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Computational issues in complex water-energy optimization problems: Time scales, parameterizations, objectives and algorithms

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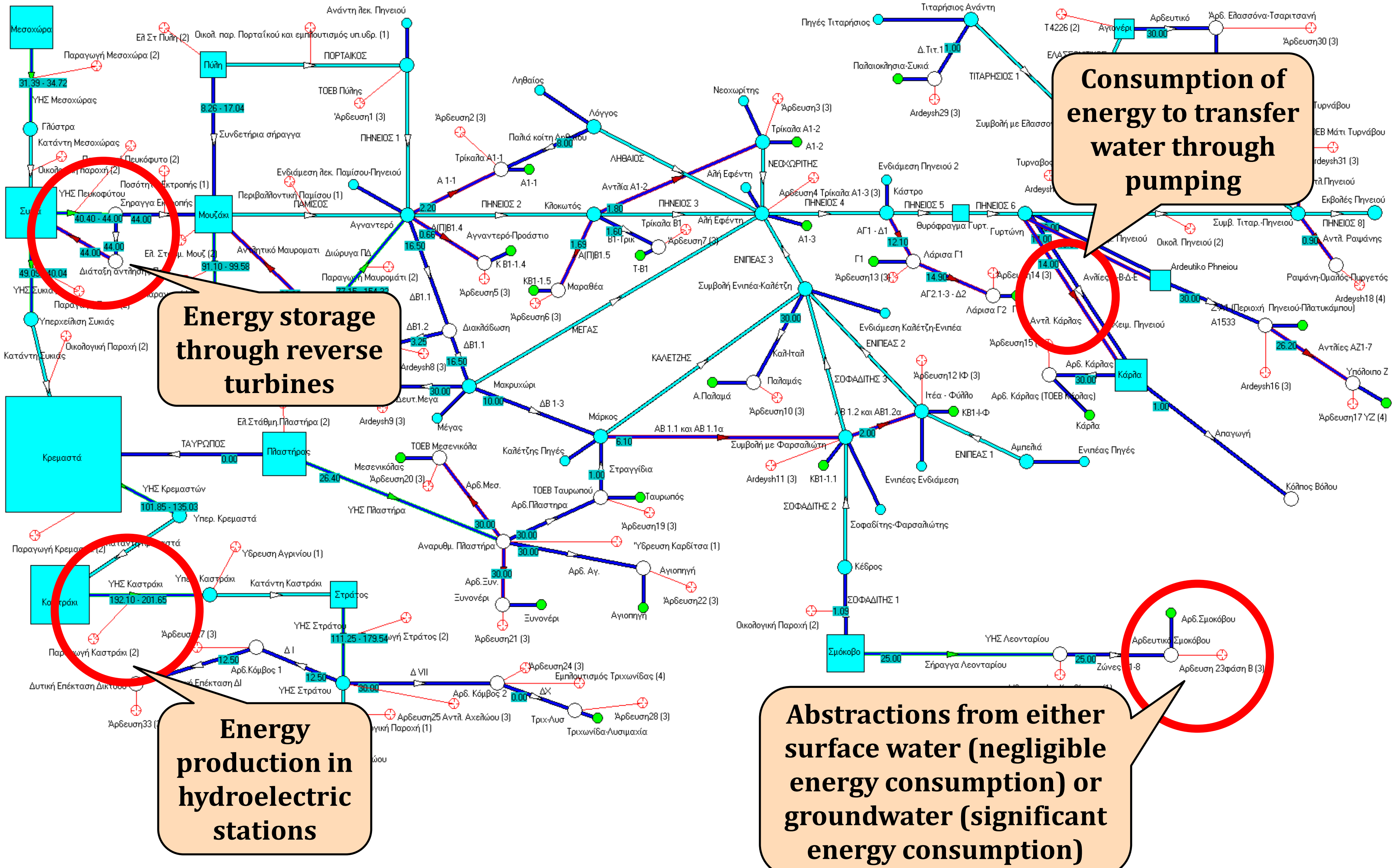
Motivation: The water-energy nexus

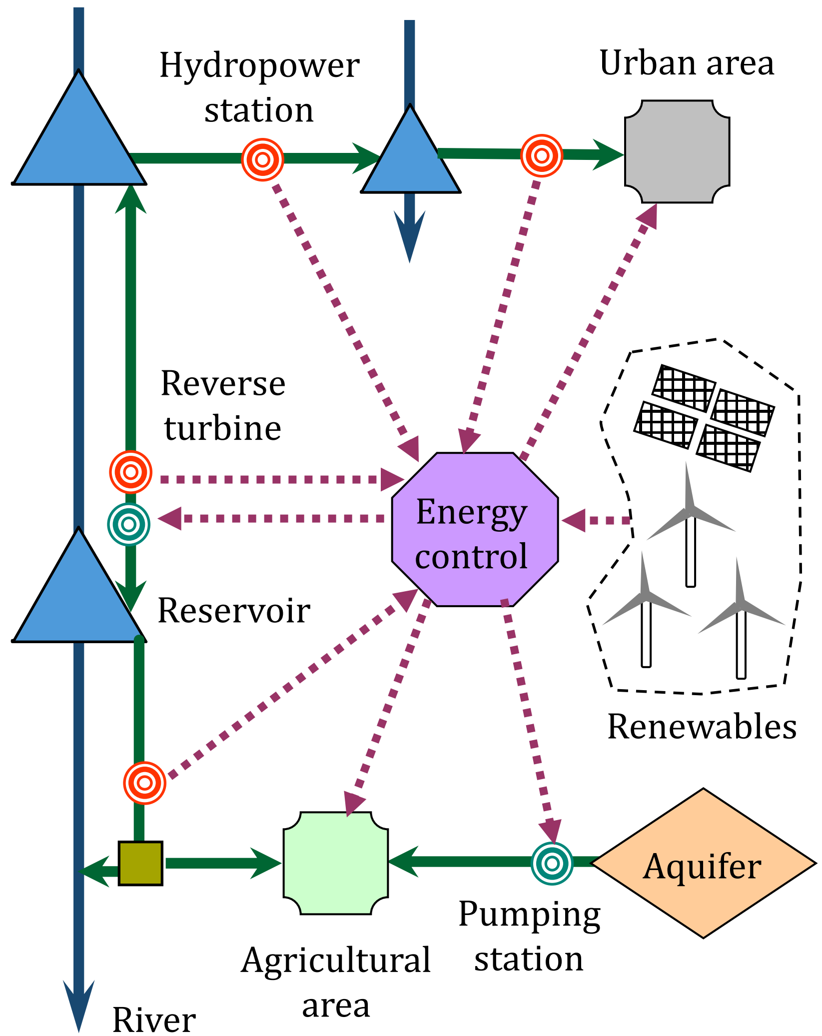
- Water as **energy producer**
  - Hydropower (large and small-scale plants);
  - Irrigation of biofuels;
  - Cooling of thermal power plants;
- Water as **energy consumer**
  - Pumping along water conveyance and distribution networks;
  - Groundwater abstractions from wells and boreholes;
  - Water treatment (e.g., desalination);
- Water as **energy buffer (pumped-storage)**
  - Pumping water to an upstream reservoir, taking advantage of the excess of energy (e.g., during night hours), and then retrieving this water to generate hydropower, is the only means for *energy storage at large scale*;
- Water as **energy regulator**
  - Large hydroelectric reservoirs are irreplaceable means for the stability and economic efficiency of the electric systems at the *national level*;
  - The role of pumped storage has gained further importance after the expansion of *renewables*, given that the variability of renewable energy production cannot follow the corresponding demand.

CRESSENDO project: Modelling of the Acheloos-Peneios water-energy system



From conventional water resources management to integrated water-energy management

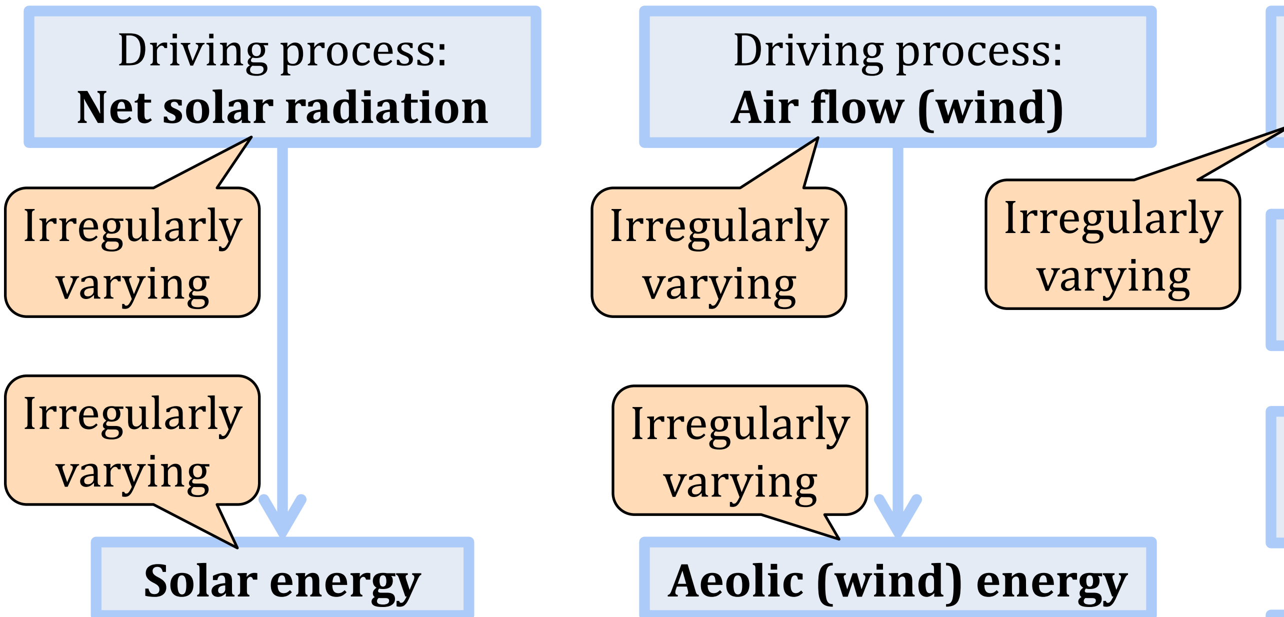
- The typical **water management** problem:
  - Seeks an optimal allocation of water resources (closed water balance, i.e. system inflows = system outflows);
  - Hydropower production is considered as *objective* to maximize;
  - Energy consumption in pumps and boreholes is handled in terms of minimization of operation costs.
- The **water-energy management** problem:
  - Seeks the optimal allocation of both water and energy resources (closed *water balance*, closed *energy balance*);
  - Energy demand is considered as *constraint* (similarly to water uses);
  - Additional energy sources (e.g., renewables) may also be accounted for in the overall energy balance.

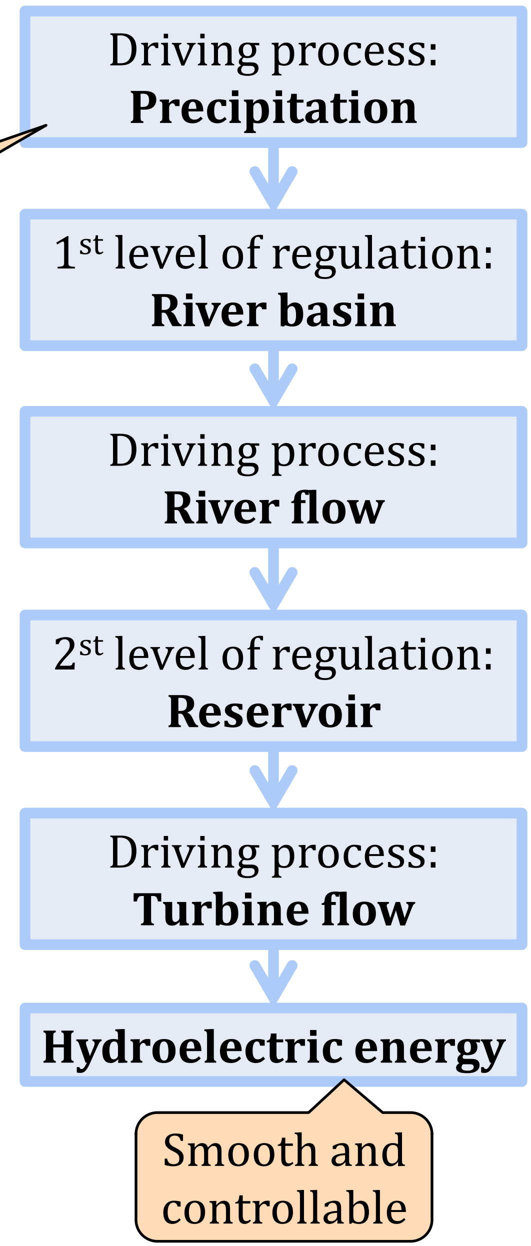


Conjunctive modelling of water-energy systems

- The **modelling challenge**:
  - The representation of two simultaneous fluxes (water & energy) and their interactions increases the number of *decisions* and the number of *constraints*;
  - Since energy production from renewables (hydropower, solar, wind) is driven by randomly varying meteorological processes, stochastic approaches are essential considering synthetic input data of *large length* and *fine temporal resolution*;
- Major **computational issues** to answer:
  - time step of simulation;
  - parameterization of system control;
  - objectives and performance criteria;
  - implementation of simulation and optimization procedures;
- Simplifications on **energy management**:
  - Energy fluxes are not subject to topology or conveyance capacity restrictions, since the overall accounting is implemented in a dummy “energy control” node that joins all energy producers and consumers;
  - Energy demand for domestic, commercial and industrial uses is known;
  - Energy demand associated with water uses (e.g., agricultural), which depends on the current water management policy, is estimated to be equal with the energy consumption of the previous time step.

The time scale issue: hydro vs. solar/wind energy

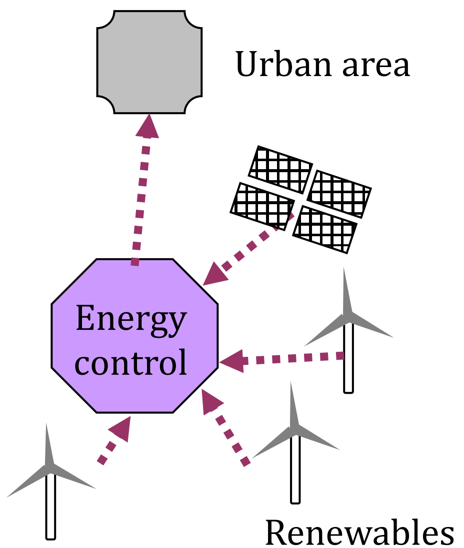




- The time scale of simulation of each energy source depends on the variability of the associated input and output processes, i.e. meteorological and energy fluxes.
- Large scale hydrosystems comprise natural and artificial regulating mechanisms that allow employing coarse simulation steps, e.g. **monthly**.
- Solar and wind energy follow the variability of solar radiation and wind velocity, respectively, thus requiring much finer temporal resolutions, e.g. **hourly**.

Coupling time scales via split of energy components

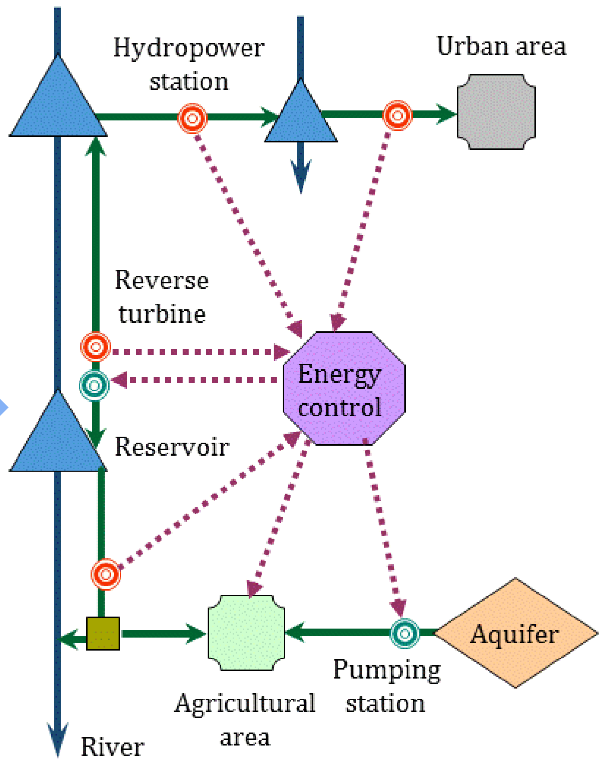
- **Step 1**: Hourly simulation of energy generated by solar panels and wind turbines.
- **Step 2:** Estimation of hourly energy excess or deficit, accounting for hourly demand for electricity (domestic, commercial and industrial).
- **Step 3**: Daily simulation of water resource system (including turbines, reverse turbines and pumps), accounting for daily deficit and excess of energy .



Simulation of hourly energy balance

Daily energy deficit: to be fulfilled by activating hydroelectric stations

Daily energy excess: primarily available to fulfill water uses through pumping, the remaining amount is available for pumped-storage during excess period (hours/day)



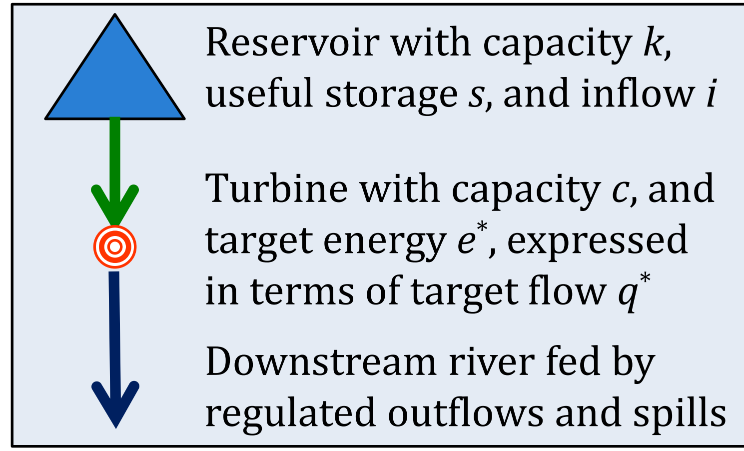
Simulation of daily water-energy balance

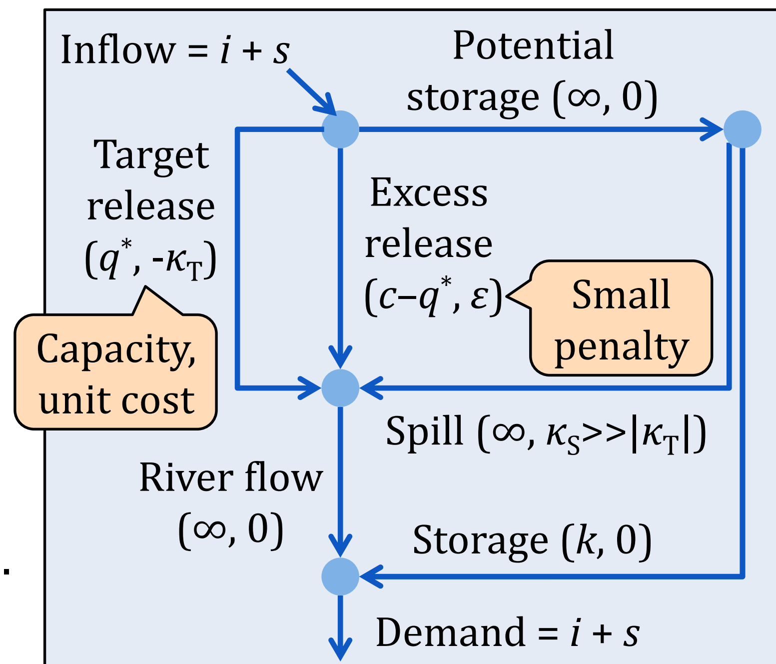
Parameterization of hydrosystem operation

- Model requirements on the parameterization of the operation policy of the system:
  - **simplicity**, to aid decision-making and implementation by practitioners;
  - **parsimony**, to minimize the number of control variables thus substantially facilitating the optimization procedure.
- Main controls are expressed in terms of **dimensionless energy targets** for power production and consumption, which are assigned to the associated components.
- At the beginning of each step (day), the **actual energy targets** are updated on the basis of the corresponding dimensionless targets, which are used to distribute the total energy deficit/excess to all energy components.
- In the case of pumped storage machines, the **conveyance capacity** of penstocks at each direction is updated, accounting for hours of deficit (forward operation of turbines) and excess (reverse operation, i.e. pumping).
- Energy targets are transformed to equivalent **minimum flow constraints**, in order to force the model releasing the required amount of water to produce (or consume) the desirable amount of energy.
- Additional controls may be assigned to selected components of the hydrosystem:
  - Allocation rules for reservoir storages;
  - Water level constraints (min, max);
  - Flow constraints (min, max);

Linear network programming approach for step-by-step simulation of water-energy fluxes

- Formulation of a **graph model**, in which links represent individual water or energy fluxes of the conceptual system.
- Graph properties are nodal inflows and link capacities and unit costs (**real or artificial**), that are automatically updated at each step.
- The **optimal allocation of fluxes** is expressed in terms of a network linear programming (NLP) problem, ensuring:
  - Strict fulfilment of all physical constraints ;
  - Hierarchical fulfilment of user-defined targets and constraints;
  - Minimization of real-world operational costs (e.g., due to pumping);
- The mathematical formulation of NLP (e.g., sparse matrices) allows using **very fast and accurate solvers** (specific versions of simplex).
- For n time steps are solved n NLP problems.



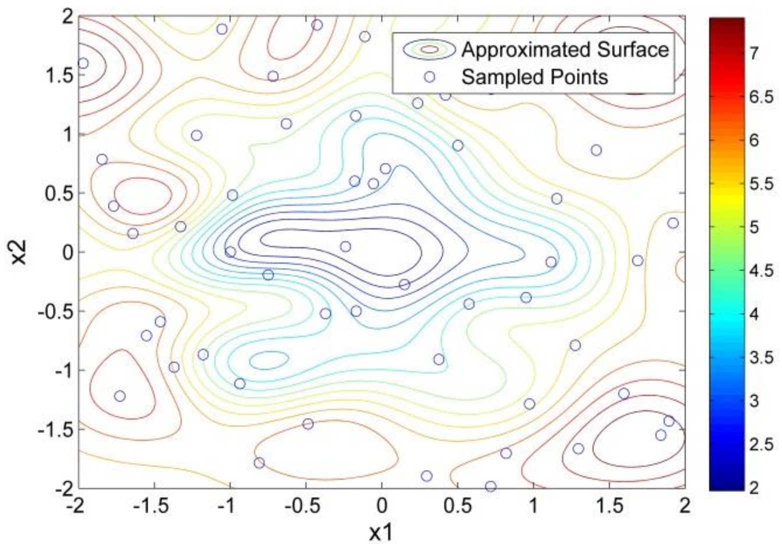


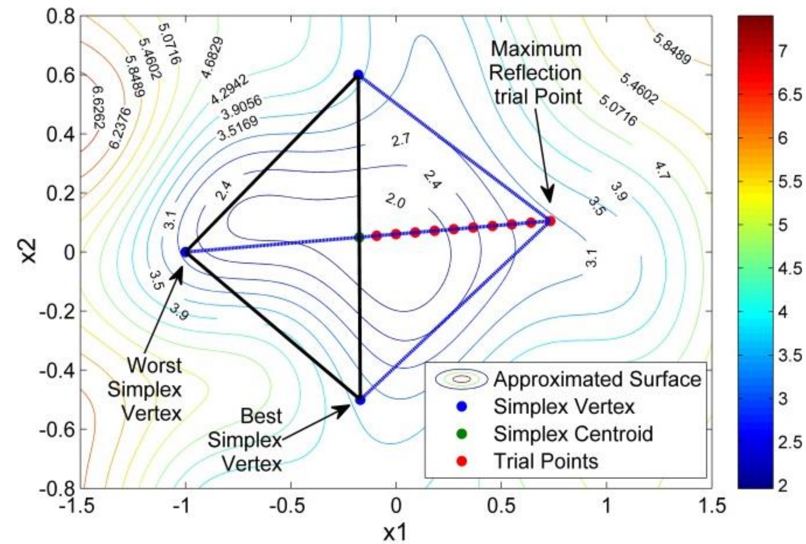
Probabilistic evaluation of system performance

- Water-energy systems are subject to multiple and usually conflicting objectives:
  - Maximization of **economic benefits**, from water and energy production;
  - Minimization of **operational costs** (pumping);
  - Minimization of **water and energy deficits** (may also be expressed in terms of equivalent resource costs).
- The economic evaluation is not straightforward:
  - **Energy prices** are not constant, since they strongly depend on the temporal distribution of energy production;
  - Given that the system inputs are uncertain, its outputs, including the aforementioned economic quantities, are also **uncertain**.
- Problem handling:
  - Assessment of **firm** and **secondary energy**, to account for high and low prices of energy industry;
  - Probabilistic evaluation of system performance, based on **reliability** criteria (both the frequency and magnitude of deficits are important);
  - Use of **synthetic inputs** of large length generated by advanced stochastic models to ensure accurate probabilistic estimations;
  - **Multiobjective analysis** to identify compromise operation policies.

Effective and efficient optimization through the Surrogate-Enhanced EAS algorithm

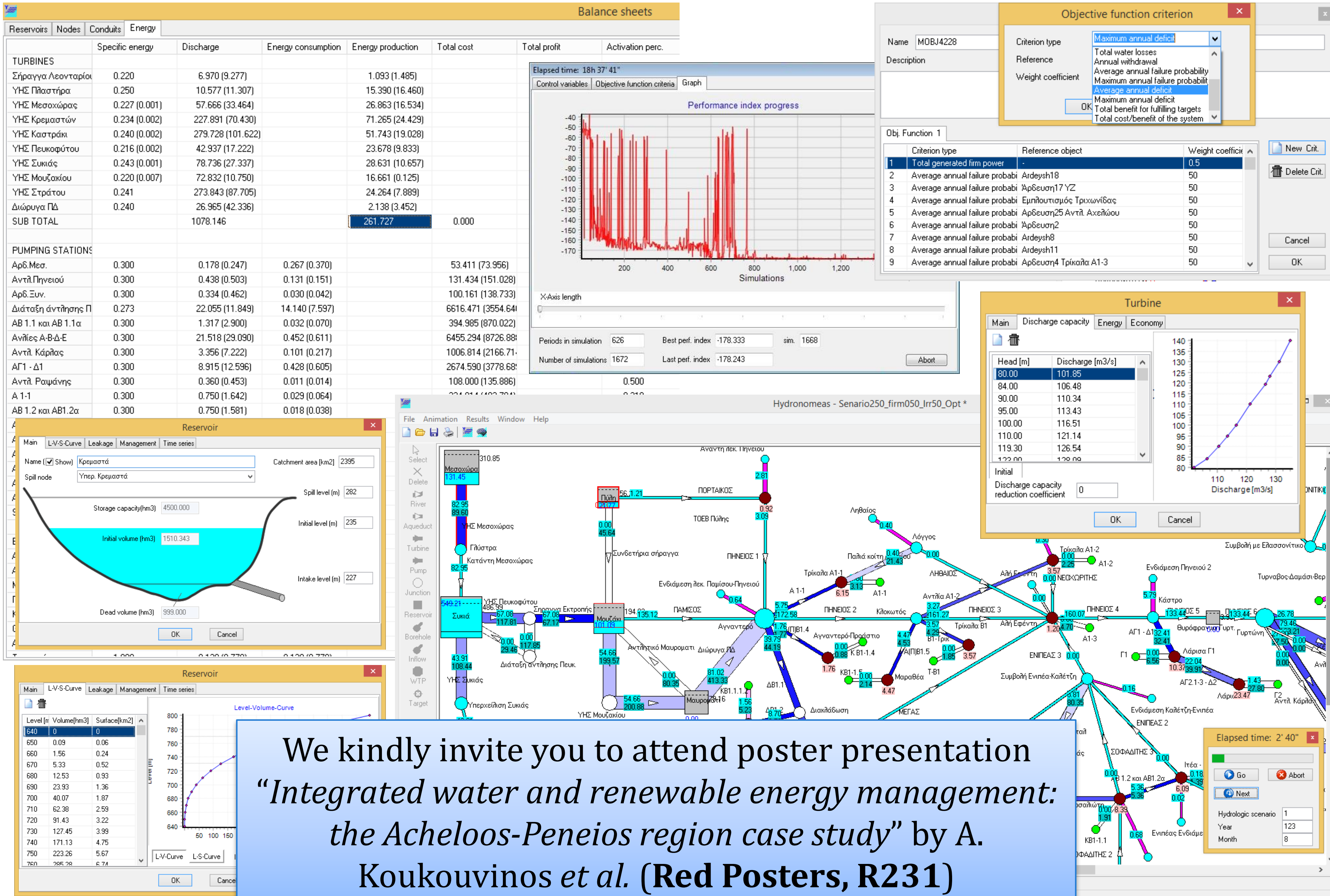
- Recently developed version of the evolutionary annealing-simplex (EAS) algorithm, suitable for **global optimization problems on a budget** (i.e., problems requiring time expensive simulations to evaluate the objective function).
- All visited points within search are used to progressively improve the approximation of the actual geometry of the response surface via a **surrogate model** (e.g., RBF).
- SEEAS takes advantage of the information gained by the surrogate model to assist the generation procedure (mainly employed by means of **simplex transitions**).





Tsoukalas I., P. Kossieris, A. Efstratiadis, and C. Makropoulos, Surrogate-enhanced evolutionary annealing simplex algorithm for effective and efficient optimization of water resources problems on a budget, submitted to *Environmental Modelling & Software*, 2015.

Ongoing implementation: Hydronomeas 5.0



We kindly invite you to attend poster presentation “*Integrated water and renewable energy management: the Acheloos-Peneios region case study*” by A. Koukouvinos *et al.* (**Red Posters, R231**)

Concluding remarks

- In the new energy scene **renewables** play dominant role in energy planning and management at the national and peripheral scale, also reveling the key importance of water as producer, consumer and regulator of energy.
- **System-based** approaches that have been successfully implemented in typical water resources management problems should be revisited and improved, to provide integrated solutions for **conjunctive water and energy modelling**.
- Ongoing research seek a generalized methodological framework, employing the **parameterization-stochastic simulation-optimization** scheme to water-energy systems of any topology and spatial extent.
- Effective and efficient solutions are provided to address a number of **computational shortcomings**, which are apparent within several stages of the methodology.
- Currently, the **methodology** and the associated **software** (Hydronomeas) are tested in the largest and more complex water-energy system of Greece in the context of a research project titled "*Combined Renewable Systems for Sustainable Energy Development*" (CRESSENDO) .

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Related publications

- Efstratiadis, A., and D. Koutsoyiannis, An evolutionary annealing-simplex algorithm for global optimisation of water resource systems, *5th International Conference on Hydroinformatics*, Cardiff, UK, 1423–1428, IWA, 2002.
- Efstratiadis, A., D. Bouziotas, and D. Koutsoyiannis, The parameterization-simulation-optimisation framework for the management of hydroelectric reservoir systems, *Hydrology and Society, EGU Leonardo Topical Conference Series on the Hydrological Cycle*, Torino, EGU, 2012.
- Efstratiadis, A., D. Koutsoyiannis, and D. Xenos, Minimising water cost in the water resource management of Athens, *Urban Water Journal*, 1(1), 3–15, 2004.
- Efstratiadis, A., Y. Dialynas, S. Kozanis, and D. Koutsoyiannis, A multivariate stochastic model for the generation of synthetic time series at multiple time scales reproducing long-term persistence, *Environmental Modelling and Software*, 62, 139-152, 2014.
- Koutsoyiannis, D., A. Efstratiadis, and G. Karavokiros, A decision support tool for the management of multi-reservoir systems, *Journal of the American Water Resources Association*, 38(4), 945–958, 2002.
- Koutsoyiannis, D., and A. Economou, Evaluation of the parameterization-simulation-optimization approach for the control of reservoir systems, *Water Resources Research*, 39(6), 1170, 2003.
- Koutsoyiannis, D., and A. Efstratiadis, The necessity for large-scale hybrid renewable energy systems, *Hydrology and Society, EGU Leonardo Topical Conference Series on the Hydrological Cycle*, Torino, EGU, 2012.
- Koutsoyiannis, D., C. Makropoulos, A. Langousis, S. Baki, A. Efstratiadis, A. Christofides, G. Karavokiros, and N. Mamassis, Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability, *Hydrology and Earth System Sciences*, 13, 247–257, 2009.
- Nalbantis, I., and D. Koutsoyiannis, A parametric rule for planning and management of multiple reservoir systems, *Water Resources Research*, 33(9), 2165–2177, 1997.
- Tsekouras, G., and D. Koutsoyiannis, Stochastic analysis and simulation of hydrometeorological processes associated with wind and solar energy, *Renewable Energy*, 63, 624–633, 2014.
- Tsoukalas, I., P. Kossieris, A. Efstratiadis, and C. Makropoulos, Surrogate-enhanced evolutionary annealing simplex algorithm for effective and efficient optimization of water resources problems on a budget, *Environmental Modelling & Software*, 2015 (submitted).