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On the hydropower short-term scheduling of large basins, considering nonlinear programming, stochastic inflows and heavy ecological restrictions

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ABSTRACT

Large hydro basins are difficult to optimally operate, due to extended water travel times, numerous tributaries to the same reservoir, uncertainties in the water inflows and different characteristics and efficiencies of the hydro plants. Also, optimal management must consider ecological restrictions, guarantying legal and social requirements. This paper proposes an advanced optimization tool, improving economic profits while meeting European and local regulations. Nonlinear relationships between efficiency, height and stored water are represented through piecewise linear functions, without requiring integer variables. Uncertainties in the water inflow and large travel times are considered by using stochastic scenarios. The Guadalquivir Basin, in southern Spain, with 18 reservoirs, a minimum of 50 h between head and mouth of the considered section and strong flow restrictions is analyzed in the study. Results show the robustness of the model and the validity of statistical studies for short-term studies, given a large chain of reservoirs, dry circumstances and strong operation constraints.

Nomenclature

Constants:

g	gravitational acceleration (m/s^2)
M	conversion factor of water discharge from (Hm^3/h) to (m^3/s) and conversion of power (MW) into energy (MWh). It should be noted that periods of 1 h are considered in the simulations

Parameters:

$C_{i,Te}^{\exp}$	future value of the water
C_t	expected price of the energy (€/MWh), hour *t*.
$h_i^{\max}$	the maximum gross head, i.e., the difference between the head intake level and the tailrace level
$h_i^{\min}$	the minimum gross head, i.e., the difference between the head intake level and the tailrace level
hr	the number of reservoirs without electrical generation
k	coefficient of penalty factor.
k_1,k_2	penalty factors for ecological restriction flow and human consumption, respectively. $k_2 = 10k_1$
k_3	penalty factor for spillage flows
$m_{i,1}$	the slope of the first section for the dam's hydropower plant *i* in the function $v_{i,t}$-h
$m_{i,j} = \frac{v_{rj,i} - v_{rj-1,i}}{h_{i,j} - h_{i,j-1}}$	the slope of each section for the dam's hydropower plant *i* in the function $v_{i,t}$-h
n	total number of reservoirs, including conventional and run-of-the-river
nr	the number of conventional reservoirs with hydropower plants
nt	total number of sections linearized in the head/volume stored curve, Fig. 2
nwr	the number of run-of-the-river hydropower plants
$q_1^{CH}, \ldots, q_{nd}^{CH}$	consumption values each day of the *nd* different days
$q_{i,t}^{EF}$	the minimum (ecological) flow to be maintained in the river downstream of reservoir *i* [Hm^3/h]
$q_i^{HC\max}$	maximum transmission capacity of the water pipes for irrigation, industrial and urban consumptions

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$q_i^{S\max}$	maximum spillage capacity of plant *i*
$q_i^{T\max}$	maximum production capacity of plant *i*
T	total of stages (h)
t_v	travel time of the water between reservoirs.
$v_{i,1}$	the specified volumes at the beginning of the horizon in hour $t = 1$ for plant *i*
$\upsilon_{i,T}^{Final\_V}$	specified amount of water in reserve at the end of the period t = T.
$\upsilon_{i,1}^{Initial\_V}$	amount of reserved water at the beginning of period, hour 1.
$v_i^{\max}$	maximum capacity of reservoir *i*
$v_{r,j,i}v_{\min,2,\ldots,}v_{\max}$	values of the stored volume for each section for the dam's hydropower plant *i*
α_i	linear parameter of the relationship between net efficiency and head
λi	number of reservoirs upstream of reservoir *i*, considering all branches upstream of *i*
$\eta_i^{\max}$	maximum performance index for plant *i*
$\eta_i^{\min}$	minimum performance index for plant *i*
η_i^0	minimum net efficiency corresponding to the minimum turbine height of the hydropower plant *i*

Variables:

$h_{i,t}$	net head at reservoir *i* and hour *t*
$q_{i,t}^{AF}$	individual flows into reservoir *i* at period *t*, not considering the flows coming through the river from the previous reservoirs; the predicted water inflow in period *t* (*t* ∊ T) [Hm^3/h]
$q_{i-1,t}$	the flow into reservoir *i* at period *t* through the river from an upstream reservoir (or reservoirs)
$q_{i,t}^{HC}$	output water consumption for irrigation, industrial and urban uses delivered by reservoir *i*, hour *t*.
$q_{i,t}^S$	deviated (spilled) water volume at hour *t* in reservoir *i* [Hm^3/h]
$q_{i-1,t-t_v}^S$	spilled volume at hour (*t-tv*) from upstream reservoirs
$q_{i,t}^T$	water flowing through the turbine, hour *t* and plant *i* [Hm^3/h]
$q_{i-1,t-t_v}^T$	water flowing through the turbine at hour (*t-tv*) from upstream plants
qr1, qr2	Slack variables for reductions in environmental flow and irrigation, industrial and urban consumptions, respectively. *qr1* has a larger penalty factor than *qr2*
$s_{i,j,t}^{left}$	Slack variables at left side of *vr*
$s_{i,j,t}^{right}$	Slack variables at right side of *vr*
$v_{i,t}$	useful volume stored in the reservoir *i* at the end of the period T = *t*
$v_{ri,t}$	water storage of reservoir *i* at the end of stage *t*
$\eta_{i,t}$	net efficiency of plant *i*

1. Introduction

Over the last several decades, the annual water consumption in developed countries has steadily increased. Cities have increasing water demands and modern agriculture techniques require large amounts of water; therefore, the ecosystems demand more water than is often available [1]. In this process, irrigation is critical, providing at least 40% of the total worldwide food and fibre supply [2]. Despite these problems, irrigation, social uses of the water and hydropower generation continues to be necessary and important components of the world's well-being and growth.

Lower limits in the water flows (called ecological flows) are frequently used to reduce the effect of human activities on the environment [3]. In basins with strong ecological restrictions, regulation can significantly modify the optimal hydro operation. In some cases, there should be a recognition of the costs imposed on hydro operators in terms of lost profits, as well as the consideration of potential environmental impacts that result from the need for utilizing other energy sources, such as conventional power generation [4]. Several authors study the impact of ecological restrictions on power generation, including the effect in economic benefits of considering different ecological flows [5] and how ramping restrictions affect generation, preventing production during peak periods, [6]. These restrictions may force turbines to operate with inappropriate flow or head values outside of their respective design ranges, reducing overall plant efficiency and increasing the risk of cavitation and mechanical vibrations [7].

The EU legislation for watershed management, such as the European Water Framework Directive (WFD) [8], involves considerable economic and coordination efforts between producers and users. WFD objectives are to prevent deterioration and to improve the status of aquatic ecosystems by promoting the sustainable use of water. River basin management plans constitute the channel for applying WFD. Some authors study the impacts of the WFD economic tools in different environments, [9–11]. This work focuses on the Guadalquivir River in southern Spain. This basin is operated by river basin management plans performed by the Hydrographic Confederation of Guadalquivir River (CHG, in Spanish), following WFD and Spanish directives, [8,12].

Optimal scheduling of reservoirs for short-term horizons has been extensively studied, with the aid of optimization models and different mathematical methods. In [13–18], reviews of the main mathematical models developed for optimal hydro operations are performed. Also, a multi-objective approach to the short-term scheduling of a hydro system is proposed in [19]. The importance of controlling the head of reservoirs to optimize the complete hydro system and the profits in hydropower plants (HPPs) is highlighted in [20]. In [21], a comparative analysis of the results obtained from linear and nonlinear programming models is conducted. They conclude that the nonlinear models, more complex and accurate, are particularly suited for establishing guidelines for real-time operations. A comparison on the management of water using linear, nonlinear and genetic algorithms is performed in [22], concluding that nonlinear programming is more accurate and faster than the other algorithms. Short-term hydro systems can be adequately represented using nonlinear approaches, representing the head-stored water dependency through a mixed-integer model [23,24]. A similar mixed-integer approach is proposed in [25], to solve the short-term optimal scheduling problem. The model optimizes water time delay, which is the time required for discharging water from an upstream reservoir to its downstream reservoir. In [3], four scenarios combining three objectives: ecological flow, water supply and hydropower generation, are considered. In each scenario, a different objective is optimized, while the other objectives are represented as target constraints. In [26], the expected benefit-to-go function of hydro plants is linearized and stored in the form of cuts, solving a Stochastic Dual Dynamic Programming. A convex hull approximation of the true hydropower function is used and the algorithm is applied to the Nile River Basin. In [16], an integrated economic-hydrologic modeling framework is proposed, to estimate the social and economic gains from improvement in the allocation and efficiency of water use. In the considered basin (Maipo Basin, Chile), all hydropower stations are run-of-the river and benefits from power generation are relatively small compared to off-stream water uses. The focus of the modeling is on the agriculture sector and to a lesser extent on the non-agricultural water sectors. In [27], a four-dimensional model of hydro generation for the short-term hydrothermal dispatch is proposed, considering head and spillage effects.

In this literature, most of nonlinear approaches consider small hydro systems, due to the difficulty of obtaining optimal solutions of nonlinear problems with large number of variables, mainly when many of them are integer. In large basins, the extension of the area, the different geographical localizations of tributaries and dams and the long travel time required by the water from head to mouth of the river make adequate performing stochastic analyses for the optimal management of the basin. Applications of nonlinear programming to stochastic multi-reservoir systems are rare, due to the extreme computational requirements [28]. This paper presents an alternative for the representation and optimization of large hydro systems using nonlinear representation and reaching strong operational constraints. In this new formulation, the head of each reservoir is calculated using a piecewise linear approximation related to the morphology of the reservoir, without requiring integer variables, and a statistical consideration of the water inflows in short time schedule is performed, due to the large travel time for water between first and last considered reservoirs. Different types of reservoirs (conventional with electrical generation, conventional without electrical generation and run-of-the-river) are represented, with emphasis in the study of water for irrigation, industrial and urban (IIU) consumptions. The algorithm is applied to a large real river basin with 18 hydraulic infrastructures and strong ecological and human consumption constraints. Significant variations in the statistical distributions of the main variables are observed for the optimal basin operation. The results show that the statistical distribution of the main variables changes along the basin, showing differences related with types of reservoir, travel times, ecological constraints, IIU consumptions and storage capacities of the reservoirs. In addition, the simulations in the model of the real basin show that the uncertainty of the economic profit is larger than the uncertainty of the water inflows. This increase in the uncertainties is probably due to the nonlinearities in the model and the extension of the basin.

2. Short-Term hydro optimization model

In this paper, a nonlinear model for a large and interconnected basin is presented. The basin is operated in the day-ahead electricity market in a coordinated way. More than one owner is present in the basin; however, in this work, they are assumed to offer the best option for all the owners of the basin. The owners are operating in a price-taker concept, that is, they have no market power.

In hydro basins with reservoirs connected in series and parallel ways, there is a spatial-temporal coupling among the flows. In large basins, travel times for the water between head and mouth of the river require the representation of large time horizon, even for short-term studies. In the present case, three consecutive days conform the horizon. As the short-term analysis is daily performed, only the results for the first 24 h are applicable, in a moving timeframe approach.

The proposed formulation in based in the Guadalquivir River basin. However, it is generic and can be used for any other large basin with heavy use restrictions.

2.1. The types of hydraulic infrastructures

Three types of hydraulic infrastructures are here considered: conventional reservoirs with electrical generation, conventional reservoirs without electrical generation and run-of-the-river plants. The balance equation of reservoirs with a HPP considers the water in the reservoir in the previous period, the natural inflow, contributions from the upstream reservoirs, water flow through the turbine and spilled and IIU consumed flows. The equation is generally formulated as:

$$v_{i,t} = v_{i,t-1} + q_{i,t}^{AF} + q_{i-1,t} - q_{i,t}^{T} - q_{i,t}^{S} - q_{i,t}^{HC} \quad \mathrm{i} = 1 \ldots \mathrm{nr} \tag{1}$$

The water travel times, spilled volume and water volume flowing through the turbine at hour (t–t_v) from the upstream reservoirs, are considered in the formulation through $q_{i\text{-}1,t}$, without requiring integer variables.

Run-of-the-river plants have negligible storage capacity. Therefore, Eq. (1) is modified by removing the related terms, as in (2).

$$q_{i,t}^{AF} + q_{i-1,t} - q_{i,t}^{T} - q_{i,t}^{HC} - q_{i,t}^{S} = 0 \quad \mathrm{i} = 1 \ldots \mathrm{nwr} \tag{2}$$

Some conventional reservoirs do not have electricity generation abilities. However, they have storage capacities that allow more cost-effective use of resources and better flooding control in the basin. In these infrastructures, the volume for electrical generation is removed from (1), resulting in (3).

$$v_{i,t} = v_{i,t-1} + q_{i,t}^{AF} + q_{i-1,t} - q_{i,t}^{S} - q_{i,t}^{HC} \quad \mathrm{i} = 1 \ldots \mathrm{hr} \tag{3}$$

In (4), the water flow from upstream reservoirs is calculated, adding water volumes flowing through the turbine and spilled volumes in immediate upstream reservoirs. This water is available after the water travel times between dams. In large hydrological systems, many tributaries can inflow to a reservoir. In the present case, up to 6 branches flow into the same reservoir.

$$q_{i-1,t} = \sum_{\lambda i} \left(q_{i-1,t-t_v}^{T} + q_{i-1,t-t_v}^{S} \right) \quad \mathrm{i} = 1, \ldots, (\mathrm{nr} + \mathrm{nwr}) \tag{4}$$

2.2. Representation of the reservoirs

2.2.1. Head-water stored relationship

The head and level of water in the reservoirs present a nonlinear relationship, and several approaches have been used to represent it. In [29], head-dependency on discontinuous operating regions and discharge ramping constraints in 2 cascaded hydro systems with up to 7 cascaded reservoirs is considered. In [30], the nonlinearity between the head level and the actual hydropower generated is represented using a two-segment linear curve with breakpoints at the full gate position, considering best efficiency positions and the minimum flow. The nonlinearities of the relationship among the power produced, the water discharged and the head of the reservoir can be also considered through the discretization of a set of non-concave curves, [23]. In this paper, integer variables are used to select the operation point in the non-concave curves and the piecewise section of the curve.

In an alternative approach, electrical power, net head, turbine water discharge and its non-linear relationship can be represented using a so called under-relaxed iterative procedure, where the net head is successively updated until convergence is reached [31]. In [32], an enhanced linearization technique is introduced, presenting a mixed-integer model of the head effect and adopting a specialized approximation methodology for the three-dimensional relationship among power production, water volume and flow. This approach also requires integer variables to change from one section to another of the piecewise linear curve.

Optimal management of real large basins, including many hydro plants and long travel times, is difficult to calculate using conventional solvers. In present example, the upper and medium section of Guadalquivir basin requires the representation of 18 hydraulic infrastructures (16 of them with HPP's) during more than 50 h. The head/water curve of each plant in each hour must be represented by several linearized parts. Using previous approaches, many integer variables would be necessary, resulting in large computational times and probable convergence problems. As in the previous literature, the present formulation also utilizes piecewise linear functions to represent the nonlinear behaviour. However, integer variables are not required, using slack variables and a penalty factor in the objective function. Complementary variables allow a simple and accurate representation of the nonlinear variation of the reservoir head curve with the stored water, in each reservoir.

In Fig. 1, the green curve represents the relationship between the accumulated water and the net head in a reservoir. This curve depends on the morphology of the reservoir. In present approach, this curve is discretized by parts [33]. In this reservoir, 4 parts are required to linearize the nonlinear curve. Eq. (5) represents the linearized curve.

$$h_{i,t} = h_i^{\min} + m_{i,1} v_{i,t} + \sum_{j=1}^{nt} (m_{i,j+1} s_{i,j,t}^{right}) \quad i = 1, \ldots, \mathrm{nr} \tag{5}$$

In (5), the net head is a function of the constant initial net head ($h_{i,t}^{\min}$), the initial gradient ($m_{1,i}$) multiplied by the stored volume (second part of (5)) and the successive variations in the gradient ($m_{i,j+1}$) multiplied by complementary variables ($s_{i,j,t}^{right}$). These complementary variables measure the distance at the right side of each discretization limit $vr_{i,t}$, until reaching $v_{i,t}$. As an example, if at time t the volume in the reservoir i is in the interval between $vr2,i$ and $vr3,i$ ($vr2,i \leqslant v_{i,t} \leqslant vr3,i$) complementary variables $s_{i,j,t}^{right}$ are: $s_{i,1,t}^{right} = (v_{i,t} - vr1,i)$, $s_{i,2,t}^{right} = (v_{i,t} - vr2,i)$ and $s_{i,3,t}^{right} = 0$, with $s_{i,1,t}^{right}$ and $s_{i,2,t}^{right}$ measuring the distance at right of $vr1,i$ and $vr2,i$, respectively.

The value of complementary variables, measuring distances at left ($s_{i,j,t}^{left} \geqslant 0$) and right ($s_{i,j,t}^{right} \geqslant 0$) of discretization limits $vr_{i,t}$ is obtained in (6).

$$v_{i,t} + s_{i,j,t}^{left} - s_{i,j,t}^{right} = vr_{i,j} i = 1, \ldots, \mathrm{nr}\, j = 1, \ldots, \mathrm{nt} \tag{6}$$

$$\left.\begin{array}{l} s_{i,j,t}^{left} \geqslant 0 \\ s_{i,j,t}^{right} \geqslant 0 \end{array}\right\} \tag{7}$$

Complementary variables ($s_{i,j,t}^{left}$) are minimized in the objective function by a small penalization factor k. In this way, the minimum values of the complementary variables are calculated. Complementary variables assume not negative values, (7). Using complementary instead integer variables, the optimization problem can be solved easily, and larger systems with many variables can be represented and analyzed.

As in the literature, it is assumed that the net head varies with the discharge hourly. This assumption is justified for relatively small storage level variations, which holds for the case study.

2.2.2. Net efficiency

Net efficiency varies with net head, [28,34]. In the present work, a linear mathematical expression of net efficiency is represented. When the net efficiency has a nonlinear relationship with the net head, the same approach adopted with the head-water stored association can be adopted, through piecewise linear curves and complementary variables.

$$\eta_{i,t} = \eta_i^0 + \alpha_i h_{i,t} \tag{8}$$

With $\alpha_i = \frac{\eta_i^{\max} - \eta_i^{\min}}{h_i^{\max} - h_i^{\min}}$

2.3. Operational constraints

2.3.1. Environmental restrictions

Several authors have highlighted the importance of environmental restrictions in water operation planning, studying the economic impact of this assessment for optimal operation. The revenues of a HPP are very sensitive to the presence of these restrictions as well as to their magnitudes. Environmental constraints reduce the amount of water available to produce electricity and therefore limit the ability of HPPs to adapt the power supply to the demand [35]. In this formulation, ecological flows are considered as minimum water discharge limits. Flow discharge can be provided for both turbine discharge and spillage. For very reduced water inflows, ecological flows cannot be

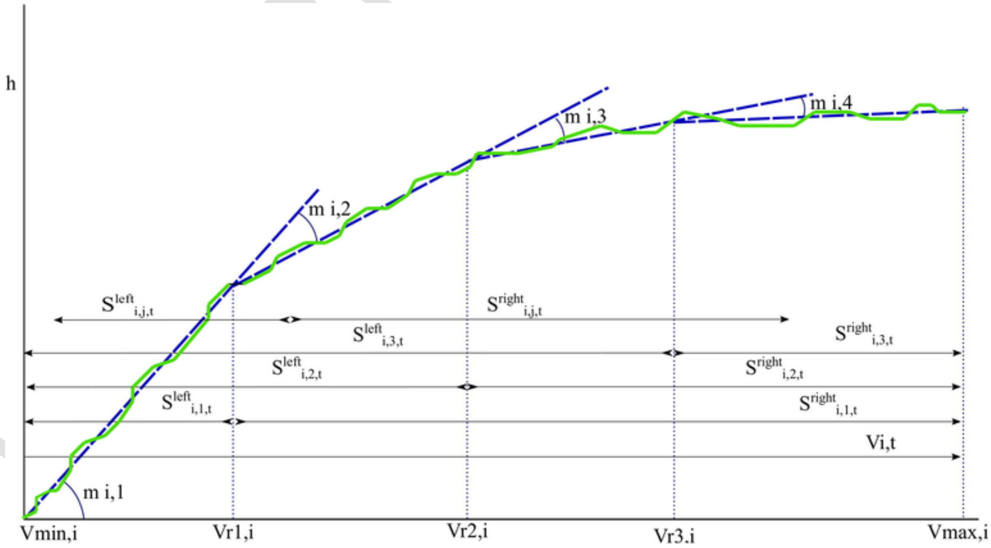

Fig. 1. Piecewise linear head/volume stored curve.

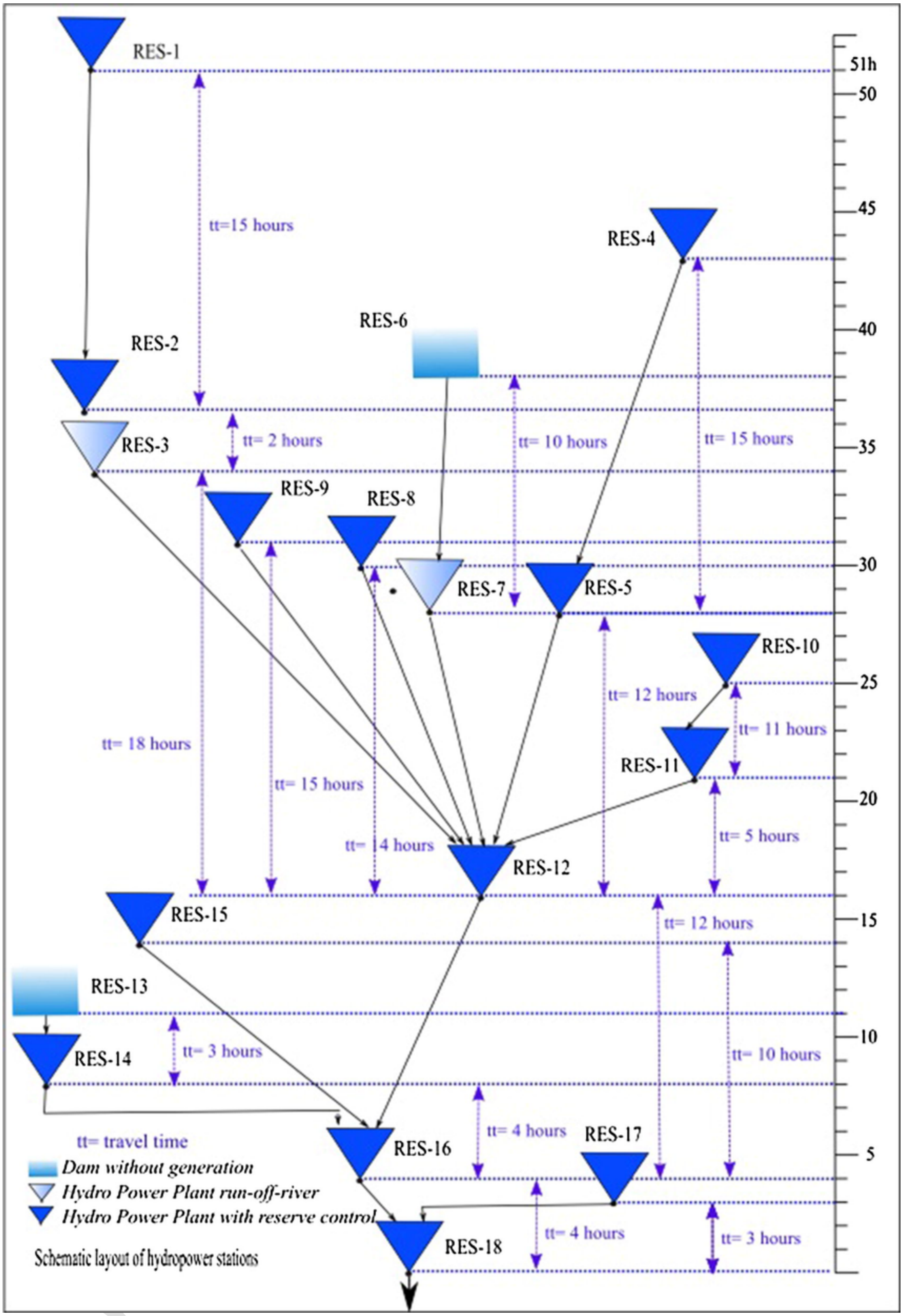

Fig. 2. Schematic layout of the basin.

met. In these cases, variable *qr1* allows the convergence of the algorithm, reducing the ecological constraints. In the objective function, *qr1* is penalized with a high cost, larger than the other prices in the function, assuring that only in extreme situations the specified ecological constraint is not respected.

$$q_{i,t}^{T} + q_{i,t}^{S} \geqslant q_{i,t}^{EF} - qr1 \quad \mathrm{i} = 1, \ldots, (\mathrm{nr} + \mathrm{nwr}) \tag{9}$$

In the present case, maximum ecological ramps are not included. They are not determined in the Guadalquivir River Basin. However, in other hydro systems, these restrictions can be easily included in the model.

2.3.2. IIU consumption

Most of the plants in the basin provide water for IIU uses. Furthermore, some are exclusively used for this, without electricity generation capacities. In a previous work, the authors calculate the costs related to the IIU water consumption from a basin, showing the economic significance of the calculation [34]. In this work, water consumption is represented as a daily specified expenditure for each plant in the basin. As the horizon is more than 24 h, daily consumption can be different for each day depending to the water demand forecast, as shown in (10). In some simulations with very low water inflows, IIU consumption cannot be satisfied. To allow the algorithm convergence in these cases, an additional variable *qr2* is included, reducing the IIU consumption requirements. In the objective function, *qr2* is penalized with a high cost. Water flows for IIU uses are also hourly limited by the size of water pipes, as shown in (11).

$$\sum_{t=1}^{24} q_{i,t}^{HC} \geqslant q_{1}^{CH} - qr2 if\, t \leqslant 24 sum_{t=24}^{48} q_{i,t}^{HC} \geqslant q_{2}^{CH} - qr2 if\, 24 < t \leqslant 48$$

$$0 \leqslant q_{i,t}^{HC} \leqslant q_{i}^{HC\,\max} \quad \mathrm{i} = 1 \ldots \mathrm{nr} \tag{11}$$

2.3.3. Initial and final states of the reservoirs

The initial reservation status of each reservoir at the start of the simulation period is known and expressed in (12).

$$v_{i,1} = v_{i,1}^{Initial\_V} \quad \mathrm{i} = 1 \ldots \mathrm{nr} \tag{12}$$

To calculate the optimal level of reservoirs at the end of the simulation period, two alternative options are available in the program: (a) using the future value of stored water, in objective function (18), or (b) pre-specifying the optimal final reserve at the end of the simulation time, (13).

$$v_{i,T} = v_{i,t=T}^{Final\_V} \quad \mathrm{i} = 1 \ldots \mathrm{nr} \tag{13}$$

In the present paper, option (b) is adopted, with $v_{i,T}^{Final\_V} = v_{i,1}^{Initial\_V}$ for all reservoirs. It must be stressed that the final stage in the reservoirs specified in (13) is related with the 3 days represented horizon. However, as the short-term schedule is daily executed, the algorithm calculates the optimal final level at the end of the first day, considering the forecasts for the next two days while fulfilling with legal constraints in all periods.

2.4. Bounds on the variables

Some variables are bound by equipment or operational limits. Upper and lower limits in the water released by the turbine, useful reserve in the reservoir, spillage in the dam and head are represented in (14)–(17), respectively.

$$0 \leqslant q_{i,t}^{T} \leqslant q_{i}^{T\,\max} \quad \mathrm{i} = 1, \ldots, \mathrm{nr} \tag{14}$$

$$0 \leqslant v_{i,t} \leqslant v_{i}^{\max} \quad \mathrm{i} = 1, \ldots, \mathrm{nr} \tag{15}$$

$$0 \leqslant q_{i,t}^{S} \leqslant q_{i}^{S\,\max} \quad \mathrm{i} = 1, \ldots, \mathrm{nr} \tag{16}$$

$$h_{i}^{\min} \leqslant h_{i,t} < h_{i}^{\max} \quad \mathrm{i} = 1, \ldots, \mathrm{nr} \tag{17}$$

2.5. Objective function

The goal of the optimization problem is to calculate the optimal production of coordinated HPPs in a basin, considering hourly expected prices in the market. The objective function to be maximized is expressed as:

$$\begin{aligned} Max \sum_{t=1}^{T} \sum_{i=1}^{nr} C_t M \eta_{i,t} g q_{i,t}^{T} h_{i,t} + \sum_{t=1}^{T} \sum_{i=1}^{nwr} C_t M \eta_i h_i g q_{i,t}^{T} \\ + \sum_{i=1}^{n} C_{i,Te}^{\exp} v_{i,T} - \sum_{t=1}^{T} \sum_{i=1}^{nr} \sum_{j=1}^{nt} ks_{i,j,t}^{left} \\ - k_1 qr1 - k_2 qr2 - k_3 \sum_{t=1}^{T} \sum_{i=1}^{n} (q_{i,t}^{S}) \end{aligned} \tag{18}$$

First and second terms of (18) maximize the profits of traditional and run-of-the-river HPPs, depending on the expected prices C_t in the market and the power output of the units. Power output is expressed as a product of the net efficiency of each plant, $\eta_{i,t}$, the net head, $h_{i,t}$, the water flow rate through the turbine, $q^{T}_{i,t}$, in each time period *t*, a conversion factor *M* and gravity *g*. The net efficiency varies with the net head on each HPP (8), and the net head has a nonlinear dependency with the stored water in the reservoir, (5). The third term of Eq. (18) includes, in a simple way, the future value of water stored in the reservoirs. Fourth term adds a small penalty factor to the complementary variables $s_{i,j,t}^{left}$, to avoid possible multiple values in the head calculation when the water released by the turbine is zero in an hour. Following two terms of the objective function are penalty factors for environmental flow and human consumption, allowing the convergence of the algorithm in very low flow situations. The last term allows the introduction of additional penalties for spillage flows, maintaining the water in the upper section of the basin.

The optimization problem is composed by objective function (18) and restrictions (1)–(17). All equality and inequality constraints are linear expressions. Objective function concentrates the nonlinear expressions, consisting in multiplication of variables. All the variables are continuous and non-negative. This formulation is easily and quickly solved for most of commercial optimization solvers, even for a large number of variables. The proposed formulation is adequate for large time horizons and statistical analyses, due to small *cpu* times in the resolution.

4. The basin of study

In the present work, the proposed formulation is applied to upper and medium basin of Guadalquivir river, Southern Spain. This region is extensively studied in the literature. Guadalquivir Basin faces a serious problem of decreasing resources and a management historically associated with the economic development of the region [36,37]. An improvement in water-use efficiency could be the key to mitigating water shortages and reducing environmental problems [38]. However, irrigation modernization has produced a rebound effect in the region [39]. Increased efficiency in irrigation increased (rather than decreased) the consumption rate of water [40]. Some authors [41] consider that a reduction in irrigated areas may be inevitable in the region, with implications for the regional economy and employment in the Andalusia region. Several approaches to improve the water use in the region are found in the literature [37–44].

In this paper, upper and medium trams of Guadalquivir River basin are analyzed. The 18 hydraulic structures (16 conventional reservoirs with electrical generation, 2 conventional reservoirs without electric generation and 2 run-of-the-river with electrical generation) are cascaded on several parallel routes (Fig. 2). Travel times are represented in the vertical axis of the figure. At least, 50 h are required to simulate the water travel time between first and last reservoirs. In the figures, RES means reservoir.

Most of the dams in the basin provides water for IIU uses. This utilization has priority, according to Spanish law. Legislation establishes also that water needs for ecological use should be set in the respective basin plans. Specific ecological values, as determined by the CHG for the basin, are used in this study.

For extended horizons, the forecast of natural inflows from outside the studied basin have associated some degree of uncertainty. Therefore, water forecast is represented here through a Gaussian distribution, with hourly mean and variance values. Two hundred scenarios are generated with this distribution, following a Monte Carlo approach. In each scenario, water forecast is added to water traveling between the dams in the basin from the previous day operation, to calculate the expected water inflow in each plant. Infiltration, flow-returns and evaporation effects are neglected, but they can be added when necessary. Price uncertainty can be also considered in the scenarios for the Monte Carlo simulation. In the here presented cases, it is not included.

Real data are used to represent the basin, including travel times of water, hydro plants and reservoirs characteristics, IIU consumptions and ecological flows, taken from several sources [45–48]. Typical features are assumed, when some data are not available. The mean and variance of the water forecast is obtained from typical inflows, derived from historical series [49]. For simplicity in the analysis of the results, only inflows in the basin heads (RESs 1, 4, 6, 8, 9, 10, 13, 15 and 17) are here considered, and the same inflow curve is represented in them. Fig. 3 shows the water inflow forecast curve as a main hourly value and the corresponding standard deviations. In the profile, the main estimative has clear hourly differences, with higher values at the first day and at hour 60. The standard deviation slowly increases with the horizon and has a medium value of 0.0013 Hm^3/h. The coefficient of variation, the ratio between standard deviation and mean values, is a measure of the dispersion of statistical distributions. In this case, the average coefficient of variation for the water inflows is 0.65%, for the first 24 h.

In addition to the water forecast presented in Fig. 3, a constant inflow of 0.00576 Hm^3/h is included in RES-3 at the first two hours, representing water flowing by the river from the upper hydro plant at the beginning of the programmed period. RES-3 is a run-of-the-river plant and it has an ecological constraint of 0.00576 Hm^3/h downstream. Therefore, this constant value must be represented, to assure ecological constraints at the beginning of the day.

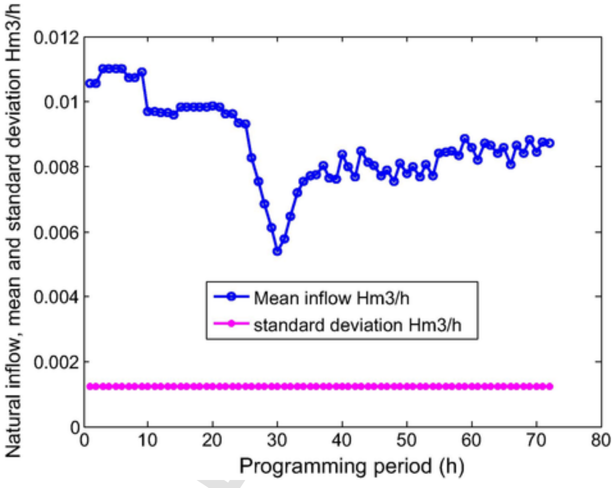

Fig. 3. Statistical distribution of water inflows in RESs 1, 4, 6, 8, 9, 10, 13, 15 and 17.

In the present analysis, typical prices in the Spanish daily market of March 2015 are used, extracted from OMIE (Market Operator, in Spanish) [50]. Additional penalties for spillage actions are not considered ($k_3 = 0$) in the simulations.

5. Results

Two hundred scenarios are generated, based on the expected average values of the inflows and uncertainties represented in Fig. 3. In each one of them, optimization problem (1)–(18) is solved, to calculate the optimal management in each scenario. Hourly periods of discretization are considered in the simulations. The optimization problem, for 18 hydraulic infrastructures with 16 hydro plants in the configuration of Fig. 2 and 72 h of horizon, results in 14,259 variables and 14,329 constraints. The model is implemented on a conventional computer with an Intel Core i5 750 processor and 4 GB of RAM using CONOPT under GAMS. The *cpu* time for the 200 scenarios is approximately two minutes.

Fig. 4 shows the statistical distributions of the storage level and the water flowing through the turbine used for producing electricity in each reservoir from the 200 simulations. In each curve of the water flowing through the turbines, the price profile in the period is included, for analysis purposes.

From Fig. 4, the statistical distributions of the flows in the river differ significantly from the statistical distributions of the water inflows. Even similar hydro infrastructures in the heads of the basin adopt different behaviours. RES-6 and 13 do not have electrical generation. From Fig. 4, RES-6 performs hourly variations, for maximum profits in the downstream HPP of RES-7. However, RES-13 has downstream RES-14, a reservoir with large storage capacity and electric generation. Therefore, RES-13 discharges at the beginning of the programming period all its forecasted inflow, increasing the head of RES-14 and then the generation performance. From these results, dams without electric generation not only help with flood control and human consumptions, but also perform real-time management of water flows in the basin, meeting restrictions and enhancing the generation performance and profits.

The other plants in heads of the basin, HPPs in RES 8, 9, 15 and 17, also deplete the reservoir at first hours, improving water height (and therefore, generation efficiency) of downstream reservoirs. Water inflows recover the desired final at the end of programming period. As expected, most other HPPs increase the production in high price peri-

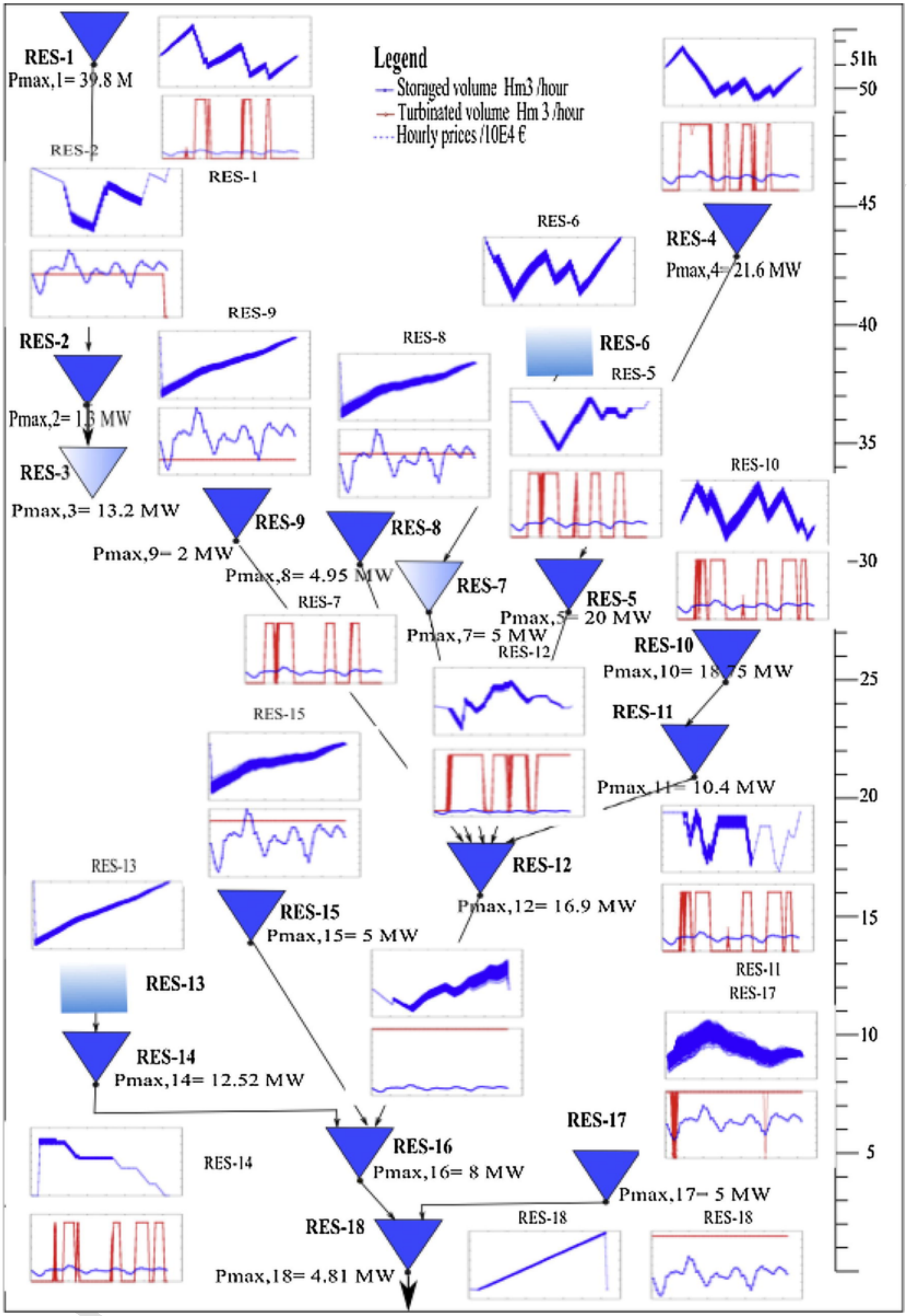

Fig. 4. Management of water volume flowing through the turbines and the stored water volume.

ods, increasing profits for the integrated operation. Differences in the schedule operation of the 200 scenarios are more evident in downstream reservoirs and in the early hours of the simulation period, with very stable values at last hours.

In Fig. 5, statistical distributions of water for IIU consumption and spilled water are presented. Most of the reservoirs do not have spilled volumes; therefore, in these plants, this curve is not represented. Spilled volumes represent energy not used for electricity production; therefore, in general, spilling water is not advantageous. However, generation efficiency depends on the water height in the reservoir; therefore, sometimes it is convenient to spill water at early hours, as shown in some of the upstream reservoirs.

Downstream RES 16 and 18 spill water at the end of the programming period, maintaining a higher reserve at all hours and improving

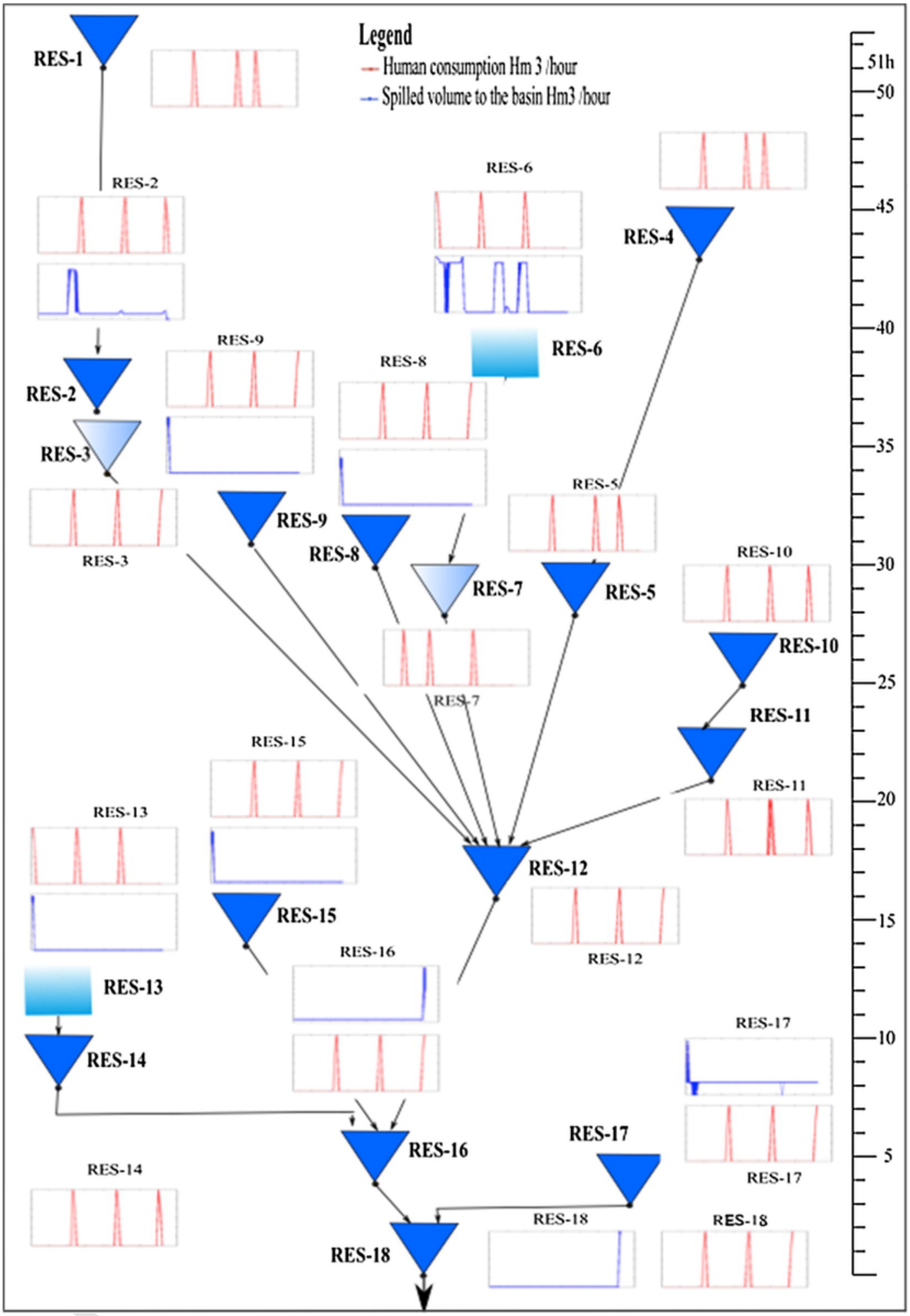

Fig. 5. Management of spilled volumes and volumes for human consumption.

generation performance. The final spilled water is required to maintain the same initial and final water levels in the reservoirs. It must be highlighted that this spilling action at hours 71 and 72 is not really performed, because only the programming of first 24 h is applicable; however, this information is used to design the specified stored values for the next periods and to avoid unnecessary spilled water.

RES-2 has continuous spilled water. The installed power of the plant in this reservoir is $q^T max = 0.00445\,\mathrm{Hm}^3/\mathrm{h}$. However, the run-of-the-river RES-3, downstream of RES-2, must maintain an ecological discharge into the basin of $0.00576\,\mathrm{Hm}^3/\mathrm{h}$ without external inflows. Therefore, RES-2 discharges water to reach the required ecological flow after RES-3.

From Fig. 5, IIU consumptions are performed in two different ways in the basin. If the reservoir does not have turbines, volumes are assigned at the beginning of each day. When the reservoir has generation capacities, volumes are transferred at the end of each day. This mode of operation allows the plants to operate with a higher level of reserves and higher performance.

As previously specified, one of the most critical situations in this basin occurs at RES-3. This is a run-of-the-river plant without its own inflow that must meet restrictions of IIU consumption and ecological flow. For 200 scenarios, the behaviour of this reservoir is shown in Fig. 6. Both restrictions are always met in the performed simulations.

The ecological constraints require constant water flow, Fig. 6. In this context of scarce water, electricity production with higher prices is only possible in the first day.

In Fig. 7, the Bell curve of the total profits for the stochastic scenarios and the frequency of the results in the two hundred scenarios are depicted. The median value of profits is 1.0685e + 08 €/day, and the standard deviation is 1.5285e + 06 €/day. The coefficient of variation for the profits is 1.4%, which is 115% larger than the coefficient of variation for the water inflows (0.65%, see Fig. 3). Due to the nonlinear representation of the basin, the uncertainties in the profits are larger than the expected uncertainties in the water forecast.

As depicted in Fig. 7, the most probable results are a little biased upside the medium value; 20% of the scenarios have a profit between 1.074e + 08 and 1.082e + 08 €/day.

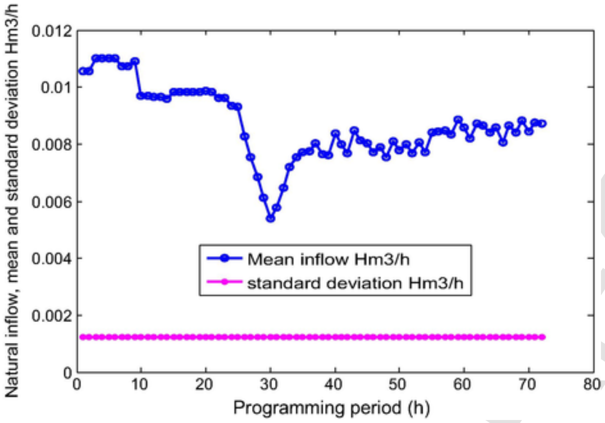

Fig. 6. Results for the two hundred scenarios in RES-3.

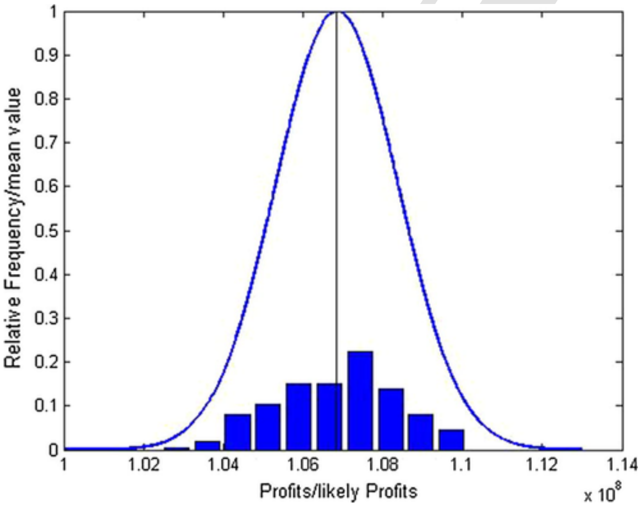

Fig. 7. Bell curve of total profit.

6. Conclusions

In some regions, hydraulic management is strongly affected by human consumption and ecological constraints. This is an issue that has received attention in both Spanish and other European jurisdictions. This work proposes a new tool for coordinated management of large basins to comply with restricted constraints, government regulation on water resource allocation, technical characteristics of the reservoirs and hydropower production profits. The results show that coordinated resource management meets legal requirements while obtaining ecological, economic and social benefits. Statistical studies are performed, analysing the behaviour of the main variables in the short-term horizon. The expected profit in the coordinated action is presented as a statistical variable, calculating the average most probable value and the uncertainties associated to the production.

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