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

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ABSTRACT

1. The water-energy nexus under uncertainty

1.1. Setting the scene

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 (Machell et al., 2015). The performance of water-energy systems is strongly depending on hydroclimatic processes and human behaviors, while both components are highly uncertain and unpredictable in a long-term perspective. In this vein, the typical engineering approach across the water-energy nexus, in which the role of society is reflected in rather simplified means, e.g., in terms of water and/or energy demands, legal constraints, technical specifications and management rules, is insufficient. Herein, we propose the incorporation of the human factor to the long-term management policy of water-energy systems, since the social and the technical system are inextricably linked (Walker et al., 2015). 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 and hydrometeorological fluctuations, and black-swan events, respectively. By coupling the two major research fields, namely the water-energy nexus and the social behavior, in an uncertainty-aware framework, we introduce the concept of *stochastic socio-hydrological systems.* In this context, the response and adaptation of society plays the role of music, while the plethora of disturbances the role of the conductor.

1.2. The social component and its modelling

In order to establish a comprehensive approach for representing such complex sociotechnical systems, we first outline and explain all important synergies, complementarities and conflicts induced by the social factor. In addition to the obvious interaction of water and energy demands, also driven by weather conditions, we investigate several other social drivers, including decision-making, management policy and operation, and reaction to external influences and pressures.

An important issue, which deserves further investigation, is the response time of each factor. In particular, media and public awareness campaigns may take longer to create tangible effects, while sharp changes in energy and water prices may induce faster reactions. Furthermore, we also study the effect of crucial, urgent and abnormal circumstances, which are totally unpredictable and may affect both the micro- and macro-behavior of an entire society over the longer term. These include geopolitical changes, economic crises, pandemics, as well as long-term water shortages, causing major changes to spatiotemporal patterns of water and energy consumption. To simulate the human component of sociotechnical systems, we take advantage of recent advances in agent-based modelling (ABM), which integrate complex adaptive system theory and distributed artificial intelligence (Bonabeau, 2002). The key principle of ABMs is to divide a complex system into representative elements, called agents, characterized by their own data, knowledge and behaviors. By adopting a bottom-up approach, as demonstrated in Figure 1, to study the agent interactions both with the technical system and among each other, at the micro level, it will allow us to draw conclusions about the system's (emergent) behavior at the macro level.

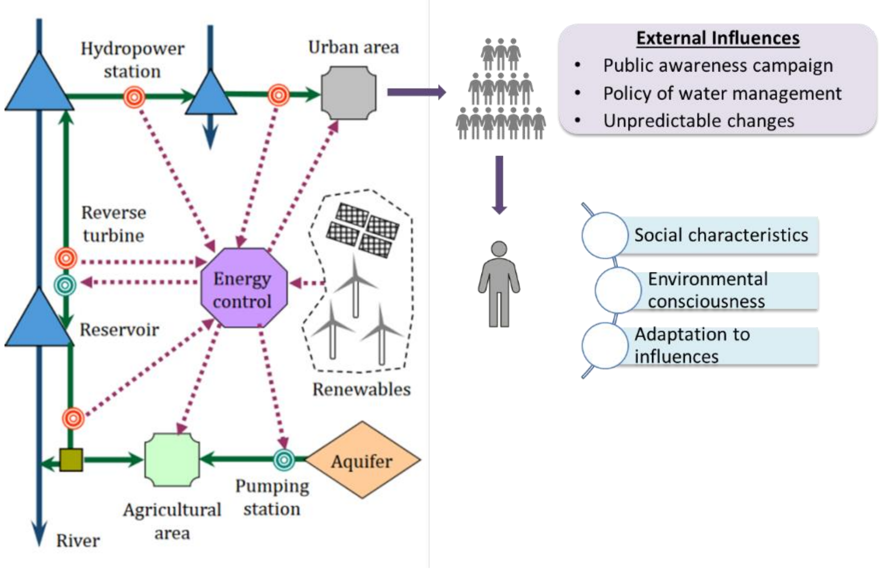

Fig. 1. Conceptual demonstration of a water-energy system taking account for the social component.

1.3. The hydrometeorological component and its modelling

In a highly fluctuating and eventually changing climate, the historical data of crucial hydrometeorological drivers, e.g., rainfall, runoff, and evaporation, provide insufficient information for the long-term assessment of water-energy systems under the stress-testing paradigm. To overcome this, we use stochastic models in order to provide synthetically-generated input time series that reproduce the probabilistic regime of the process of interest, as reflected in the historical data, and their long-term changes, that are of key importance in the assessment of reliability, sustainability and resilience of water-energy systems (Koutsoyiannis et al., 2009).

2. Revisiting the long-term management of the Athens water-energy system

As a proof of concept of the proposed framework, we analyze the complex and highly extended water-energy system of Athens, Greece, and we push it beyond its standards, in order to determine its turning point of resilience. Specifically, the water-energy system of Athens addresses intrinsically uncertain water supply and irrigation demands that may stress it across all scales, and it is also subject to a number of operational and environmental constraints. This system includes two interconnected reservoirs (Mornos, Evinos), providing water via gravity, as well as the natural lake Hylike, lying in a karstic background, providing water through pumping, with significant cost. In this vein, we investigate whether this system is successful, robust, and resilient under numerous external influences and stresses, by using as a key information the human's behavior.

The core simulation model employs a simplified representation of the main system elements, to estimate the abstractions from the three reservoirs, driven by synthetic inflow data of 2000 years length, and stochastic demands. The inflows are generated a priori, through the anySim stochastic simulation package (Tsoukalas et al., 2020). On the other hand, the demand data are provided by an ABM procedure, which accounts for dynamic information obtained from the simulation model, by means of storage conditions and associated water prices.

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