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Revisiting the management of water-energy systems under the umbrella of resilience optimization

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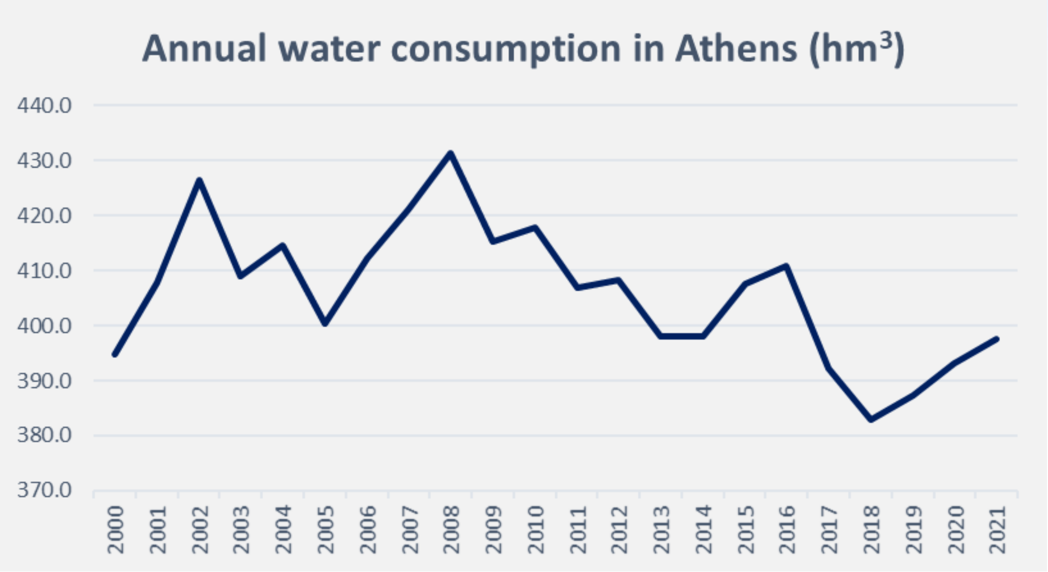
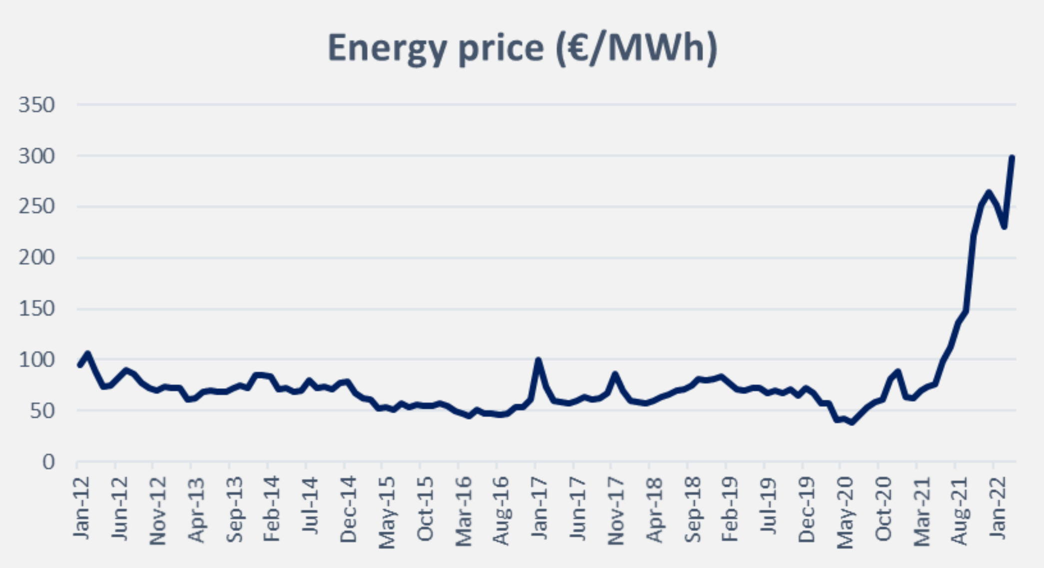
Motivation: The concept of optimality in the water-energy nexus

- All typical systems analysis problems across the water-energy nexus (strategic planning, design, long-term management, real-time control) are formalized as **multicriteria optimization** problems.
- Major hypothesis: optimization of major control components (reservoirs, hydropower stations, pumps, etc.) under **steady-state** conditions.
- The steady-state approach in water-energy optimization ignores significant **facets of change**, regarding:
  - the system's properties (technical, economic);
  - the hydrometeorological drivers (major assumption: the statistical characteristics of the observed data dictate the future hydroclimatic regime);
  - the complex interactions of society against all kinds of external signals, which are reflected in the water and energy demands;
  - the deviations of the theoretical optimal policies from their application in the field.
- Under this context, the underlying optimization task is solved subject to a set of reasonable (?) hypotheses that lead to a unique **optimal solution**, which is assumed representative (?) of future conditions.

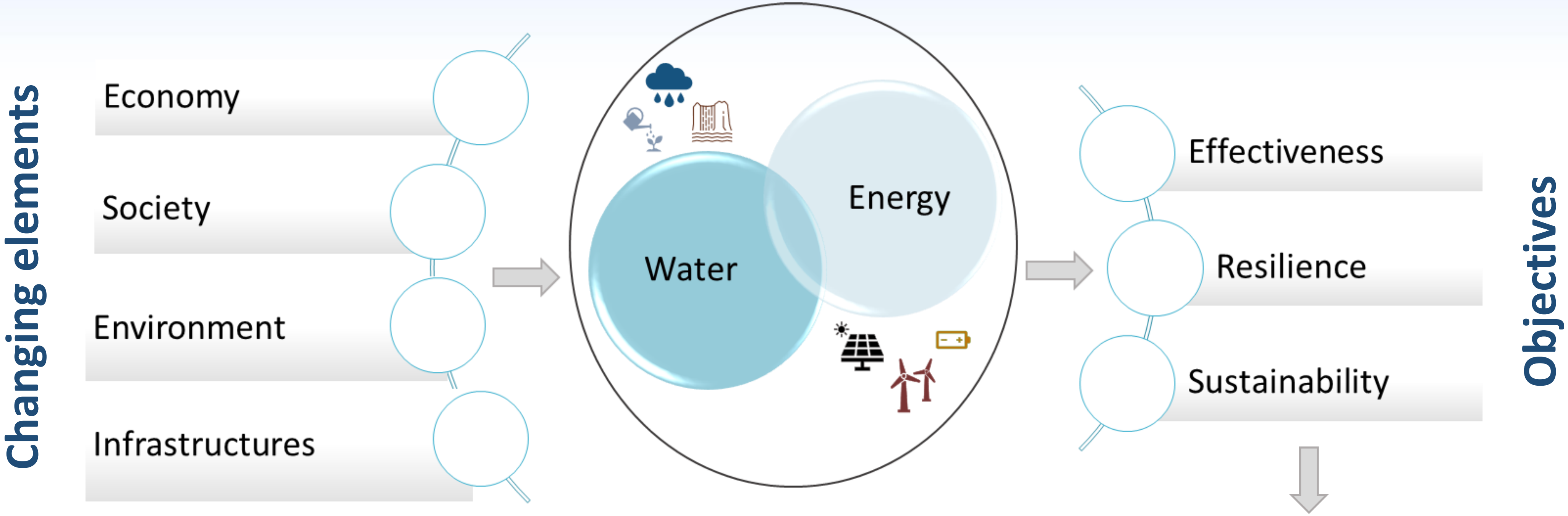
Is the steady-state hypothesis realistic?

- All aspects of real-world water-energy systems are subject to **unpredictable changes** across all scales.
- Part of this changing behavior can be systematically modelled through **probabilistic approaches** that allow to represent "structured" randomness, namely:
  - Hydrometeorological inputs, expressed as stochastic processes (yet under the stationarity hypothesis);
  - Uncertainties embedded within modelling procedures (e.g., by assigning randomly varying parameters).
- The rest (and maybe most important!) part of change refers to non-systematic behaviors, mainly associated with **social reactions and interactions** and **abnormal ("black-swan") events** (e.g., economic, energy, health crises), which cannot be explained (and described) in probabilistic means.





Embedding resilience within the water-energy nexus

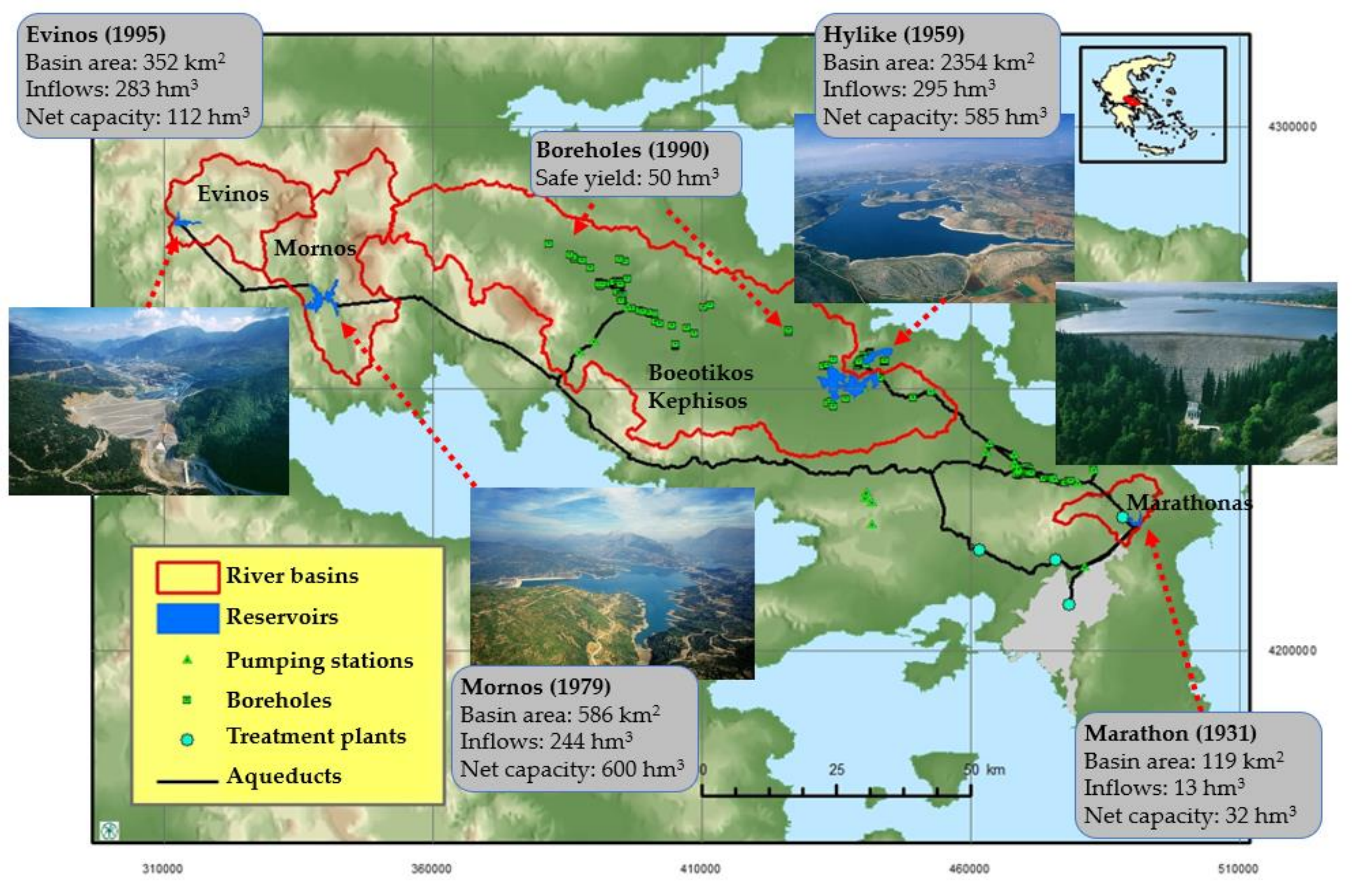


The concept of resilience imposes a paradigm shift, i.e., seeking for optimal solutions that remain robust across increasing pressures to water-energy systems, which are **beyond their “normal” operational conditions**.

Decision-making

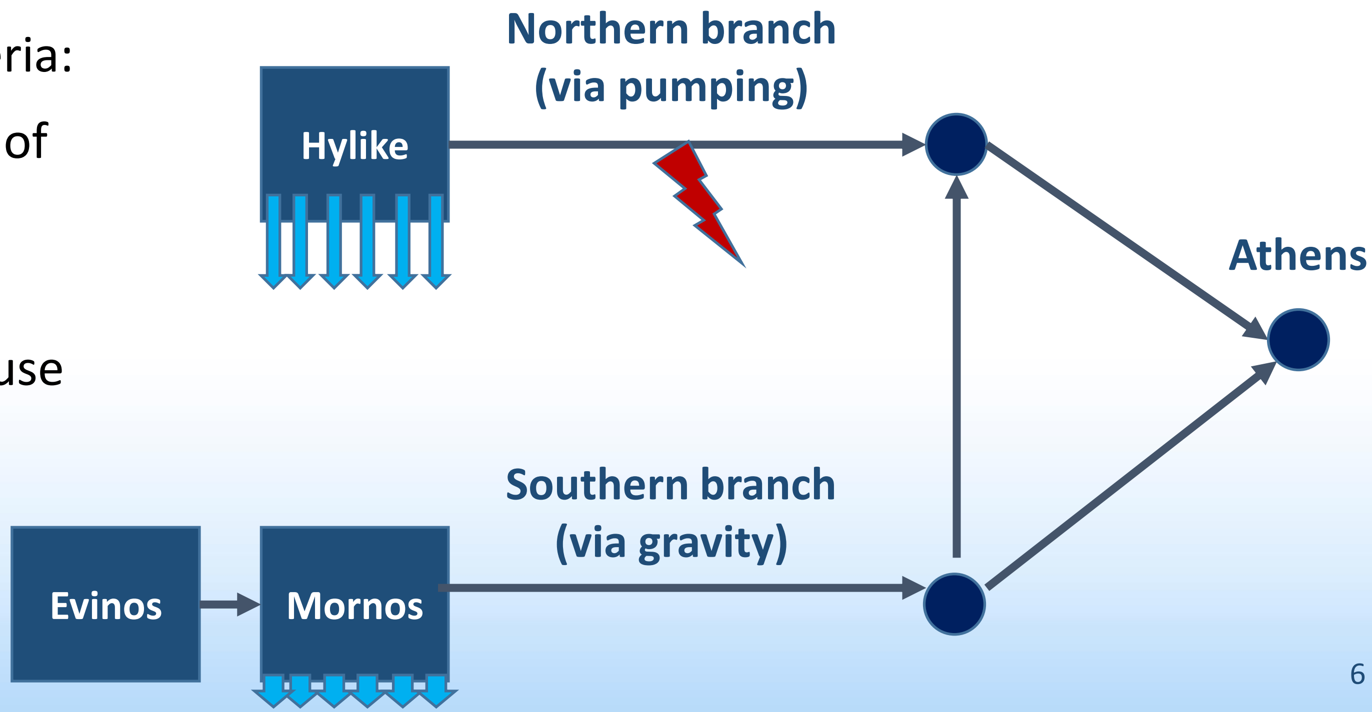
The raw water supply system of Athens

- Extends over an area of 4000 km^2.
- Comprises four reservoirs, 350 km of aqueducts, 15 pumping stations, dozens of boreholes (emergent resources), and four water treatment plants.
- Provides drinking water to the Athens Metropolitan area (~4 million people), also serving domestic, industrial, irrigation and environmental uses across the aqueduct network.
- Mean annual inflow 850 hm^3, mean annual demand 480 hm^3.



Management challenges (also responding to the question where is the water-energy nexus?)

- Water abstraction and conveyance from lake Hylike and the boreholes through pumping, with significant impacts to the **operational cost** of the system (in contrast to Evinos-Mornos complex, operating via gravity).
- Hylike lies on an extended karst background, resulting to substantial underground losses that may reach up to half of its storage capacity (~300 hm^3/year);
- The long-term management policy of the water-energy system is subject to two conflicting criteria:
  - Maximization of **reliability** → minimization of water losses → systematic use of Hylike
  - Minimization of **energy (pumping) cost** → systematic use of Evinos-Mornos, minimal use of Hylike and groundwater resources
- Desirable **reliability level**: 99% (annual basis)



Water-energy management framework: methods and tools

- The exploration of the water-energy policy options is employed through the use of **Hydronomeas** software, driven with synthetic data that are produced via the **anySim** package; both are key components of a broader decision support system for the supervision and management of the water resource system of Athens.
- The methodological framework is based on the triptych:
  - **Parameterization** of the management policy of the water-energy system, by means of operational rules of its major control elements (reservoirs, boreholes);
  - **Stochastic simulation** of the system's dynamics:
    - Representation of inflows and demands as stochastic processes → generation of **synthetic time series** that reproduce the probabilistic regime and dependence structure of parent historical data;
    - Stepwise allocation of unknown water and energy fluxes, for given inflows, demands and operation rules → formalization as a **network linear programming** problem.
  - **Optimization** of the long-term performance of the system, expressed in **multicriteria** terms (statistical metrics that are accounted for are reliability, energy consumption, pumping cost, deficits, etc.).

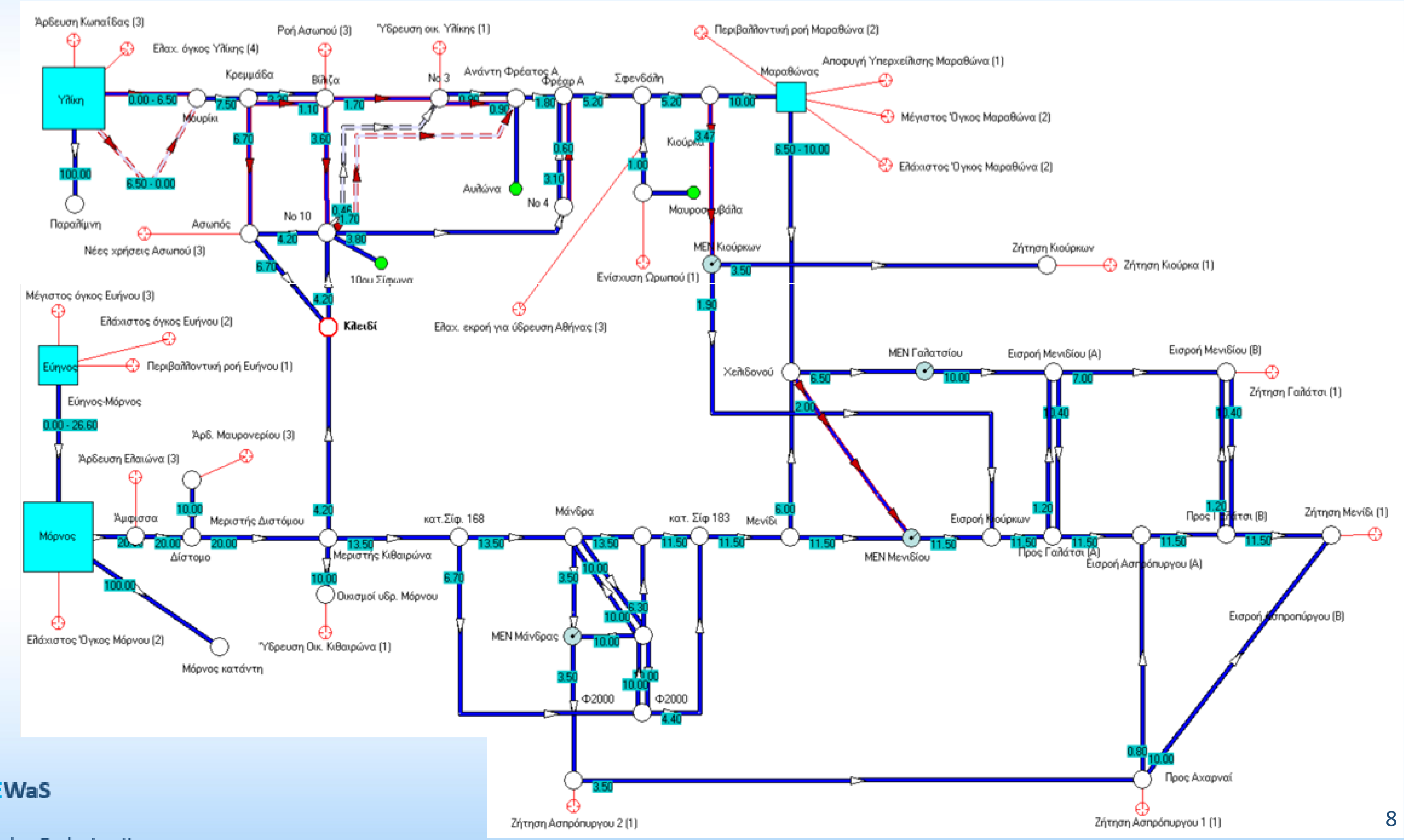
Conceptual model of the water resource system of Athens

The parameterization-simulation-optimization framework, implemented within Hydronomeas:

Nalbantis & Koutsoyiannis (1997); Koutsoyianns *et al.* (2003); Koutsoyiannis and Economou (2003); Efstratiadis *et al.* (2004)

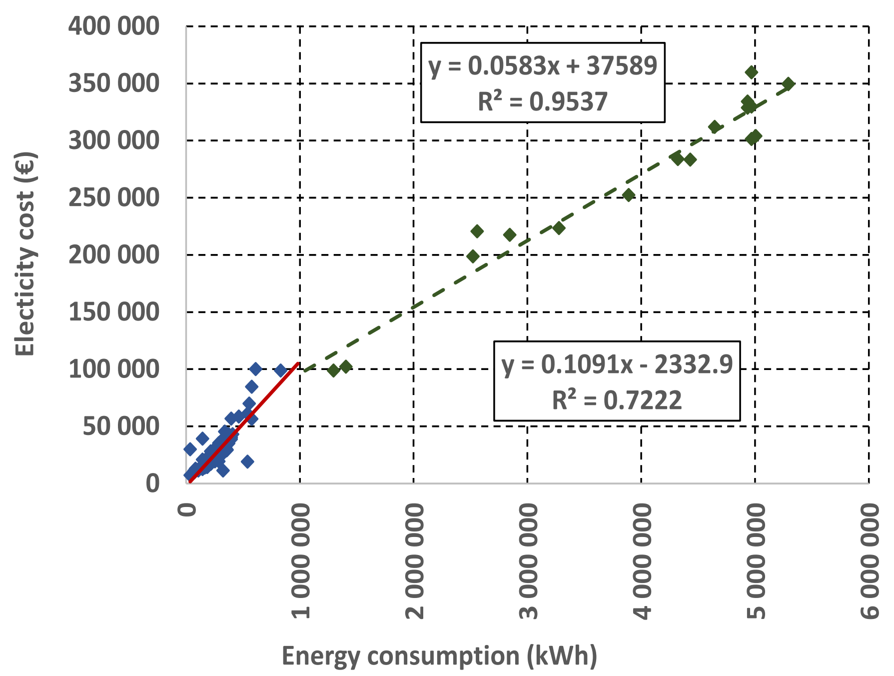
THe anySim package for stochastic simulation and time series generation:

Tsoukalas *et al.* (2020)



Baseline scenario: inputs & assumptions

- Simulation horizon: 2000 years (24 000 months)
- Constant demands, following typical seasonal patterns (Athens: 400 hm^3/year ≈ mean annual value of last decade);
- Hierarchical classification of water uses and constraints:
  - **High priority**: water supply and environmental uses;
  - **Medium priority**: reservoir storage controls (min, max);
  - **Low priority**: irrigation uses.
- Optimized operation rules by minimizing an overall cost function:
  - **Mean annual deficit cost** (assignment of unit penalties 1.0 €/m^3 for water supply and 0.20 €/m^3 for irrigation, to ensure the desirable reliability level of 99% for Athens).
  - **Mean annual energy cost** (pumps, boreholes);
- Alternative rules, manually configured to be more conservative.

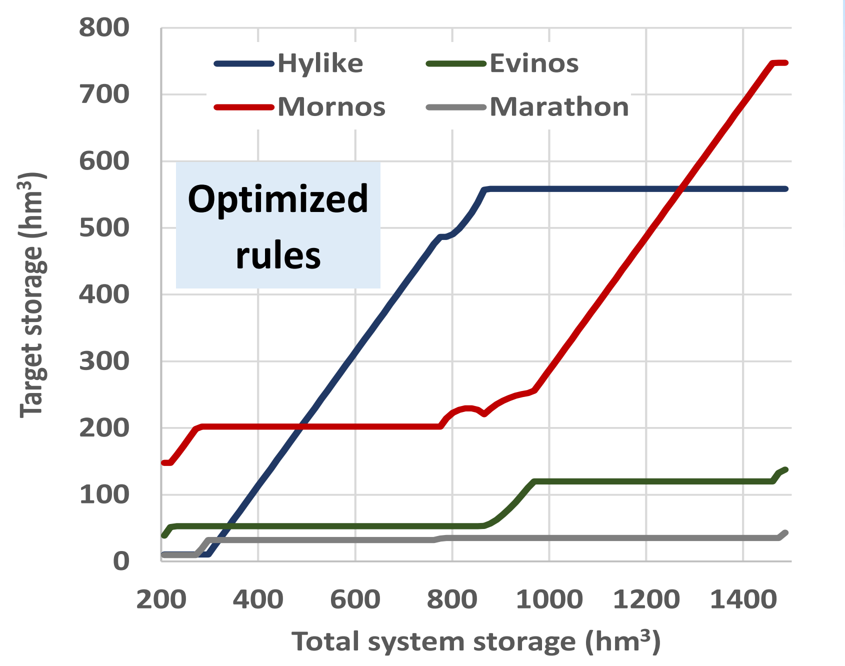


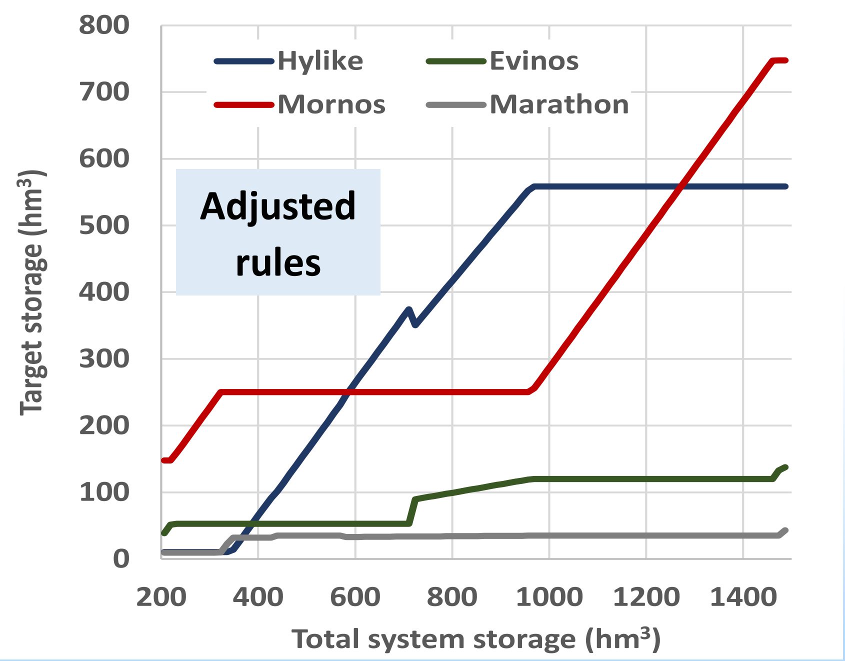
Electricity (pumping) costs, generally expressed as stepwise linear functions of monthly energy consumption; the associated parameters (activation cost, variable costs) are empirically derived on the basis of historical data (example for central pumping station at lake Hylike)

Baseline scenario: operation rules & results

	Optimized	Manually adjusted
Reliability of Athens' water supply (%)	99.0	99.7
Abstraction from Mornos (hm^3)	442.9	442.0
Abstraction from Hylike (hm^3)	25.2	29.7
Abstraction from boreholes (hm^3)	10.2	7.3
Energy consumed in pumps (GWh)	24.2	30.0
Energy consumed in boreholes (GWh)	9.9	6.8
Total energy consumption (GWh)	34.1	36.9
Total energy cost (million €)	2.73	2.90
Water supply deficit (hm^3)	0.26	0.11
Irrigation deficit (hm^3)	0.76	1.36

Which rule is more resilient, when the system is stressed beyond "normality" (baseline scenario)?





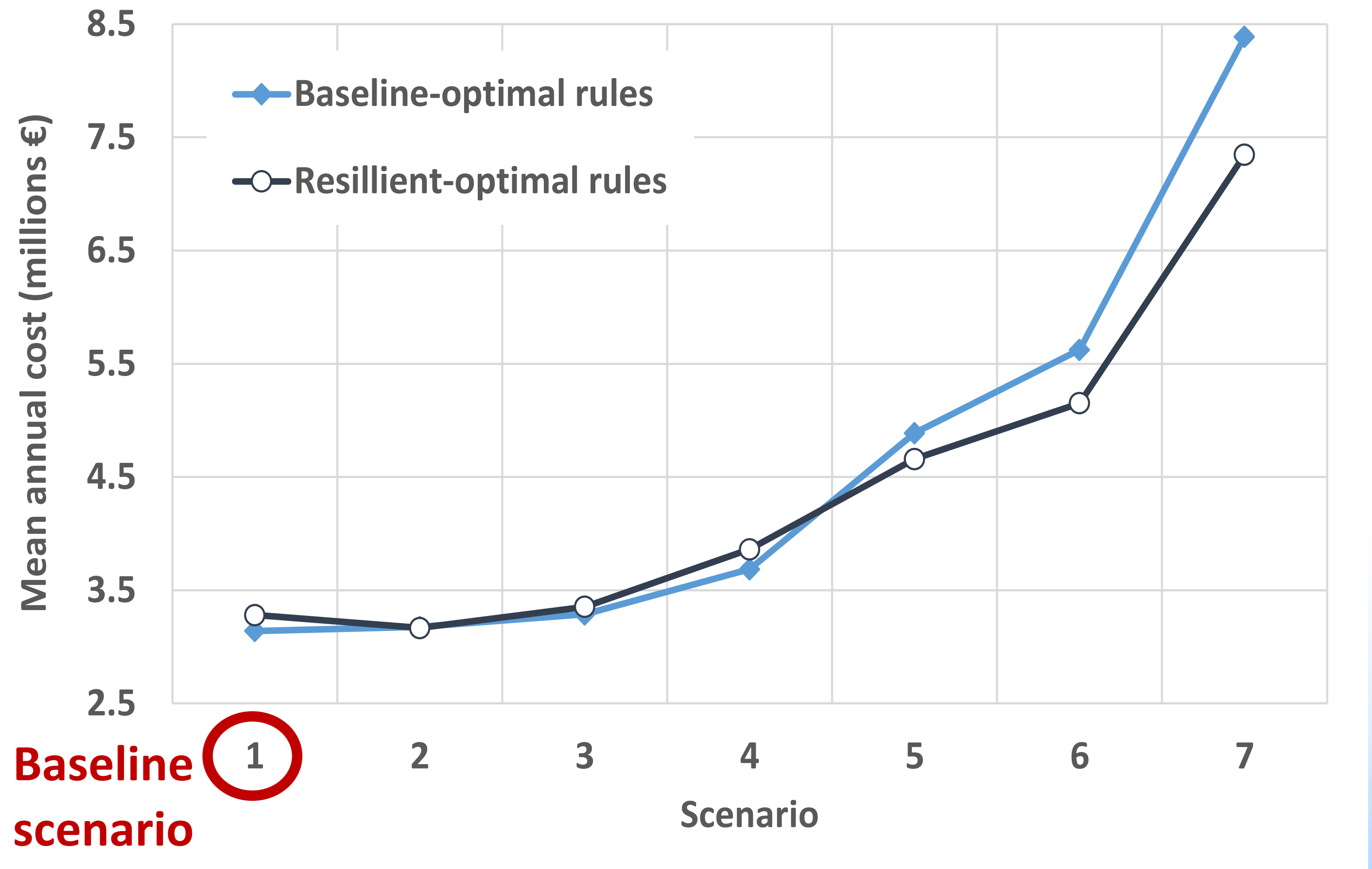
Stress scenarios

- Assessment of two operational policies (optimal, conservative) against **six stress scenarios**, reflecting different aspects of potential disturbance (**socioeconomic, hydroclimatic, technical**).
- All scenarios represent **plausible deviations from "normality"** (baseline scenario assumptions), inducing important yet not structural changes to the system's state.

id	Description	Driver of change
1	Baseline scenario	
2	Setting of irrigation targets in a higher priority level	Social
3	50% decrease of available groundwater resources	Hydroclimatic
4	20% increase of pumping cost	Economic
5	Increase of leakage losses across aqueducts from 5 to 10%	Technical
6	Increase of Athens's demand to 430 hm^3 (max. observed value)	Socio-economic
7	Increase of Athens's demand to 450 hm^3 (long-term projection)	Socio-economic

Evaluation of operational rules against scenarios of varying stresses

- For the first three stress scenarios the optimal rule is equivalent or slightly overperforms the conservative one.
- The other three scenarios highlight that **the conventional definition of "optimality" does not promise resilience against situations where the system is pushed beyond of its standards**.
- Following the concept proposed by Makropoulos *et al.* (2018), provided that **the area below the two curves represents an overall cost metric**, the second rule should be preferred, as more resilient.
- The conventionally optimal rule for the last scenario ensures an unacceptable low reliability (91.3%), while the resilient rule still achieves an acceptable reliability level (96.2%), with a relatively small increase of mean energy cost (4.77 vs. 4.33 M€).



Conclusions

- Triggered by the **violent changes** that span over all aspects of **sociotechnical systems**, it is essential to reconsider the far-reaching quest of **optimality** under the concept of **resilience**.
- In the context of the **water-energy nexus** , the incorporation of resilience within the configuration of management policies is a crucial presupposition towards the road to **sustainability**.
- Taking as example the challenging water-energy system of Athens, we revisit its long-term management policy, conventionally handled as an optimization problem under **steady-state conditions**.
- By stressing this under a number of **plausible disturbances**, caused by **social, economic, hydroclimatic and technical changes**, we manifest the necessity for adopting more conservative (in terms of reliability), although more expensive, operation rules than the ones optimized against the baseline scenario.
- Forthcoming research steps aim at enhancing the proposed protocol, by designing a procedure for the automatic generation of stress scenarios, formalized in **stochastic setting**, and establish a generalized optimization approach by setting as objective function a **resilience metric** that accounts for the global system's response against all stress scenarios.

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Thank you!

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