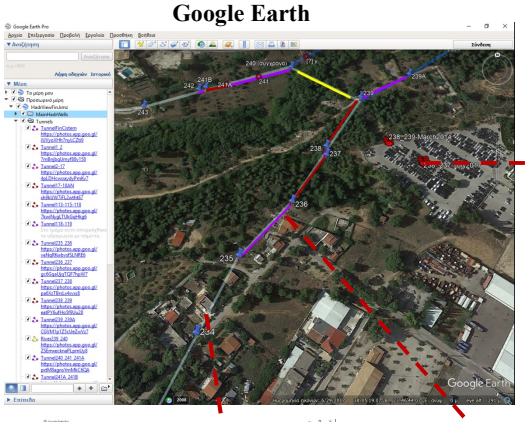
There are several damages in the aqueduct



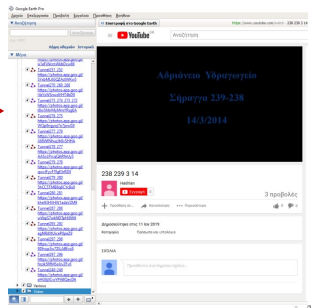
Enhancement and Promotion

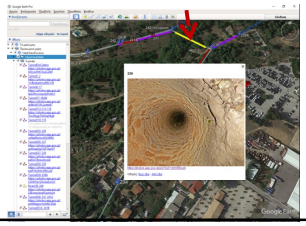
Web data base https://www.itia.ntua.gr/en/docinfo/1934/

Google Earth

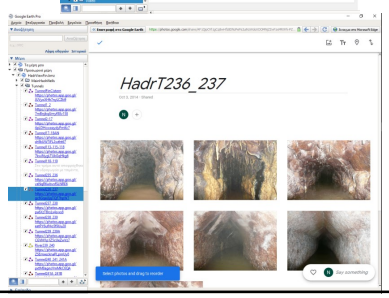


YouTube





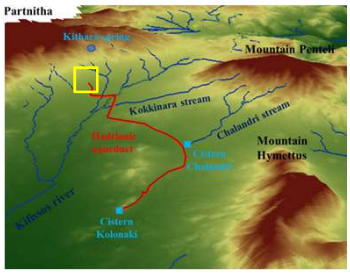
Google Photos



Enhancement and Promotion

Restoration and maintenance works

Olympic village area –inclined gallery



- Restoration of tunnel entrance and inclined gallery
- Protection of tunnel entrance from floods and sediments
- Installation of lighting and instrument for air quality measurements

Enhancement and Promotion

Restoration and maintenance works

Inclined gallery

Enhancement and Promotion

An interested community where cross-disciplinary collaboration works

EYDAP
Hellenic Culture
HELLENIC REPUBLIC
Ministry of Education
Research and Religious Affairs
Δήμος Μεταμόρφωσης
Δήμος Φιλοθέης-Ψυχικού
ΝΕΑ ΓΕΝΙΑ ΤΟΥ ΟΛΥΜΠΙΑΚΟΥ ΧΩΡΙΟΥ
PennDesign
National and Kapodistrian UNIVERSITY OF ATHENS
UNIVERSITY OF PATRAS
ARISTOTLE UNIVERSITY OF THESSALONIKI
HELLENIC OPEN UNIVERSITY
SWEDISH INSTITUTE at ATHENS
THE AMERICAN SCHOOL OF CLASSICAL STUDIES AT ATHENS
EUROPA NOSTRA
St GEORGE
ΔΟΤΥ

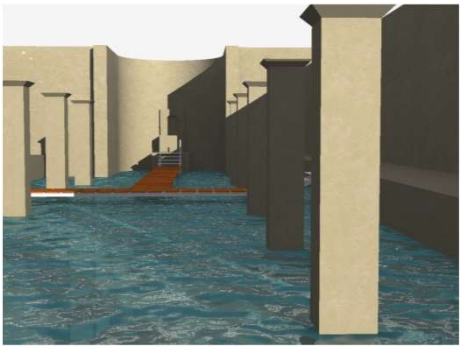
Enhancement and Promotion

Proposal for 14 Hadrian's Aqueduct Visit Sites

10 of them will have a green zone. A bike route along the aqueduct connects them.

Enhancement and Promotion

Existing situation and future plans for the entrance to the reservoir in Kolonaki



Enhancement and Promotion

Existing situation and future plans of the open reservoir in Kolonaki

Enhancement and Promotion

Example of Water Use Plan in Panormou Metro Station

May-June: 35 m^3 per day

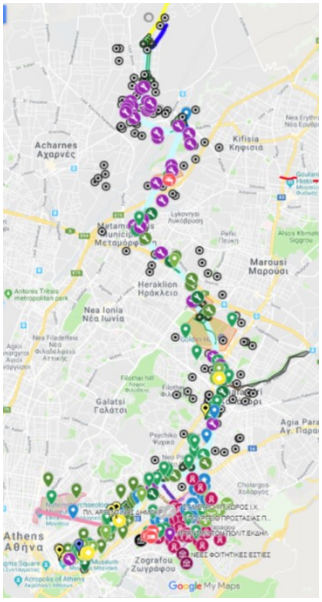
October-April: 10 m^3 per day

Enhancement and Promotion

Water and Cultural Capital for the plans of Chalandri Municipality

Enhancement and Promotion

Creating a Water Management Plan-
Supporting awareness about water use of the Hadrianic

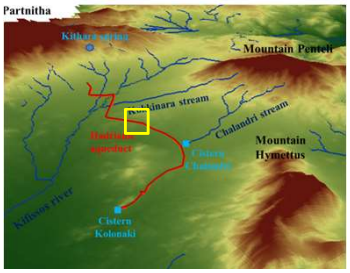


Athens is affected more by climate change than most other European capitals. It has had to deal with alternating periods of extreme drought and heavy rain. While looking for nature based solutions, city leaders came up with some interesting ideas.

Enhancement and Promotion

Using the water

Pump station in Metamorfosis (close to well 175)



Well 175

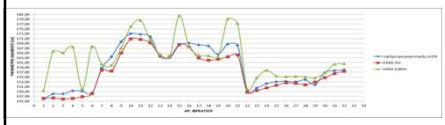
Pump station

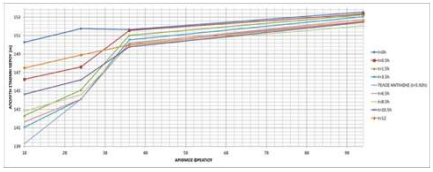
60.000 m^3 of water per year are pumped for irrigation of municipal green areas

Enhancement and Promotion

Scientific research

Well depth and flow analysis in collaboration with students





Research project

https://www.itia.ntua.gr/en/project_reports/197/

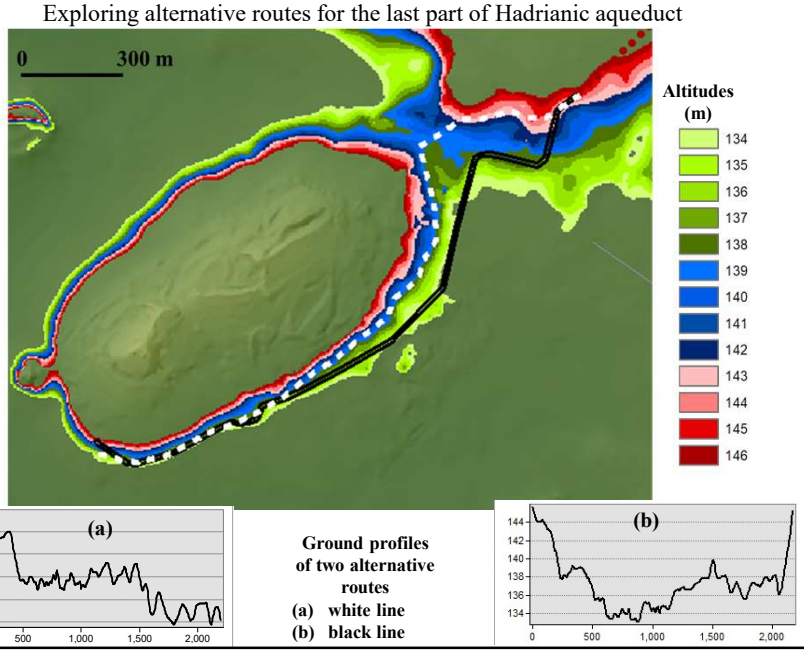
Diploma theses in NTUA

- P.-N. Stefanou, Hydrological research of Hadrianic Aqueduct, Diploma thesis, Department of Water Resources and Environmental Engineering – National Technical University of Athens, March 2019.
- C. Tsiouri, Hydraulic investigation of Hadrian aqueduct, Diploma thesis, 260 pages, Department of Water Resources and Environmental Engineering – National Technical University of Athens, October 2018.

Enhancement and Promotion

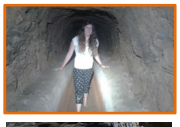
Scientific research

Exploring alternative routes for the last part of Hadrianic aqueduct



Ground profiles of two alternative routes
(a) white line
(b) black line

Acknowledgments



It would be impossible to do this research without the assistance of several people. Each one contributed in his own way.
Their common characteristic was their curiosity for such a nearby but unknown hydraulic work and their interest for one of the most important monuments of ancient technology and our cultural heritage.
These people create a vivid network that could offer a lot in the future.