Adaptive Management of Barriers in European Rivers (AMBER)

River conservation actions – Greece AMBER National Workshop

8th May 2019, Ministry of Environment & Energy

Dams and their environmental impacts in Greece: insights, problems and challenges

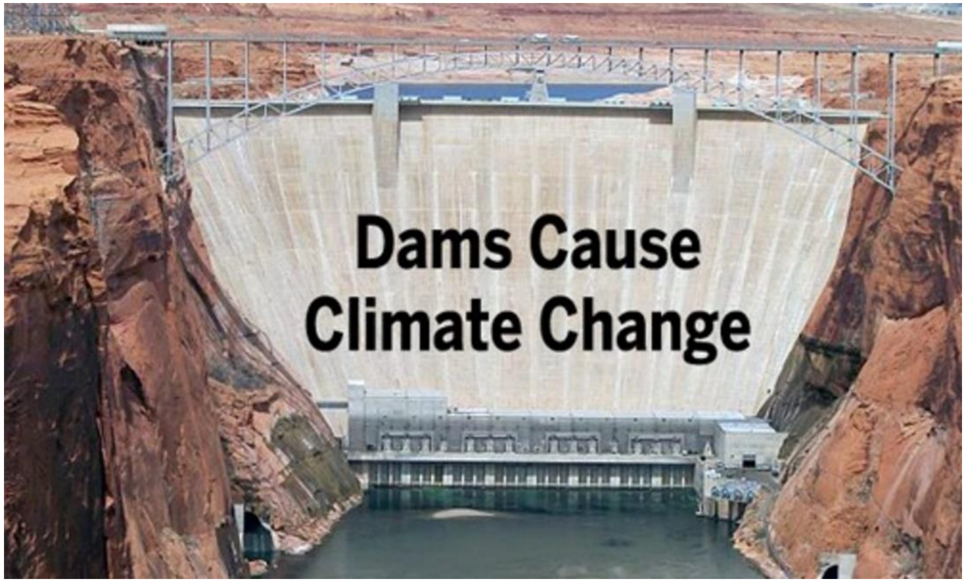
Andreas Efstratiadis

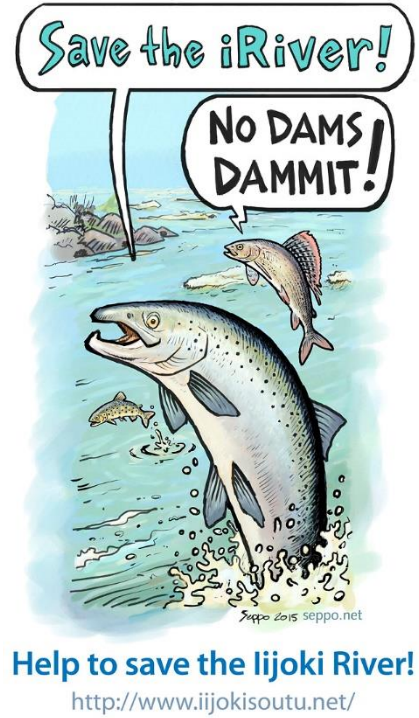
Dr. Civil Engineer, Lab Teaching Staff, elected Assistant Professor

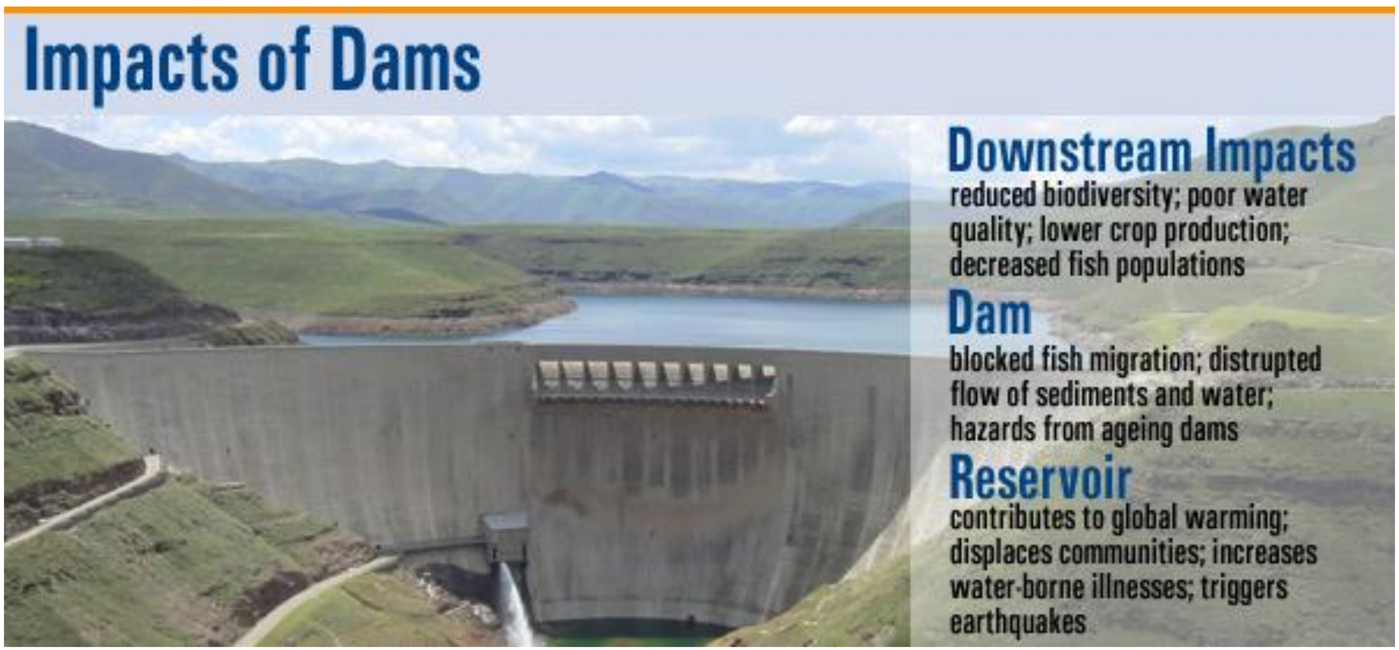
Department of Water Resources & Environmental Engineering, School of Civil Engineering, National Technical University of Athens

Presentation available online: www.itia.ntua.gr/1951/

Running opinions about dams



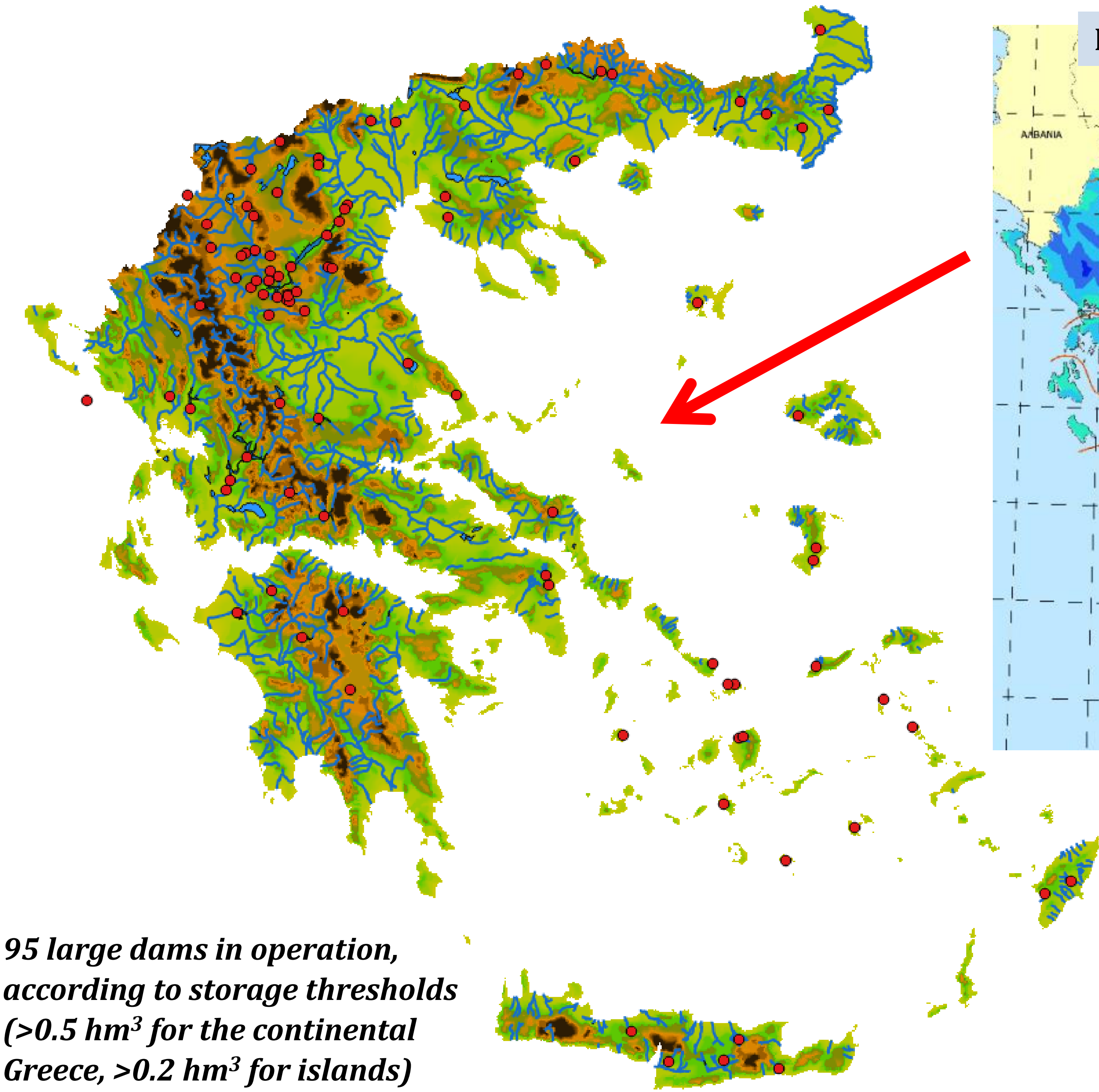




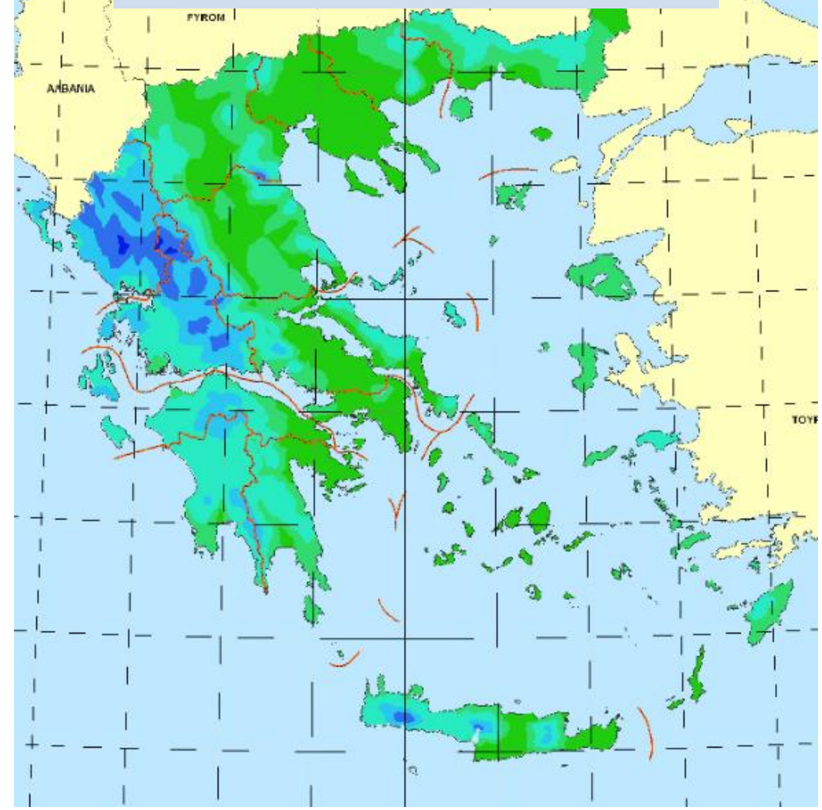
Greek dams vs. running opinions (and some introductory questions for motivation)

- Are our dams (still) useful from a socio-economic perspective?
- Are our dams dangerous?
- Which is the lifetime expectation of old Greek dams?
- Do we need new large dams in Greece?
- Do our dams cause severe environmental impacts to riverine systems?
- Can we mitigate some of these impacts?
- Which of these impacts are not reversible?
- Is it possible to improve the management policy of our reservoirs?
- Is it possible to establish a fair balance between human and environmental needs?
- Is it realistic (and rational) to remove dams (and which ones)?

Large dams of Greece



Mean annual rainfall over Greece



Source: Koutsoyiannis *et al.* (2008)

95 large dams in operation, according to storage thresholds (>0.5 hm³ for the continental Greece, >0.2 hm³ for islands)

Raw data sources about dams in Greece: Greek Committee on Large Dams (2013) and Nikos Mamassis (2019; unpublished repository)

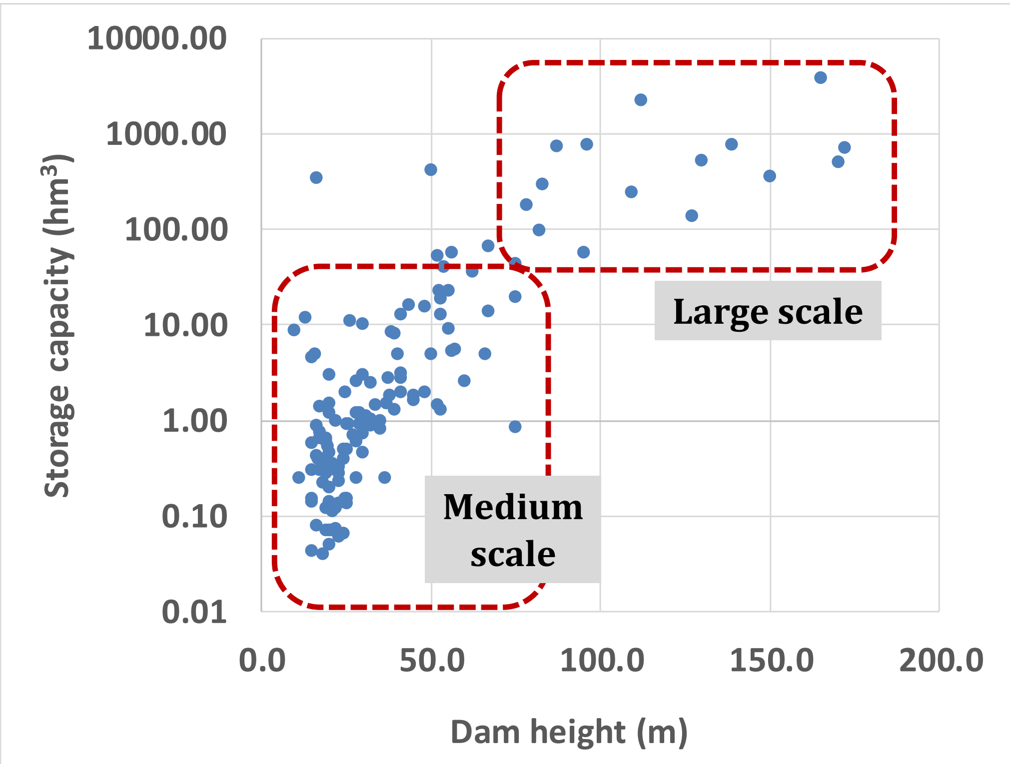
Overview of dams in Greece

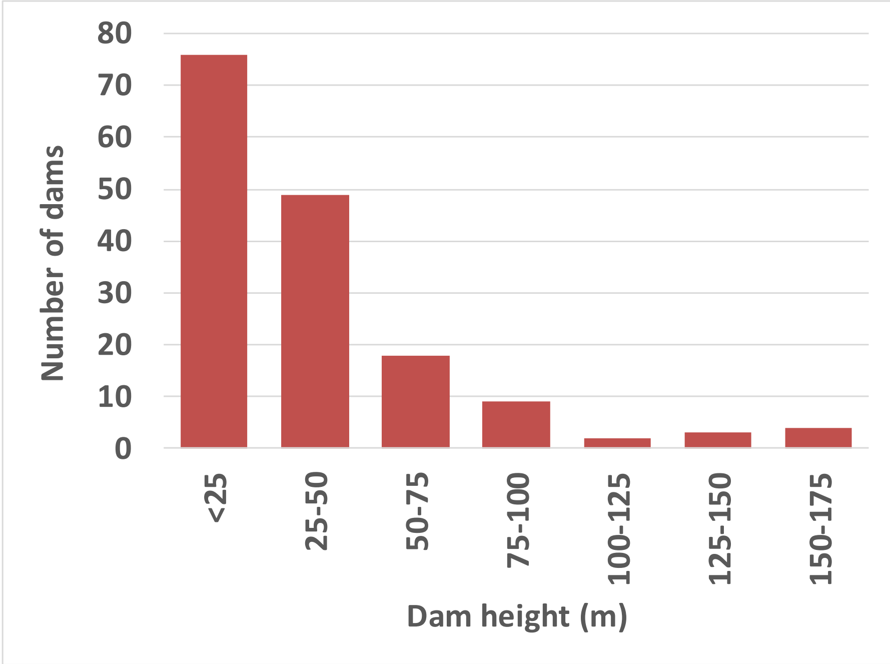
- Most of large dams have been constructed from the late 50’s to the late 90’s, to serve hydroelectricity uses; the latter are operated by the Public Power Corporation (PPC);
- Multi-reservoir systems:
  - Achelous (Plastriras, Mesochora, Kremasta, Kastraki, Stratos)
  - Aliakmonas (Helarion, Polyfyro, Sfikia, Asomata, Agia Varvara)
  - Nestos (Thesavros, Platanovrysi)
  - Arachthos (Pournari I, Pournari II)
  - Athens water supply system, extended over four river basins (Evinos, Mornos, Boeoticos Kephisos – Hylike, Charadros)
- Main diversion dams:
  - Marathon, Mornos (full diversion to Athens)
  - Evinos (partial diversion to Mornos)
  - Plastiras (full diversion to Thessaly plain)
  - Aoos springs (partial diversion to Arachthos)
  - *Sykia (under construction)*
- Pumped-storage reservoirs:
  - Sfikia ↔ Asomata
  - Thesavros ↔ Platanovrysi

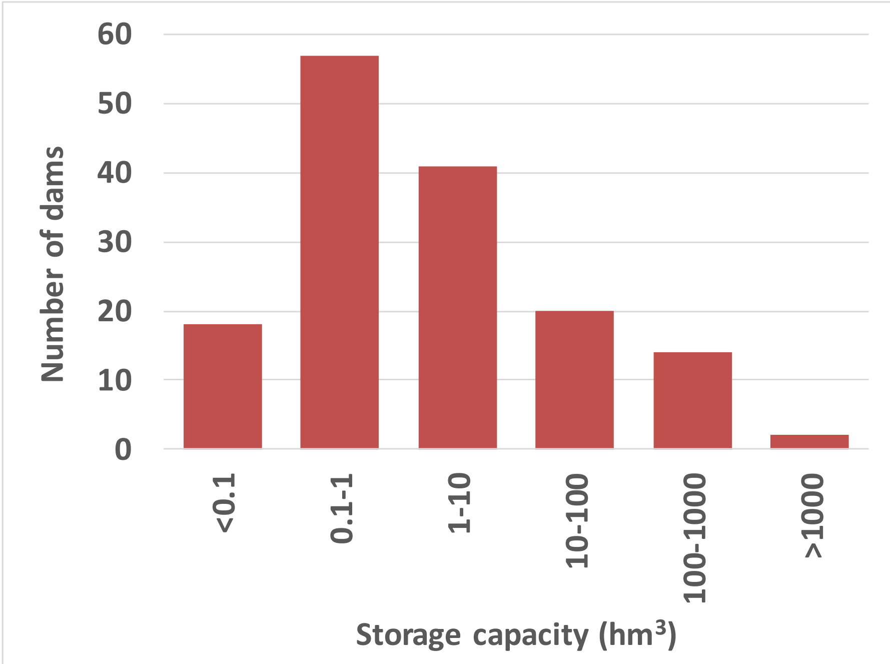
Remark: According to the Greek law (KYA 173829/2014), dams are classified into three categories. Very small dams (weirs) of height less than 5 m are classified into category B, considered having negligible or local only impacts to the environment, while large dams are classified into categories A1 (height > 50 m) or A2.

Few statistics about Greek dams

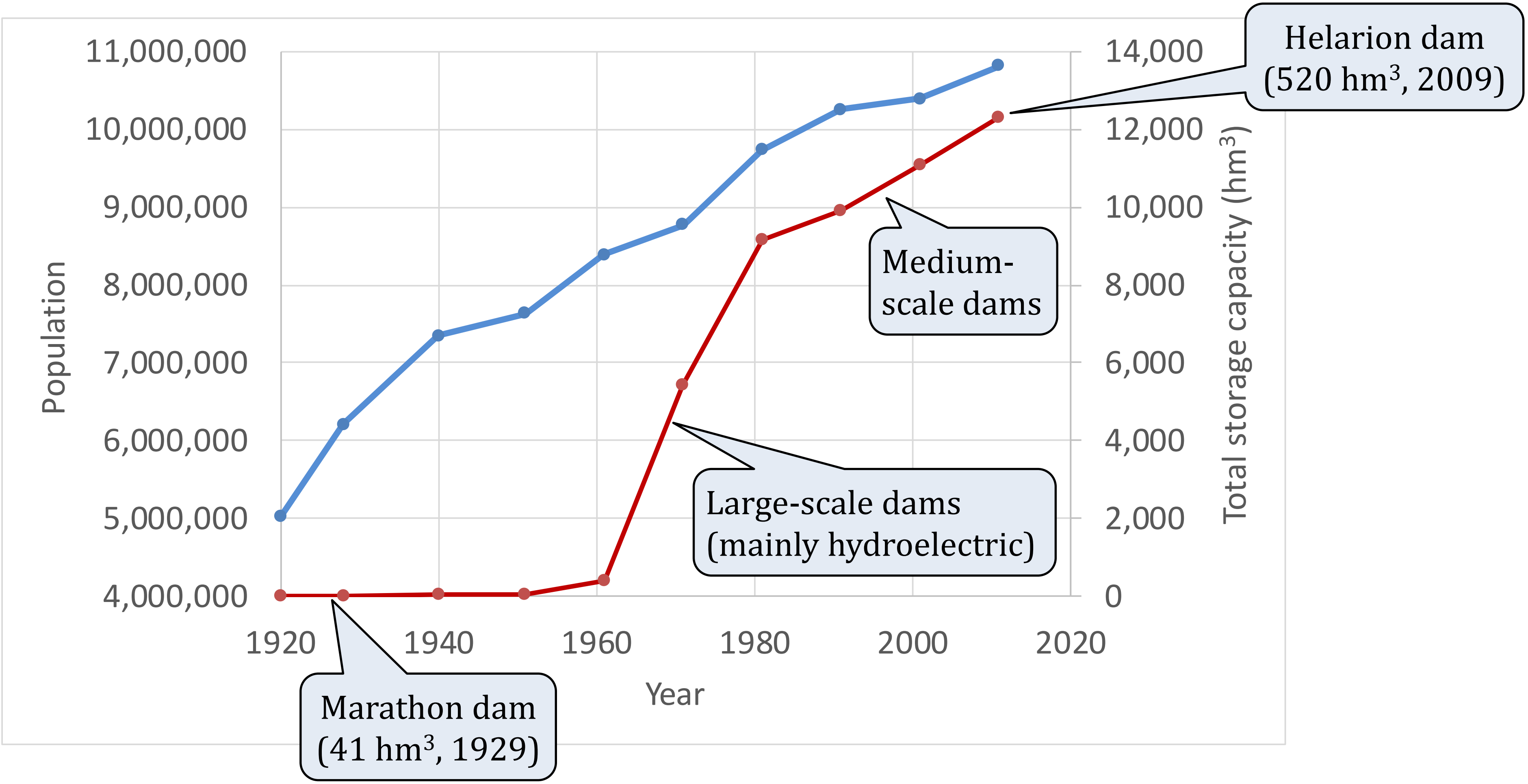
- 32 large-scale dams with height >50 m, four them exceeding 150 m, mainly for hydroelectric production (Thessavros @ Nestos, 172 m)
- 125 medium-scale dams with height 5 to 50 m, serving local water supply and irrigation uses
- 16 reservoirs of total storage capacity >100 hm^3, two of them exceeding 1000 hm^3 (Kremasta @ Achelous, 3828 hm^3)







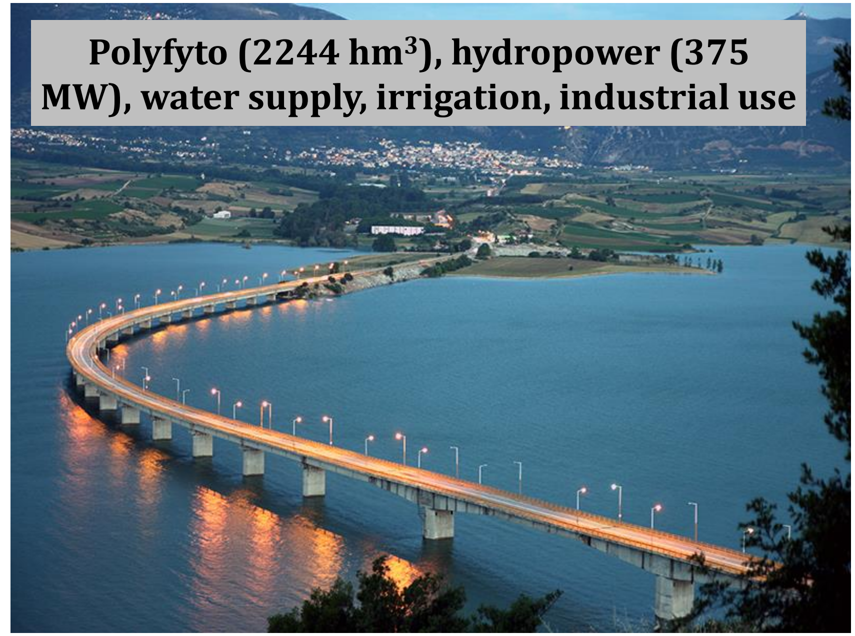
Historical evolution



- Total storage capacity ~ 12 800 hm^3 (Kremasta + Polyfyto = 6070 hm^3)
- Per capita storage capacity: 1951 → 5 m^3; 1961 → 47 m^3; 1971 → 620 m^3; 1981 → 943 m^3; 1991 → 965 m^3; 2001 → 1065 m^3; 2011 → 1140 m^3
- Potentially stored water per capita is equivalent to a daily water supply of ~300 L/d.

Largest hydroelectric dams (in terms of power capacity)

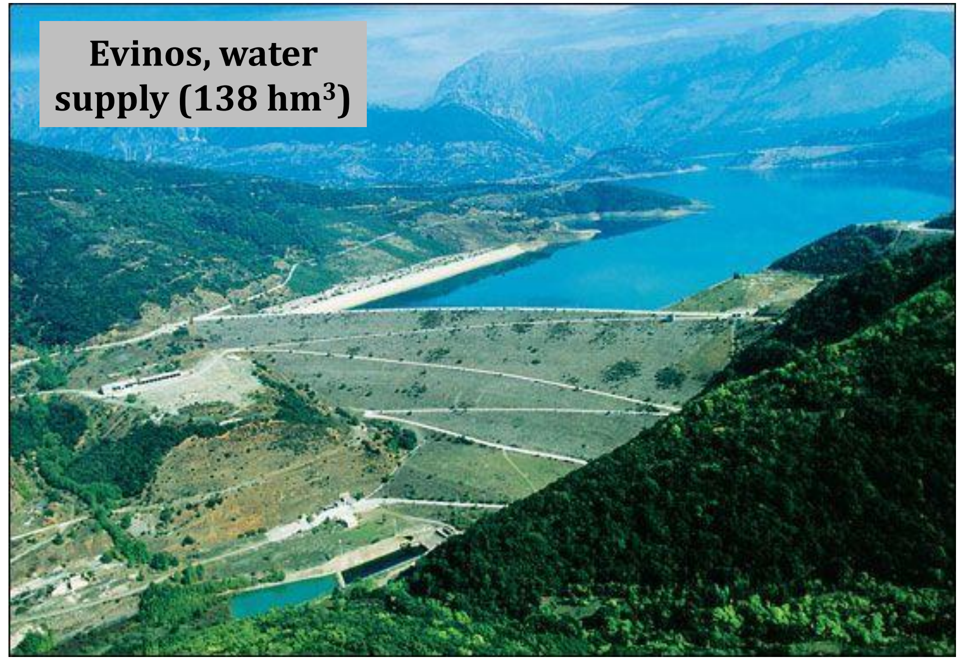

Kremasta (3828 hm^3) hydropower (437 MW)

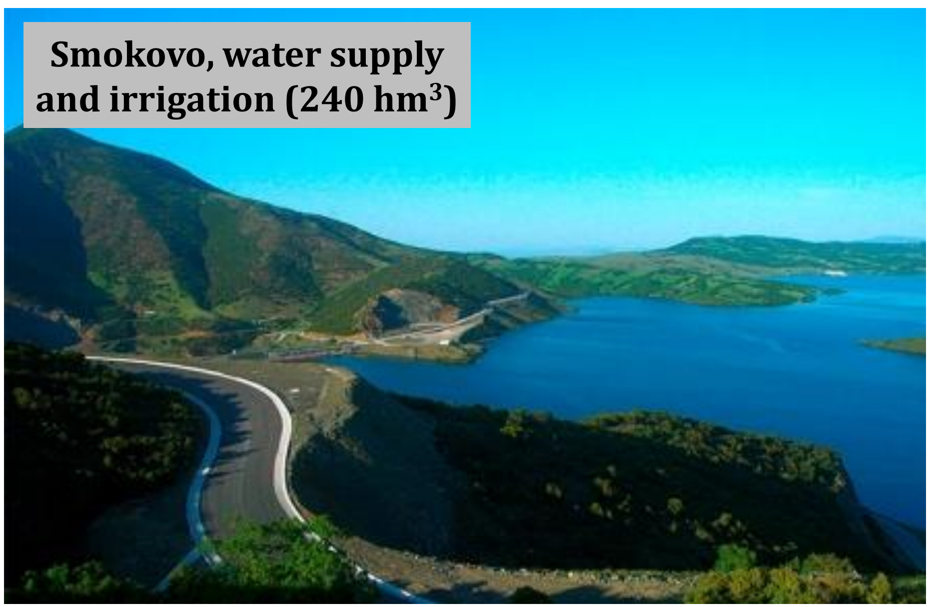

Polyfyto (2244 hm^3), hydropower (375 MW), water supply, irrigation, industrial use

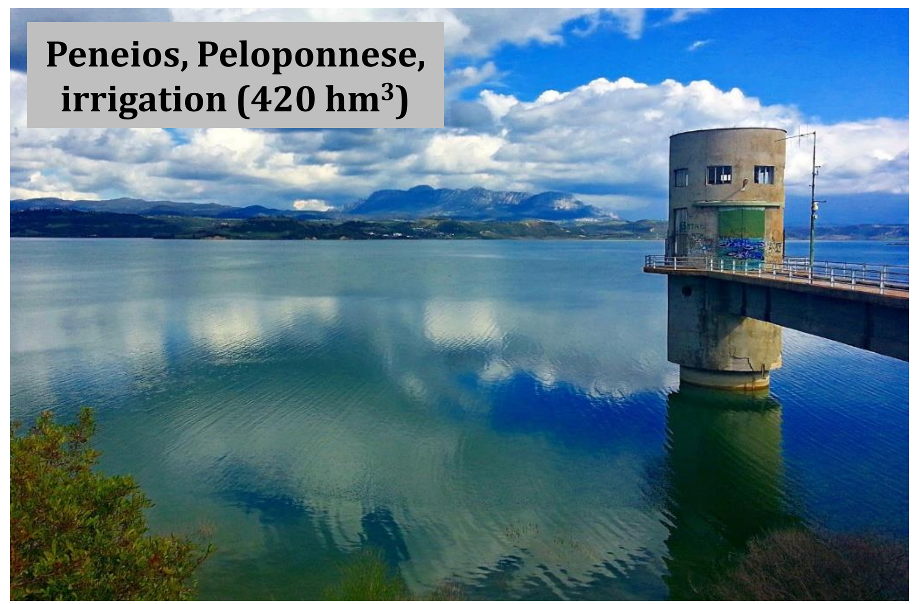

Thesavros (705 hm^3), hydropower (384 MW)


Kastraki (785 hm^3) hydropower (320 MW), water supply

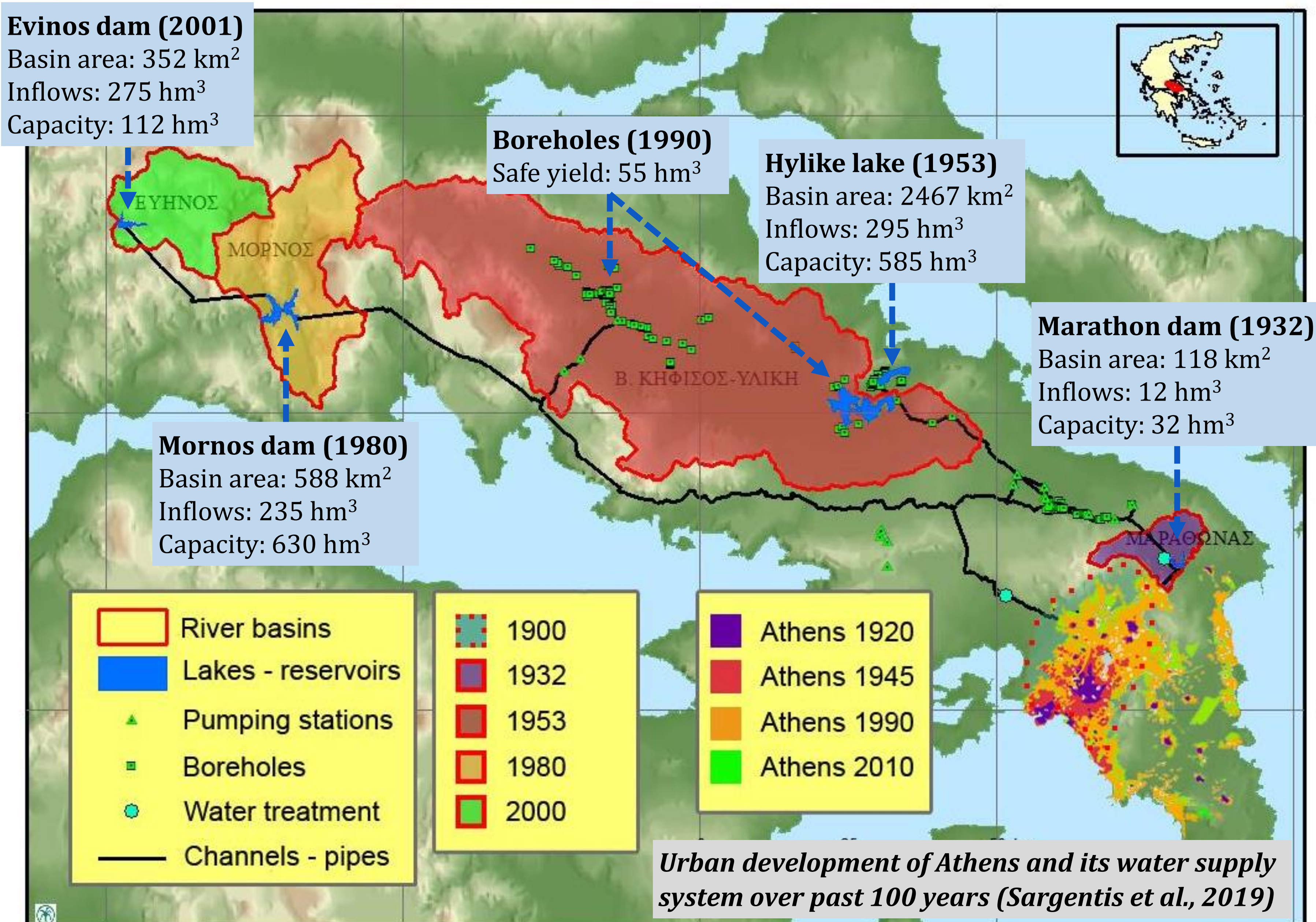
Largest water supply and irrigation dams







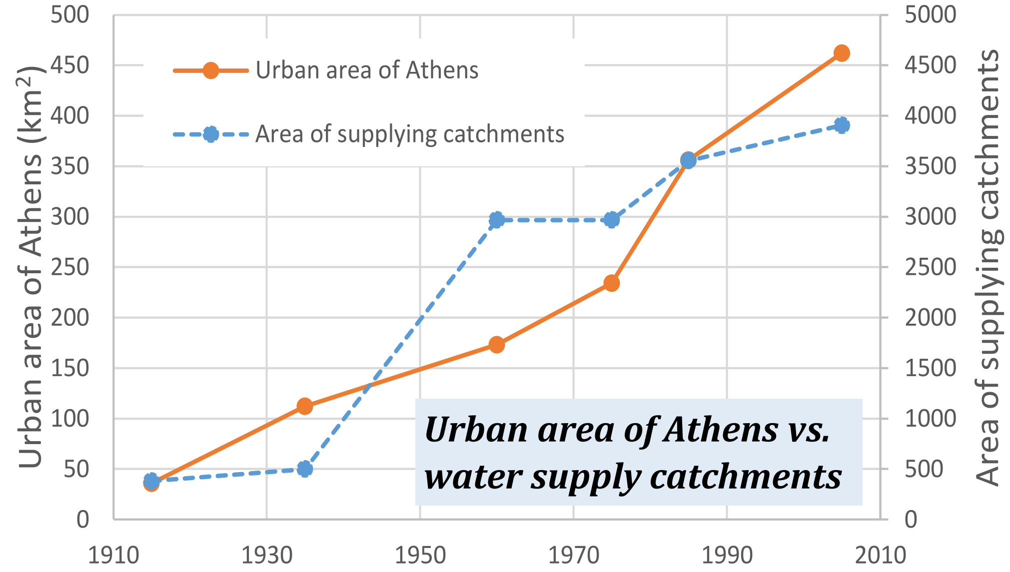
Are our dams useful? The case of Athens water supply system



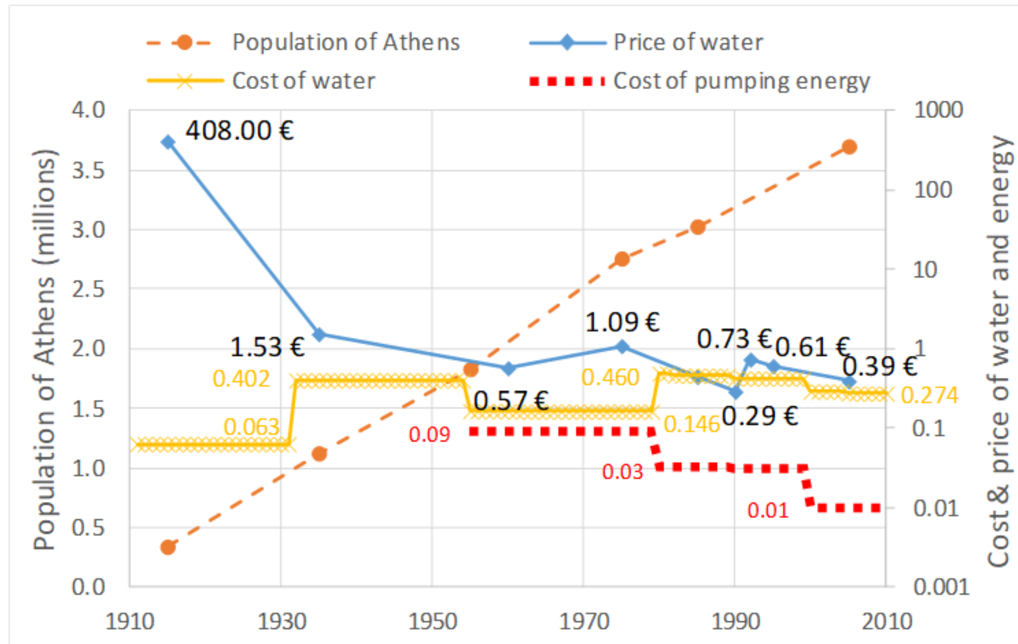
Urban development of Athens and its water supply system over past 100 years (Sargentis et al., 2019)

Could Athens be viable without (large) dams?

- The Athens area has grown about 10 times during last century, and the extent of the water supply system has increased accordingly.
- After the construction of Marathon and the development of the water distribution network (from 1926), the price of water dropped from ~400 €/m^3 to ~1.5 €/m^3 (deflated values).
- The cost of pumping also dropped by an order of magnitude, since Hylike is only used as auxiliary resource.
- The current price of drinking water is 0.39 €/m^3, while the cost of raw water is 0.14 €/m^3 (Makropoulos *et al.*, 2018).
- The large-scale water supply system of Athens simultaneously ensures a **very low price of water and very high reliability, i.e. 99% on annual basis**.



Urban area of Athens vs. water supply catchments



Evolution of population, cost and price of water, and cost of pumping over last 100 years (Sargentis et al., 2019)

A hypothetical removal of Marathon dam

- **Several reasonable and "reasonable" arguments:**
  - Marathon is the oldest dam of Greece – its economic life has been has long been over.
  - Its lifetime reaches one century, thus the reservoir is expected to be filled by sediments.
  - The lifetime of concrete is about a century, thus the dam may be dangerous.
  - From a water management perspective, its contribution to the Athens water supply system is negligible (1.5% of surface inflows, 2.5% of total storage capacity).
  - The dam interrupts the flow to the downstream river – river Charadros has disappeared.
- **So, let it flow … or not?**
  - The sole large-scale regulating tank near Athens, which allows smoothing peak daily demands;
  - Absolutely essential in case of emergency (ensures backup water storage for one month);
  - Removing this element from the hydrosystem would result to an increase of failure probability to 3%, in order to fulfill the current water uses.

View downstream of the dam: river Charadros is missing (Google Earth)

Good news regarding lifetime of Greek dams

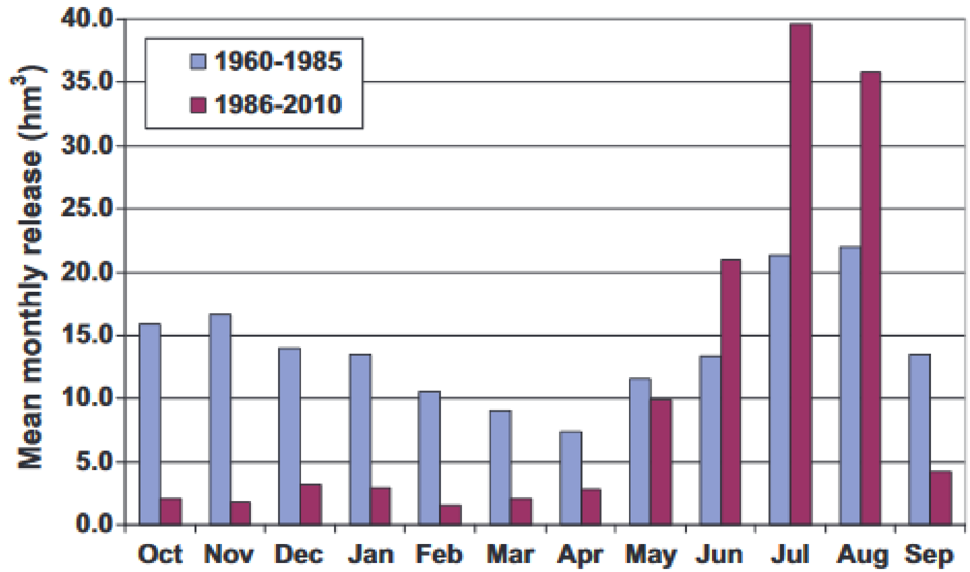
- According to in situ studies at two reservoirs with clearly different characteristics, i.e. Kremasta (Zarris *et al.*, 2002) and Marathon (Xanthakis, 2011), the **sedimentation rates considered within the design of the dams have been significantly overestimated**.
- Both dams are expected to be **fully operational for 200 years**, before their dead volume being covered by sediments.

	Kremasta	Marathon
Dead volume, design value (hm^3)	394	10.6
Years of operation (until in-situ measurements)	34	80
Deposits (hm^3)	66.6	4.7
Mean annual deposit rate (m^3)	2 081 250	58 640
Catchment area (km^2)	3292	118
Mean annual sedimentation (t/km^2)	1005	508
Expected time for filling the dead volume	~200 years	~180 years

Remark: Even when a hydroelectric reservoir is silted, the energy production does not stop – the hydraulic head cannot disappear! The dams continues its operation without regulation capacity (surplus inflows cannot be stored), thus producing secondary instead of firm (peak) energy, exactly like a small (run-of-river) hydroelectric plant (case of Louros dam).

The dams change the environment but their objectives are also changing: The case of Plastiras dam

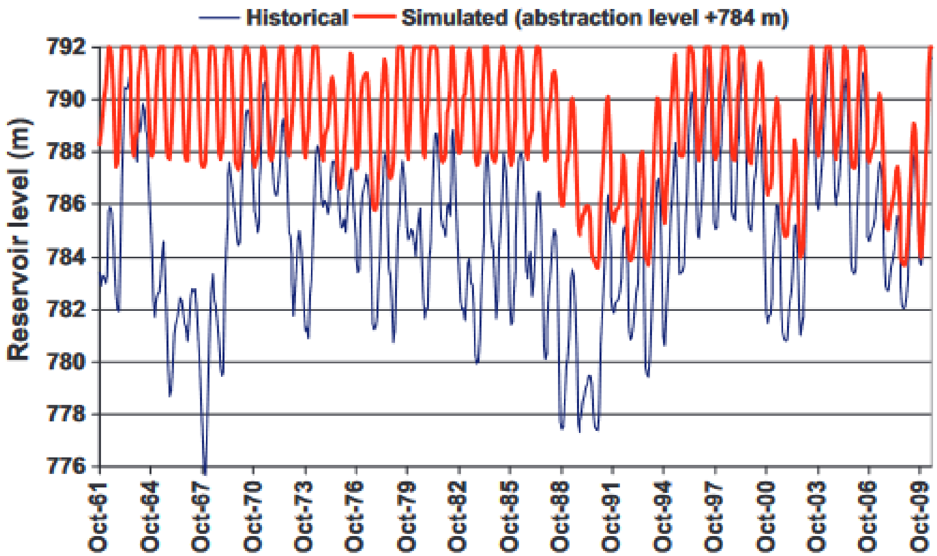
- The oldest large hydroelectric project (130 MW), constructed in the late ‘50s.
- Full diversion of the upper course Tavropos stream (tributary of Achelous) to the adjacent Thessaly plain, to take advantage of the available elevation difference (head ~ 580 m).
- Multipurpose dam, also serving irrigation and water supply uses, downstream of the power station (thus after the water passing the turbines), with changing priorities:
  - 1960-80: hydropower (operation of turbines ~4 hours per day to produce peak energy)
  - 1980-95: shift to irrigation, imposing substantial change of the seasonal distribution and the time schedule of outflows
  - 1995-today: touristic development, as result of the exciting landscape (**environmental change with positive socioeconomic impacts**), and degradation of water quality (eutrophication), asking for keeping the reservoir level as high as possible
- Need for a rational management policy to **compromise all conflicting objectives**.
- See details in Christofides *et al.* (2003), and Efstratiadis & Hadjibiros (2011).



Mean monthly outflows during 1960–1985 (primary use: hydropower) and 1986-2010 (primary use: irrigation)

Landscape quality as new criterion in reservoir management

- A multidisciplinary approach was employed, seeking for establishing a **minimum allowable level for agricultural abstractions** and **stabilizing the annual releases** for irrigation and drinking water supply. Several minimum allowed level scenarios were examined, to assess the variation of the corresponding criteria as a function of the reservoir level:
  - annual release vs. reliability;
  - water quality (chlorophyll-a);
  - landscape aesthetics.

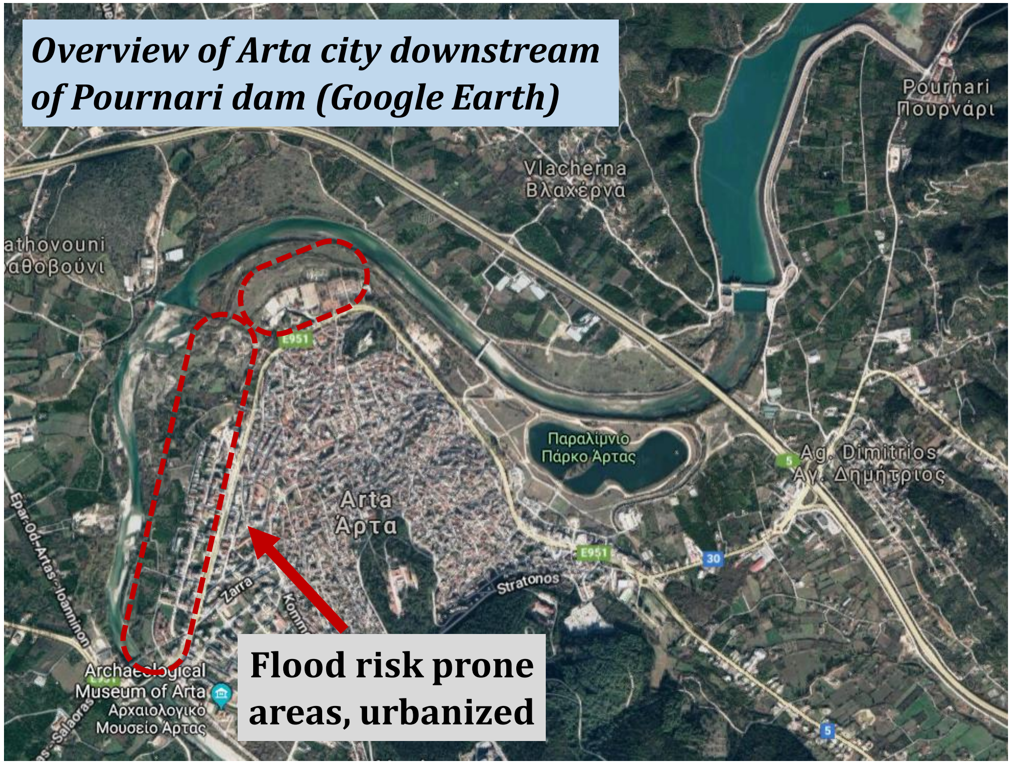


Comparison of historical and simulated reservoir levels, assuming a minimum level for agricultural abstractions of +784 m and an annual target release of 126.3 hm^3 (Efstratiadis & Hadjibiros, 2011).

The photographs on the left, showing the transition area of Plastiras reservoir, have been taken on the north and south part of the lake when its level was at +781.3 m. On the right the same photographs are digitally processed to show how the landscape would be if the lake were full (Christofides et al., 2003).

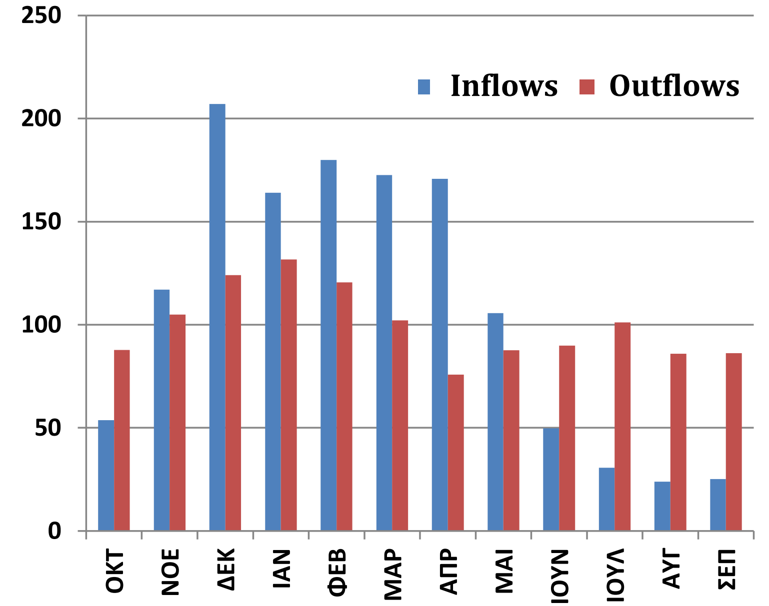
The absolute myth: dams cause floods!

- In addition to typical water uses, all dams by definition operate as **major flood control structures**, as they can store huge quantities of water and route them downstream with safety, through the turbines (hydroelectric dams) and, occasionally, the spillway. In fact, their design ensures **protection against extremely rare floods** (5 000 to 10 000 years).
- Large dams have changed the flow regime of the biggest rivers of Greece and, particularly, the temporal distribution and spatial extent of floods. Given that the discharge downstream of dams become much more stable if compared to the previous pristine conditions, a false impression was established regarding the natural regime of most rivers, since **the "memory" of high flow events was lost**.
- Inhabitants of surrounding areas and even local authorities, **erroneously assuming that the flood risk has been eliminated have exploited floodplains**, mainly for agricultural and (in some cases) for urban development purposes (Koutsoyiannis *et al.*, 2012).
- Propper management of dams upstream of human-developed floodplains attempt to minimize the frequency of spills, although **spilling is a normal operation of dams**.

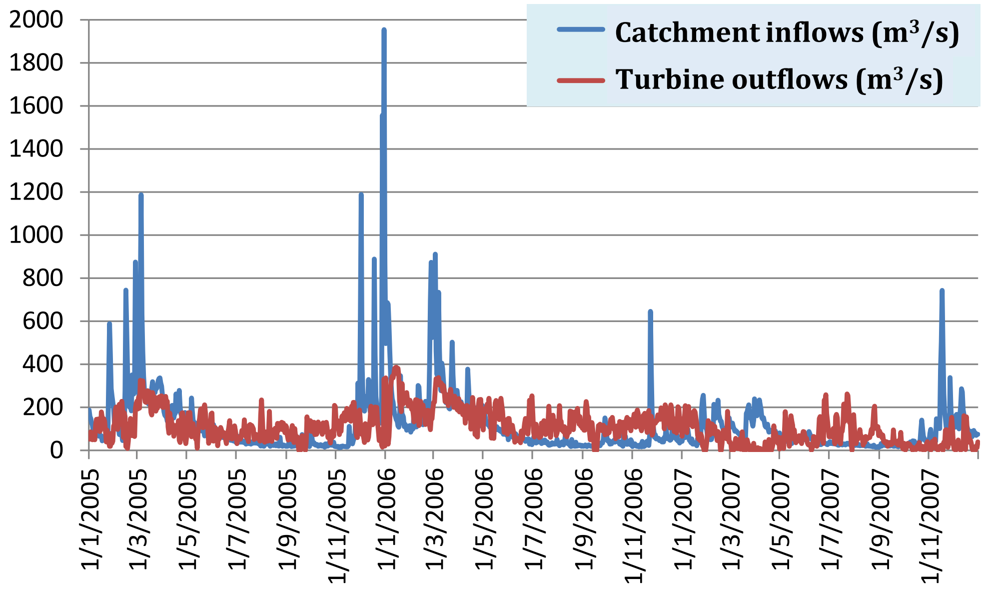


Impacts of large dams to flow regime

- Reduction of water availability:
  - Involves all dams serving consumptive water uses (irrigation, water supply)
  - Total interruption of flow, in case of diversion dams (Marathon, Mornos, Plastiras);
- Change of flow regime (case of hydroelectric dams):
  - Seasonal to over-annual regulation of flows;
  - Retention or significant smoothing of floods (which is **key advantage of all dams**);



Mean monthly flow regime, 1965-2010 (Kremasta reservoir, Achelous)



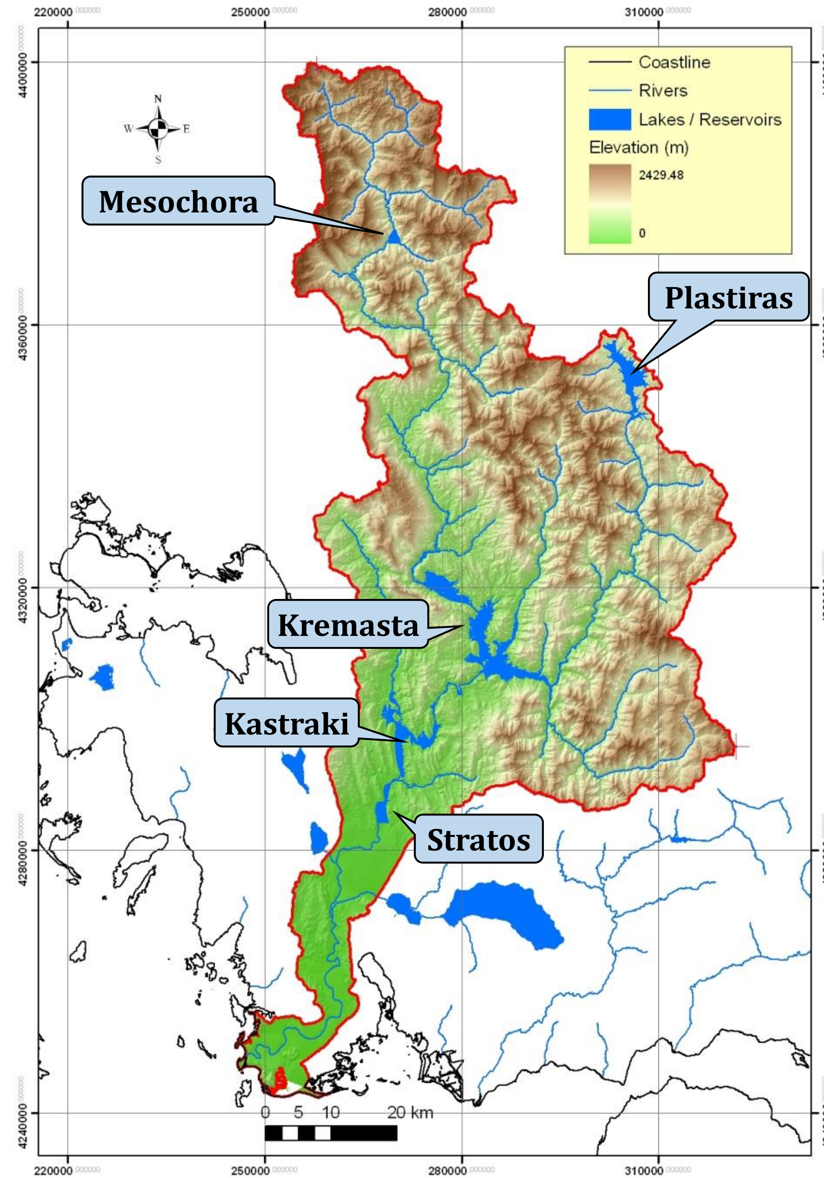
- Hydropeaking: release of large amounts of water during peak hours, to produce firm energy (**key purpose of hydroelectric works**, ensuring stability of the power system and significant reduction of energy cost);
- **Mitigation**: construction of a small-scale regulating work at the outlet of the main reservoir system, to ensure a permanent outflow (Pournari II, Agia Varvara);

Greek dams and environmental flows

- The concept of environmental flows (EF) has been historically regarded as the **technical response to the degradation of aquatic ecosystems caused by human interventions** (e.g., water overuse and flow regulations; cf. Efstratiadis *et al.*, 2014, Tegos *et al.*, 2018):
  - Early approaches: release of a constant discharge, either defined as a percentage of mean annual flow or estimated on the basis of dry-period flow data;
  - Later approaches: release of a seasonally-varying discharge, to follow the pattern of natural flows;
  - Modern "holistic" approaches: considering all facets of the flow regime (quantity, frequency, duration, timing, rate of change) as well as all biological, geomorphological, physical and chemical processes that form and maintain river ecosystems.
- In Greece, the maintenance of environmental flows downstream of dams was imposed only after mid 90's (first case: Evinos dam, operating from 2001);
- Assessment of EF is subject to multiple difficulties:
  - Limited availability of long term and reliable hydrological data;
  - Lack or highly uncertain biological and geomorphological data to allow linking river biota (e.g., fish habitat) characteristics with hydrological and hydraulic quantities;
  - Lack of standards (except for small hydroelectric works) in the presence of many literature approaches of varying complexity, resulting to totally different outcomes;
  - Lack of well-established methodologies for ephemeral and intermittent rivers;

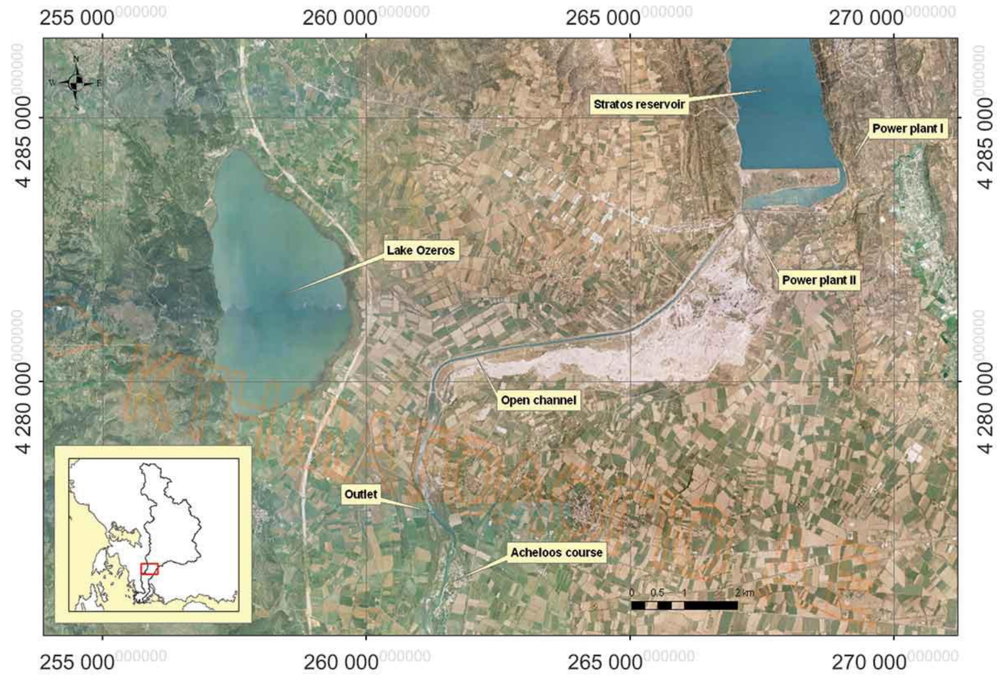
Environmental terms for the operation of the hydroelectric reservoir system across Achelous river

- Achelous: heavily modified river (the largest of Greece, in terms of runoff), hosting ~40% of total hydroelectric power capacity of the country.
- Multi-reservoir system designed and operated for more than 50 years without any provision for environmental protection.
- **1995**: Environmental impact assessment study of the upper Achelous project, envisaged, among others, the maintenance of a constant minimum flow of 21.3 m^3/s downstream of Stratos Dam (Hydroexygiantiki, 1995).
- **2007**: Incorporation of environmental terms involving the existing scheme of works (Kremasta, Kastraki, Stratos) within the national legislation.
- **2009**: PPC appointed a new technical study to investigate the suitability of the formerly proposed environmental terms, the adaptation of the current management practices and the construction of new works, if necessary (ECOS Consultants, 2009).



E-flows in practice

- Assessment of EF based on daily flow data through alternative approaches, providing a wide range of desirable flow values.
- Implementation of EF policy by taking advantage of the storage capacity of the channel downstream of Stratos dam, which allows regulating the outflows and ensures continuous discharge in the estuary.
- **Artificial flooding** (1400 and 2000 m^3/s, once per one and five years, respectively).



Source: Efstratiadis *et al.* (2014)

Method	**EFs at the estuary (m^3/s)**	**Remarks**
5-year min. monthly flow	21.3	Legislative constraint (EIA study, 1995)
5-year min. monthly flow (updated)	22.2	Statistical analysis of minimum monthly flows (1965-2008)
Tennant method (10% MAF)	13.7	Poor conditions assumed, since the river is heavily modified
French freshwater fishing law (2.5% MAF)	3.5	1/40 of mean annual flow assumed for existing works
U.K. standards (Q_{95})	18.9	Estimated on the basis of daily flow-duration curves
Q_{90}	22.9	
Q_{364}	11.9	
BFM, basic flow (Q_b)	14.0	Statistical analysis of daily to up to 100-day moving average flow data (seasonally varying)
BFM, basic maintenance flow,	17.6 – 34.1	
RVA, 25% quantile of monthly flow	15.3 – 142.1	Computed via the IHA/RVA 7.0 package
RVA, 75% quantile of monthly flow	37.1 – 409.6	
Wetted perimeter - discharge	13.1 – 20.4	Breakpoint analysis at five characteristic cross-sections, between Stratos and estuary

What about small hydropower plants?

- According to Greek legislation the hydraulic power generated by hydroelectric plants, which have a total installed capacity more than 15 MW, is considered as renewable (Act 3468/2006 on the Production of Electricity from Renewable Energy Sources, Art. 27, par. 4).
- The cumulative capacity of all small hydroelectric plants that are currently in operation (122 units) is 240 MW; totally, 410 units have been licensed with capacity up to 915 MW* (for comparison, the power capacity of Kremasta is 437 MW).
- Most of them only comprise a weir, i.e. a water intake structure in which water is abstracted from the main flow through a trash rack over a gutter; next the water is diverted to a head pond and returns to the river after passing through the penstock (**run-of-river plants**).
- Although considered “greens” (in contrast to “evil” hydroelectric dams), several green problems are encountered in practice:
  - Break of **river connectivity**;
  - Definition, implementation and monitoring of **e-flows**;
  - **Fish passage** facilities are of questionable effectiveness.

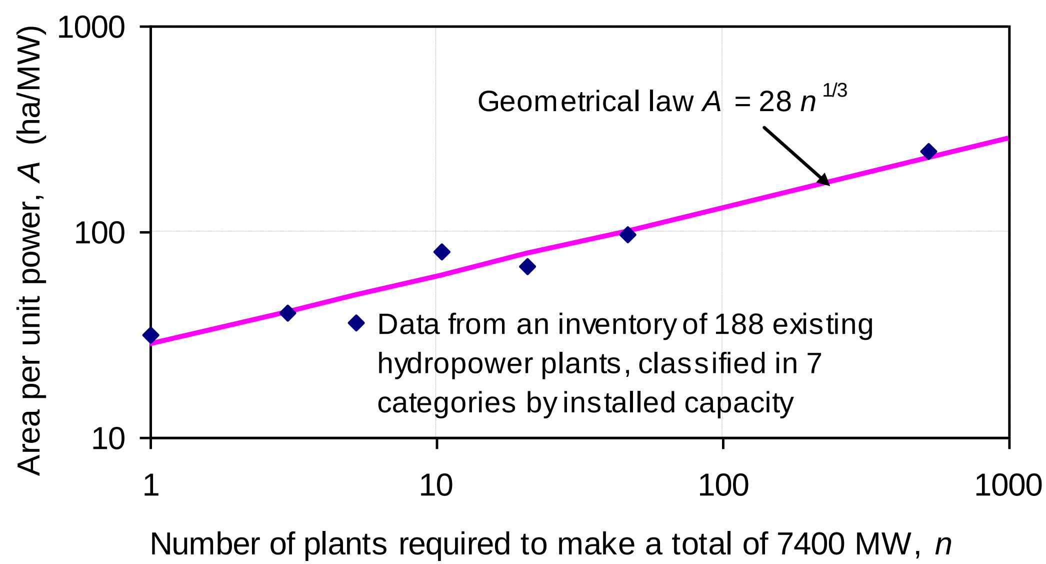

Main components (inlet, spillway, fish passage, diversion channel) of small hydroelectric plant at Theodoriana

(*) http://microhydropower.gr/wp-content/uploads/2019/02/20190208_Verdetec-19-RAE_Dr.-DP.pdf

Are actually many small water projects better than few large ones? The key issue of scale

- Consider the case of Marathon dam, creating a reservoir with useful capacity 32 hm^3, which extends over an area of 2.57 km^2.
- Let also consider a rectangular water supply tank with dimensions 40×25×5 m (5000 m3).
  - Equivalent number of small-scale tanks = 6400
  - Equivalent surface = 6.40 km^2 (~2.5 times the area of Marathon)
- Which of the two schemes would be more expensive and less efficient in an operational context?
- Which one would cause more environmental impacts?

Remark: If a certain volume *V* is divided in *n* geometrically similar shapes, the total area is proportional to $n^{1/3}$ and the total perimeter is proportional to $n^{2/3}$. This rule has implications on several fields, from the area occupied by reservoirs to the hydraulic losses in pipes, turbines and pumps. The issue of scale in water resource systems is thoroughly discussed by Koutsoyiannis (2011).

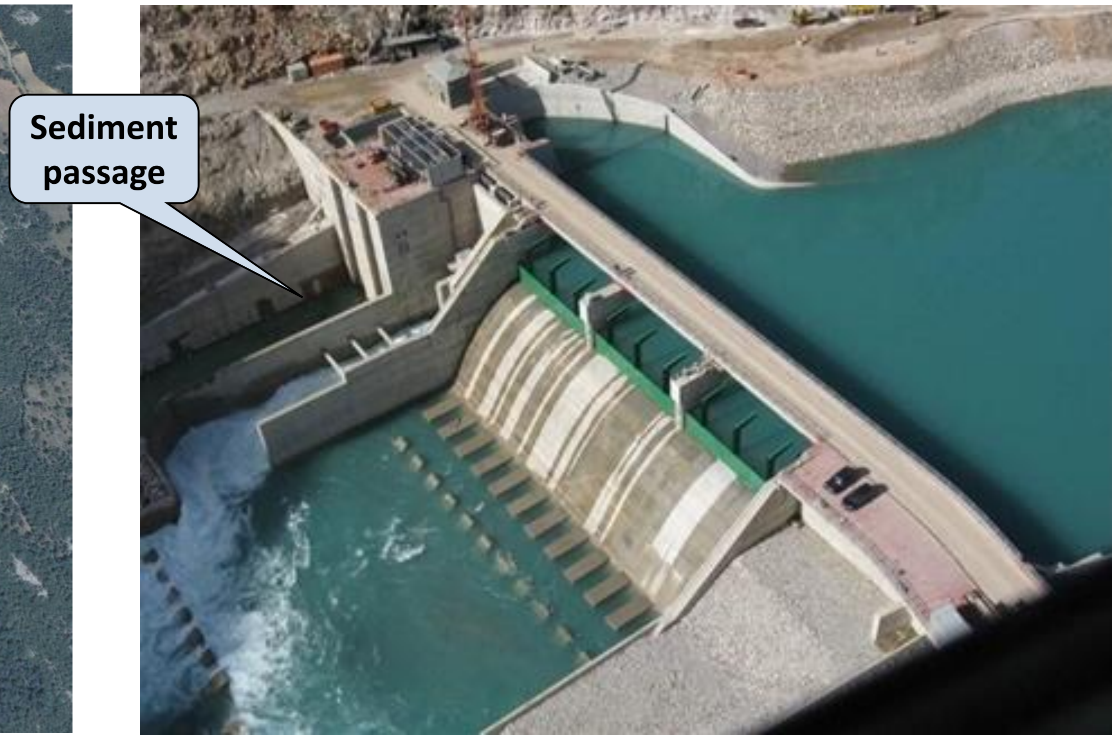


Real problems of Greek dams – asking for realistic solutions

- Sub-optimal and unsustainable **operation policies**, in an attempt to handle multiple objectives and conflicting interests:
  - Technological advances offer plethora of methodologies and computational tools for optimizing water management practices;
  - Is it easy to implement theoretically optimal policies in practice?
  - Is it easy to imply the application of such policies?
- Due to limited human and financial resources, the **supervision and maintenance** of a number of medium and small-scale dams (mainly for irrigation purposes) is not satisfactory:
  - Low-cost automatic monitoring infrastructures
  - Monitoring infrastructures also require supervision and maintenance.
- **Assessment and implementation of e-flows** (under limited data or totally missing data):
  - Need for systematic measurements (river quality & quantity)
  - Need for methodologies adapted to Greek rivers;
  - Need for supporting works (allowing regulations)
- A new element in dam operation: **artificial flooding**
  - Beneficial effects on the river geomorphology, sediment transport, water quality and the downstream ecosystem's revitalization;
  - Discourages illegal occupation and change of use of the wider river bed (floodplains).

Modern dams make it better: Dafnozonara @ Achelous

- In-stream, low head, small hydroelectric dam (2009)
- Dam height 12 m, increased head via overturning gates along the spillway
- Power capacity 5.93 MW, mean annual energy production 40 GWh



Is there space for new dams in Greece?

- Greece's low exploitation of hydropower potential (31%) allows for **further development of hydroelectricity**, which is the most effective renewable technology.
- The multipurpose character of large hydropower projects can also help resolving **water scarcity** and **groundwater degradation** problems (Acheloos-Thessaly scheme).
- Several small and medium-scale dams may also needed to meet increased water and food supply needs at specific areas (e.g., islands), to improve the **reliability** of associated hydrosystems and **minimize deficits** (particularly during summer months).
- There is plain space for developing **reversible** (pumped-storage) plants, either by constructing new storage projects as well as by employing technical adaptations to older ones, thus formulating **hybrid renewable energy systems**, by mixing hydroelectricity with other renewable sources (wind, solar, biofuels).
- In contrast to running opinions, **large water projects** may be preferable than equivalent small ones:
  - because only these are energy-efficient and multi-purpose;
  - because they are much more resilient against the perpetually changing climate;
  - because they can be less damaging for the environment;
  - because of the economy of scale;
- Proper design and control of water projects and associated hydrosystems can ensure a **fair equilibrium** between **anthropogenic and environmental needs**.

Epilogue: Removing dams or put them in operation? The Greek drama of upper Achelous hydroelectric dams

- The most impressive example of modern Greek irrationalism against dams are the Mesochora (160 MW) and Sykia projects (120 MW), in the Upper Achelous River. The dam and the hydropower plant of Mesohora are ready since 2001, while the dam at Sykia is incomplete (total investment >500 M€).
- Putting the Mesochora project in immediate operation would ensure ~340 GWh/year of hydroelectric energy, corresponding to a benefit of ~25 M€/year for the national economy.
- Recent discussion: Tyralis *et al.* (2017).

References

- Christofides, A., A. Efstratiadis, D. Koutsoyiannis, G.-F. Sargentis, & K. Hadjibiros, Resolving conflicting objectives in the management of the Plastiras Lake: can we quantify beauty?, *Hydrology and Earth System Sciences*, 9(5), 507-515, 2005.
- ECOS Consultants S.A., *Specific Technical Study for the Ecological Flow through Stratos Dam*, Public Power Corporation, Athens, 2009.
- Efstratiadis, A., A. Tegos, A. Varveris, & D. Koutsoyiannis, Assessment of environmental flows under limited data availability – Case study of the Acheloos River, Greece, *Hydrological Sciences Journal*, 59(3-4), 731-750, 2014.
- Efstratiadis, A., & K. Hadjibiros, Can an environment-friendly management policy improve the overall performance of an artificial lake? Analysis of a multipurpose dam in Greece, *Environmental Science & Policy*, 14(8), 1151-1162, 2011.
- Greek Committee on Large Dams, *The Dams of Greece*, 2013 (http://www.eeft.gr/Fragmata_Elladas_201311.pdf).
- Hydroexygiantiki S.A., *Integrated Study of the Environmental Impacts from Acheloos Diversion*, Directorate for Acheloos Diversion Works, General Secretariat of Public Works, Ministry of Environment, Planning & Public Works, Athens, 1995.
- Koutsoyiannis, D., A. Andreadakis, R. Mavrodimou, A. Christofides, N. Mamassis, A. Efstratiadis, A. Koukouvinos, G. Karavokiros, S. Kozanis, D. Mamais, & K. Noutsopoulos, *National Programme for the Management and Protection of Water Resources*, Department of Water Resources & Environmental Engineering, NTUA, 2008.
- Koutsoyiannis, D., Scale of water resources development and sustainability: Small is beautiful, large is great, *Hydrological Sciences Journal*, 56(4), 553–575, 2011.
- Makropoulos, C., A. Efstratiadis, G. Karakatsanis, D. Nikolopoulos, & A. Koukouvinos, Estimation of financial cost of raw water - Final report, *Update of Financial Cost of Raw Water for Athens Water Supply*, Department of Water Resources & Environmental Engineering, NTUA, 2018.
- Koutsoyiannis, D., N. Mamassis, A. Efstratiadis, N. Zarkadoulas, & Y. Markonis, Floods in Greece, *Changes of Flood Risk in Europe*, edited by Z. W. Kundzewicz, Ch. 12, 238-256, IAHS Press, Wallingford – International Association of Hydrological Sciences, 2012.
- Sargentis, G.-F., R. Ioannidis, G. Karakatsanis, S. Sigourou, N. D. Lagaros, & D. Koutsoyiannis, The development of the Athens water supply system and inferences for optimizing the scale of water infrastructures, *Sustainability*, 2019 (in press).
- Tegos, A., W. Schlüter, N. Gibbons, Y. Katselis, & A. Efstratiadis, Assessment of environmental flows from complexity to parsimony – Lessons from Lesotho, *Water*, 10(10), 1293, 2018.
- Tyralis, H., A. Tegos, A. Delichatsiou, N. Mamassis, & D. Koutsoyiannis, A perpetually interrupted interbasin water transfer as a modern Greek drama: Assessing the Acheloos to Pinios interbasin water transfer in the context of integrated water resources management, *Open Water Journal*, 4(1), 113–128, 12, 2017.
- Xanthakis, M., *Soil erosion study in mountainous basins with modern technological tools*, PhD thesis, Harokopio University, 2011.
- Zarris, D., E. Lykoudi, & D. Koutsoyiannis, The evolution of river sediment deposits in reservoirs as a dynamic phenomenon – Application to the Kremasta reservoir, *Proceedings of the 6th Panhellenic Conference of the Greek Geographical Society*, Thessaloniki, 2, 363-370, Aristotle University of Thessaloniki, Greek Geographical Society, 2002.

Acknowledgments: N. Mamassis for providing data for Greek dams; D. Koutsoyiannis for exchanging ideas and for his fruitful suggestions.