The parameterization-simulation-optimization framework for the management of hydroelectric reservoir systems

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1. Introduction

The optimal control and management of large-scale hydroelectric reservoirs remains a challenging task in water resources modelling due to the large number of variables, the nonlinear system dynamics, the uncertainty of future inflows and demands, as well as the multiple and often conflicting water uses and constraints. With regard to this inherent complexity, older approaches (e.g. linear, nonlinear, dynamic or stochastic dynamic programming), as well as more advanced concepts and tools, such as fuzzy logic and neural networks, fail to offer an **holistic** approach of the problem.

On the other hand, the **parameterization-simulation-optimization (PSO) framework** (Koutsoyiannis & Economou, 2003) provides a feasible and general methodology applicable to any type of hydrosystem, including complex hydropower schemes. It uses **stochastic simulation** to generate consistent synthetic inputs. The operation is represented through a **simulation model**, which is as faithful as possible, without demanding any specific mathematical form that would possibly imply oversimplifications. Finally, to optimize the system performance and evaluate its control variables, a **stochastic optimization** procedure is employed. The latter is substantially facilitated, since the entire representation is parsimonious, i.e. the number of control variables is kept as small as possible. This is ensured through a suitable system **parameterization**, in terms of parametric expressions of operation rules for the major system controls (e.g. reservoirs, power plants).

The PSO framework is implemented within the **HYDRONOMEAS** decision support system (DSS), which has been successfully applied for the operational management of water resources, including the water supply system of Athens (Koutsoyiannis *et al.*, 2003). In this study, both the modelling background and the functionalities of the DSS are upgraded to handle hydropower generation components, as well as pumped storage facilities. This new version is tested in a challenging case study, involving the simulation of the Acheloos-Thessaly hydrosystem.

2. The Acheloos–Thessaly hydrosystem

Acheloos is one of the most important rivers in Greece, characterized by very high runoff (mean annual value of 4370 hm^3 in its estuary). It comprises several existing hydropower plants (Kremasta, Kastraki, Stratos), producing ~35% of hydroelectric energy of Greece. Apart from the existing scheme of projects, future configurations are also investigated, involving the interbasin transfer of part of the upstream water resources to the adjacent plain of Thessaly for irrigation.

The transfer scheme was initially accompanied by conventional hydropower plants, but the use of pumped storage technology was suggested, thus upgrading the firm energy production of the system. The upcoming diversion will lead to a complex hydrosystem, comprising seven reservoirs, both in serial and parallel connection, with a total installed capacity of 1700 MW. Apart from energy generation, the system will serve irrigation uses (annually 450 hm^3 in the lower course of Acheloos and 600 hm^3 in the Thessaly). Environmental flow constraints are also considered downstream of the new dams (currently, an ecological flow of 21.3 m^3/s is set for the Stratos dam).

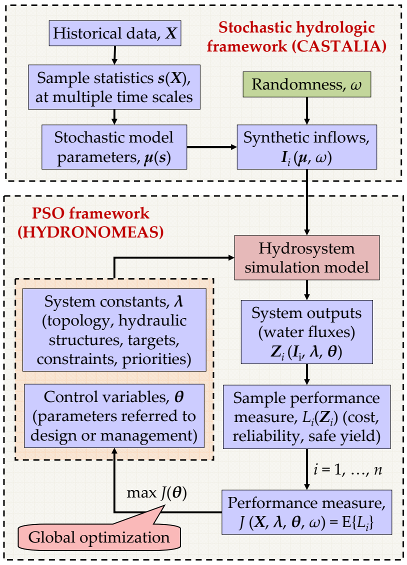
For each configuration, we seek the optimal management policy, on the basis of multiple performance criteria that account for both economy and reliability. Various formulations of the objective function are investigated, combining different types of benefits from water and energy production (distinguishing for firm and secondary energy) and pumping costs.

Acheloos river basin

3. Outline of PSO framework

- ❑ Quantification of the **uncertainty** of hydrological inputs by employing **stochastic** (Monte-Carlo) methods; generation of **synthetic time-series** of runoff, rainfall and evaporation using the CASTALIA software;
- ❑ **Schematization** of system layout through a **network-type** representation of the real-world components; incorporation of **virtual** components and properties, to represent targets, constraints and priorities;
- ❑ **Parameterization** of processes and controls on the basis of **parsimonious operation rules** for key system components (reservoirs, power plants);
- ❑ **Simulation** of system operation using **network linear optimization**, to allocate the system fluxes (storage, flows, losses, abstractions) across the network; in this context, a NLP problem is solved at each time step, ensuring a **physically-consistent** description of the system dynamics and a faithful representation of all constraints and conflicting water uses.
- ❑ Definition of a **global performance criterion** $J = J(\boldsymbol{\theta})$, derived through simulation, on the basis of system parameters $\boldsymbol{\theta}$; J may combine **multiple objectives**, such as safe yield (i.e. maximum water production for a specific reliability level), reliability (associated to specified water uses), hydropower production (usually firm energy), costs, benefits, etc.
- ❑ Optimization of system performance and evaluation of its parameters via **stochastic optimization** (evolutionary annealing-simplex method).
- ❑ Representation of the optimal management policy in terms of user-friendly graphs, interpretation of all simulated fluxes in **probabilistic terms**, and extraction of statistical characteristics of all model outputs.

Hydronomeas web page (software & papers): http://itia.ntua.gr/en/softinfo/4/



Stochastic hydrologic framework (CASTALIA)

Historical data, $\boldsymbol{X}$

Sample statistics $\boldsymbol{s}(\boldsymbol{X})$, at multiple time scales

Stochastic model parameters, $\boldsymbol{\mu}(\boldsymbol{s})$

Randomness, ω

Synthetic inflows, $\boldsymbol{I}_i(\boldsymbol{\mu}, \omega)$

PSO framework (HYDRONOMEAS)

Hydrosystem simulation model

System constants, $\boldsymbol{\lambda}$ (topology, hydraulic structures, targets, constraints, priorities)

Control variables, $\boldsymbol{\theta}$ (parameters referred to design or management)

System outputs (water fluxes) $\boldsymbol{Z}_i(\boldsymbol{I}_i, \boldsymbol{\lambda}, \boldsymbol{\theta})$

Sample performance measure, $L_i(\boldsymbol{Z}_i)$ (cost, reliability, safe yield)

$i = 1, \ldots, n$

Performance measure, $J(\boldsymbol{X}, \boldsymbol{\lambda}, \boldsymbol{\theta}, \omega) = \mathrm{E}\{L_i\}$

max $J(\boldsymbol{\theta})$

Global optimization

4. Performance measures for energy management

In order to expand the methodology thus including hydropower components, it is essential to determine suitable control variables $\boldsymbol{\theta}$ to express the hydropower policy, and suitable performance measures $J(\boldsymbol{\theta})$.

Two alternative approaches were developed regarding the performance criteria; the first one is a **firm energy maximization** approach, given by:

$$J(\boldsymbol{\theta}) = f\left(\sum_{i=1}^{n} E_i(t)\right)$$

where f denotes the firm energy of the system, estimated on the basis of simulated energy $\sum^{n} E_i(t)$, where n is the number of hydropower units. The firm energy is determined as that corresponding to a desirable reliability level α for hydroelectric energy production (e.g. $\alpha = 99\%$).

The second approach is based on a **cost/benefit function**, based on the profit P_i^t obtained from each group i of n targets at each time step t, i.e.:

$$P_i^t = c_i^B \cdot \sum_{i=1}^{n} S_i + c_i^E \cdot \max\{(\sum_{i=1}^{n} D_i^t - \sum_{i=1}^{n} S_i), 0\} - c_i^D \cdot \max\{(\sum_{i=1}^{n} S_i - \sum_{i=1}^{n} D_i^t), 0\}$$

where the first component is the base profit from achieving target S_i, the second component is the excess profit when the produced quantity D_i^t exceeds S_i, and the third component is a deficit penalty, when $D_i^t < S_i$.

The final cost/benefit measure is the overall **mean annual profit**, given by:

$$J(\boldsymbol{\theta}) = \mathrm{E}\{P_{tot}^{year}(t)\}$$

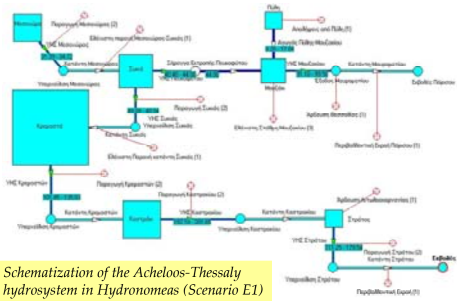
Regarding parameterization, a parsimonious approach is implemented, in which parameters $\boldsymbol{\theta}$ refer to time-constant **energy production targets** for each power plant, modeled as time-varying **minimum flow constraints**.

5. Case study and modeling scenarios

The new optimization criteria are evaluated within several modeling scenarios, which correspond to different configurations of the Acheloos-Thessaly hydrosystem, with significant **practical interest**.

First, we investigate the incorporation of the Mesochora dam in the existing system (Kremasta, Kastraki, Stratos), thus formulating two scenarios. Scenario A1 refers to the existing system, whereas Scenario A2 also includes Mesochora dam. The latter is already constructed and ready for use, but remains out of operation due to **strong social and ecological oppositions** (Koutsoyiannis 2011b).

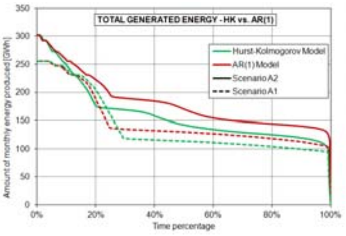
The second scheme includes all the works that are associated with the interbasin transfer of 600 hm^3 in Thessaly, including three new dams (Sykia, Mouzaki, Pyli). Two scenarios are formulated, to compare the use of **conventional hydropower units** (Scenario E1) with the use of **pumped storage** plants (Scenario E2).

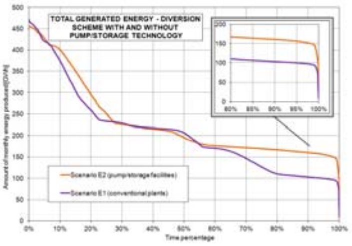


Schematization of the Acheloos-Thessaly hydrosystem in Hydronomeas (Scenario E1)

6. Key results

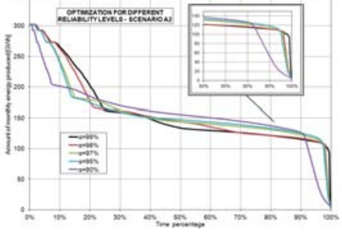
- ❑ The operation of the **Mesochora** dam will have a **strongly positive effect to firm energy** production, with regard to both the amount of energy provided and the whole system reliability.
- ❑ On the basis of Scenario A2, we also assessed the impacts of **hydrological uncertainty** to the energy production. Two sets of synthetic inflows were used, the first representing the Hurst-Kolmogorov (HK) dynamics and the second derived through a short-term autocorrelation model of ARMA-type. The results show that the commonly employed ARMA approach significantly overestimates the hydroelectric energy production, particularly the firm one, which underlines the importance of **preserving HK dynamics in stochastic simulation schemes** (Koutsoyiannis, 2011a).
- ❑ The use of **pumped storage plants** within the interbasin transfer scheme drastically **improves the temporal distribution of the produced energy**, thus allowing to maximize the overall performance of the system, i.e. maximizing the firm energy and fulfilling the rest of uses, with high reliability.



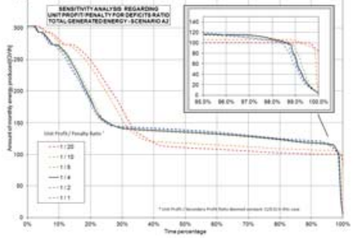


7. Sensitivity analysis

The firm energy criterion allows for maximizing the energy produced by the hydropower plants for a user-defined **reliability** level, thus providing flexibility in terms of long-term planning. On the other hand, inputs of the cost/benefit criterion are the base and excess profits, as well as an arbitrary **deficit penalty**, for each target group. These groups may refer to multiple and conflicting uses, such as energy generation or consumption (pumping cost), irrigation, water supply, etc., thus allowing for combining different objectives under a global financial criterion. Sensitivity analysis for both criteria has shown that the optimal solution is little sensitive against the user-defined inputs (reliability, penalty value).



Sensitivity against reliability



Sensitivity against deficit penalty values

8. Conclusions

- ❑ The two novel optimization criteria provided rational and reliable results, since they maximized the reliability of hydroelectric energy production and satisfied the conflicting uses and constraints.
- ❑ The case study demonstrates that the use of pumped storage facilities results in significant increase in firm energy production (from 1128 GWh with conventional plants to 1764 GWh per year).
- ❑ Improper representation of the long-term hydrological uncertainty, by ignoring the HK dynamics within stochastic simulation, leads to significant overestimation of the energy production values.
- ❑ As a general method, PSO method can handle **integrated water-energy management problems**; in this context HYDRONOMEAS can be further developed as multi-purpose tool, to provide decision support for the planning and the management of **hybrid renewable energy systems**.

References

Koutsoyiannis, D., and A. Economou, Evaluation of the parameterization-simulation-optimization approach for the control of reservoir systems, *Water Resources Research*, 39(6), 1170, doi:10.1029/2003WR002148, 2003.

Koutsoyiannis, D., G. Karavokiros, A. Efstratiadis, N. Mamassis, A. Koukouvinos, and A. Christofides, A decision support system for the management of the water resource system of Athens, *Physics and Chemistry of the Earth*, 28(14-15), 599–609, 2003.

Koutsoyiannis, D., Hurst-Kolmogorov dynamics and uncertainty, *Journal of American Water Recourses Association*, 47(3), 481–495, 2011a.

Koutsoyiannis, D., Scale of water resources development and sustainability: small is beautiful, large is great, *Hydrological Sciences Journal*, 56(4), 553–575, 2011b.