Department of Water Resources and Environmental Engineering –
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Master's Programme
Water Resources Science and Technology

Adaptation of methodological framework parameterization - simulation - optimization to hydroelectric reservoir systems: Computational challenges, new operation rules and implementation within Hydronomeas 2020 software

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Extended Abstract

The planning and management of reservoir systems which are primarily used to cover hydroelectric energy demands is an issue of particular interest, since they exhibit a multitude of benefits, and several peculiarities as well. The main advantages are the long - term regulation of inflows, offered by the storage capacity of the reservoirs, and the fact that power plants have the ability to commence their operation instantly, providing energy when needed. Therefore, through an appropriate scheduling of the turbine operation, these systems are able to produce both base as well as peak energy, and thus their role in the overall energy mix is very important. Apart from peak energy, which is the most typical case, the hydroelectric reservoirs quite often produce excess energy, in order to save water that would be otherwise released through the spillway. This form of energy is called secondary, and its price is lower than the peak one.

It is well-known that the energy production by hydroelectric reservoirs is based on the transformation of the hydrodynamic energy of the water stored in the reservoir, to kinetic energy of falling water, next to mechanical energy in the turbines and finally electrical energy. The hydropower is the product of the water released from the turbines multiplied by the head; the latter is created by the elevation difference between the water level in the reservoir and the outlet level of the power station (the exact definition depends on the turbine type). In this respect, for a given energy production target, the amount of water to be released also depends on the head. Actually, the nonlinearity of the flow-energy transformation, the ability of producing excess energy and the extent of the electricity grid, render the management of hydropower systems significantly different and more challenging than the management of water resource systems the only serve consumptive uses.

The context of our research is the modelling of hydroelectric reservoir systems that are aimed to cover a global energy demand, which is configured as a parameterization - simulation - optimization (PSO) problem. The handling of such problems is greatly facilitated by the use of appropriate operational rules, which express the hydrosystem control on the basis of a relatively small number of parameters. Our backbone is the PSO approach and the associated parameterization employed within the decision support system Hydronomeas, which is adapted in order to account for the complexities and peculiarities of hydroelectricity. As a result, the major objective of this thesis is the development of generic and improved operational rules for the management of multiple hydroelectric reservoirs, and their implementation within the existing methodological framework of Hydronomeas.

Taking into account the above objectives, a new digraph model was created which has its background in the theory of graphs and the transshipment problem. The key idea is the configuration of a virtual model comprising nodes and edges, to represent the energy fluxes across multi-reservoir hydropower systems of any topology, and their transformation to water fluxes. Figure 1 presents a theoretical example of three parallel reservoirs, which are used to cover the total energy demand of such a system. **T** is used to symbolize the reservoirs, whereas **Z** represent the total energy demand of the system and **X** corresponds to a cumulative sink node, which is introduced for ensuring a balanced configuration of the transshipment problem. The amount of energy transferred from reservoirs is symbolized $\boldsymbol{x}$, $\boldsymbol{u}$ symbolizes the maximum power that can be produced or transferred (which is easily translated into flow capacity), and $\boldsymbol{k}$ is the unit cost or profit of each route. Under this formulation, there are multiple alternative solutions (i.e., feasible combinations of energy fluxes) that fulfill the model constraints, while the aim is to find the one that minimizes the total cost of the system, thus fulfilling the total energy demand or, at least, minimizing the total deficit with respect to the running target.

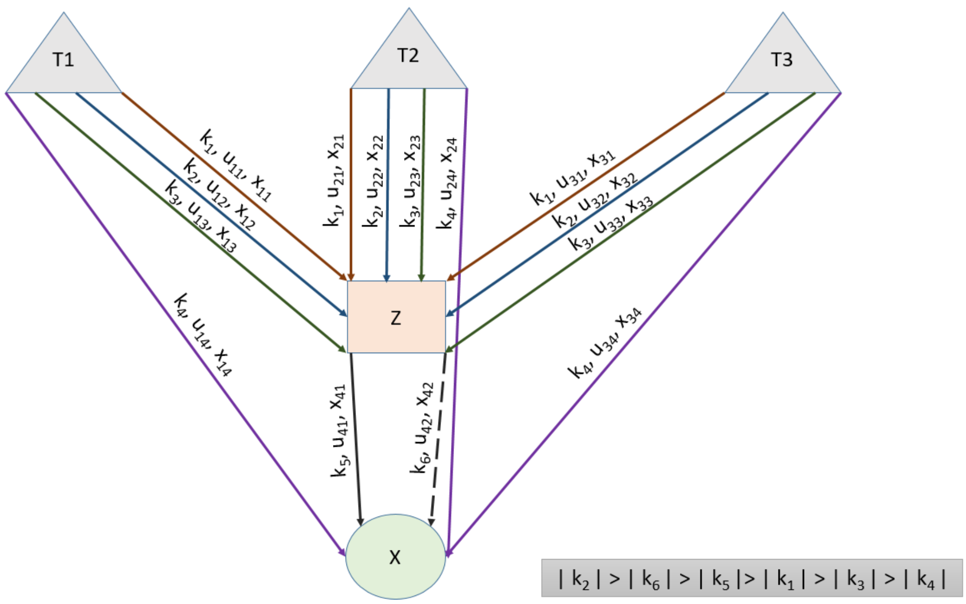

Figure 1: Digraph model of three parallel reservoirs

The new digraph model and the associated methodological framework, which are developed in a Python programming environment, also implement a novel operational rule for allocating energy targets to each reservoir. This rule differs from the one used so far in Hydronomeas. In particular, each reservoir is initially asked to cover a percentage of a total energy target. If one or more reservoirs cannot meet their target or when a reservoir is forced to over-produce energy (i.e. as a means to avoid spills), the model allows for the reallocation of energy targets between all system components; this is a key advantage over the existing operational rule of Hydronomeas, which is more suitable for consumptive water uses. As long as a reservoir manages to meet its own energy target and has the ability to generate additional energy, it can contribute to the system by offering extra amount of energy to cover deficits that may arise in other reservoirs. Thus, if a reservoir cannot meet its own target, the system can receive at least a part of this energy deficit from the other reservoirs. Or, in case of over-production of one of the reservoirs, the other energy targets are lowered, in order to sum up to the global energy production target. On the contrary, Hydronomeas treats each reservoir of the system separately, i.e. each one produces energy according to its capacity and target, without allowing reallocations since the total energy of the system is the sum of individual energy production targets that are assigned to the reservoirs. Due to this difference, the new digraph model provides much better results, in terms of energy production and associated metrics (reliability, profit) for any reservoir system and any topology.

Another important contribution of this thesis is the investigation of several computational issues that mainly arise from the discretization of the water balance equations and essential simplifications made in the context of simulation models. Such issues are the formulation of the simulation model (explicit or implicit) and the selection of the time interval of computations, which is typically determined by the temporal resolution of input data (i.e. inflows). Taking as example the hydroelectric reservoir of Kremasta, for which there are available daily inflows for a 42-year period, it is first demonstrated that the use of an implicit scheme requiring only one iteration cycle ensures much more stable results, since the level-dependent quantities (head, discharge capacity, power production) are estimated by considering the average level at the beginning and the end of each simulation step.

Next, a number of theoretical investigations are employed, by means of sensitivity analyses. In particular, a simulation/optimization model is established and it is run with different time steps (daily, pseudo-daily, monthly, etc.) in order to examine how this affects its results. From this analysis it emerged that the average annual spill volumes decrease as the time step increases. For example, in the simulation case study concerning the reservoir of Kremasta, comparing the daily step and the monthly one, there is a noticeable difference in spill volumes. This is due to the fact that in monthly step simulation, a large inflow (which would take the reservoir over its capacity limit and spill) is evenly distributed over several days (throughout the month) and as a result the net monthly capacity of turbines allow a greater outflow. On the contrary, in daily step, the possibility of spill concerns each day separately and thus it is concentrated in a small number of days. In this case, the daily capacity of turbines is more possible to be inadequate to receive the total amount of spill, and as such the total volume of spills is increased. In the same case study, regarding the average annual benefit / cost, it arises that the benefit from the daily step is greater that the corresponding monthly one. As a result, it's obvious that the selection of time step actually affects the accuracy of simulation but in any case, the modeller should take into account the trade-off between achieving a satisfactory accuracy with respect to the computational cost that is analogous to the time resolution.

The proposed modelling framework is initially tested and validated in a number of challenging theoretical problems involving hydroelectric reservoirs in series and in parallel, in which it is examined a wide number of possible operation modes of hydropower systems. The model is flexible across the different topologies and ensures in all cases an optimal and realistic allocation of the desirable energy fluxes.

Next, the model is tested in two real-world hydroelectric reservoir systems in Greece, i.e. the two parallel reservoirs of Plastiras and Smokovo (Figure 2), at Western Thessaly, and the three cascade reservoirs along river Achelous, i.e. Kremasta, Kastraki and Stratos (Figure 3). In the real-world cases, for which some essential simplifications are made, the outcomes are also compared of our approach with a similar configuration employed within the current version of Hydronomeas. Table 1 provides summary results for the two case studies, while the optimized energy - duration curves are illustrated in Figure 4 and Figure 5. For both systems it can be easily concluded that the new digraph model ensures better results with respect to Hydronomeas.

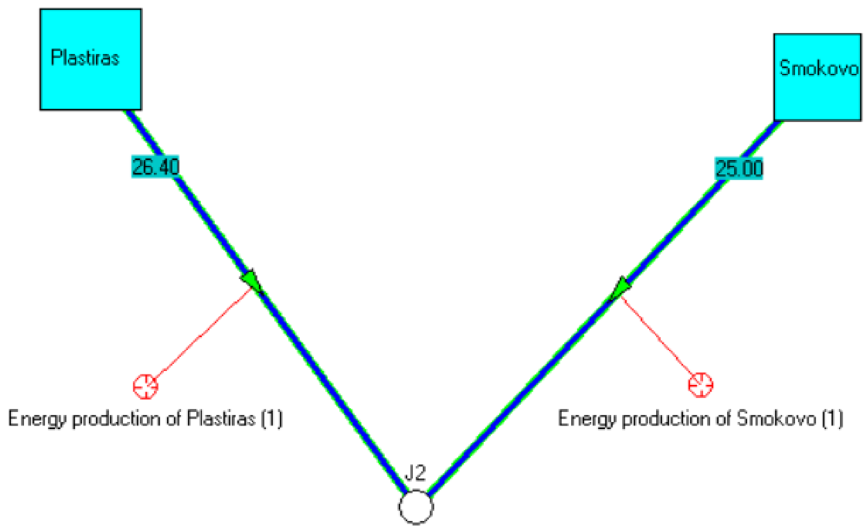

Figure 2: Schematization of two parallel reservoirs of Plastiras and Smokovo in Hydronomeas environment

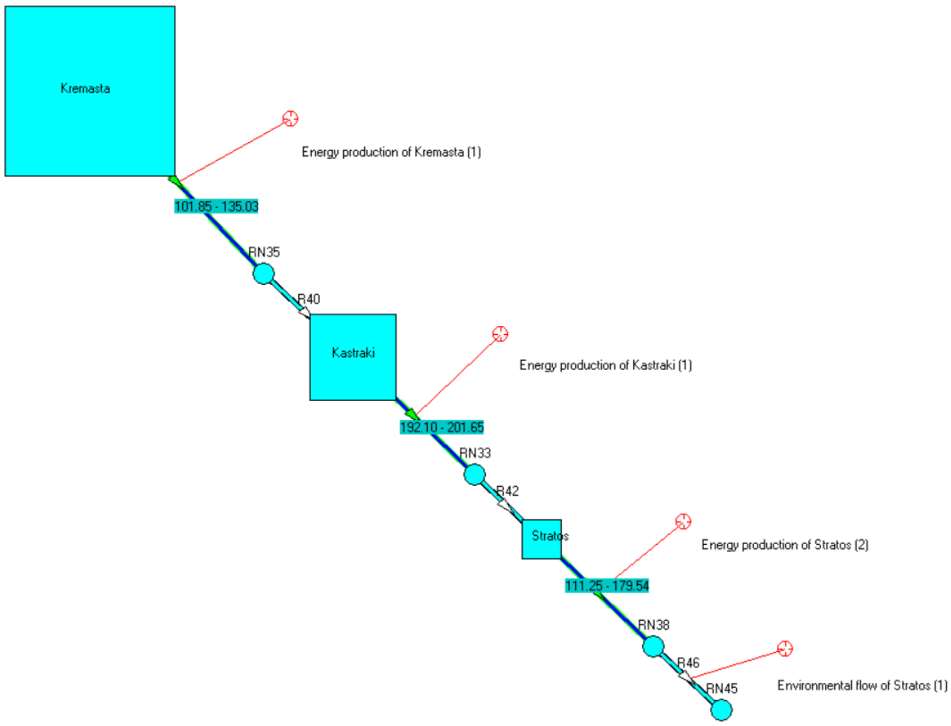

Figure 3: Schematization of three cascade reservoirs of Kremasta, Kastraki and Stratos in Hydronomeas environment

Table 1: Optimization results

Firm energy production in the system (Ef) (GWh/month)		
	Plastiras - Smokovo	Kremasta - Kastraki - Stratos

Hydronomeas software	18.36	121.82
Digraph model	22.70	138.00

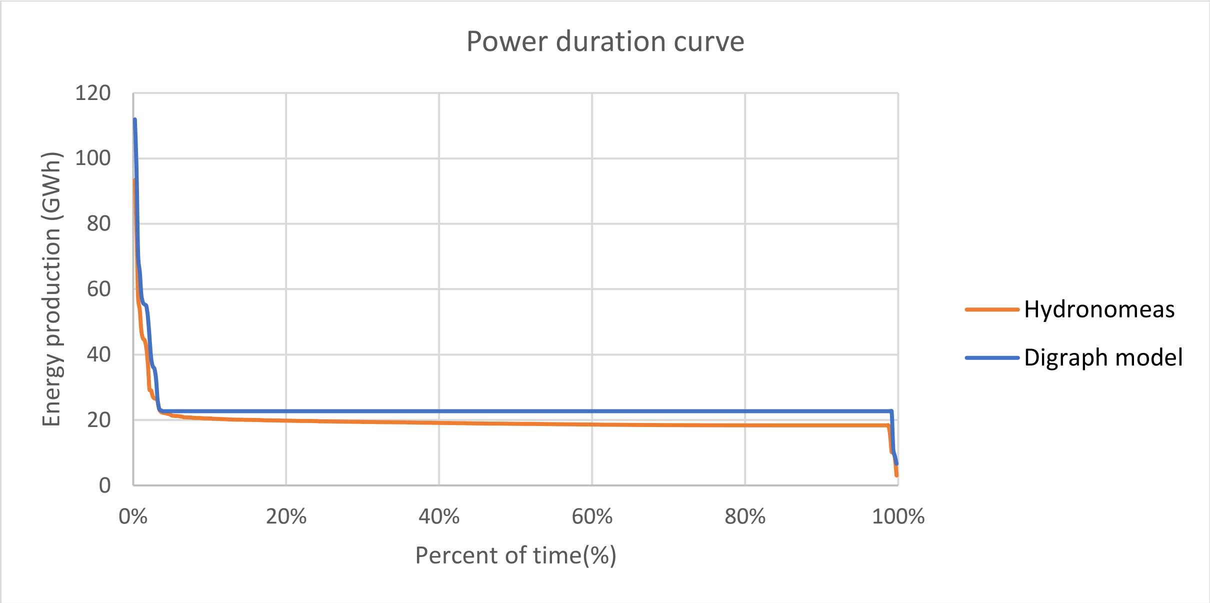

Figure 4: Power duration curve of Plastiras - Smokovo

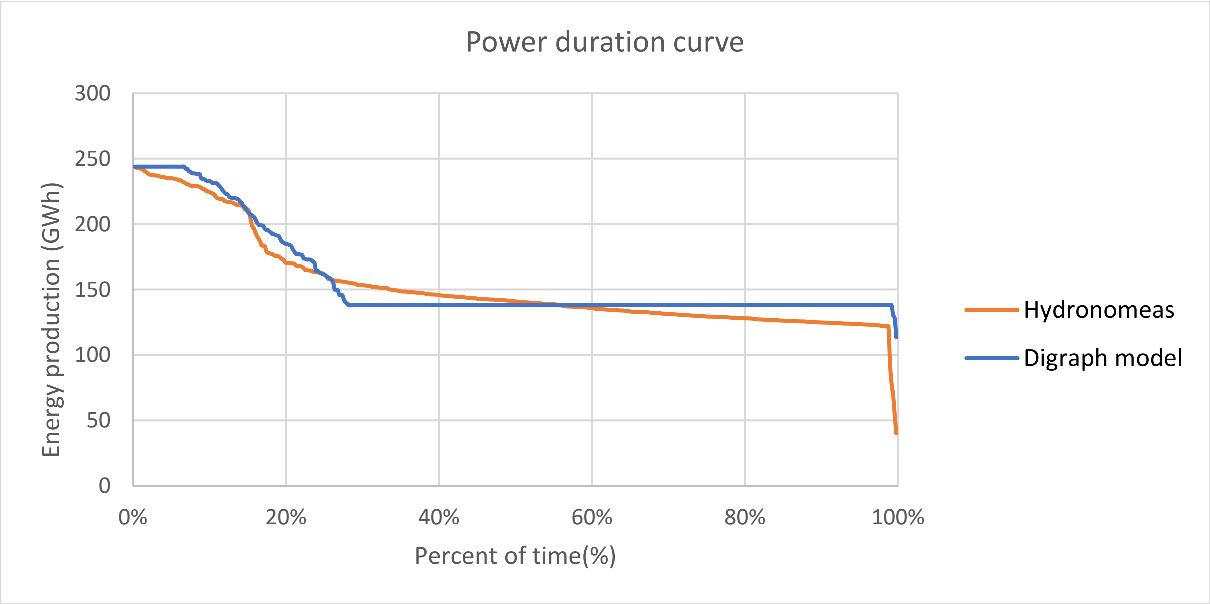

Figure 5: Power duration curve of Kremasta - Kastraki - Stratos

In the context of future steps, key research target is to integrate the energy allocation operational rule in the next version of the decision support system, called Hydronomeas 2020. The latter is developed in Python environment and will be released as a freeware package until the end of this year. The overall methodology will comprise the “parallel” implementation of two graph optimization models, one for the water fluxes and one for the energy fluxes. This scheme may also conclude additional power production and consumption components, and particularly renewable energy sources and hybrid schemes, also comprising pumped-storage plants.