# Water technology and management in Ancient Greece: Legacies and lessons

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Lecture notes

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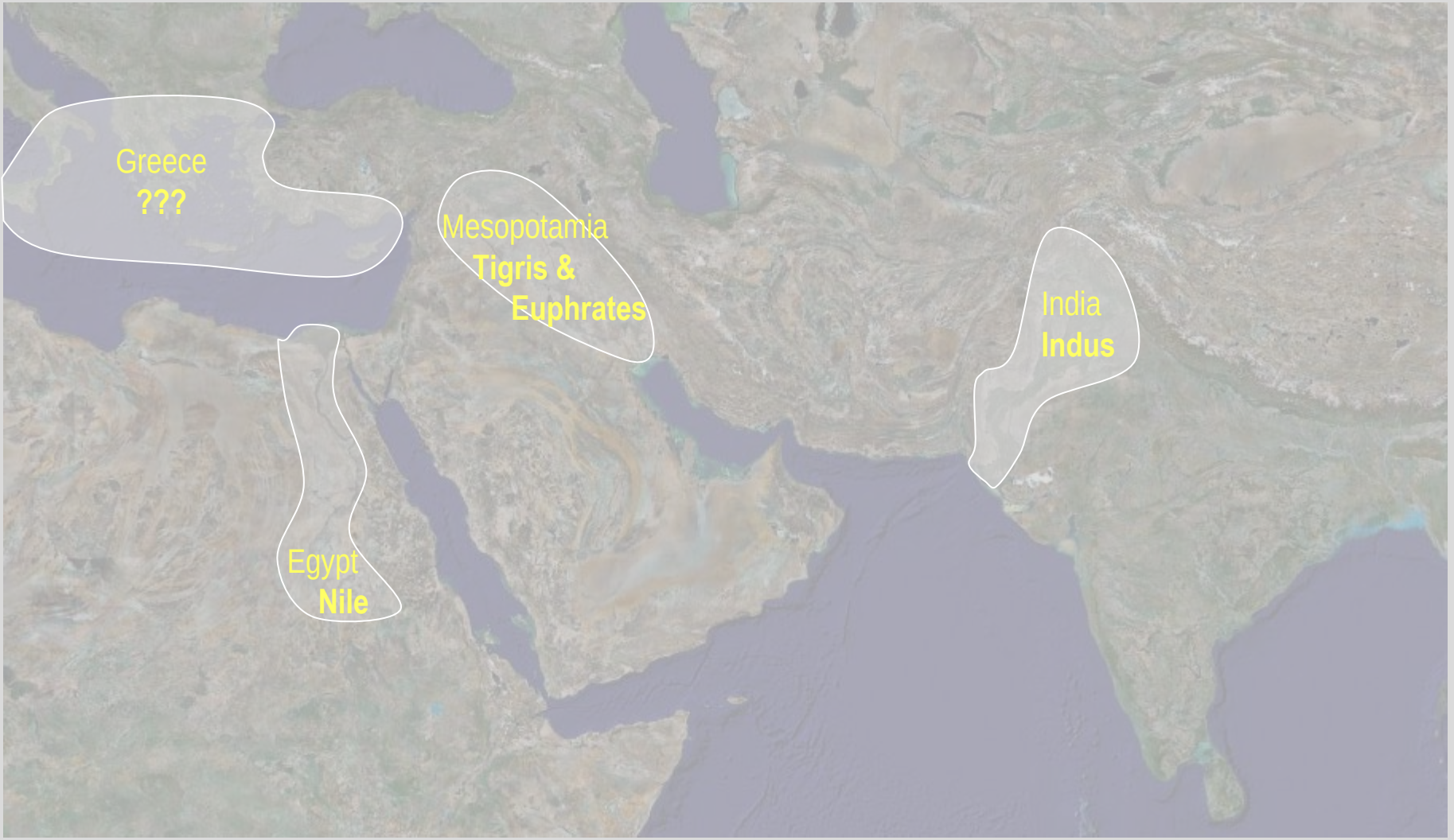
# Ancient civilizations that preceded Greek civilization




- Earlier civilizations flourished in large river valleys (water abundance)
- Greece does not have large rivers (water scarcity)

# Climate and the Greek civilization

- Why ancient Greeks chose the driest places for their cities?

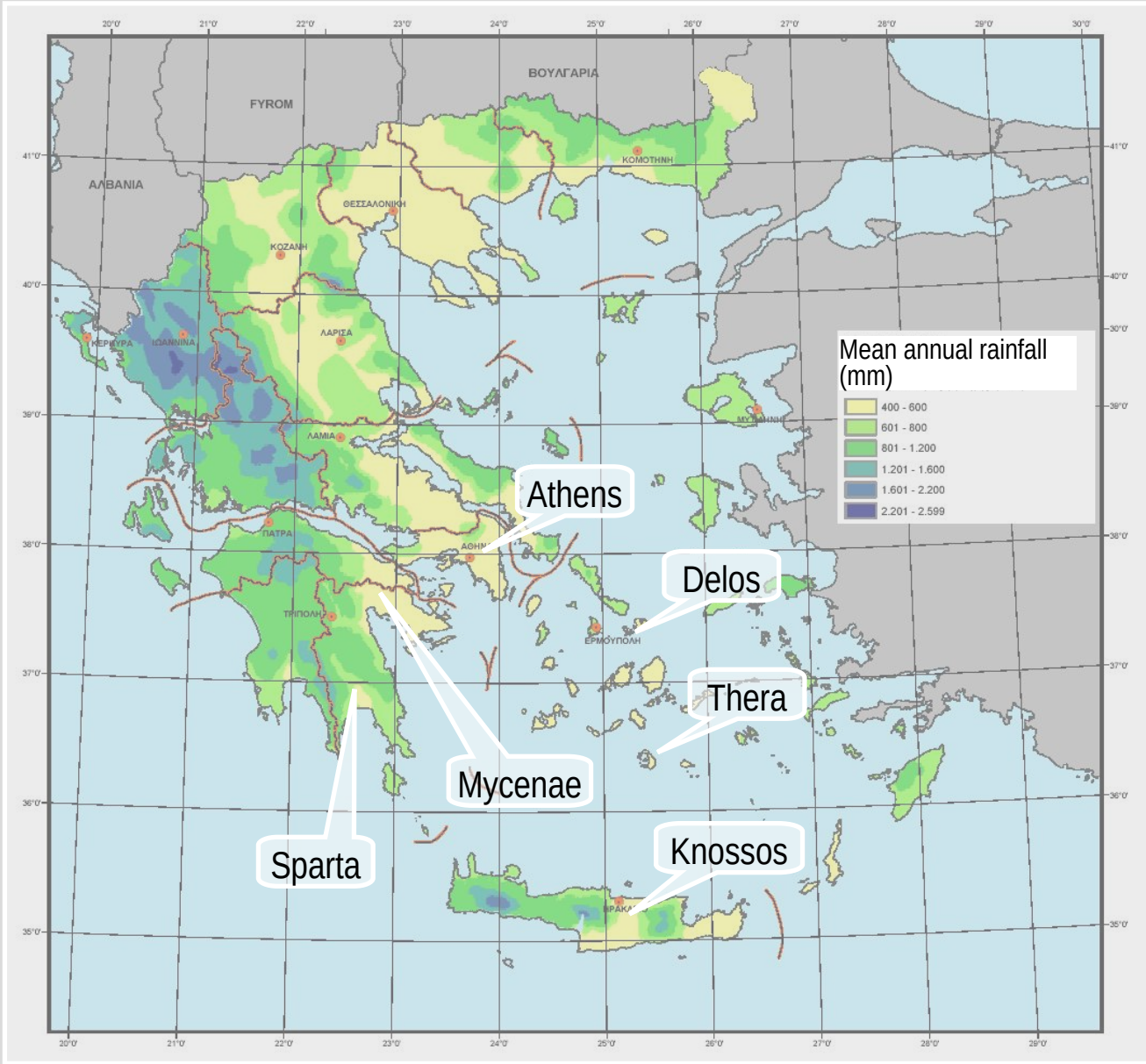
Or

- Why the settlements on driest places were the most flourishing?

  (Life in dry climate is more convenient and healthier?)

- What are the consequences/impacts of water scarcity on cultural progress?

  (Can scarcity trigger progress in technology and management?)



# Is abundance a paradise?

Adam and Eve used to have a good time in Paradise (Eden), a place with abundance of everything – including **water**

However, they were expelled from this nice place as a punishment because Eve could not resist to the goods of the **knowledge** tree

Pictures by the artist Tommy Christopher Canning, http://www.art-of-divinemercy.co.uk/Creatio.htm

# Water scarcity and the myth of the competition of Athena and Poseidon

- To choose their patron god, Athenians organized a competition for two candidates: Athena (goddess of wisdom) and Poseidon (god of waters).
- Poseidon offered abundant spring water.
- Athena offered the olive tree and an explanation why it would be wiser to choose her gift.
- Athenians opted for wisdom.

- Scarcity may not be a punishment (as in the biblical story) – but a choice
- Wisdom may be more powerful than abundance

**What is paradise?**

**Abundance (no effort required)**

**Or**

**Scarcity (triggering knowledge/wisdom and progress)**

# The Minoan civilization and its "modern" sanitary life style
# A note on history of Minoan civilization

- Located in Crete island
- First cultural achievements since *ca*. 3000 BC
- Progressed especially in the Middle Bronze Age (*ca*. 2100-1600 BC)
- Prospered even more in the early phases of the Late Bronze Age (*ca.* 1600-1400 BC)
- Mostly known from large houses and luxurious palaces (e.g. Knossos, discovered by Evans, Zakros, Mallia, Gortys, Phaestos)
- Halted at about 1450 BC (reasons not known – only hypothesized)

# The Minoan civilization and its “modern” sanitary life style – Water resources development

- Groundwater exploitation (Knossos, Zakros, Palekastro)
  - Springs combined with aqueducts and/or cisterns
  - Wells
- Rainwater collection (Phaestos, Chamaizi)
  - Cisterns

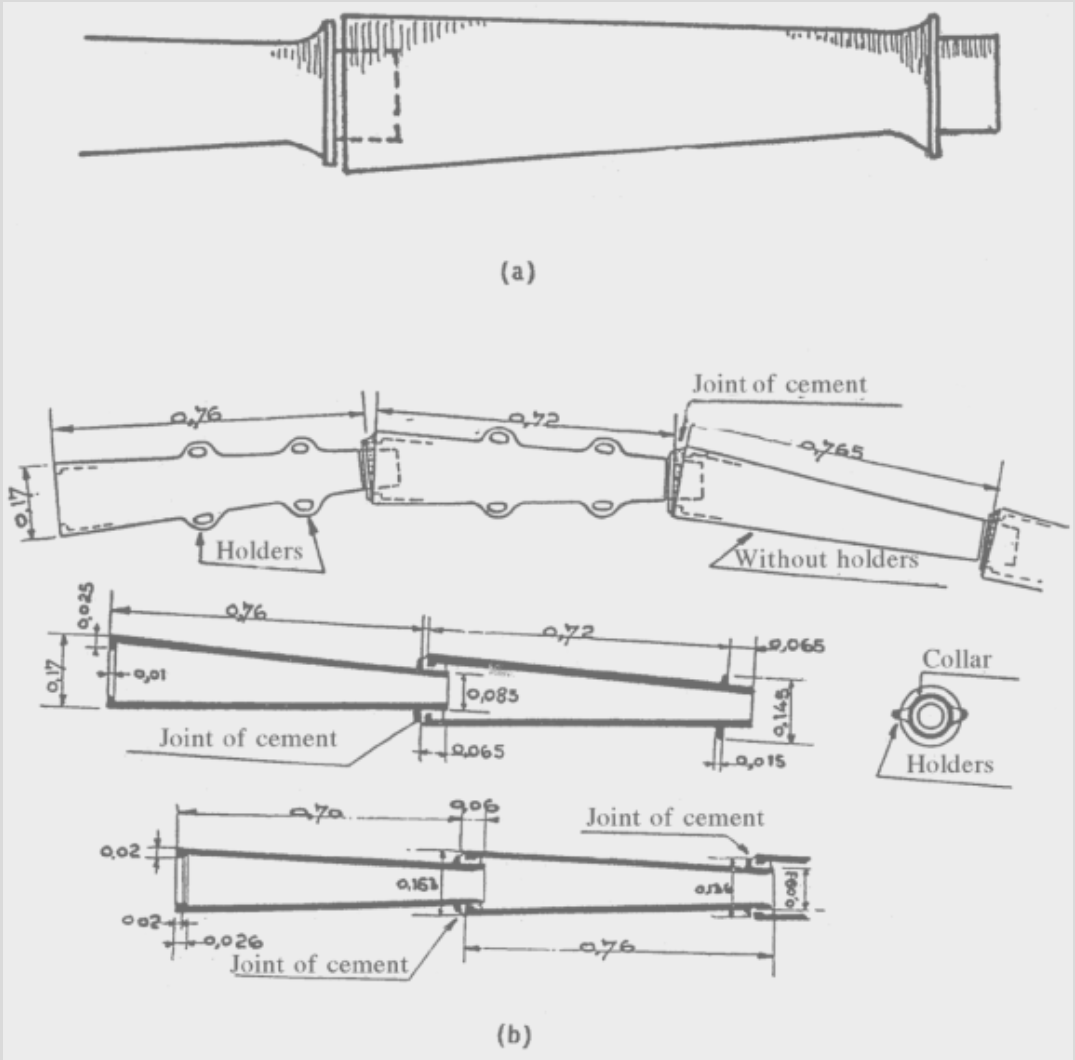
Well used for water supply at Palekastro

Cistern at the pre-palatial house complex in the vicinity of the village Chamaizi, near the town of Sitia dated in the turn from the 3rd to the 2nd millennium BC

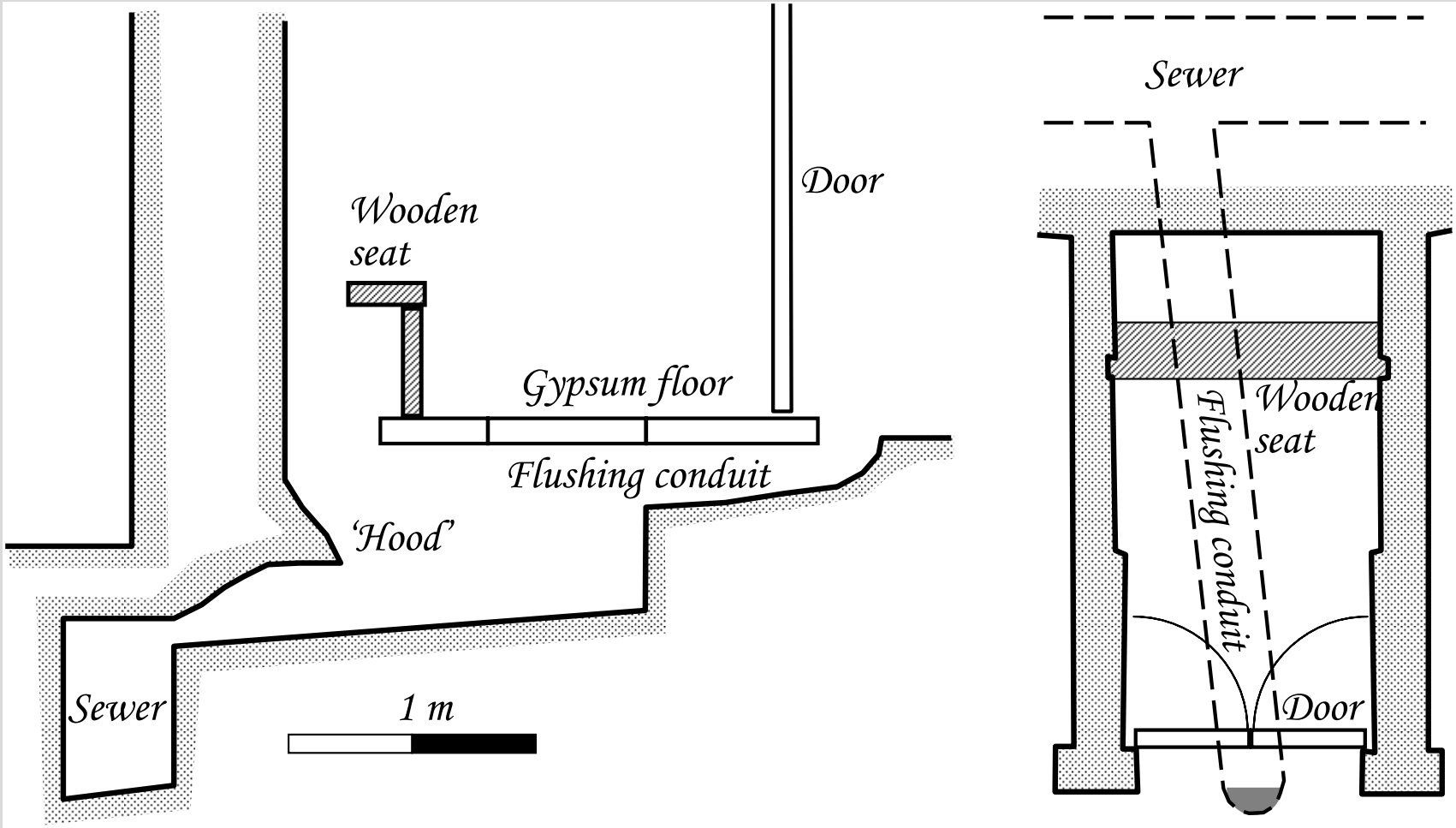
# Minoan water supply systems

In the Knossos Palace, water was conveyed from springs at distances 700 m – 5 km using terracota pipes

Terracotta pipe sections (Buffet and Evrard, 1950)



# Minoan toilets




Section and plan of ground-floor toilet in the residential quarter of Palace of Minos

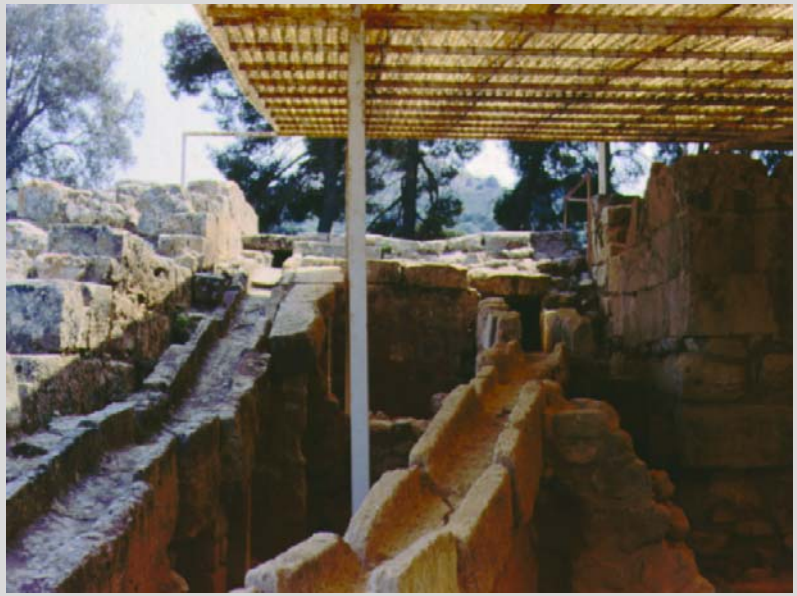
# Minoan sanitary and storm sewers

Part of restored stairway with parabolic runnels in Knossos Palace

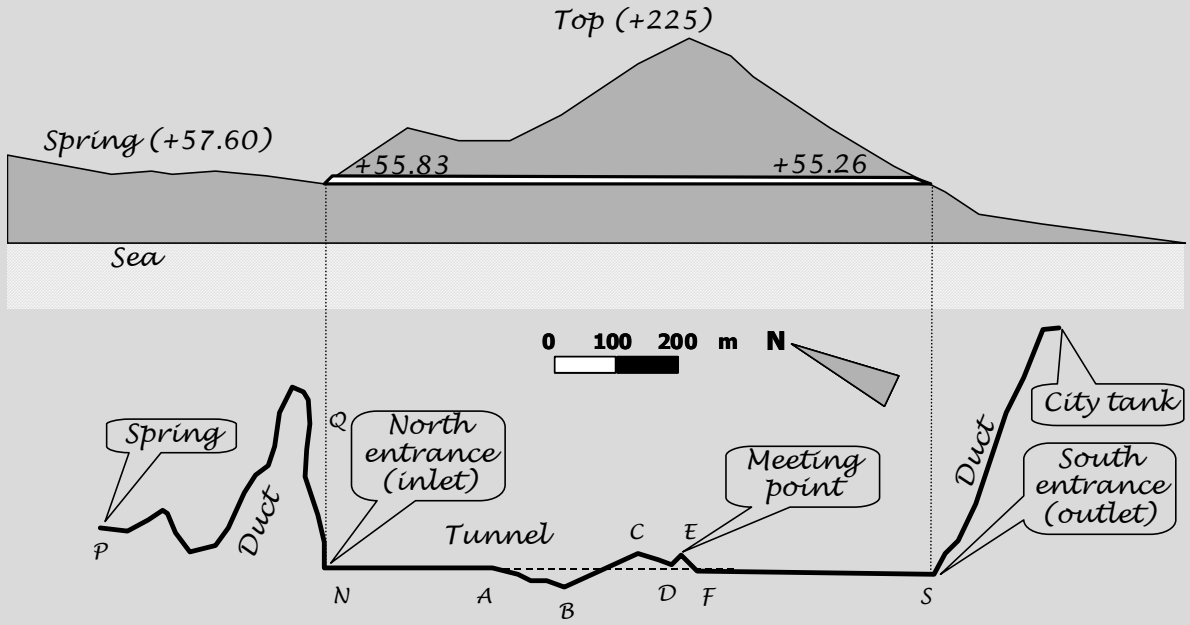
*One day, after a heavy downpour of rain, I was interested to find that all the drains [of the Villa Hagia Triada] acted perfectly, and I saw the water flow from the sewers through which a man could walk upright. I doubt if there is any other instance of a drainage system acting after 4000 years.*

Angelo Mosso from his visit in Aghia Triada (Escursioni nel Mediterraneo e gli scavi di Creta, Treves, Milano, 1907)

Parts of the sanitary and storm sewer systems in Agia Triadha



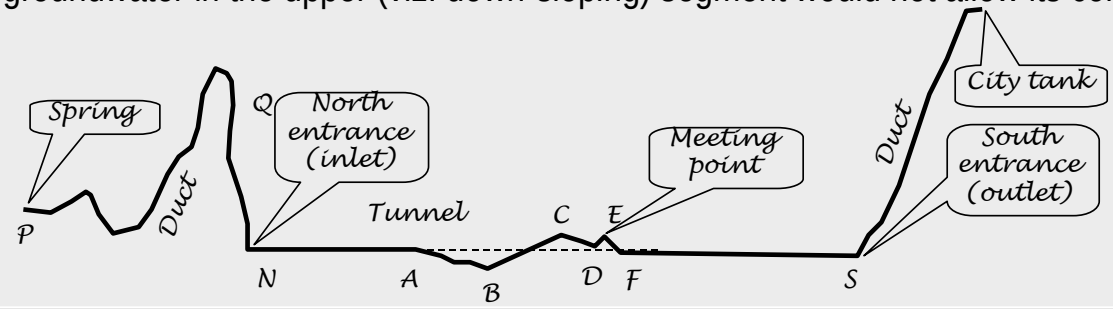
# The water supply of Samos and the awesome feat of Eupalinos



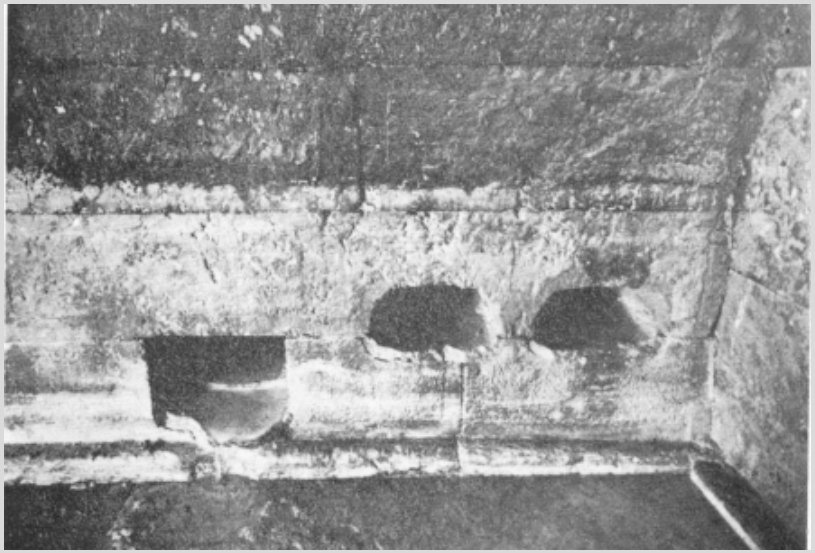

The most famous hydraulic work of ancient Greece was the aqueduct of ancient Samos, which was admired both in antiquity (e.g. Herodotus) and in modern times. The most amazing part of the aqueduct is the 1036 m long, dug from two openings, «Εὐπαλίνειον ὄρυγμα», or “Eupaninean digging”, after Eupalinos, an engineer from Megara. Its construction started in 530 BC, during the tyranny of Polycrates and lasted for ten years. Owing to the text of Herodotus, Guerin (1856) uncovered the entrance of the aqueduct. Only ninety years later, between 1971 and 1973, the German Archaeological Institute of Athens uncovered the entire tunnel.

# What were the great achievements of Eupalinos?

1. He constructed the first known deep tunnel in history; shallow tunnels are much easier to construct (quanat technology).
2. As done in modern construction practice, he started from two openings (N and S). It is evident that the two construction lines met in point E.
3. To carve segments of the same straight line (NA and SF) from two points in a mountainous terrain, he must have had a good working knowledge of geometry and geodesy. There is evidence that Eupalinos solved the problem with simple means and in an accurate manner by walking over the mountain and putting poles up along the path in a straight line (a simple method used even today in engineering geodesy, but for simpler problems – not for the construction of tunnels). Then he lined up the workers in the tunnel segments with these poles.
4. Simultaneously, he showed that from an engineering point of view a straight line may not necessarily be the best path. Thus, at point A he left the straight line NA and followed the direction AB, a plausible explanation for this being that he found a natural fracture or rift and broadening this he was able to proceed much faster.
5. He found a clever geometrical way to eliminate the impact of uncertainty in position and direction (magnified due to already abandoning of the straight line route) and ensure the intersection of the two construction lines: By deliberately abandoning the straight line routes at points D and F and changing direction to the left and right, respectively, made it mathematically certain that the two lines would intersect.
6. He also found an especially clever engineering solution to account for the hydraulic principle that water needs a gradient to flow. In the horizontal tunnel he achieved the necessary gradient by excavating a slopping channel along one side of the floor; in places where due to slope the depth of the channel would be very high, a second small tunnel below the main tunnel was built. The choice of a horizontal main tunnel was dictated by the fact that a sloping one would be impossible to construct from two sides given the technological means of the time; note that the accumulation of groundwater in the upper (viz. down-sloping) segment would not allow its construction.



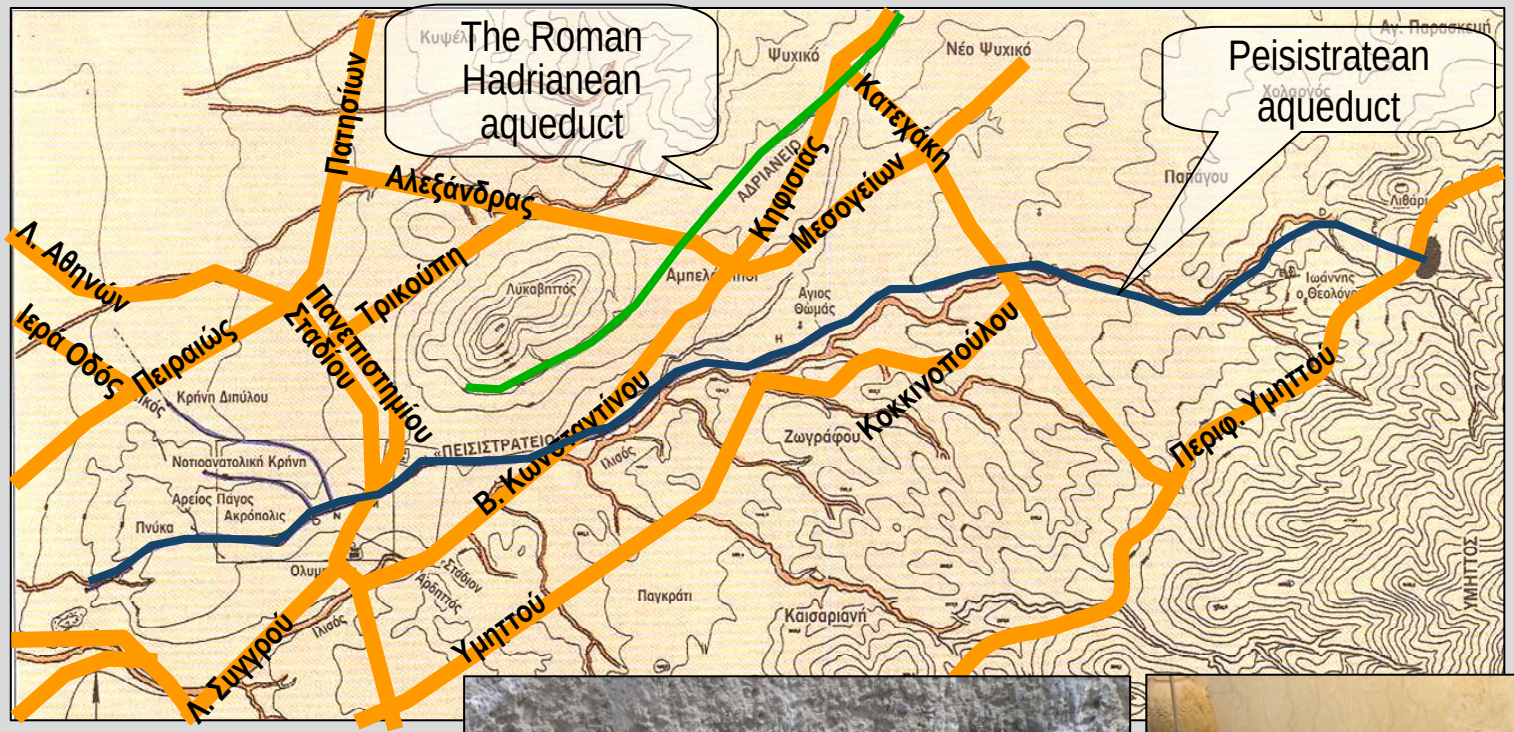
# The Athens case: The initial stage of water supply



The interior of the tank of the Clepsydra spring at Acropolis (photo from Papademos, 1975).

- Athens was the most important city of antiquity with a population of more than 200 000 during the golden age (5$^{th}$ century BC)
- Athenians put great efforts into the water supply of their anhydrous city. The first inhabitants of the city chose the hill now known as Acropolis for their settlement due to the natural protection it offered and the presence of three natural springs, the most famous being “Clepsydra”.
- Natural springs were not enough to meet urban water demands. Therefore, Athenians used both groundwater, by practicing the art of drilling of wells, and stormwater, by constructing cisterns.
- In addition, the water from the two main streams of the area, Kephisos and Ilissos, whose flow was very limited in summer, was mainly used for irrigation.

# The Peisistratean aqueduct



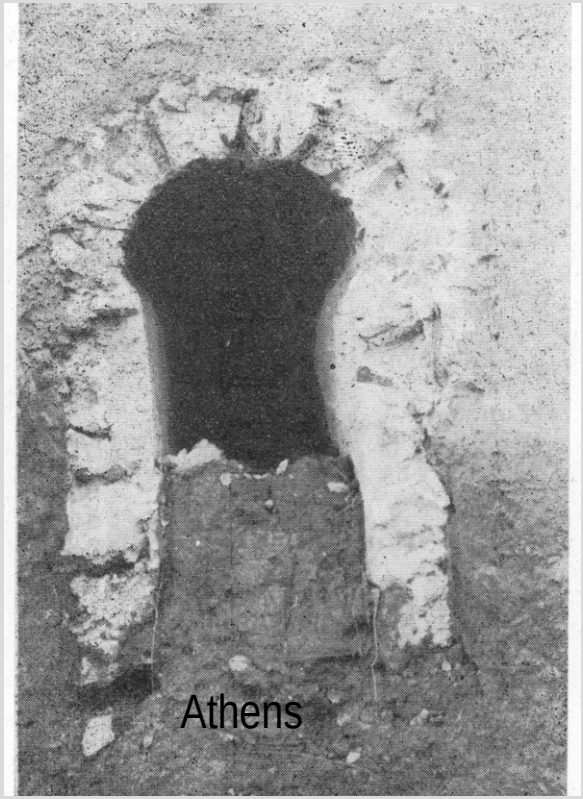

The first major hydraulic project in Athens was constructed under the tyrant Peisistratos (in power between 546-527 BC) and his sons.

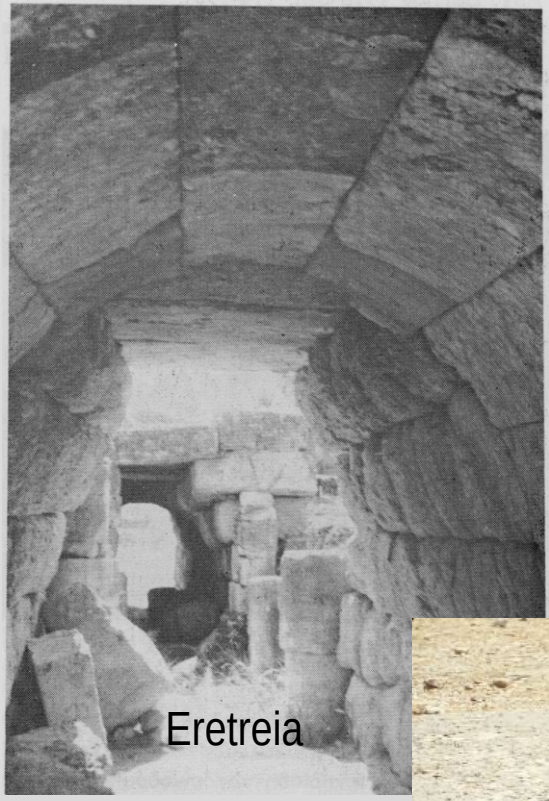
Mostly carved as a tunnel at a depth reaching 14 m.

Ceramic pipeline at the bottom.

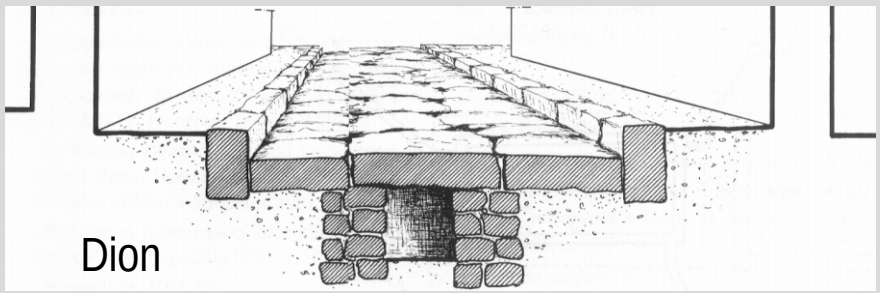
Greek hydraulic constructions were mostly subterranean for security reasons (not no be exposed to aliens, e.g. in case of war)

# Athens and other cities in classical period: Storm sewers


Athens


Eretreia


Athens


Dion


Cassope

# Legislation

- Apart from the structural solutions for the water supply and sewerage of Athens, the Athenian civilization developed a framework of laws and institutions for water management.
- The first known regulations were designed by Solon, the Athenian statesman and poet of the late seventh and early sixth century BC, who elected archon in 594 and shaped a legal system by which he reformed the economy and politics of Athens. Most of his laws have been later described by Plutarch (47-127 AD), from whom we learn:

  > "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 liiters) twice a day from their neighbours; for he thought it prudent to make provision against need, but not to supply laziness." (Plutarch, Solon, 23).

- As the city's public system grew and aqueducts transferred water to public fountains, private installations like wells and cisterns tended to be abandoned. As the latter would be necessary in times of war because the public water system would be exposed, the owners were forced by regulation to maintain the wells at a good condition and ready to use
- Other regulations protected surface waters from pollution. An epigraph of *ca.* 440 BC contains the "law for tanners", who are enforced not to dispose their wastes to Ilissos river.

# Institutions

- A distinguished public administrator, called «κρουνῶν ἐπιμελητής», (Superintendent of Fountains), was appointed to operate and maintain the city's water system, to monitor enforcement of the regulations and to ensure the fair distribution of water.
- From Aristotle (Athenaion Politeia, 43.1) we learn that this officer was one of the few that were elected by vote whereas most other officers were chosen by lot; so important was this position within the governance system of classical Athens.
- Themistocles himself had served in this position.
- In 333 BC the Athenians awarded a gold wreath to the officer of fountains Pytheus because he restored and maintained several fountains and aqueducts.
- The entire regulatory and management system of water in Athens must have worked exceptionally well and approached what today we call sustainable water management. For example modern water resource policymakers and hydraulic engineers have in recent international conferences emphasized the nonstructural measures in urban water management and the importance of small-scale structural measures like domestic cisterns. Such cisterns have two advantages: They reduce the amount of stormwater to be discharged and provide a source of water for private use (like watering of gardens).

# Institutions for building public hydraulic works

- It was a common practice in ancient Greece that competition announcements, project specifications and project contracts were written on marble steles erected in public sites so that everyone would have known all project details and, simultaneously, the breach of contract would be difficult. As Tassios (2002b) puts it, if someone wished to violate some terms, he would "stumble on them".
- To validate the fact that *scripta manent*, the contracts of certain projects were revealed in excavations. As a typical example, the contract for draining and exploitation of the lake Ptechae (probably identified with the Dystos Lake in Southern Euboea), which is between the Eretrians and the engineer-contractor Chairephanes (2nd half of 4th century BC), was revealed in Chalkis (1860) and is kept in the Athens Archaeological Museum. The project is what we call today BOT – Build, Operate, Transfer. The rather wordy (like construction contracts of today) contract is written on a Pentelian marble stele with dimensions: 87 × 47 × 9 cm (Papademos, 1975). On the surface relief sculptures show the Gods that were worshiped in the region, Apollo, Artemis and Leto. A carved scripture in 66 verses signed by more than 150 people contains the construction contract, which starts as follows:

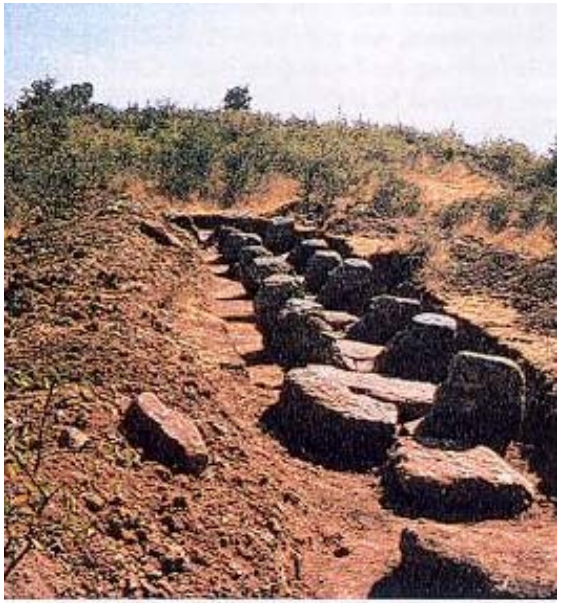
  «Κατὰ τάδε Χαιρεφάνης ἐπαγγέλλεται Ἐρετριεῦσιν ἐξάξειν καὶ ξηρὰν ποιήσειν την λίμνην τὴν ἐν Πτέχαις …» (In this, Chairephanes promises to the Eretrians that he will drive away the Ptechae lake and make it land …)
- The first 35 verses are the main contract. In the continuation two resolutions of the parliament are given. With the first one asylum is granted to Chairephanes and his collaborators for the whole duration of the contract and in the second resolution the keeping of the contract is confirmed by oath to Apollo and Artemis; against misdemeanors moral and material sanctions (penalty for breach of contract) are foreseen such as the confiscation of their property and the dedication of it to Artemis.

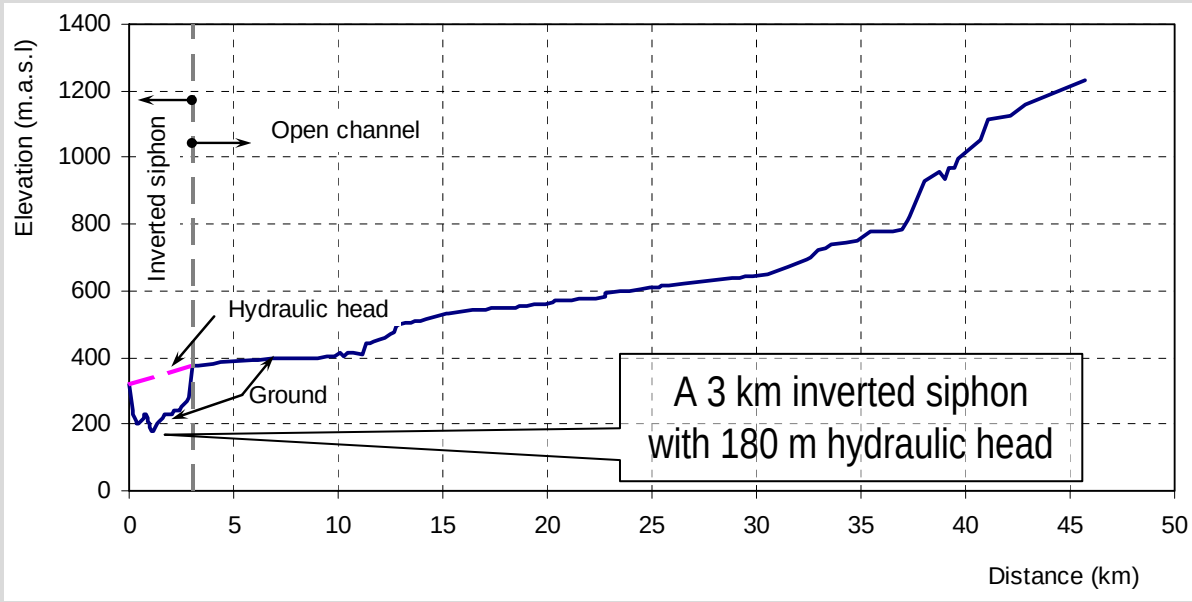
# Institutions for building public hydraulic works (2)

A summary of the main contract for draining of the lake Ptechae (adapted from Papademos, 1975)

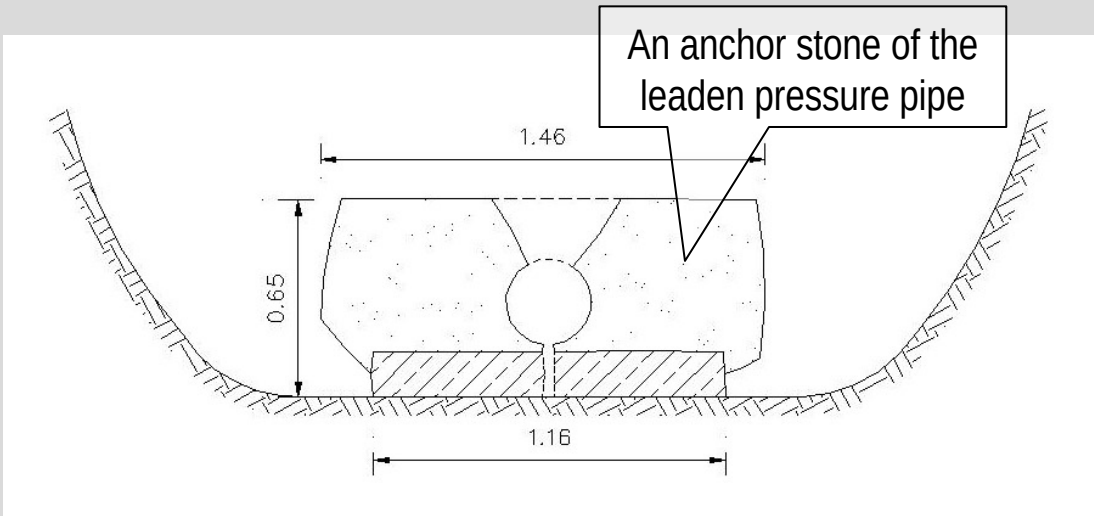
1. Between the city of the Eretrians representing the 31 municipalities of the Eretrian region and the contractor Chairephanes, a contract is made concerning the draining of the Ptechae Lake.
2. The draining works include the construction of drainage canals, sewers, and wells for the drainage of water to natural underground holes or cracks, and miscellaneous protection works including wooden or metallic railings.
3. In addition, irrigation works, such as the construction of a reservoir with side length up to 2 stadia (360 m) for storing irrigation water, and sluice gates, are included in the contract.
4. It is agreed a 4-year construction period that could be extended in case of war.
5. The contractor is granted the right to exploit the dried fields for 10 years (extended in case of war), starting by the finishing of the drying works.
6. The contractor is granted the privilege of custom free import of materials (stones and wood).
7. The contractor is obliged (a) to pay all labor costs without any charge for the people Eretria; (b) to pay the amount of 30 talents in monthly installments as a rental for the permission to exploit the lake for 10 years; (c) to maintain all works for the exploitation period, in order to be in good condition after the finishing of the contract; (d) to compensate the land owners by one drachma per foot of land area that is to be the expropriated for the construction of works; and (e) to avoid harm on private property as much as possible by locating the works in non cultivating areas.
8. In case of death of the contractor, his heirs and collaborators will substitute him in the relations to the city.
9. Penalties are enforced against any person trying to annul the contract.
10. The contractor is obliged to submit a good construction guarantee up to the amount of 30 talents.

# Hellenistic period: The Pergammon aqueduct






The Hellenistic period (323-146 BC) is characterized by significant progress in mathematics, physics, and technology. This progress allowed, for first time in history, application of the the pressure flow on large technological scale for water conveyance



# Greek inventions for hydraulic mechanisms and devices

- Today's hydraulic projects are typically equipped with electromechanical equipment, e.g. pumps.
- Although in antiquity several devices were in use to lift water to a higher elevation, the first pump with the modern meaning is Archimedes's helix or water-screw. Archimedes was a Syracusian mathematician and engineer (287-212 BC) considered by many to be the greatest mathematician of antiquity or even of the entire history. The invention of the water screw is tied to the study of the spiral, for which Archimedes wrote a treatise entitled On Spirals, in 225 BC.
- This pump is an ingenious device functioning in a simple and elegant manner by rotating an inclined cylinder bearing helical blades around its axis whose bottom is immersed in the water to be pumped. As the screw turns, water is trapped between the helical blades and the walls, thus rises up the length of the screw and drains out the top.


Archimedes's water screw in its original form as depicted in an Italian stamp along with a bust of Archimedes (from http://www.mcs.drexel.edu/~crorres/Archimedes/Stamps/)

Archimedes's water screw in its modern form, as implemented in the wastewater treatment plant of Athens (1 of 5 screws that pump 1 million $m^3$ per day).

# Comparison with present time state

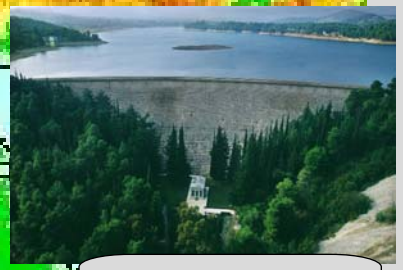
- Most principles related to water technology and management were known to ancient Greeks
- Modern advances are mostly related to apparatus:
  - plastic and concrete pipes,
  - automated pressurized urban water distribution systems,
  - electromechanical equipment such as pumps,
  - effective mechanical equipment for the construction of hydraulic works.
- The essential progress of modern times is the better understanding and mathematization of hydraulics which allows better design and management of hydraulic works and much larger scales of application.
- On the other hand, current practices are inferior to ancient ones in terms of
  - durability, sustainability and safety of works,
  - balance between large and small scales of system components,
  - balance between the involvement of the private and the public sectors.

# Ancient Greek and modern civilization
# A technological link

Evinos

π. Β. Κηφισσός

Hylike lake

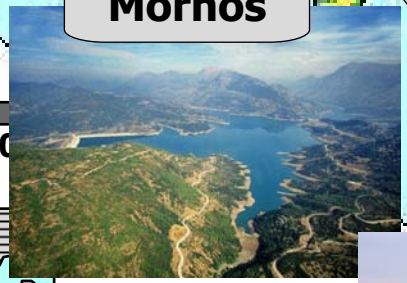


Marathon

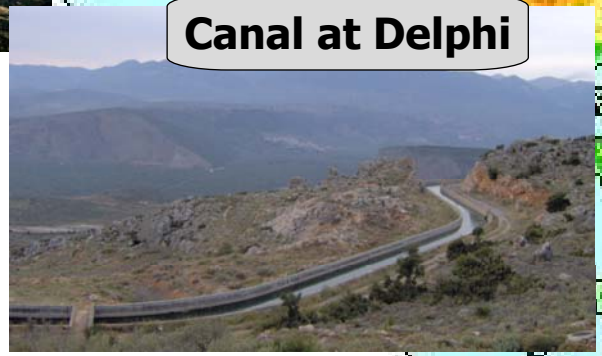
π. Εύηνος

π. Μόρνος

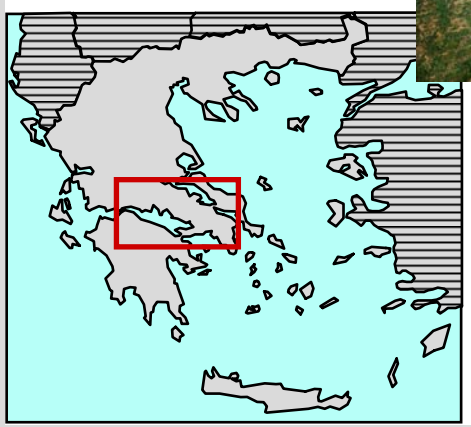
Mornos



Canal at Delphi



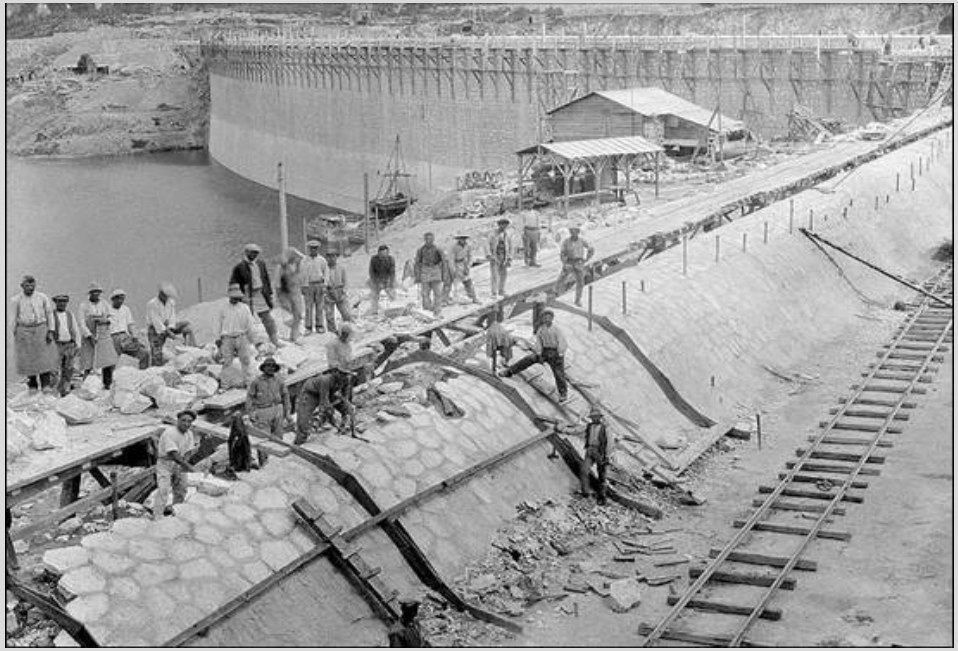
Athens



# Marathon dam (a Greek-American link)

Current view with elements pointing to the antiquity:

- the dam is covered by Pentelic marble (the same used in Parthenon)
- the control building is a copy of an ancient temple in Delphi



Dam construction by the American company Ulen, 1928

Spillway construction, 1928

# An ancient Greek analogue: The Alyzia dam

The dam (most likely built in the classical period to protect the downstream plain from floods and sediments) is in perfect condition 2500 years after its construction

The stone-carved spillway has formed an irregular shape by erosion through centuries

The spillway in operation

# Ancient Greek and modern civilization
# An American assessment

*We frequently hear people speak of "modern sanitation" as if it were something rather recently developed, and there appears to be a prevalent idea that municipal sewerage is a very modern thing that began some time about the middle of the last [19th] century. Perhaps these ideas do something to bolster up a somewhat wobbly pride in modern civilization […], but when examined in the light of history these ideas are seen to be far from new or even recent. Indeed, in the light of history it is a matter of astonishment, if not chagrin, that man in this respect has progressed so very little, if at all, in some four thousand years. […] All in all, the archaeological researchers on this [Minoan] site yield a picture of a people who had progressed far along the path of comfortable and hygienic living, with a considerable degree of beauty and luxury in the surroundings. And this had been accomplished some four thousand years ago.*

Harold Farnsworth Gray (Sewerage in Ancient and Medieval Times, *Sewage Works Journal*, 12 (5), 939 - 946, 1940).

# Ancient Greek and modern civilization: A non-technological link

**Ithaca**

As you set out for Ithaca
hope your road is a long one,
full of adventure, full of discovery.
Laistrygonians, Cyclops,
angry Poseidon - don't be afraid of them:
you' ll never find things like that on your way
as long as you keep your thoughts raised high,
as long as a rare excitement
stirs your spirit and your body.
Laistrygonians, Cyclops,
wild Poseidon - you won't encounter them
unless you bring them along inside your soul,
unless your soul sets them up in front of you.

Hope your road is a long one.
May there be many summer mornings when,
with what pleasure, what joy,
you enter harbours you're seeing for the first time;
may you stop at Phoenician trading stations
to buy fine things,
mother of pearl and coral, amber and ebony,
sensual perfume of every kind -
as many sensual perfumes as you can;
and may you visit many Egyptian cities
to learn and go on learning from their scholars.

Keep Ithaca always in your mind.
Arriving there is what you're destined for.
But don't hurry the journey at all.
Better if it lasts for years,
so you're old by the time you reach the island,
wealthy with all you've gained on the way,
not expecting Ithaca to make you rich.

Ithaca gave you the marvellous journey.
Without her you wouldn't have set out.
She has nothing left to give you now.
And if you find her poor, Ithaca won't have fooled you.
Wise as you will have become, so full of experience,
you'll have understood by then what these Ithacas mean.

**Konstantinos Kavafis (1911)**