Stress-testing for water-energy systems by coupling agent-based models

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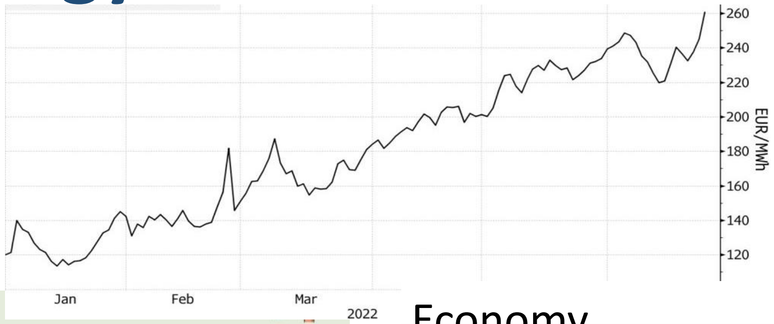
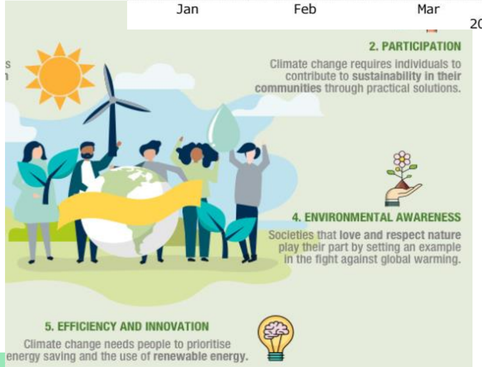
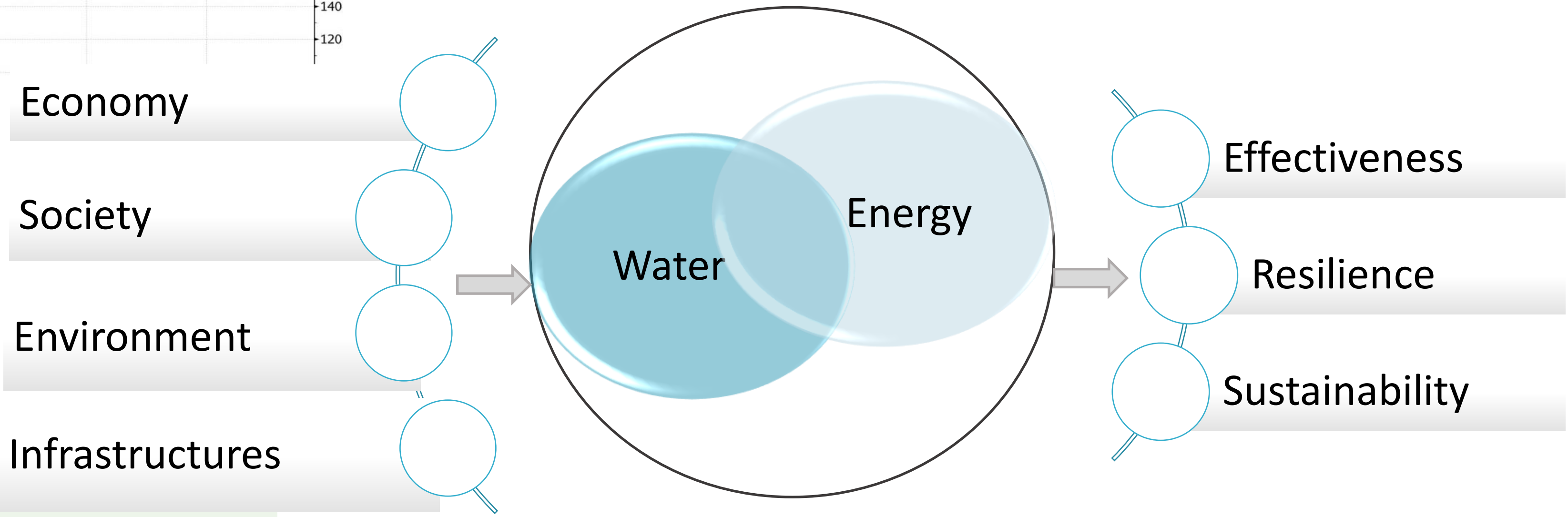
Motivation: The water-energy nexus as sociotechnical system

- The conventional modelling approaches systems across the water-energy nexus adopt the hypothesis of **steady-state** conditions, regarding the system's components.
- The steady-state approach in the management of water-energy systems misuses or 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, a comprehensive modelling framework of human agency in the context of water-energy systems under inherently varying environmental and socioeconomic conditions is necessary.

Water-energy nexus under uncertainty

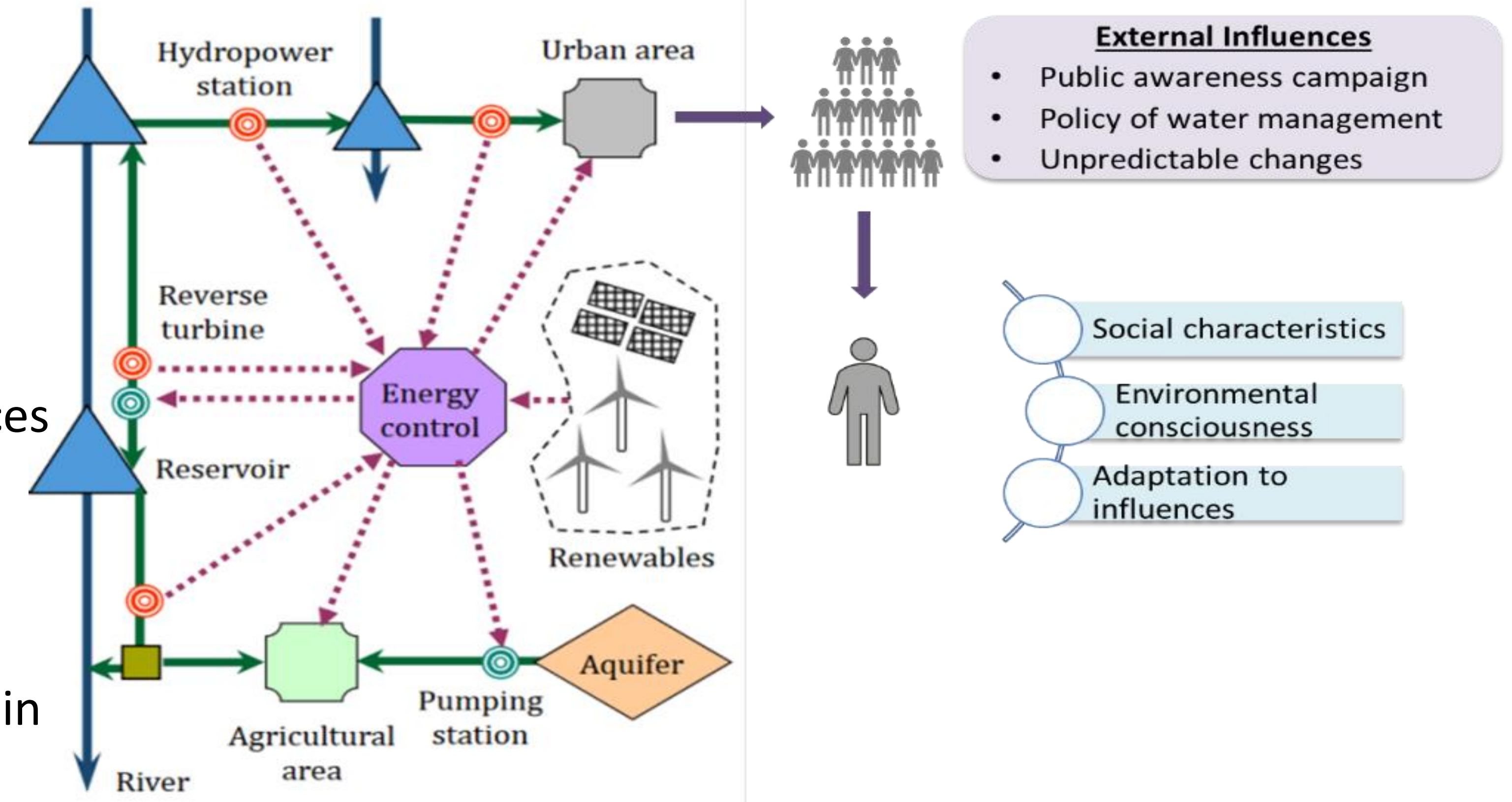






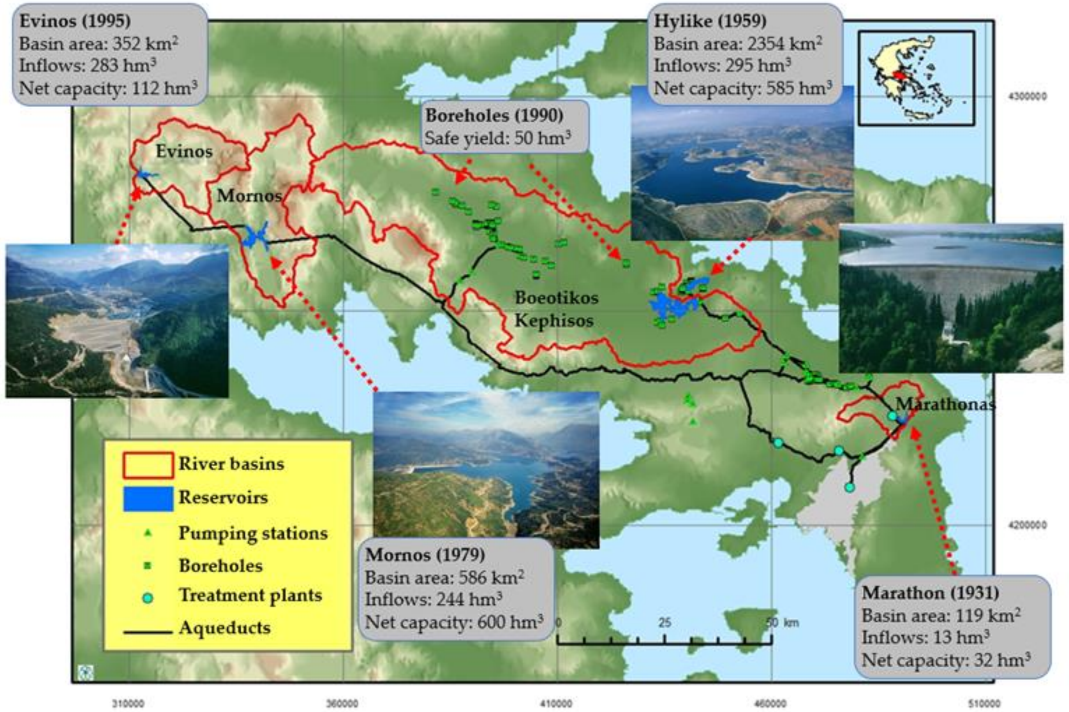
The social component in the water energy nexus

- Exploration and explanation of the sociotechnical factors across the water-energy nexus.
- Representation of the dynamic interaction between the human factor, i.e., the socio-economic system, and its technical background, i.e., water and energy resources and associated infrastructures.
- Transition from the theoretical context of sociology to a mathematical concept, in order to describe the complex and uncertain rules of society that are reflected in the water and energy consumption.



Proof of concept: The raw water supply system of Athens

- Key-characteristics of the raw water supply system of Athens:
    - Extends over an area of around 4000 km²,comprises four reservoirs, 350 km of aqueducts, 15 pumping stations, several dozens of boreholes, and four water treatment plants.
    - Last decade, the annual consumption did not exceed 400 hm³, while in the past it has exceeded 430 hm³.
- The mean annual inflow to the four reservoirs is 825 hm³, almost equally distributed to the three main reservoirs.
- The southern branch (Mornos aqueduct) carries water via gravity from the interconnected reservoirs of Evinos and Mornos, while the northern one transfers water from Hylike and the boreholes through pumping, with considerable cost.



Hylike is a natural lake, lying in a karstic background, and may lose half of its storage capacity in one year due to leakages

The water supply system of Athens as sociotechnical prototype: Methods and tools

Technical Component

- 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**.
- The methodological framework of the model is based on the triptych:
  - Parametrization of the operational policy of the system;
  - Stochastic simulation of the system's dynamics;
  - Optimization of the long-term performance of the system.

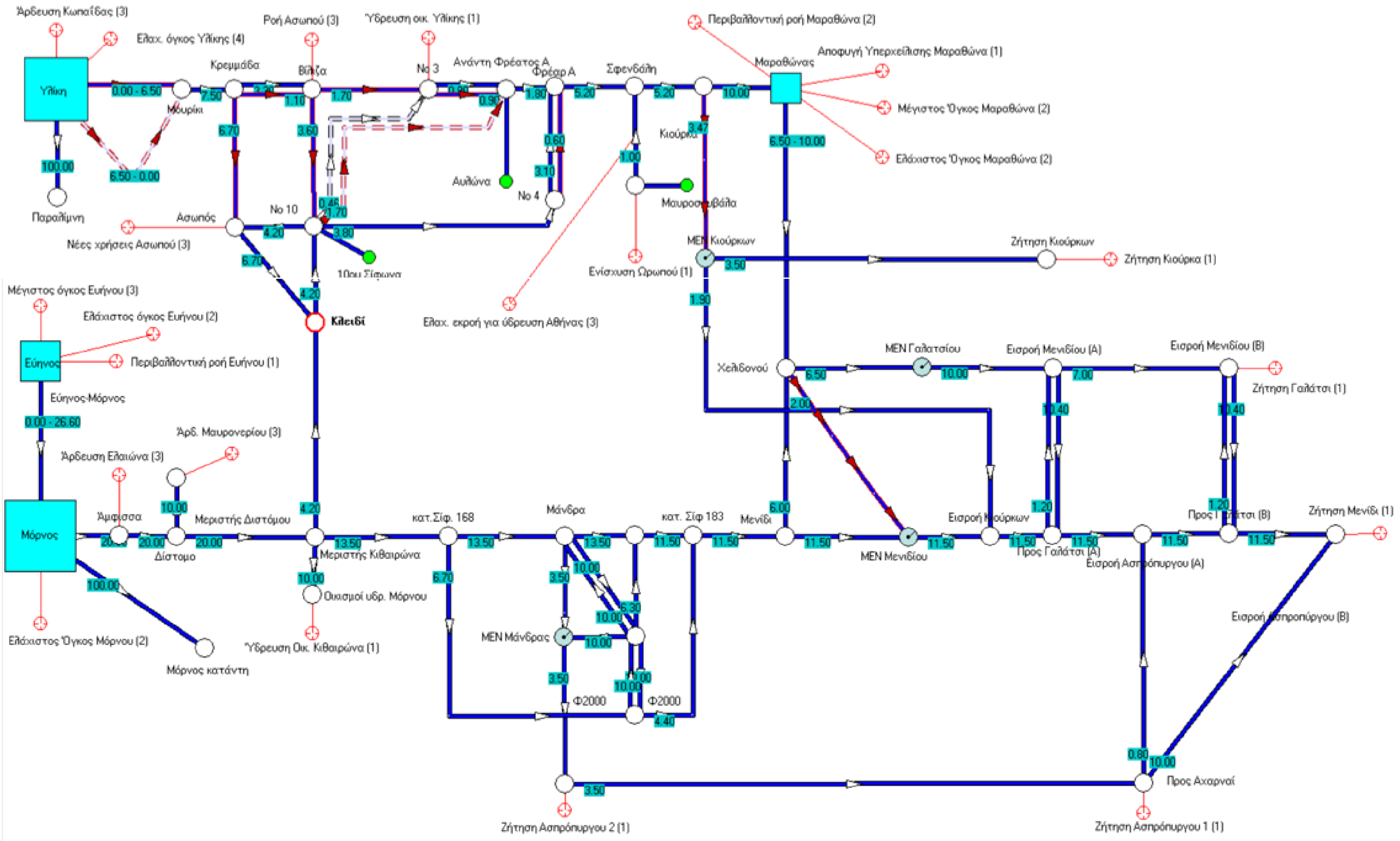
Socioeconomic Component

- The representation and the quantification of human factor is employed through **agent-based models** (ABM).
  - The water consumptions are considered as varying inputs (i.e., external demands), and are affected by internal and external influences, from the local and global socioeconomic environment (e.g., public awareness campaigns and energy price.)

Modelling Athens’s water system

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

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



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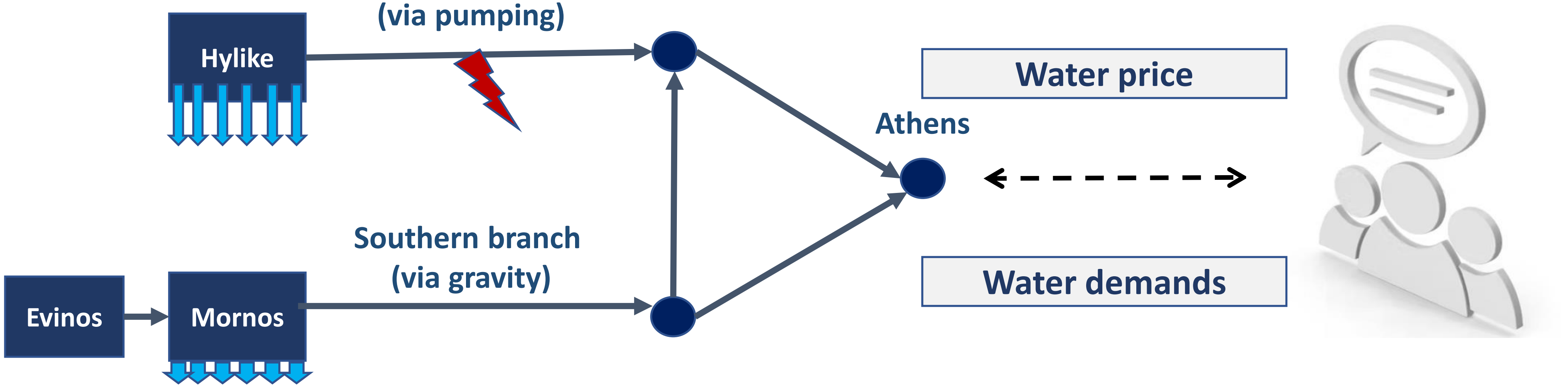
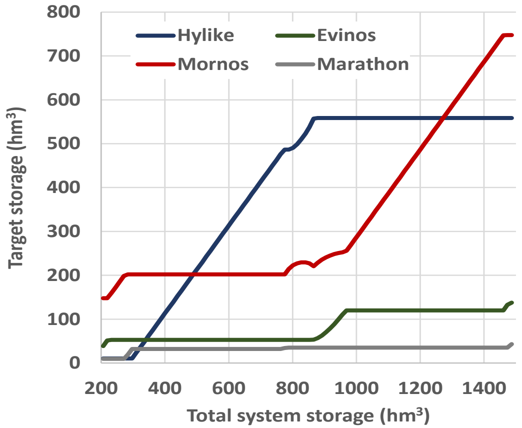
Modelling Athens's society

- **ABM** is the most promising tool, since it can both represent the socio-economic element and address the need for dynamic interaction of this within the water system.
- Herein, an agent-based modeling (ABM) tool will be used to simulate the behavior of the water users of the Athens's water system.
- Household agents are sub-grouped according to their characteristics: **Age, Income, Education level, Environmental Awareness**
- Their water consumption is driven by a) their **social network** (agent-agent) and b) the **external influences** (agent-environment).

Coupling of technical and social components



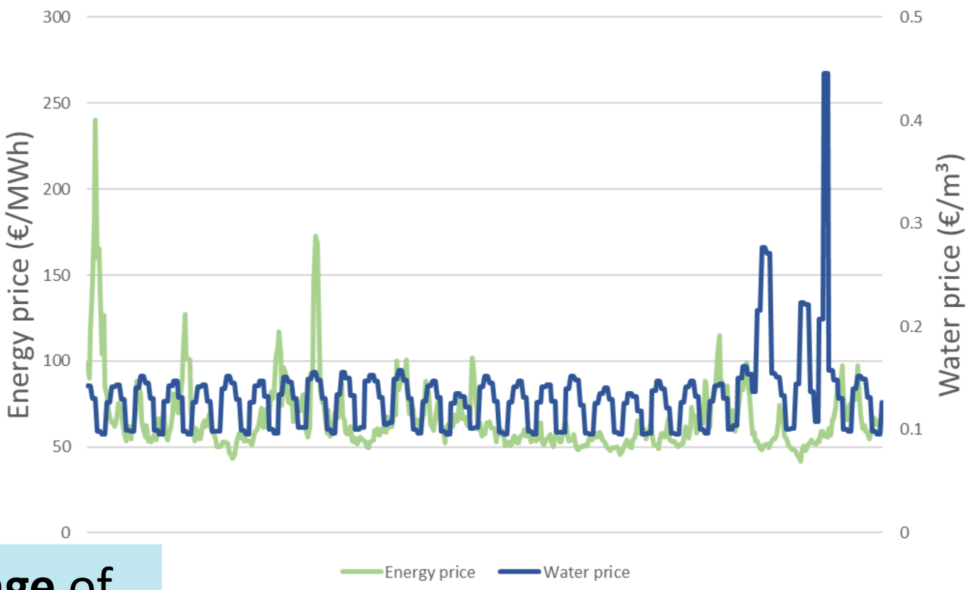
- The **operational rules** of the water resource system of Athens are extracted after a simulation-optimization procedure



- The **behavioral rules** of the Athens's households are based on the social theory, and they are adaptive to abnormal changes.

Coupling of technical and social components: Inputs

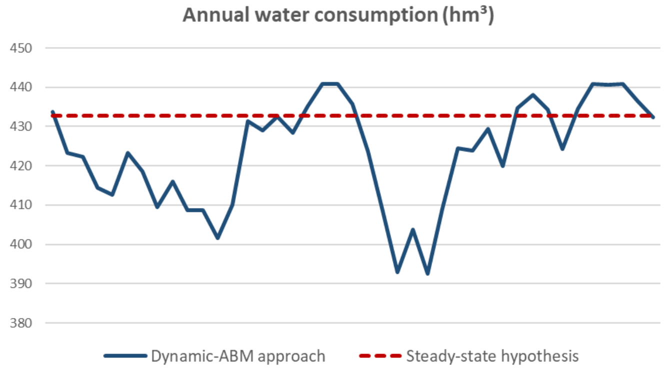
- Given the operational rules of the water system, the system is driven by monthly synthetic rainfall, runoff and evaporation time series of 2000 years length to produce the water balance
- A sample of 2000 years of energy price is generated based on the historical data and thus the water price depends on a)the energy price, b) the energy consumption, and c) the policy of the water utility.
- ABM uses the information of water price and the storage level of the entire system to **adapt** the water consumption.



Low water storage of the Athens's system "activates" media and public awareness campaigns to inform the society about water conservation

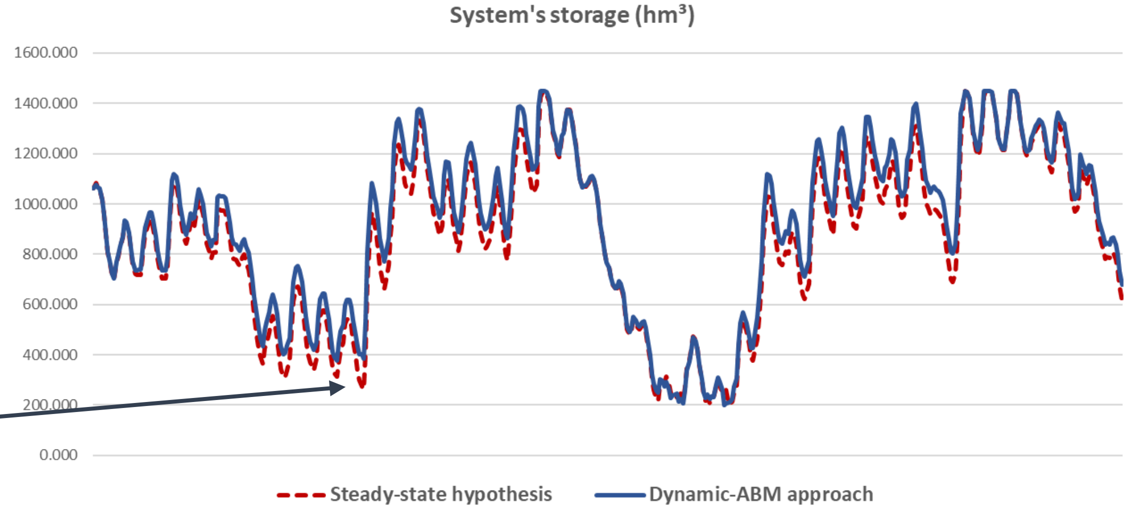
Coupling of technical and social components: Results

- The modelled water system runs with a **steady-state demand** (according to an observed pattern) through Hydronomeas software, extracting:
  - The optimized operational rules for the four reservoirs
  - The monthly storage of the system
  - The water price, as a result of the energy consumption due to water abstraction and the energy price



- The ABM uses as input the storage of the system and the water price. The agents interact with their environment (neighbors) and their individual stimulus (campaigns, water bills), resulting to **dynamic demands**.
- Finally, the water system re-runs as demand input that are extracted by ABM model.

Maximum relative distance: 7.8%



Conclusions

- Managing water resources for growing demands of energy and food while sustaining the environment is the greatest challenge of our era, especially when we are dealing with complex adaptive natural–human systems.
- Herein, a key result is the integration of the mathematical formalization of the human factor, from a bottom-up perspective, by adapting and enhancing agent-based theory, with technical simulations, e.g., water-energy planning and management models, under the novel prism of stochastic socio-hydrological systems.
- To assess the management of such systems, we attempt to stress-test them under different disturbances, which are driven by both expected and highly unpredictable changes e.g., socioeconomic by means of highly varying energy price, and hydrometeorological fluctuations.
- 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 generalised optimisation approach in order to generate new operational rules for the water system based on the ABM’s demands.

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