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Development of a management tool for reservoirs in Mediterranean environments based on uncertainty analysis

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Abstract. In compliance with the development of the Water Framework Directive, there is a need for an integrated management of water resources, which involves the elaboration of reservoir management models. These models should include the operational and technical aspects which allow us to forecast an optimal management in the short term, besides the factors that may affect the volume of water stored in the medium and long term. The climate fluctuations of the water cycle that affect the reservoir watershed should be considered, as well as the social and economic aspects of the area. This paper shows the development of a management model for Rules reservoir (southern Spain), through which the water supply is regulated based on set criteria, in a sustainable way with existing commitments downstream, with the supply capacity being well established depending on demand, and the probability of failure when the operating requirements are not fulfilled. The results obtained allowed us: to find out the reservoir response at different time scales, to introduce an uncertainty analysis and to demonstrate the potential of the methodology proposed here as a tool for decision making.

1 Introduction

The setting up of simulation models capable of studying the response of a system like a reservoir has become a fundamental tool for its management. These models can attain a greater relevance in the case of regulating systems of fluvial networks subjected to a hydrological variability of an extreme nature at an annual and seasonal scale. This is the case of the Mediterranean climate, where flow events are few and intense, and in which it is necessary to attend to supply demands from a wide network for irrigation, urban consumption and energy production. Simulation must be carried out under diverse scenarios, namely, different environmental, social, economic, territorial and energetic conditions, which involves fluctuations in the inflows to the system and in the demands due to variations in the population, changes in land uses, in hydro-electric production policy or discharges needed to feed the fluvial channel maintenance downstream.

In the light of the Water Framework Directive, diverse global models for reservoir management have been proposed in terms of water demands and their planning. Among others, Wang et al. (2009) suggested a simulation model based on neural networks. These networks are defined from a "self-training" process made over the available measured dataset. All the reservoir demands can be taken into account in the resulting model, which can usefully assess the definition of the operating criteria for the reservoir. Pulido-Velazquez et al. (2008) modelled the surface-groundwater flows in a watershed using a hydro-economic approach, from which these authors proposed management in terms of opportunity costs. Pallottino et al. (2005) proposed a system for decision making which took into account climate uncertainty and the hydrological processes by means of a scenario simulation analysis, so that it could be an alternative in the case of not being able to adopt probabilistic rules or determinist models to represent that uncertainty. Jørgensen and Bendoricchio (2001) set the bases for the development of a model for the analysis of risks from pollution applicable to reservoirs. Cabecinha et al. (2009) used a Stochastic-Dynamic methodology to forecast how the changes in land uses affected water quality in reservoirs, by linking them to the ecological state of water.

With the aim of obtaining a global model for reservoir management, Gómez-Beas (2008) developed a first approximation for the numerical integration of the non-linear continuity equation, applied to Rules reservoir (southern Spain) under a set of simplifying hypotheses. This author obtained annual evolution curves of the stored volume for diverse input/output scenarios starting from the stochastic simulation of the inflow series to the reservoir based on available records.

The objective of this work was to develop a management model for reservoirs in Mediterranean watersheds which takes into account the uncertainty associated with the water inflows due to the time variability in the climate, and which is able to assess, from this, the optimal operating criteria for a given set of objectives. The resulting model supplies information on the reservoir's evolution state in terms of the volume of water stored, as a result of the balance between the inflows to the reservoir and demands imposed on the supply system. To set up the model, a grey box type system was opted for, i.e. a system for which its fundamental governing equations are known, even when certain processes may not be contemplated in those equations, and which permits a direct control over the regulation elements of the outflows. Thus, in only one scheme, the control over the system and the verification of its service and exploitation conditions are integrated, with the aim of preventing the operational stoppage of the supply network. The model was applied to Rules reservoir in Granada (southern Spain), where agricultural and urban demands coexist in a special environment, in which the presence of snow allows the occurrence of two filling cycles in this reservoir: one due to rainfall events during autumn–winter, and a second one due to snowmelt during spring. Different scenarios related to operation criteria were performed to show the usefulness of the model as a decision-making tool, whose application to another reservoir can be directly achieved just by changing the project parameters, and generating local stochastic samples from the measured/simulated inflow data. This method can be especially useful when little information is available about the inflow regime.

2 Study area and water demands

The system studied in this paper is Rules reservoir, which is the dynamic system for the regulation and control of water supply for urban consumption and irrigation to the coastal area of the Guadalfeo river watershed in the south of Granada (southern Spain) (Fig. 1). The basin climate is the result of the interaction between semiarid Mediterranean and Alpine climate conditions (Aguilar, 2008), with an average annual rainfall of 656 mm, and 107.5 $\mathrm{hm^3\,yr^{-1}}$ of inflows to the reservoir.

Firstly, in order to set up the management model, a study was made on the demand data for each existing water use, as well as their distribution throughout the year. The estimates used in this study were made from data available included in the Southern Basin Hydrological Plan (PHCS, 1999), and they must only be considered as approximate values of the current situation, which may have changed due to variations in land uses, or variations in the priority criteria for demand guarantee and/or distribution.

The urban supply to the Granada coastal population is the priority demand met from the reservoir. In PHCS (1999) a volume of 13 $\mathrm{hm^3\,yr^{-1}}$ was established for this use. On the other hand, the supply pipeline was designed for a maximum flow of 1 $\mathrm{m^3\,s^{-1}}$, which corresponds to a volume of 30 $\mathrm{hm^3\,yr^{-1}}$. Along with these data, it is necessary to take into account the seasonal nature of the coastal population, where summer tourism causes a considerable increase in the water demand, this period being estimated to last from 30 June to 15 September every year. From this information, the value of the demanded flow for urban supply use was set at 0.95 $\mathrm{m^3\,s^{-1}}$, which corresponds to that required by the peak seasonal population and 0.268 $\mathrm{m^3\,s^{-1}}$ during the rest of the year.

As for the water intended for agriculture, starting from the irrigation provisions established by the PHCS (1999) for the irrigable area of Motril-Salobreña with a horizon of 20 yr, a provision of 113.62 $\mathrm{hm^3\,yr^{-1}}$ was obtained. This volume is distributed throughout the year according to crop needs. As a first approximation to this model, a typical crop of the area, subtropical fruit trees, was considered.

Together with these principal demands satisfied from Rules reservoir, those intended for the production of hydroelectric energy, which is considered with a maximum flow of 2.5 $\mathrm{m^3\,s^{-1}}$, and for the preservation of the river ecosystem downstream, for which an ecological flow of 1 $\mathrm{m^3\,s^{-1}}$ was provided, should also be taken into account.

3 Methods

3.1 Model conceptual schemes

The interpretation of Rules reservoir as a dynamic system of the regulation and control of supplies for the coastal area of the Guadalfeo river watershed, make it necessary to use a control and verification model against failures, within which the fluvial regime, with its principal features in terms of its annual and hyperannual contributions, is represented. In the setting up of this model, its architecture is defined as a structure of calculation blocks, which together operate as a dynamic system of a single input and a single output; i.e. a system in which the impulse is a temporal series of measured or simulated flows, and the response is the sequence of the states of the reservoir, interpreted as its storage capacity, a consequence of certain work and demand conditions.

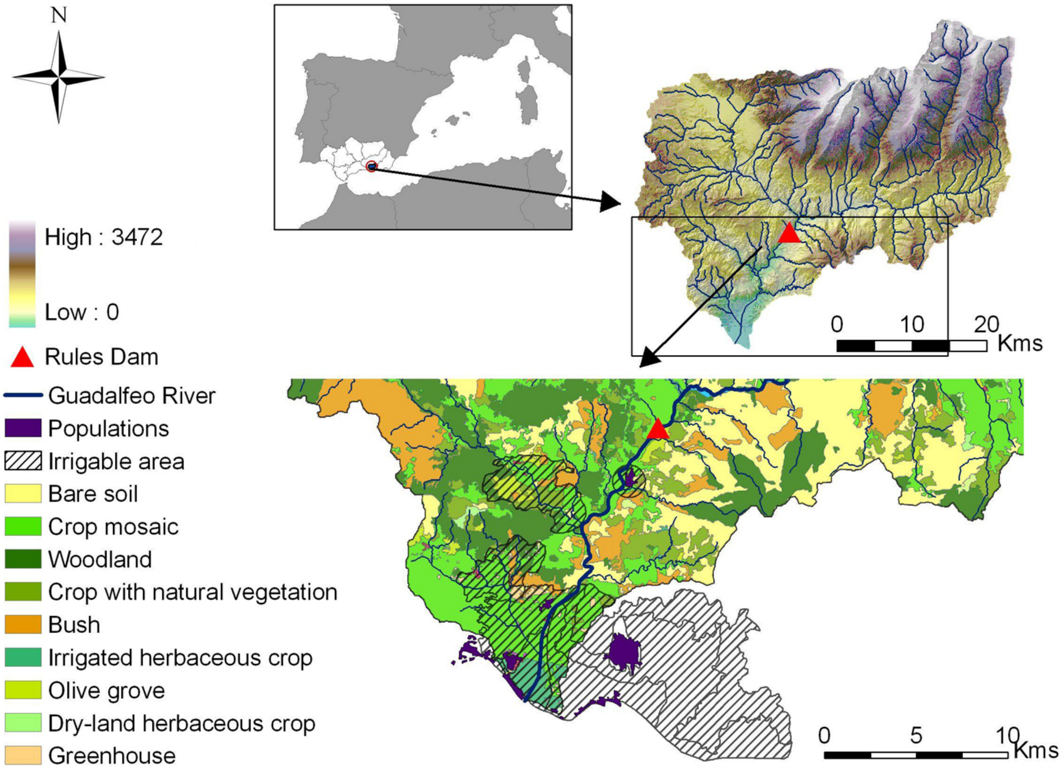

Fig. 1. Situation, Digital Elevation Model and land uses of Guadalfeo river watershed. Urban areas and irrigable areas furnished from Rules reservoir are also shown.

The model adequately describes the behavior of the reservoir in the form of an advanced control grey-box type tool for system identification, i.e. a system resulting from the combination of black-box type and physical models (Tulleken, 1993). The black-box type models are based on observed data and obtained by means of experimentation, whereas the physical models are founded on specific knowledge of the response of the processes. With the aim of obtaining the advantages of both models, their combination was opted for so that the black-box type model evolves towards a grey-box type model physically more consistent with the reality of the system being studied.

In order to carry out the control and verification, the failure mode associated with the operational stoppage limit state was considered (Losada, 2001); i.e. that in which the service is reduced or temporarily suspended due to causes outside the system. In the case of the system supplied from the reservoir, the failure is defined as the drop in reservoir level below the operational thresholds established, which is translated into a halt in the supply system due to insufficient water resources, implying an unacceptable social repercussion. In order to avoid that situation, a regulation is made of the system's outflows, which consists of acting dynamically on the supply intakes, calculating their opening from the reservoir level and instantaneous demand data by the integration of the continuity equation at every time step, and taking into account the situation of the reservoir at previous moments. In the case of the reservoir level dropping below the risk threshold, the outflow is reduced, and even stopped, during the time necessary to ensure the system's recovery so that the service can be guaranteed during a period of time. According to the priority established by the PHCS (1999), the model distinguishes between urban supplies and the remaining uses.

The verification was carried out by the integration of the continuity equation under the necessary conditions, assimilating the reservoir at a variable control volume in the time with a single input, the inflow series, and several outputs, namely, the outflows from the intakes, the loss of volume from evaporation which takes place from the water surface, and, eventually, the outflow of the reservoir spillway. In order to integrate the continuity equation applied to the reservoir, two simplifying hypotheses have been defined. The first one refers to the density of the water stored; from the different work accomplished in Rules reservoir (Cruz, 2005; Quevedo, 2005), summer thermal stratification takes place every year, which is not always stable, giving rise to a turbulent mixture processes due to the action of the wind or to the interaction with the perimeter of the reservoir. During the rest of the year, well mixing is fully achieved and the water density is uniform throughout the water column. Thus, in the model, the water density was assumed to be constant over the time and uniform in the whole control volume. The second simplifying hypothesis admits a prismatic reservoir volume for each differential depth, so that the differential volume for each step time can be calculated from the differential depth and the plane reservoir surface, calculated by means of a polynomial fit from measured data.

In accordance with the above, the modes of failure in the system were verified through the Eq. (1):

$$\frac{\mathrm{d}}{\mathrm{d}t}\int S_\mathrm{e}(H)\cdot \mathrm{d}H = [Q_\mathrm{in}(t) - Q_\mathrm{out}(t)] \tag{1}$$

where S_e is the reservoir water surface [L^2], $\mathrm{d}H$ is the depth differential [L], Q_in is the inflow to the system [$\mathrm{L}^3\,\mathrm{T}^{-1}$], and Q_out comprises the reservoir outflows [$\mathrm{L}^3\,\mathrm{T}^{-1}$], according to Eq. (2),

$$Q_\mathrm{out} = Q_\mathrm{outlet} + Q_\mathrm{spillway} + Q_\mathrm{evap} \tag{2}$$

Q_outlet is the sum of the outlet flows for each supply intake to satisfy demand [$\mathrm{L}^3\,\mathrm{T}^{-1}$], calculated according to the Eq. (3),

$$Q_\mathrm{outlet} = C\cdot\sqrt{2\cdot g}\cdot S_\mathrm{out}\cdot(H-\mathrm{Cota})^{\frac{1}{2}} \tag{3}$$

where C is a coefficient associated with the charge losses through diverse elements and is comprised between 0 and 1, S_out is the total drainage section of corresponding intake [L^2], and H-Cota represents the charge on the piping axis [L].

Q_spillway is the spillway outflow [$\mathrm{L}^3\,\mathrm{T}^{-1}$], in the case of this occurring, calculated from the Moñino's fit (Moñino, 2004) according to experimental data in the expression of the Eq. (4).

$$Q_\mathrm{spillway} = A\cdot(H-P)^B \tag{4}$$

where H-P is the effective charge [L], calculated as a difference between the total depth and the crowning height of the spillway, provided that H-P is higher than zero, and A and B are parameters obtained experimentally for this spillway in particular.

Q_evap is the daily evaporated flow in the reservoir [$\mathrm{L}^3\,\mathrm{T}^{-1}$], obtained through the formula of Neitsch et al. (2002) in the Eq. (5),

$$Q_\mathrm{evap} = 10\cdot\eta\cdot\mathrm{ET}_0\cdot S_\mathrm{e} \tag{5}$$

where η is the evaporation coefficient estimated as 0.6, ET_0 is the potential evapotranspiration obtained with the formula of Penman-Monteith [$\mathrm{L\,T}^{-1}$] and S_e is the reservoir free surface [L^2].

The model was programmed in the module of Matlab, Simulink, within which the main processes can be formulated analytically, thus turning it into a grey-box type model. In Fig. 2 the model flow diagram is depicted. First, the model gives a reading of input data, namely, the inflow, the demand, the reservoir level at the previous moment, ET_0, among others. Next, it integrates the continuity equation, obtaining a new reservoir level for the present moment. The following step is the calculation of expected outflow which can be released with each of the intakes only depending on that level, without applying the pressure loss or the valve opening criteria. After reading the demand data, the opening degree of each valve is calculated in terms of the reservoir level at that moment and at the previous time step, of the demand and of the thresholds established. Finally, the pressure loss coefficient is applied to the outflow, and this value is used for the flow balance in the next time step.

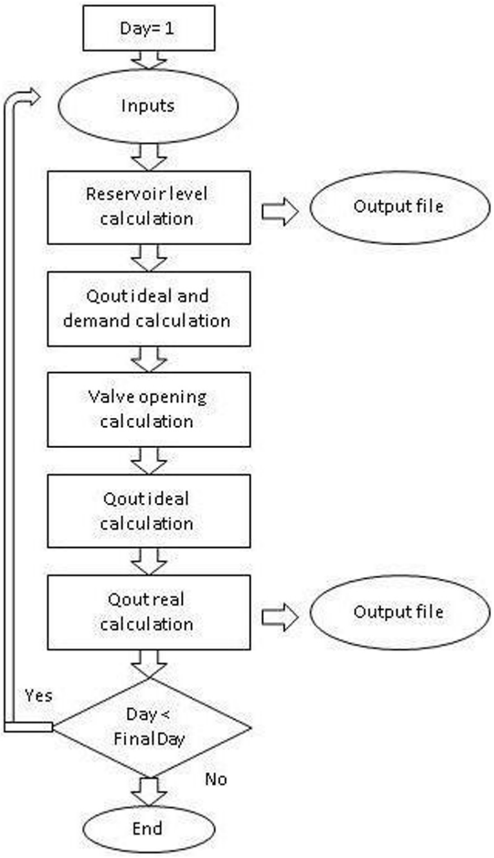

Fig. 2. Flow diagram of management model.

3.2 Uncertainty analysis

With the aim of planning for the short, medium and long term management of a reservoir by means of uncertainty analysis, a model with an appropriate structure for a large number of simulations in parallel is required, which must be capable of not losing the accurate information of detail. The technique that best fits this structure is the simulation by Monte Carlo integration, which was applied to a synthetic sample of N replications of a T-yr daily inflow series following the procedure depicted in Fig. 3 (Baquerizo and Losada, 2008; Polo and Losada, 2010).

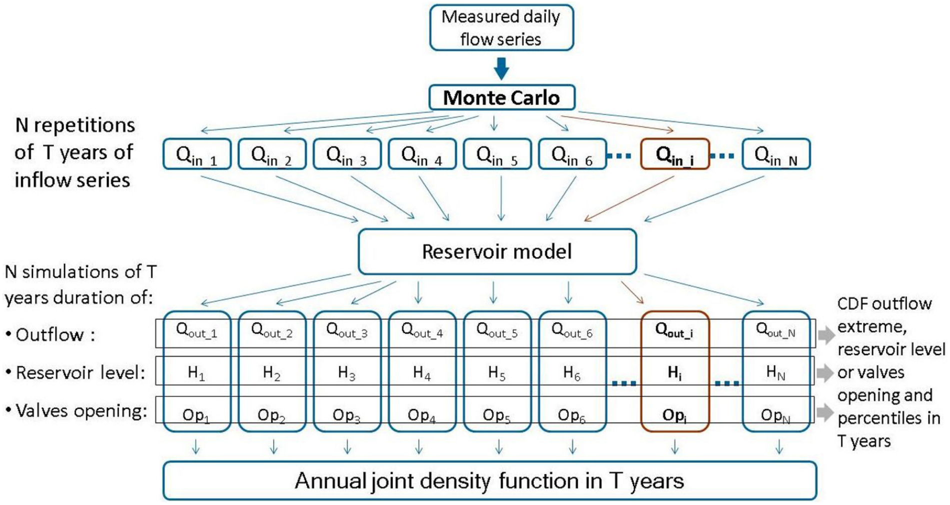

Fig. 3. Scheme of the procedure followed to derive probability functions for the variables selected.

The initial daily inflow series was obtained by the hydrological simulation of the contributing area by the distributed and physically-based model WiMMed (Polo et al., 2009), widely calibrated and validated in the study site (Aguilar, 2008; Egüen et al., 2009) for the available inflow dataset during the 1991–2005 period. A complete description of this model can be found in Herrero et al. (2010, 2011); its specific focus on the spatiotemporal distribution of the meteorological variables should be pointed out, and its being capable to reproducing the high variability in Mediterranean climate regions. This simulated series maintained the original measured data but included the no-data periods and corrected the existing non-quality data. Taking as a reference this 10-yr daily inflow series, the construction of replicated input series to the model were carried out by means of Monte Carlo simulation. In order to perform this simulation a study was made of the distribution function of random variables which define the nature of the inflows to the reservoir with respect to its magnitude and annual distribution. Once the parameters defining those functions were obtained, some series of inflows fitting those parameters were constructed. The resulting series allow the realization of a large number of simulations in parallel, and from them it is possible to extract information relative to averages and confidence intervals of the objective random variables which define the reservoir response, interpreted as an instantaneous storage capacity, resulting in demands and regulation criteria. By making a study of the distribution functions of each of these variables separately, or of the joint distribution function of all of them, it is possible to make a scenario analysis on the variation in the operation system parameters. In this study, 500 inflow series, each of them consisting of ten years of daily inflow, were simulated from the empirical distribution functions obtained from the available 15-yr daily inflow dataset in the period 1991–2005.

4 Results

4.1 Water flow in the reservoir

First, the hydrological simulation of a 10-yr series representative of the watershed was carried out. For this, a series of inflows to the reservoir was elaborated taking data measured in the period from 1991 to 2005, reconstructed with an alternation of dry, medium and wet years. The objective of making this series was to highlight the effect of the hydrological variability in the watershed in the management of the reservoir's resources, and the effect of the regulation carried out by the application of the model on the final result, represented as the volume of water stored at the end of the 10-yr simulation. Thus, it was aimed to emphasize the flexibility of the model in simulating any sequence of inflows to the reservoir. Figure 4 shows the reservoir state evolution in terms of the water level throughout the simulation. The inflow series and the outflow curves for each supply intake have also been plotted.

From this figure, the annual and seasonal variation of inflow, a characteristic of Mediterranean climate, can also be noted, with very long dry periods in summer and heavy rainfall events in autumn–winter, which is reflected in the volume of stored water in the reservoir, and therefore, due to the regulation criteria established, in the outflows. The two annual cycles of the reservoir's filling can also be seen. These are more notable in the hydrological year between day 1100 and day 1500 of the series, this being a wet year. The first cycle with a larger volume coincides with the time of the heaviest rainfall events, and the second corresponds to the snowmelt in the spring. On the other hand, because of the seasonal nature of the population variability, higher supply flows are observed in the summer, a time when rainfall is scant, so that the outflows of the rest of the intakes are affected, even interrupted,

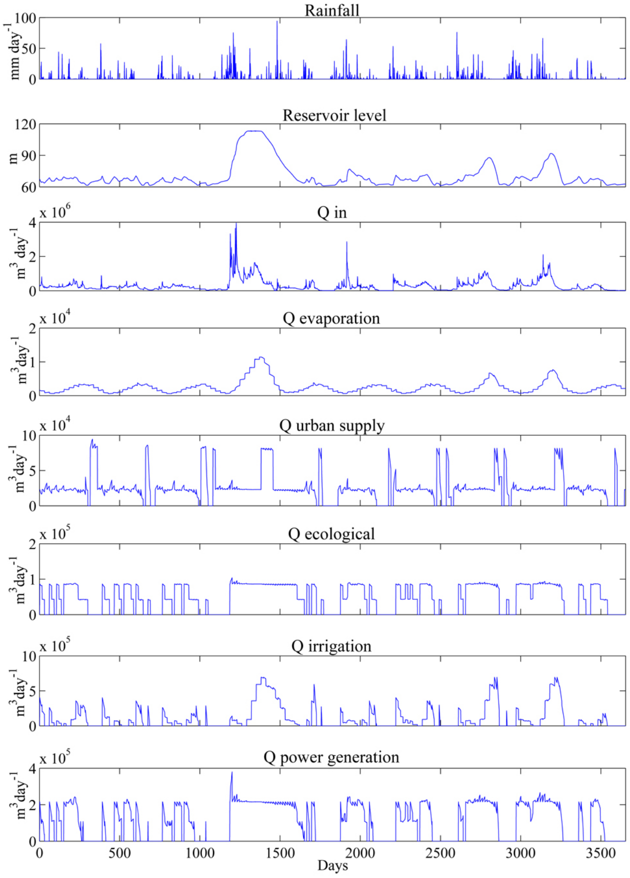

Fig. 4. Simulation results of a 10-yr series.

due to the priority established on the urban supply use, which is likewise reflected in the fewer number of days of interrupted urban supply.

4.2 Scenario analysis

The next step was to carry out a scenario analysis due to the variation in diverse system parameters, specifically, in the demands and in the period of time in which it was desired to guarantee supplies. For this purpose, a simulation was made of 500 series of the daily inflow with a 10-yr duration obtained by Monte Carlo simulation. These synthetic series were the input to the reservoir management model, simulating with each of them for four scenarios. That is, the functional thresholds were fixed so that the opening and closing of the valves was carried out in such a way that there was a volume of water stored necessary to ensure supplies during a period of time of 15 days, 1 month, 2 months or 3 months. Thus, 500 series of results were obtained for each of the scenarios simulated.

With this set of synthetic data, a frequency analysis was performed in order to estimate the density probability function of two variables: the reservoir state at the end of each ten-year series, represented by the stored volume; and the number of days on which the urban supply intake remained closed in that period of time as a consequence of the management carried out by means of the functional thresholds. For this work it was decided to assess the behavior for these two variables, and this could be done for any other variable resulting from the model. Starting from this analysis of frequencies, it will be possible to quantify the uncertainty associated with the natural processes produced in the watershed flowing into the reservoir, as well as being the basis for decision making. In order to facilitate the interpretation of these functions, a fit of each data series was carried out through Gaussian and Fourier functions. These fits are depicted in Fig. 5a–b, and in Tables 1 and 2 the goodness of each fit is shown by means of R-square parameter.

Table 1. Types of fit and goodness of fit for each density probability function of the final state of the reservoir compared to its initial state.

Data series	Type of fit	R-square
15 days demand volume	Fourier of 5 degree	0.8430
1 month demand volume	Fourier of 7 degree	0.9722
2 months demand volume	Fourier of 5 degree	0.9582
3 months demand volume	Fourier of 6 degree	0.9746
15 days 50 % demand volume	Fourier of 7 degree	0.9539
1 month 50 % demand volume	Fourier of 6 degree	0.9257
2 months 50 % demand volume	Fourier of 5 degree	0.8724
3 months 50 % demand volume	Fourier of 6 degree	0.8672

Table 2. Types of fit and goodness of fit for each density probability function of the number of days of closed urban supply intake.

Data series	Type of fit	R-square
15 days demand volume	Gaussian of 1 degree	0.5849
1 month demand volume	Gaussian of 1 degree	0.5154
2 months demand volume	Gaussian of 1 degree	0.5335
3 months demand volume	Gaussian of 1 degree	0.5803
15 days 50 % demand volume	Gaussian of 1 degree	0.9351
1 month 50 % demand volume	Gaussian of 1 degree	0.8845
2 months 50 % demand volume	Gaussian of 1 degree	0.9430
3 months 50 % demand volume	Gaussian of 1 degree	0.9435

The highly non-linear behavior of the objective variables selected, the final state of the reservoir and the number of days of interrupted water supply, can be observed in Fig. 5a–b from the different results obtained by changing the guarantee period duration in the operation criteria. The increase in this parameter does not produce an orderly trend of change in the maximum observed in the corresponding probability functions in any of the cases. The non-linear nature of the hydrological response of the watershed, together with the specific features of the reservoir, and the particular time occurrence of inflows along with the time guarantee, are responsible for this.

From Fig. 5a it can be observed how, for current demands, the highest frequencies are given in a ratio $H_{\mathrm{end}}/H_{\mathrm{initial}}$ of

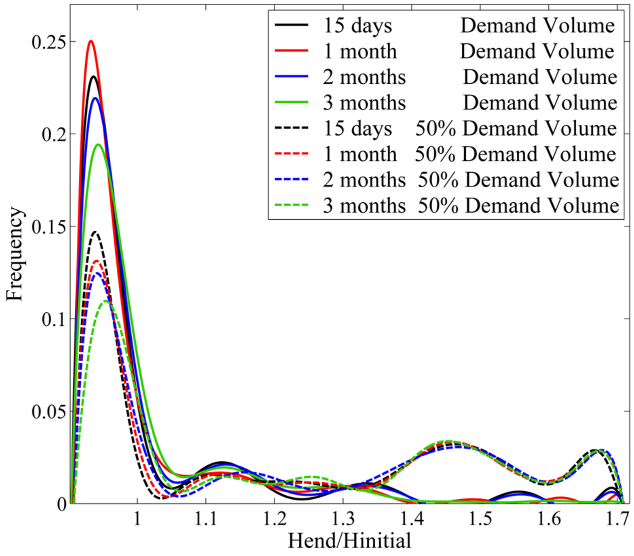

Fig. 5a. Function of probability of the final state of the reservoir compared to its initial state in a ten-year simulation.

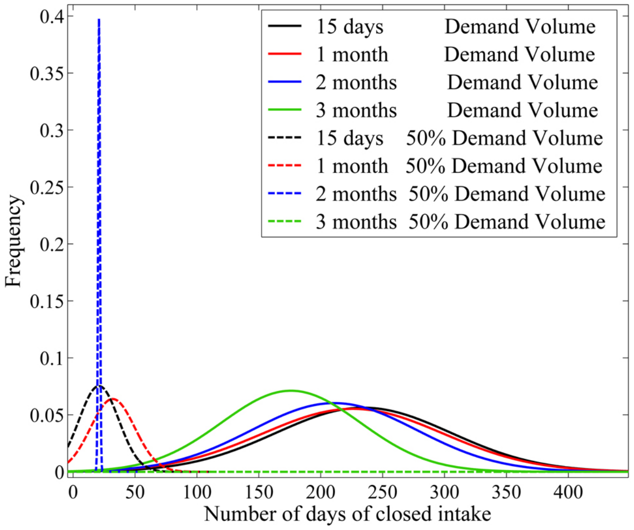

Fig. 5b. Function of probability of the number of days of closed urban supply intake in a ten-year simulation.

0.9 to 1, independently of the scenario considered, that is, for an equal final state, or even a somewhat lower one at the initial state, which underlines the functioning of the management exercised in the model. Thus, it can be concluded that with the regulation policy carried out by means of the model developed in this paper, there is a high probability that the reservoir will be found in the same situation at the end of a 10-yr series, and with an even smaller stored volume than the starting one, with the likelihood of its state improving at the end of that period of time being practically negligible, i.e. under 0.03, namely the resources received by the reservoir will be totally consumed. Also, if we complete this analysis from the results in Fig. 5b, it is observed that the maximum frequency of closing the supply intakes is around 0.1; that maximum probability corresponds to 200 days of closure with no great differences existing as a function of the guarantee criterion considered. That is to say, on 200 days of each series of 10-yr, the flow demanded is not being supplied, in this case the urban consumption, which is the priority use furnished from the reservoir. Therefore, not only are all the reservoir's resources consumed, but, in addition, there is a scarcity of water in some periods.

In view of these results, one can ask oneself which parameters or variables of the system can be acted upon in order to increase the probability of improving the reservoir's state after a period of functioning of T years, in this case ten. For this purpose, the model was run on the same series randomly simulated and under the four scenarios of the supply guarantee volume mentioned, with some demanded flows, half of those estimated for this study, as can be observed in the figure itself. For demands equivalent to 50 % of those estimated, the probability that the reservoir would be in a better situation than the initial one has considerably increased, as was to be expected, with a likelihood of improving its state by 1.5 times around 0.05, for the four criterion considered. Taking these results, it can be deduced that acting on the flows demanded will improve the future situation of the reservoir. This conclusion is reinforced by the results in Fig. 5b, in which an important reduction in the number of days, from 200 to 25, of closing the supply valve was observed, and differences are noted according to the management criteria, so that the water scarcity situations that make it difficult to supply the population have significantly diminished, with the closure days reaching 0 if a guarantee of 3 months' supply is adopted. At this point, the difference between the guarantee criteria of 2 and 3 months should be noted since the curve fitting for 2 months presents an extreme, isolated value. It has been verified that this peak in the graph is due to the fit made. However, that fit was opted for due to its goodness, represented by its R-square value (see Table 2), and because it has been observed how the rest of the curve represents the trend well. Therefore, this point has been obviated when interpreting the results shown in the figure, since a very similar behavior has been observed in the data before the fit between the series of results of the scenarios of 2 and 3 months of a supply guarantee, so that it can be concluded that the number of days of the closure of the urban supply intake tends to be cancelled as the guarantee criterion is more restrictive.

5 Conclusions

Using the reservoir management model developed in this paper, annual evolution curves of the volume of water stored are obtained, which allows for the regulation of the water supply based on some established criteria in a sustainable way with the commitments existing downstream. The parameters defined in this model characterize the reservoir in which it was applied; nevertheless, it is possible to give a general nature to the model just by varying those parameters for each particular reservoir in which it is wished to apply it.

The resulting model allowed us: to obtain results at different time scales, to introduce an uncertainty analysis, as well as to show the potential efficiency of methodology.

By means of the probability functions of the selected variables of interest, the model becomes a tool for decision-making, in such a way that it is possible to hold a criterion on the opening and closing of valves in terms of the desired reservoir situation at the end of a simulated period, or any other selected variable, taking into account the consequences of this decision in the supply system. These consequences are represented in this case by the number of days in which the minimum necessary flow for supplying the urban consumption is not met with.

The model is designed in such a way as to facilitate its inclusion in hydrological watershed models. At present its incorporation into the distributed and physically-based hydrological model (WiMMed) is being developed. This will allow us to simulate changes in land uses and their influence on the associated water flows, as well as a random generation of an inflow series with the aim of making predictions under different scenarios.

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