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.
The raw water supply system of Athens

- Extends over an area of 4000 km².
- 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 hm³, mean annual demand 480 hm³.
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 hm³/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); Koutsoyiannis 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 hm³/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 €/m³ for water supply and 0.20 €/m³ 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 Hylke)
### Baseline scenario: operation rules & results

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

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.

<table>
<thead>
<tr>
<th>id</th>
<th>Description</th>
<th>Driver of change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline scenario</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Setting of irrigation targets in a higher priority level</td>
<td>Social</td>
</tr>
<tr>
<td>3</td>
<td>50% decrease of available groundwater resources</td>
<td>Hydroclimatic</td>
</tr>
<tr>
<td>4</td>
<td>20% increase of pumping cost</td>
<td>Economic</td>
</tr>
<tr>
<td>5</td>
<td>Increase of leakage losses across aqueducts from 5 to 10%</td>
<td>Technical</td>
</tr>
<tr>
<td>6</td>
<td>Increase of Athens’s demand to 430 hm³ (max. observed value)</td>
<td>Socio-economic</td>
</tr>
<tr>
<td>7</td>
<td>Increase of Athens’s demand to 450 hm³ (long-term projection)</td>
<td>Socio-economic</td>
</tr>
</tbody>
</table>
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.
References


Thank you!

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