Object Oriented Simulation and Optimization of Hydroelectric Power Systems

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Abstract:

In this paper we present two models to evaluate the hydro scheduling of a multi-reservoir system. A simulation model based on the object oriented programming paradigm and another multi-objective optimization problem based on traditional mathematical programming tools are described. Both models are evaluated with real sized hydro basins elaborated from the Spanish hydrological system and comparisons between their results are given.

1. Introduction

Hydro energy is a very important resource to diminish the overall cost of electricity production as well as to reduce the impact in the atmosphere contamination. In most occidental countries the possible locations have been already developed and the attention is now focused on the operational effectiveness of the facilities and on maximizing their efficiency for producing electricity. In addition, many of the ecological impacts of large hydro projects can be minimized through an improved operation which requires a detailed modeling system to take into account all the alternative uses of the water.

Modeling multi-reservoir systems is an overwhelming task because of two main reasons. The first difficulty appears from the necessity of including detailed data regarding the characteristics of the involved facilities that have to be compiled, for example, the natural inflows of the reservoirs. Secondly, because the mathematical model itself is high-dimensional, dynamic by nature, non linear and stochastic.

Two approaches have been widely used to represent multi-reservoir systems: one based on optimization and the other based on simulation. Optimization is the way to obtain prescriptive optimal operational policies. Although many papers can be found in the literature representing hydro systems by optimization, we just cite one per type of problem: [Needham, 2000] as an example of a linear one, [Sjelvgren, 1989] for nonlinear, [Heredia, 1995] for network flow and [Pereira, 1991, Escudero, 1999] for stochastic optimization type. Other approaches based on stochastic or deterministic dynamic programming [Karamouz, 2005] and based on optimal control [Myzyed, 1992] have also been used.

Simulation of hydrothermal systems has been used in the past for several purposes. One is reliability analysis of electric power systems. An example of this is [Roman 1994], where a complete hydrothermal system is simulated. The merit order among all the reservoirs to supply the demand is determined as a function of their reserve level. Simulated natural hydro inflows and transmission network are considered. The goal is to determine the service reliability in thermal, hydro or hydrothermal systems. In [Sankarakrishnan 1995] and [Van Hecke 1998] the electric systems simulated do not consider the hydro topology. This simulation model takes a time step of one hour, and considers the electric network, whose node demand is defined as a function of the expected user type (industrial, residential, commercial, etc.). Variance reduction techniques are applied and the results are reliability measures. In

[Sankarakrishnan 1995] sequential simulation is compared with non-chronological methods based on the load-duration curve.

The application of any of the above mentioned methodologies depends on the necessities of the operator and on the modeling requirements. However, a recommendation to succeed in the implementation of optimization models is “to improve linkage with simulation models which operators more readily accept” [Labadie, 2004]. The coordination of optimization and simulation tools appears thus the natural path to improve the management of hydro scheduling in multi-reservoir systems.

In this paper we propose two models for the yearly hydro scheduling of a multi-reservoir system. In Section 2, a simulation model based on the object oriented programming (OOP) paradigm represents the operation of the system in a very flexible way. The simulation approach is usually preferred by operators because of its simplicity of use and because all the system complexities and dependencies can be represented. Some “system optimization” is involved in this simulation model by running the simulation in three phases. In Section 3, we state an equivalent multi-objective optimization model for minimizing the deviations of the water flow output from the targets decided by another upper level decision model. Simultaneously, the optimization model minimizes the reservoirs’ spillages as well as penalizes non provided irrigation flows. In Section 4, we present two cases of study from two Spanish hydro basins and compare the results obtained from both models. And finally, we extract some conclusions.

2. Simulation model

This section presents the hydroelectric simulation model. In order to represent the topology of the river basin, graphs appear as a natural description. The river basin comprises several reservoirs and plants, connected via water streams. In addition, inflows and river junctions have to be considered to accurately model real hydropower systems. These elements are represented as nodes of the graph modeling the river basin. The arcs connecting the nodes are the physical water flows through the basin.

Keeping in mind the wide variety of topologies that can be found in real hydroelectric systems, an effort has been made to generalize their representation. The OOP paradigm appears as a most suitable technique to tackle this problem, allowing flexible representation of the basin structure while retaining general management guidelines. Each node in the graph is held by a single object. These objects are managed almost independently, just considering the object's data and selected information of the surrounding objects, to coordinate the whole basin operation. As a consequence, the simulation adjusts the medium-term decisions and the management strategies previously fixed to the feasible outputs of the basin. In Section 2.1 the object types needed to allow flexible basin representation are described, and Section 2.2 details the simulation procedure.

2.1 Objects description

a) Reservoir

Reservoirs receive water from one or from several elements upstream, and they have at least one outgoing flow. In case of several outflows, a priority order has to be provided to decide which one to use first. Reservoirs have a maximum water volume they can hold, which will produce spills if surpassed. Additionally, minimum outflow constraints can be imposed to represent agreements related to irrigation or environmental needs.

The management of reservoirs is the most important aspect of the simulation. There are several strategies that can be chosen depending on the relevance of each reservoir:

- Pre-calculated decision table: Large reservoirs located at key points in the basin, for instance the basin head, rule the general operation of the basin. Thus, their management is analyzed by medium-term optimization models that suggest the optimal flow taking into account different factors: the current day of the year, a general hydrological situation of the basin, and the volume of both the reservoir and that of a reference reservoir.
- Production of inflows: For small reservoirs with little management capabilities, the best option is to produce the incoming flow, hence behaving as a run of the river plant.
- Towards maximum or minimum operation levels: These strategies intend to maximize energy reserve or energy production, respectively. They are suitable to medium-sized reservoirs in two different situations: the first one, when there is plenty of available energy, to try to retain most of it while avoiding spillage, and the second one when there is lack of energy, to produce as much as possible while maintaining a guarantee level.

Additional management can be performed independently from the previous chosen strategy. In first place, maximum and minimum volume curves can be set to force the reservoir not to reach a situation when spills or lack of agreed flow arise. In the second place, volume guide curves can drive the volume of the reservoir through pre-specified areas during simulation. This ensures the manager more control over the evolution of reservoirs. Finally, an additional spill control curve determines the maximum volume a reservoir can reach while contributing to avoid spills in the basin.

When the reservoir reaches this curve, there is a risk of spillages in the near future. Consequently, it doesn’t retain volume any more as a measure to avoid other reservoirs’ spills.

b) Channels

These objects behave like artificial rivers, simply carrying water between two points of the basin. The only management they perform is to set an upper limit to the flow of water through them.

c) Plants

Energy production management is the main objective of electric systems’ scheduling. In this context, hydro power plants play a key role due to their much lower costs. But concerning the simulation proposed in this paper, energy production is a byproduct and hydro plants do not perform any water management. They transform the kinetic energy of the water flowing through them into energy. This conversion uses an efficiency coefficient that is considered in this paper to depend linearly from the height of the water in the reservoir. The production is scheduled in peak and off-peak hours, giving priority to peak hours to substitute expensive thermal units. In addition, predictive maintenance is considered, modifying the power production available at each simulation step.

Finally, pumping units are also included in the simulation model. But the purpose of this pumping in the simulation is to reduce or avoid spills, and is not carried out with an economic criterion.

d) Inflows

These objects represent natural inflows from sources other than elements of the basin. They introduce water into the system, and their outputs correspond to historical records at their locations or to synthetic series calculated by other forecasting tools.

e) River junctions

These junctions group elements that share the penstock where all of them flow. As a consequence, this imposes a limit to their joint output flow. The management of this object involves two steps: the first one consists on merely simulating each element in the junction independently; in the second step, and following a priority order, each element outflow is reduced with the purpose of satisfying the common upper flow limit. This order may focus on maximizing electric production, whereas other criteria can also be considered.

2.2 Simulation model

The main objective during the simulation is to adjust each reservoir evolution to the strategy chosen for it. Nonetheless, there are also other goals that should be achieved:

- To avoid spillage, as spills mean loosing that production.
- To provide minimum stream flows previously committed.

This set of objectives is fulfilled with two phases of simulation. Additionally, one last phase is needed to calculate production. Briefly, each phase performs the following tasks:

1. Initial and independent management of each element in the basin.
2. Modification of this initial management to avoid spills and to supply minimum flows.

3. Calculation of electric production.

Each phase is described in the following subsections.

a) First phase

This phase sets a starting point for adapting the general guidelines to the current situation of the basin. For that purpose, this phase simulates each element individually in downstream sense, so that each element can know the water income it receives. Considering the input flow i as the total amount of water the element receives, each element calculates its output flow o as follows:

- Reservoirs with a volume of stored water v, decide their output depending on the strategy assigned to them:
  - Using the pre-calculated table.
  - Producing the inflows $o = i$
  - Heading to the target volume V^{target}, maximum or minimum[1]:
    $$o = i + \frac{v - V^{\text{target}}}{0.0864}$$
- Channels and power plants simply drive the input flow to their output: $o = i$
- Inflows set their output as the data from the series being simulated corresponding to the simulated day.
- River junctions perform their management as it has been previously mentioned: each element in the junction is individually simulated, and later this initial result is modified to fulfill the maximum joint flow requirement.

Besides, additional computations are performed to help reducing spillages and lack of minimum flow. This involves calculating the additional volume v^a that the element can provide, the volume v^k that the element can keep, and the same magnitudes

[1] The factor 0.0864 is the conversion coefficient from m^3/s to hm^3/day.

accumulated for the element and the upstream portion of the basin, v_{acc}^{a} and v_{acc}^{k}. For reservoirs with maximum volume $V^{\max}$, maximum outflow $O^{\max}$ and maximum pumping capacity $Op^{\max}$, these additional volumes are computed as:

$$v^{a} = \min\left(v^{f}, 0.0864\ O^{\max}\right)$$
$$v^{k} = \min\left(V^{\max} - v^{f}, 0.0864\left(o + Op^{\max}\right)\right)$$

where v^{f} indicates the volume of the reservoir after the simulation step.

For the rest of elements, these non-accumulated variables are zero-valued. The accumulated variables aggregate the non-accumulated values from that element upstream.

Furthermore, when the reservoir cannot supply its minimum required flow $O^{\min}$, the element demands additional water dv^{a} upstream:

$$dv^{a} = \min\left(v_{acc}^{a}, 0.0864\left(O^{\min} - o\right)\right)$$

And finally, when the maximum volume of water in the reservoir is reached as well as the maximum outflow, there are spills s and the reservoir demands the upstream elements to retain a volume dv^{k}:

$$dv^{k} = \min\left(v_{acc}^{k}, 0.0864\ s\right)$$

b) Second phase

This phase modifies the initial simulation to avoid the unwanted results of spills and lack of minimum flow. Thus, it is performed from the downstream to the upstream elements, obeying as much as possible the requests for additional volume or for volume to be kept. For each element receiving requests, these are fulfilled between the element and its upstream basin according to their capacities:

- For additional flow dv^{a}, the element output is increased as follows:

$$o = o + \min\left(v^a, dv^a \frac{v^a}{v^a_{acc}} \right) \Big/ 0.0864$$

and the remaining demand $dv^a \left(\frac{v^a_{acc} - v^a}{v^a_{acc}} \right)$ is transmitted upstream.

- For volume to be kept, the element output is in turn decreased like

$$o = o - \min\left(v^k, dv^k \frac{v^k}{v^k_{acc}} \right) \Big/ 0.0864$$

and the remaining demand $dv^k \left(\frac{v^k_{acc} - v^k}{v^k_{acc}} \right)$ is sent upstream.

c) Third phase

Once this stage is reached, the situation of the basin is already decided. Finally, production can be computed once the volume in each reservoir is fixed. The conversion of water flow into energy uses a coefficient k that is calculated for power plants. As it has been mentioned before, this coefficient is considered to depend linearly on the height of the water fall, measured from the top of the reservoir water level to the height of the following reservoir or the drainage pipe, whichever is higher.

In addition, production is allocated in the h^p peak hours rather than in the h^{op} off-peak hours when is possible. Thus the peak hours flow o^p and the off-peak hours flow o^{op} are calculated as:

$$o^p = \min\left(O^{\max}, o \frac{H^p + H^{op}}{H^p} \right)$$

$$o^{op} = \max\left(0, o \frac{H^p + H^{op}}{H^{op}} - o^p \frac{H^p}{H^{op}} \right)$$

Finally, the production can be computed as:

$$p = 0.0864\,k\,o$$

$$p^{p} = 0.0864\,k\,o^{p}\,\frac{H^{p}}{H^{p} + H^{op}}$$

$$p^{op} = 0.0864\,k\,o^{op}\,\frac{H^{op}}{H^{p} + H^{op}}$$

3. Optimization model

An alternative to the above described simulation model is to perform the management of a river basin with a mathematical programming problem. In this section we present a multi-objective optimization problem that decides the evolution of the basin's reservoirs minimizing the deviations of the output water flow from the targets decided by another medium-term decision model. Additionally, penalty over spillages, low reservoir levels and non provided water flows complete the problem objective function that decides the reservoirs' evolution. The penalty coefficients induce priorities over the decisions variables of the multi-objective optimization model. This problem is now described presenting the collection of sets, variables, parameters, constraints and objective function that form it.

3.1 Sets, Variables and Parameters

Set	Index	Meaning
I	i	Reservoirs
T	i	Reservoirs with pre-calculated decision tables
R	i	Run-of-the-river reservoirs
M	i	Reservoirs with target-oriented reserve level
C	c	Hydro Plants
D	d	Days
$Up(i)$	i'	Reservoirs upstream of reservoir i
$Up(i)$	c	Plants upstream of reservoir i
$Down(i)$	c	Plants downstream of reservoir i
$PumpIn(i)$	c	Plants that pump water to reservoir i
$PumpOut(i)$	c	Plants that pump water out of reservoir i

Table 1.1 Sets

$In_{i,d}$	Natural inflows at reservoir i in day d	$\left[m^3/s\right]$
$F_c^{\max}$	Maximum output flow of pant c	$\left[m^3/s\right]$
Sa_i	Minimum operation level of reservoir i	$\left[hm^3\right]$
R_i	Maximum operation level of reservoir i	$\left[hm^3\right]$
IR_i	Irrigation needs from reservoir i	$\left[m^3/s\right]$
$O_{i,d}$	Output flow proposed for reservoir i by a medium-term model in day d	$\left[m^3/s\right]$
W^{target}	Target reservoir level for reservoir i	$\left[hm^3\right]$
Pr_i	Penalizing coefficient of non supplied irrigation	
Pt_i	Penalizing coefficient for pre-calculated decision table reservoirs	
Pm_i	Penalizing coefficient for target-oriented reservoirs	
Ps_i	Penalizing coefficient for spillages	
Pw_i	Penalizing coefficient for reservoir level under minimum operation level	
$\mathrm{P}\overline{\mathrm{r}}_i$	Penalizing coefficient of non produced irrigation	
Pf_i	Penalizing coefficient of non produced water flow	

Table 1.2 Parameters

$v_{i,d}$	Final reserve of reservoir i at the end of day d	$\left[hm^3\right]$
$s_{i,d}$	Spillage flow of reservoir i in day d	$\left[m^3/s\right]$
$f_{c,d}$	Output flow of plant c in day d	$\left[m^3/s\right]$
$\overline{f}_{i,d}$	Forced output flow of reservoir i in day d	$\left[m^3/s\right]$
$pf_{c,i,d}$	Pumping flow of plant c to reservoir i in day d	$\left[m^3/s\right]$
$ir_{c,d}$	Produced irrigation flow of plant c in day d	$\left[m^3/s\right]$
$\overline{ir}_{i,d}$	Non-produced irrigation flow of reservoir i in day d	$\left[m^3/s\right]$
u_i	Identification of reservoir level under minimum operation value	$[0/1]$
w_i	Identification of reservoir level over maximum operation value	$[0/1]$
exc_i	Excess deviation of output water flow of reservoir from proposal	$\left[m^3/s\right]$
def_i	Defect deviation of output water flow of reservoir from proposal	$\left[m^3/s\right]$
$defv_i$	Defect of the reservoir level under its minimum operation value	$\left[hm^3\right]$
$defr_i$	Non supplied irrigation necessities from reservoir i	$\left[m^3/s\right]$
z	Objective function variable	

Table 1.3 Variables

3.2 Constraints

Water dynamics. For each reservoir i, the evolution of its reserve is controlled through the next constraint, which relates the final level with the initial level and computes the amount of incoming water flow and outgoing water flow. Incoming flow is due to natural inflows, other reservoirs output flows and spillages, and pumping from other reservoirs' plants. On the contrary, outgoing flow aggregates the reservoir output flows and spillage, the pumping flows to other reservoirs and the irrigation agreements that need to be satisfied and are not considered within the output flow.

$$v_{id} = v_{i,d-1} + \left[In_{i,d} + \sum_{i' \in Up(i)} s_{i',d} + \sum_{c \in Up(i)} \left(f_{c,d} - ir_{c,d} \right) + \sum_{i' \in Up(i)} \bar{f}_{i',d} + \sum_{c \in PumpIn(i)} pf_{c,i,d} \quad i \in I \right.$$
$$\left. - s_{i,d} - \sum_{c \in Down(i)} f_{c,d} - \bar{f}_{i,d} - \sum_{\substack{c \in PumpOut(i) \\ i' \in I}} pf_{c,i,d} - \bar{ir}_{i,d} \right] 0.0864$$

Output flow cancellation. The reservoir output flow needs to be cancelled when the reservoir level is under a determined minimum operation value. This need is achieved in the mathematical model combining two constraints. The first one identifies when the level is located under that under that minimum operation value, and the second constraint sets the output flow to zero in that case.

$$v_{i,d} \le \left(1 - u_i\right) Sa_i \quad i \in I$$

$$f_{c,d} \le \left(1 - u_i\right) F_c^{\max} \quad c \in Down(i), i \in I$$

Penalty under minimum operation level. However, although produced flow is cancelled, it could be obligatory to take water out of the reservoir (due to irrigation necessities, minimum biological river flow...). Even more, it could be positive for the overall management of the hydro basin. The flow obtained this way is denoted as forced output in the model. Hence, it is allowed to situate the reserve level lower than its minimum operation value, operation that will be penalized in the objective function.

$$v_{i,d} \geq Sa_i + defv_i \quad i \in I$$

Output spillage cancellation. A similar situation is modeled with the intention of avoiding unnecessary spillages. In this case, a maximum operation level is given such that preventive spillages are allowed when the reservoir level is greater than that value. This rule is introduced in the model by the formulation of two constraints. The first one identifies a reservoir situation over that maximum value. The second constraint cancels the spillage in case of being in that situation.

$$v_{i,d} \geq (1 - w_i) R_i \quad i \in I$$

$$s_{i,d} \leq (1 - w_i) M \quad i \in I$$

Irrigation. The irrigation needs that are to be satisfied can be fulfilled with the output production or with a non produced output flow. In order to improve the management of the river basin, the majority of these agreements should be given by the output flow. The model introduces two constraints related with the irrigation behavior. The first one limits the irrigation given with a produced flow. The second one penalizes non supplied irrigation flow.

$$ir_{c,d} \leq f_{c,d} \quad c \in Down(i) \quad i \in I$$

$$\sum_{c \in Down(i)} ir_{c,d} + \overline{ir}_{i,d} = IR_i - defr_i \quad i \in I$$

Management of reservoirs with pre-calculated decision tables. The management of a set of reservoirs is already proposed by another medium-term model. For those reservoirs, the proposed output flow depends on the reservoir level, on a reference reservoir level, and on a hydro index that is calculated weighting up the collection of natural hydro inflows all over the river basin. One of the problem objectives is to satisfy these proposals. For this reason, next constraint calculates the deviation of the output flow from the medium-term model proposal, which will be penalized in the objective function.

$$s_{i,d} + \sum_{c \in Down(i)} f_{c,d} + \sum_{c \in Down(i)} \overline{f}_{c,d} + \sum_{\substack{c \in PumpOut(i) \\ i' \in I}} pf_{c,i,d} + \overline{ir}_{i,d} = O_{i,d} + exc_i - def_i \quad i \in T$$

Management of the run-of-the-river reservoirs. These are commanded to produce all their incoming inflows. This constraint is forced in the model through the next constraint

$$v_{id} = v_{i,d-1} \quad i \in R$$

Management of the remaining reservoirs. As already commented, operation of these units can be oriented to maximize its stored energy reserve or to maximize its energy production. In the former case, the outgoing water flow is proposed to reach a maximum operating level and in the latter case, the outgoing water flow is proposed to allocate the reservoir level at a minimum operation level. We generalize both situations by considering a desired level V^{target} and formulating a constraint that imposes the condition that all the outgoing water flow minus the income water flow adjust to the release rate necessary to achieve that target level .

$$\begin{aligned} &-In_{i,d} - \sum_{i' \in Up(i)} s_{i',d} - \sum_{c \in Up(i)} f_{c,d} - \sum_{c \in Up(i)} \overline{f}_{c,d} - \sum_{c \in PumpIn(i)} pf_{c,i,d} \\ &+ s_{i,d} + \sum_{c \in Down(i)} f_{c,d} + \sum_{c \in Down(i)} \overline{f}_{c,d} + \sum_{\substack{c \in PumpOut(i) \\ i' \in I}} pf_{c,i,d} + ir_{i,d} = \frac{v_{i,d} - V^{target}}{0.0864} + exc_i - def_i \quad i \in M \end{aligned}$$

Objective function. As it has already been commented, the operation of the river basin elements may be interpreted as a multi-criteria optimization model whose objectives are to minimize the deviation from the instructions given by a superior model, to locate each reservoir level at a target volume and to penalize non supplied water flow requirements. An objective function is constructed that penalizes the abovementioned deviations. The coefficients attached to each penalizing variable induce a priority order among the non satisfied rules: the greater the penalizing coefficient, the greater the priority of that deviation to be minimized. Next equation presents this objective function. The order in which the expression is written indicates the priority that is used in the numerical section. Hence, minimizing non supplied irrigation is the main rule that need to be satisfied.

$$z = \sum_{i \in I} \mathrm{Pr}_i \, defr_i + \sum_{i \in I} Pw_i defv_i + \sum_{i \in M} Pm_i \left(def_i + exc_i \right) + \sum_{i \in T} Pt_i \left(def_i + exc_i \right) + \sum_{i \in I} Ps_i s_i + \sum_{i \in I} \mathrm{P}\overline{\mathrm{r}}_i \, \overline{ir}_i + \sum_{i \in I} Pf_i \, \overline{f}_i$$

4. Numerical results

The simulation model as well as the optimization problem has been tested over real-sized river basin systems. These test cases come from the Spanish hydroelectric system. Table 4.1 describes the two river basins considered.

	River Basin 1	River Basin 2
Reservoirs	9	10
Pre-calculated decision tables	2	3
Hydro plants	10	15
Natural inflows	6	7
Channels	0	1
River junctions	1	0
Historical natural inflows series	24	24

Table 4.1 Description of the hydro basins

Next table recovers the problem size of this daily optimization problem.

	River Basin 1	River Basin 2
Number of variables	105	134
Number of constraints	76	97
Number of nonzero elements	318	431

Table 4.2 Sizes of the daily optimization problem

The simulation and optimization models are solved for a collection of hydrological series. Also, special cases as dry, average and wet years are considered. The dry year and the wet case are built with 60 % and 140 % of the average inflows respectively. A single year hydro scheduling consists of the sequential simulation or optimization of the 365 days. The reservoir level after each daily calculation is the starting point for the next day operation. At this point, the initial reservoir level is used by the pre-calculated decision tables to set the outflow proposal for the new day.

The evolution of the reservoir level obtained by both the simulation and the optimization problem are quite similar. This similarity is depicted in figure 4.1, where it may be appreciated the evolution of two reservoir level during there consecutives years, obtained by the simulation model (red line) as well as the optimization problem (blue line). The minimum and maximum operation lines are depicted with dotted and continuous lines respectively. There can be observed that the optimization problem manages the water resources in a sharper manner than the simulation model, driving the reservoir level closer to the minimum operation curve than the simulation model. Other output similarities can be identified by checking spillages, and we have observed that these values almost coincide along the simulation scope.

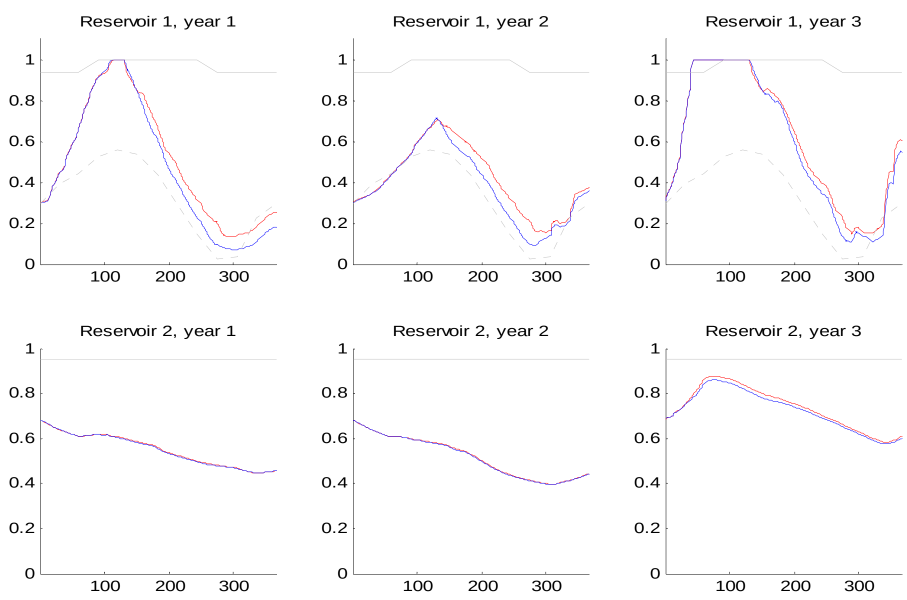

Figure 4.1 Evolution of two reservoirs in three different years

Another consequence of this slight difference in the reservoir management is translated to the hydro energy production. The more use of water resources by the optimization problems implies a bigger production of the hydro plants of the river basin.

Those values are now summarized in table 4.3. The values are normalized with respect to the production given by the optimization model for the average case.

Basin	Case	Production with Simulation Model (%)	Production with Optimization Model (%)
1	Wet	131.15	142.40
	Average	94.06	100.00
	Dry	58.97	55.92
	All series	96.52	96.69
2	Wet	125.81	147.68
	Average	94.73	100.00
	Dry	65.44	69.30
	All series	90.80	92.80

Table 4.3 Production for simulated and optimized results [p.u.]

The evolution of the reservoir levels for the 24 series of natural inflows is now depicted. Owing to the fact that the evolutions of the simulation model and those of the optimization problem are quite similar, only the evolution given by the optimization model is illustrated. Figure 4.2, 4.3, 4.4 and 4.5 represent the evolution of four reservoirs of river basin 2 normalizing the values with respect to their maximum level. The maximum operation curve is marked as a dotted line whereas the minimum operation curve is depicted with a solid line. It may be appreciated the way the model tries to locate each reservoir level between these two values. However, in extreme circumstances it is admitted to operate outside this normal operation area. An initial level under a minimum operation value (see Reservoir 2) is a realistic situation in hydro basins operation of dry years. In this case, the model conducts the evolution of the reservoir towards this minimum operation level. Another situation is also presented in this case study. In a situation where the reservoir level is kept close to the minimum operation curve, the need to provide a requested water flow could drive the level under the minimum operation value. This is a risk that needs to be assumed when managing the reservoir with this strategy. This is the situation of reservoir 1 for dry scenarios at the end of the year.

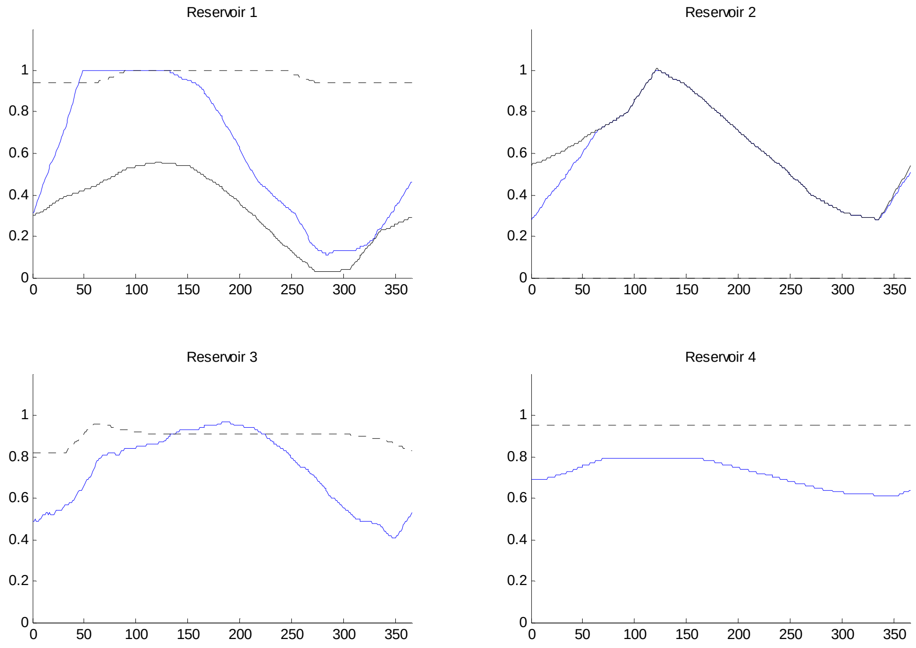

Figure 4.2 Reservoir evolutions for the wet case

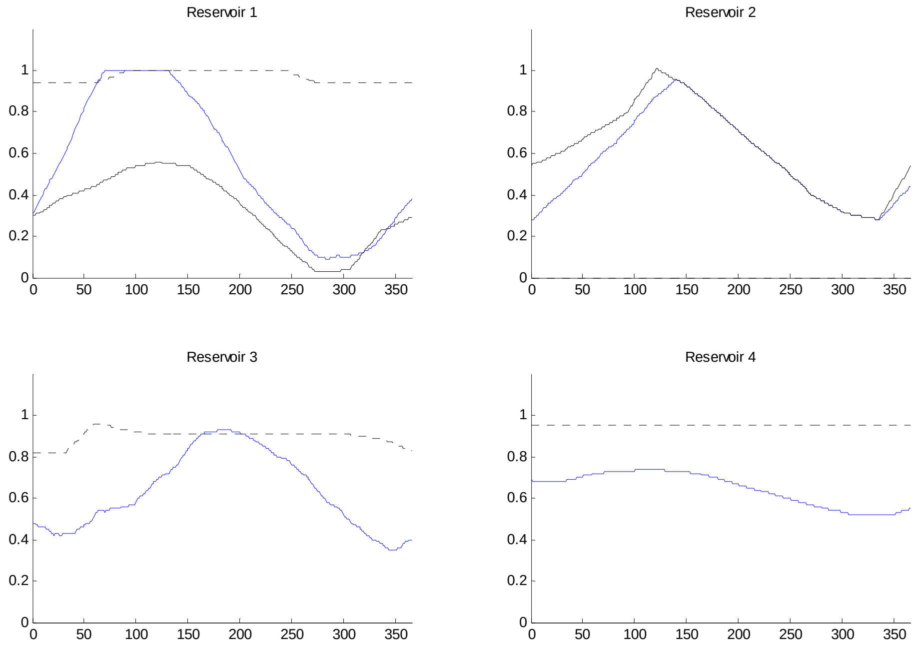

Figure 4.3 Reservoir evolutions for the average case

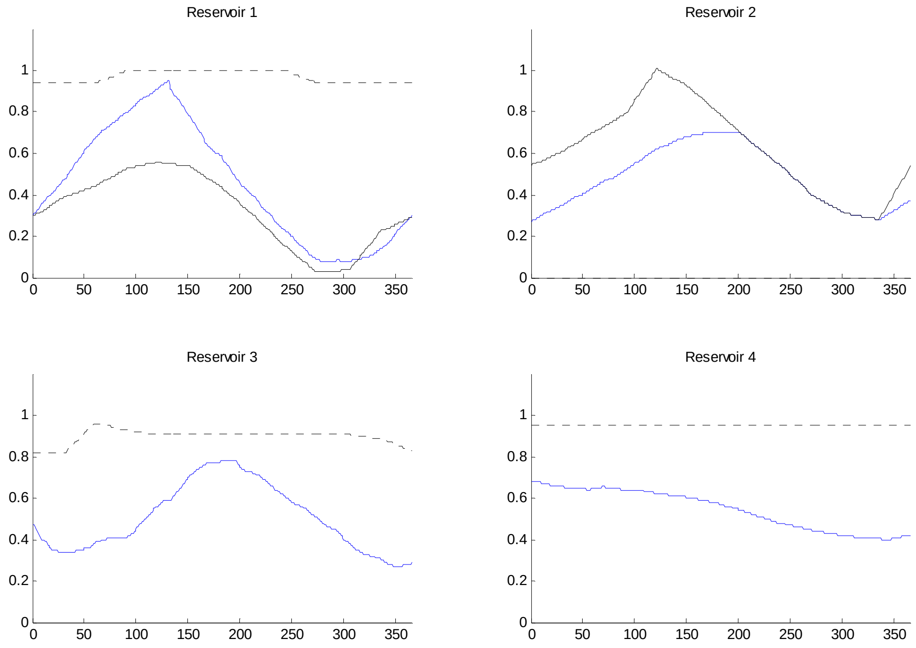

Figure 4.4 Reservoir evolutions for the dry case

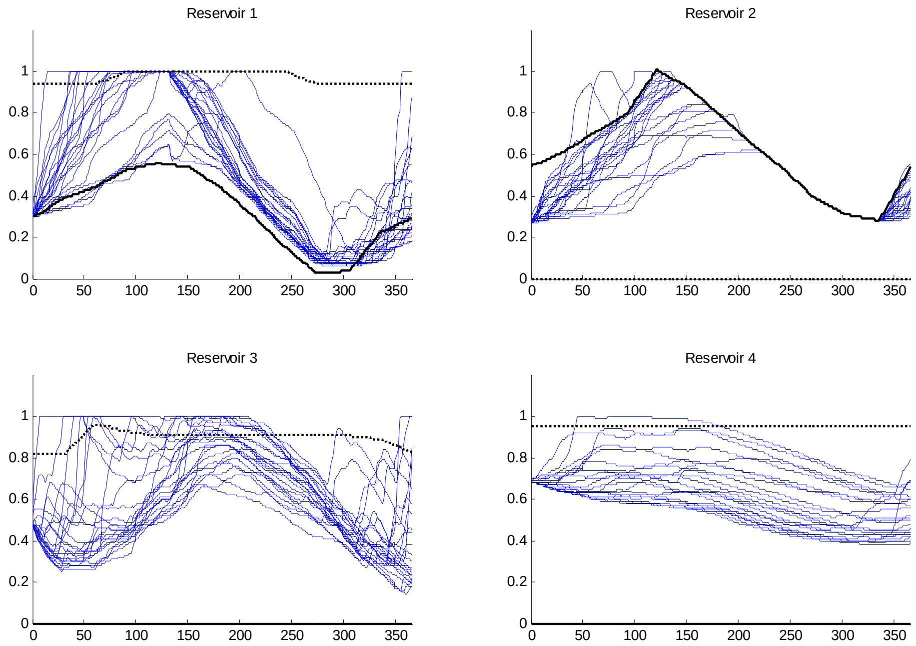

Figure 4.5 Reservoir evolutions for 24 hydrological years

5. Conclusions

We have presented a simulation model and an equivalent optimization model to evaluate the yearly management of a hydro scheduling multi-reservoir system. Although different, both models obtain similar results with can be used to benchmark the results of the other model. Both presents advantages and disadvantages that we now outline.

A disadvantage of the simulation model lies in its individual management of the elements of the basin. This myopic vision of the basin as a whole can derive in an under efficiency of the basin management. On the contrary, the use of an optimization model that considers the complete basin manages the upstream elements under a complete knowledge of the downstream elements and vice versa.

On the contrary, a disadvantage of the multi-objective optimization model lies in the necessary tuning of the penalty parameters. This is a crucial point for a correct management of the river basin. The introduction of a different collection of penalty parameters alters the priority of the deviation variables and consequently can modify the overall operation of the system. The use of the OOP paradigm settles this problem because of the individual rules that can be attached to each element of the basin.

The combined application of both models appears a natural way to improve the output of hydro-reservoir systems. In the application presented in this paper, the simulation model has been used to tune the parameters of the multi-objective problem. Reversely, the optimization model has been employed to extract heuristic criteria that were incorporated in the individual behavior of each basin element.

Our future efforts are focused on the combined application of the both models with the purpose of using the advantages of each model to overcome the weak points of the other.

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