# Simulation Applications to Hydropower Systems Management and Design

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## 1. Introduction

Hydro power plants play a key role in electric power systems, due to their low operating costs and their flexibility in real time operation. In addition, sustainability and environmental concerns support their use in current power systems, jointly with other renewable sources of energy, like wind and solar energy. The ecological impact of reservoirs can be overcome by the benefits of a good hydro production scheduling.

Simulation allows considering complex behavior in hydro plant operation at low computational costs compared with other approaches. For instance, mathematical modeling of the hydro plants in full detail may involve integer or nonlinear programming that requires increased solution times over the simpler linear programming models. In our simulation model, nearly optimal results are obtained by following the guide of longer term hydrothermal mathematical programming models to propose initial reservoir management that is later adapted to fit the peculiarities of the river basin.

In this paper we describe a simulation model based on discrete time step. This model may have different purposes: a common use is to obtain near-optimal production schedules that are physically feasible, without performing an explicit optimization; another approach is to use simulation to evaluate the costs of performing maintenance duties in different periods; it can be used to carry out reliability analysis; and finally, simulation can also be used to test different design options when considering river basin construction or expansion.

**Keywords:** Hydroelectric power plants, discrete simulation, hydro reservoirs management, electric power scheduling.

## 2. State of the art

In the literature, two approaches can be found to tackle the task of planning the operation of the hydro plants: mathematical programming and simulation. In the first methodology, [4] proposes a mixed integer model, where discharge function for each reservoir are represented by piecewise linear functions, and binary variables are used to separate different non-convex regions in these discharge functions. In this case, the objective function is to minimize the penalties due to violating maximum or minimum volumes in the reservoirs, changing abruptly outflows and releasing high volumes of water. Other mathematical programming models include the nonlinear problems [9], network flows [2], and stochastic optimization [5][1]. It can be found in [3] a review of the mathematical programming models used for planning the operation of river basin.

Considering the simulation approach, the objective has been mainly the reliability assessment of the power systems. For instance, [7] performs a simulation of the whole hydrothermal system in order to asses its service reliability. It evaluates different reliability indices by sampling outages of power plants and network buses, as well as determining water inflows and demand levels. This sampling procedure is enclosed in a discrete simulation. In [8] and [10] simulation model considers the transmission network but not the hydro scheme, with the same aim of computing reliability measures. An hourly sequential simulation model is developed, sampling the outages of power plant and transmission elements. Additionally, variance reduction techniques are applied to obtain a more efficient simulation process.

In contrast with these works, the model described in this paper performs a sequential simulation with the objective of prescribing a near-optimal operation. The main objective is set by a longer-term mathematical programming that cannot consider the hydro system in full detail, but provides a goal that incorporates the economic sense of the electric system operation. The simulation model then takes into account all the details of the reservoirs, adapting the overall decisions to a more realistic framework.

# 3. Simulation model

The simulation model described in this section is a medium term model included in the general set of models used in the electric power plant scheduling. This means it receives longer term instructions about the optimal way to allocate water use through the year, and it transmits daily hydro production to shorter term models that may prepare the corresponding market bids. The longer term model has to take into account the whole hydrothermal power system, so as to be able to properly schedule each hydro section.

The simulation model consists of two main parts: the basin elements representation and the simulation algorithm, which are described in the following two sections.

## A. Data representation

River basin elements can be divided into three main categories: reservoirs, power plants and channels. Reservoirs are by far the most important elements in the management of the basin from a hydrological point of view and thus they are fully explained later in this section.

The power plants associated with the reservoirs are independently modeled to allow more flexibility in the river basin representation. For instance, a power plant may draw water from either of two different reservoirs, depending on the choice of the operator. Although electric power generation is the main result regarding power system operation, for a simulation seeking a rational schedule of water use, it is a byproduct. Hence, they transport water from the upstream reservoir to downstream elements delivering the corresponding power, but no special management is required for these elements.

Channels are used to model non-natural water flows that may exist in the basin. During simulation, water flows from the power plants to the downstream reservoirs, then to their corresponding power plants and so on. This continues until the river mouth is reached, unless there is an artificial outflow to other elements, which physically does not follow the natural river path. These situations are modeled by means of channels.

For the reservoir management, an outflow proposal is initially made, and this computation process can be divided into two steps:

• An initial outflow is obtained according to longer term instructions. Depending on the reservoir size, the detail used to compute this outflow changes. For the more relevant reservoirs, a longer term mathematical programming model provides an optimal outflow, whereas for the less relevant ones simpler approaches are used (for instance, targeting the reservoir volume to a monthly curve objective). The outflow provided by longer term models also include pumping flows, which may operate on a weekly or daily basis, depending on the capacity of the reservoir.

• This initial outflow is later modified to fit pre-specified behaviors for the different volume areas. These volume areas have corresponding outflow limits that are intended to soften the reservoir operation, driving their volumes more smoothly to safe areas that avoid spillages and not supplying outflow agreements.

Two additional elements are needed for a complete river basin representation. These two elements are fictitious in the sense that they do not represent any physical element, but rather ancillary data management. The first one represents water inflows from rainfall or tributary rivers not represented explicitly. These elements are in charge of inserting into the system the hydro series that will be further discussed in the next section.

The remaining element is the river junction, which introduces the limitation of the flow occurring when several elements share a common penstock to produce water. Such a case can be found when two power plants share the output channel of a reservoir. In this case, each individual element can hold a maximum flow, but the common penstock may limit the sum of both flows to a value lower than the sum of the individual limits. An additional flow reduction might represent the amount of time that is lost when stopping one operation mode to change to another one. An example of this can be when one power plant produces with water from one reservoir and later another one pumps water to another reservoir using the same penstock.

## B. Simulation method

The general idea of the simulation method is to carry on reservoir management as close to longer term instructions as possible. Bearing this in mind, the algorithm has been split into three passes, where each one covers the whole river basin computing different concepts:

▪ In the first pass, the basin is simulated in downstream order, computing the outflow proposal for each reservoir independently of the overall basin situation. This proposed outflow, which was presented in the previous section, is then transmitted downstream through power plants and channels. This may cause spillages or the inability to fulfill outflow agreements in some reservoirs, as this is not the aim in this pass.

To help reduce these problems in the following pass, each element also records the individual capability to modify its output, considering the increase and decrease in its outflow that it can perform without breaking any management rule. This information is also considered in addition to the accumulated modifications of upstream river elements.

▪ In the second pass, performed from the river mouth upstream, the outflow proposal for each reservoir is modified to avoid spillages and to prevent

not to satisfy the outflow agreements. These undesired situations are communicated to the elements upstream for them to help avoiding these situations. This can be performed by modifying upstream outflows and even preventing spillages by increasing upstream pumping flows, if this is needed. Each element contributes to this objective proportionally to its ability compared to the one of the whole set of upstream elements, which was computed in the previous pass.

- Finally, the third pass computes final power productions once the water flows are decided as close as they can be to the optimal ones (computed by the longer term hydrothermal model) while causing as little problems as possible.

These simulations use two different types of hydro series as water inflow: on the one hand, historical data from the past years can be used to recover past situations that may happen; on the other hand, synthetical series can be computed based on a subset of the historical series (for instance, the series corresponding to the most dry years), applying monthly coefficients that modulate the year inflow profile.

## 4. Simulation tool

For the analysis presented in this paper, a simulation tool is used. This tool has been developed based on Object Oriented Programming, due to the fairly independent computations required for each basin element. This allows the representation of the basin as a set of objects that interact with each other in each simulation pass in a very limited way: the water flows, and the spillages and lack of agreed outflows.

With this abstract representation of a river basin, the consideration of a new one is greatly simplified. There are two main steps to be taken in this process:

- First, the river basin topology has to be described, including the type of each element and the connections amongst them. This includes reporting the power plant associated to each reservoir, which reservoir receives the spills from each reservoir, the channels linking elements in the basin, or which power plants that share their penstock, for instance.

- Then, the individual technical characteristic of the elements of the river basin have to be provided. For example, this means supplying the maximum outflow of each power plant, the coefficients of the conversion function from water flow to energy produced, the maximum and minimum volume curves, the management strategies and guiding curves for each reservoir.

The simulation tool builds upon Excel workbooks, which hold the input data needed to represent the river basin structure and the individual elements data. This interface allows the user to easily interact with the system, providing the input data and analyzing the output results

of the simulations performed. The core of the tool is coded in Visual Basic for Application, and uses the somewhat limited features of this language to implement the Object Orientation paradigm.

## 5. Application to hydroelectric management

In this section a case study is analyzed. This case is based on a real basin, where it will be demonstrated in the usual tasks that a utility performs. These tasks include common management ones like yearly planning of the hydro production, which is the test conducted in this section, but also include more rare short scope analysis in presence of exceptional circumstances like water floods or droughts. Simulation can also be used to locate the best period of time to carry out maintenance or enlargement works. Finally, outflow agreements and design of new reservoirs can be evaluated employing this simulation approach that provides a measure to support the decision process. The test of river elements designs is performed in the following section.

This section presents an example of the management of a large reservoir with annual operation. This kind of reservoirs plays a key role in the river basin, as they are the most representative and thus drive the overall management. Two variations of the study case are considered, each using a different avoided cost profile for the year:

- Case 1a: Consider the profile of predicted avoided costs, which is considered as the base case.

- Case 1b: Modify the base case, introducing different avoided costs for selected months: it considers a higher avoided cost in April, while in July the cost is lower.

The river basin used in this section does not correspond to a real river basin, although it has been created starting from situations very close to real ones. As such, it contains realistic river configurations that prove the capabilities of the simulation model proposed. More particularly, the hydroelectric scheme that has been simulated comprises 9 reservoirs and their corresponding power plants, configured in a main river with two tributary ones joining at the middle and final parts of it. The reservoirs are ruled by management strategies according to their respective sizes, as it has been previously described.

In the following results, simulations have been performed for 24 series of hydro inflows at the main reservoirs. These series comprise daily values for one whole year each, although the beginning of the simulation has been set to the 1st of April. For previous dates, the following graphs present data that has been fixed to provide an initial trajectory. This behaves in a similar fashion to what would be the normal use where historical values would set the starting point.

In Figure 1 the evolution of the volume for the annual reservoir is shown, for each of the simulated series. It can be seen that the first 3 months correspond to the period

fixed by the user, prior to the 1st of April, and hence the figure shows only one trajectory. From that point on, 24 series depict the volume for each simulation. During the remaining months of spring and summer there is little variation amongst the different series, because the amount of rainfall is already decreasing, while much more diversity can be seen in the last months of the year, due to the winter precipitations. There is a considerable number of years where the volumes are driven through similar paths, but there are also several years of low hydro inflows, signaled by lower volumes in the graph.

On the other hand, Figure 2 shows the evolution for the volume of the same reservoir in case 1b, i.e. when the avoided cost is higher in April and lower in July with respect to the values in the base case. As a result, the volume of the reservoir during the month of April is kept lower, due to a more intensive use of the water that can be used to reduce the increased costs of that month. Conversely, during the month of July the situation is reversed, and the volume is driven higher because the cost that can be avoided with that water is smaller and thus it is advisable to keep water for further use.
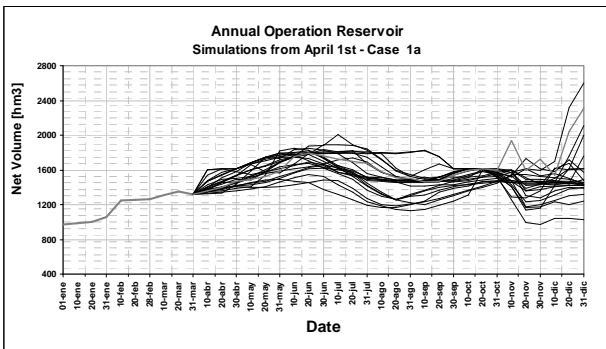


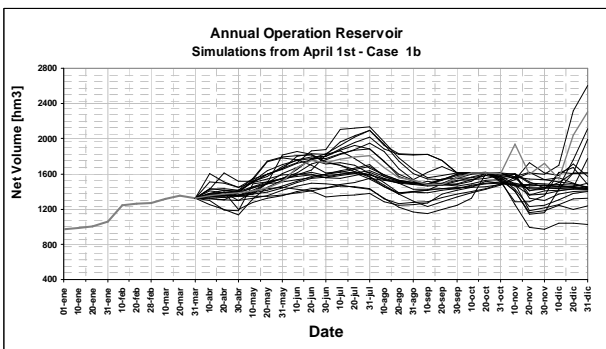**Figure 1. Net volume results for a reservoir in case 1a**



**Figure 2. Net volume results for a reservoir in case 1b**

## 6. Application to hydroelectric scheme design

The design of a hydroelectric scheme comprises a great number of variables, mixing economic, technical, environmental and social decisions. The management of the elements of the basin has to be estimated for the set of plausible hydro inflows series that the system will find during its lifetime. This set of inflows will usually be obtained statistically from historical information of the same series. Although the design may directly imply a few elements or variables of an element, the whole

system is affected because of the interconnected nature of the operation of river basins. Thus, it might be insufficient to analyze the independent behavior of a single reservoir or power plant, and the whole set of hydroelectric elements (both existing and planned) have to be taken into account in their final layout. Furthermore, there are several design elements that can be optimized, such as the power and number of turbines, install pumping turbines, the maximal outflow, reservoir dimensions, and other similar factors.

Iberdrola has recently obtained the franchise for the operation of four hydroelectric power plants in Portugal, which compose the Támega scheme. The Hydro Generation Department of Iberdrola Generación is conducting studies to analyze the project of the Támega hydroelectric scheme. The Energy Management Department is supporting these design decisions by employing the hydraulic simulator, which provides some metrics that can be used in this process. With these results, the Hydro Generation Department can compare the improvement on hydro management of different design solutions according to different metrics such as energy production, ecological impact or high inflows handling.

This section presents some theoretical studies for different design hypotheses regarding the Támega scheme. In the first place, case 2 focuses on the avoided spills in Daivões planned reservoir regarding the pumping capacity of the Padroselos planned power plant located upstream in a tributary river. The comparison is established amongst two options that are described next:

- Option 2a considers that Padroselos has no pumping unit, and thus can only use the turbine of his associated power plant.

- Option 2b, on the other hand, studies the case when Padroselos had two pumping units that may allow extracting water from Daivões.

Figure 3 shows the graphical results for these two cases. In the design option 2b, considering two pumping units at Padroselos, it can be seen that due to a pumping operation of just two days, the volume of spills that can be avoided in Daivões is 30 $hm^3$, whereas the capacity project for this reservoir is approximately of 68 $hm^3$. This shows that this pumping plant adds value to Daivões.
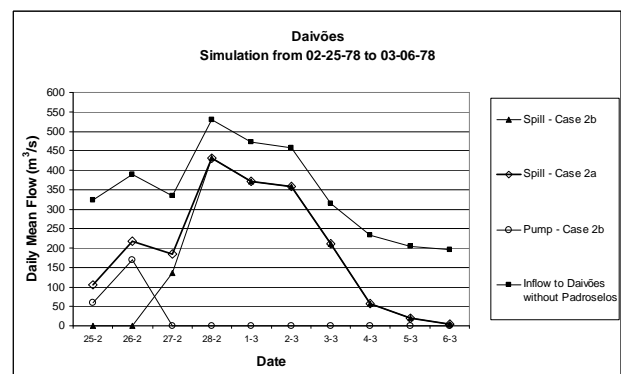


**Figure 3. Simulation from 02-25-78 to 03-06-78 considering two different design options.**

Finally, case 3 compares the effect of two different outflow limits for a power plant in Alto Támega. These two limits have been chosen quite different to make it easier to appreciate the differences, just as a theoretical test. These two cases are described next:

- Case 3a considers the nominal maximum outflow.

- Case 3b considers a maximum outflow that is half of the previous one.

Figure 4 shows the results comparing case 3a and 3b, for the whole set of 24 hydro inflows series, paying attention to the spills that are produce in each situation. The thick strokes show the spills that can be found when the outflow limit is set to its nominal value, while the thin strokes depict the spills when the outflow limit is halved. It can be clearly seen that there is a reduction in the spills by considering case 3a instead of 3b, which could be expected. But this also serves for quantification of the magnitude of the spills and thus permits an economic valuation of the investment required to double the output capacity of the turbine against the reduction of losses in the spills. The simulator can then help in this economic assessment providing a technical evaluation of the design options, whether the spills, the power output, or any other suitable metric. The post-process of this information with the financial counterpart provides support for the design process.
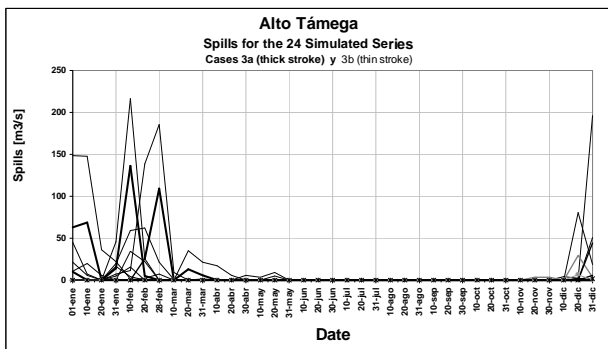


**Figure 4. Spills in Alto Támega for two outflow limits for simulation of 24 years**

## 7. Conclusions

This paper describes a simulation model that provides a physically feasible production scheduling for river basins, based upon the solution of longer term mathematical programming models and taking into account the special features of real river basins. This model is applied in this paper to a case study where its effectiveness can be assured in practical terms, considering the management needs of an electric utility. In the common use of the simulator, it is normally aimed at hydro management, although it has been applied more infrequently to the extension of existing electric assets and the design of new hydro schemes.

This simulation model belongs to the set of models applied regularly to hydroelectric energy management at Iberdrola Generación, for the short, medium and long term. It is also used for different kind of analysis like maintenance planning, works, ecological flows, international rivers flows, droughts, and other similar issues that may arise in the management of a hydroelectric scheme.

Another interesting use of this model is to support the design of modifications to current elements or new hydroelectric schemes. This support can be provided in the consideration of different aspects like, number and size of power turbines and pumping units, reservoir size, minimum flow, channels for driving tributary rivers, etc. The more complex the hydroelectric scheme is, the more helpful the use of the simulator becomes, because it allows appreciating and quantifying the interaction amongst all its elements in the diverse situations that may happen with large size inflows series.

The experience of employing the simulator has opened the opportunity of performing improvements that, on the one hand, link the real management to the longer term optimization results, and on the other hand, take into account the elements in a more detailed fashion, with the aim of a more realistic and flexible management.

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