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Procedia Engineering 89 (2014) 1260 – 1267

Procedia Engineering

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16th Conference on Water Distribution System Analysis, WDSA 2014

Optimal Management of the Jucar River and Turia River Basins under Uncertain Drought Conditions

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Abstract

This paper presents a methodology to assess the best behavior achievable for a water resources system, and we apply it to the joint system of the Jucar River and Turia River basins in Spain. The resources of the two rivers are used jointly to meet the different water uses within the region, especially urban demands and environmental requirements. The climate change effects in this area are predicted to be particularly severe in this area with great variability in drought patterns. The results are particularly suitable for evaluating the best performance of the system under uncertain conditions.

Keywords: Optimization; risk assessment; drought; water resources planning and management; AQUATOOL

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1. Introduction

Drought is a major concern for water managers in many regulated river basins throughout the world [1][2]. Especially at those in which the equilibrium between resources availability and water uses is very fragile, making that deviation below normality compromises the capacity of the system to cope with all the demands and environmental requirements. Since droughts are not isolated events but instead they develop over time in what could be considered a creeping behavior, it is very difficult to determine when an episode starts and how long will it last. This lack of knowledge makes difficult both long term and short term decision-making processes.

Because of the difficulty at detecting drought episodes occurrence, and forecasting their intensity and duration, the traditional responses to drought have been reactive, adapting the measures to the severity of impacts as long as they

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doi:10.1016/j.proeng.2014.11.432

were detected in what is called a crisis management. This approach is ineffective, poorly coordinated, and untimely; and does little to reduce the risk associated with drought [3]. Because of this, drought management has evolved in recent years towards a more risk-preventive approach. Drought planning must predict what is predictable and establish strategies of prevention and management of the growing drought risks generated within the current climate change dynamics [4]. To reduce drought risk, there must be an understanding of the hazard using climatology, improved operational monitoring, an analysis of vulnerability to understand what people and sectors may be most affected by drought, why these impacts occur, and if these relationships are changing over time [5]. This new risk management based approach to drought management has been expressed in the necessity of developing drought management plans [6] that provide a dynamic framework for an ongoing set of actions to prepare for, and effectively respond to drought, including periodic reviews of the achievements and priorities; readjustments of goals, means and resources; as well as strengthening institutional arrangements, planning, and policy-making mechanisms for drought mitigation.

Following a preventive approach in drought management requires advancing, to a certain extent, the possible impacts a drought episode may have on the water resources system. To do this it is necessary both forecasting drought characteristics and assessing their effects on the system. A common methodology is the use of indicator systems. An indicator system for a river basin is formed by a series of variables that describe the basin drought status and include: reservoir storages, groundwater piezometric levels, streamflows, reservoir inflows and precipitation. The different values taken by the indicator define what the drought status is. However, these systems are limited to determine current drought situation based on the comparison of present variables values with the variables occurred in the past. This limits the forecasting capabilities of the indicator systems. Even though they have been calibrated in such a way they can forecast similar past droughts, no drought episode is equal to other and thus it is very unlikely the indicator system is capable of advancing the real consequences of the upcoming event.

This paper introduces a methodology to assess the best behavior of a water resources system in front an uncertain hydrologic situation, as well as to evaluate the best achievable results for any mitigation option managers could envisage. We applied it to the Jucar and Turia Rivers conjunctive water resources system as a complement of the existing indicators system. We will show how the complementary use of both options allows an improved management of the system allowing water managers to optimize the settings of the measures addressed to avoid the drought event develops into a serious threat to the system.

2. Tools and methods

To show the applicability of the methodology presented we applied it to the water resources system composed by the Jucar and Turia Rivers. These two rivers suffer from recurrent drought episodes [2] and have developed an indicator system to define the situation of both systems with regard to such events. The reason to choose the two systems instead of just one is the existence of a complex union between them two at their lower courses, with an important amount of different water uses with different priorities and necessities what makes of the management of these two systems a very interesting matter of study. Additionally, the results of recent drought studies revealed the necessity to create an indicator system for the two systems at the same time due to the particular management issues of both together [7]. With the proposed methodology it will be possible to forecast which system will be in a worse condition first. This will allow anticipating measures to bring water from one system to the other that minimize the possible effects of drought, if the episode developed worse.

2.1. Area of study

The Jucar and Turia River Basins are located in the eastern part of the Iberian Peninsula in Spain (see Fig. 1). These two basins are the main of 9 water exploitation systems in the Jucar River Basin Demarcation (DHJ). In the Valencia coastal plain, where Jucar and Turia Rivers have their final parts, and between both mouths, there is a shallow lake called Albufera, with an associated wetland. Both, the lake and the wetland, represent the nexus of union between both systems, as they depend on return flows from irrigation areas belonging to both basins, and also on groundwater flows from the coastal aquifer beneath the plain.

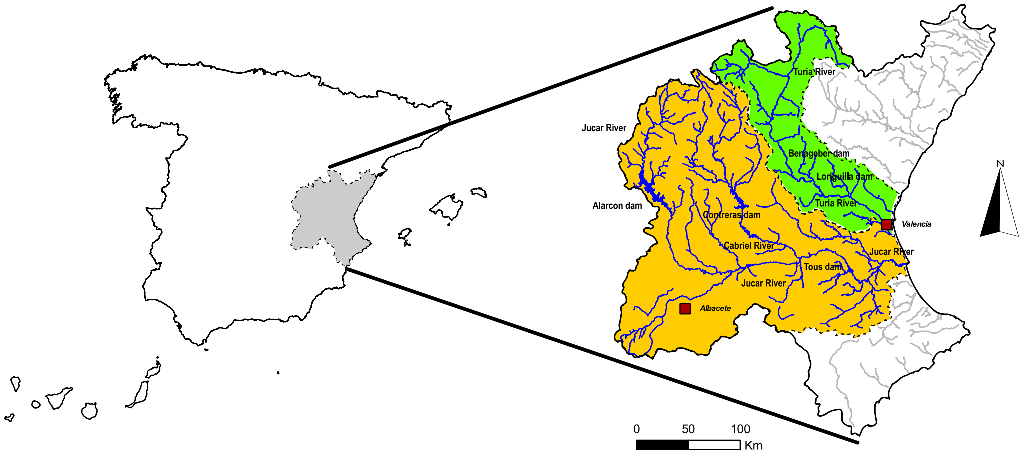

Fig. 1. Location of the Jucar and Turia River Basins in Iberian Peninsula

The Jucar River has a length of 497.5 km, traversing the provinces of Teruel, Cuenca, Albacete and Valencia, having its mouth at the Mediterranean Sea. Additionally, this water exploitation system includes the area and services provided by the Jucar-Turia Channel and the littoral sub-basins between the Albufera Lake and around 10 kilometres south from the mouth of the river. It is the most extensive system (22,261 km^2) and with more water resources at the Jucar River Basin Agency. On the other hand, the Turia River has a length of 280 km, traversing the provinces of Teruel, Cuenca and Valencia, having its mouth in the city of Valencia at the Mediterranean Sea too. It is the second most extensive system (6,393 km^2) and with more water resources at the Jucar River Basin Agency. A brief description of the study area and key issues is presented below, details can be found in [8].

Both rivers are an example of a typical Mediterranean river, characterized by a semi-arid climate consisting of irregular rainfall and seasonal summer scarcity that occurs when irrigation requirements are at their height [9]. Average natural resources reach 1,170 hm^3/year for the Jucar River and 295 hm^3/year for the Turia River. The total population depending on both river basins represents a water demand of 148.5 hm^3/year and the water demand for irrigated agriculture reaches 833.7 hm^3/year. The supply to urban areas comes mainly from wells and springs, but Albacete, Sagunto and Valencia metropolitan areas use surface water.

Both systems represent one of the most vulnerable areas of the western Mediterranean region, due to high water exploitation indexes, and to environmental and water quality problems when droughts appear. This situation has triggered an increased use of non-conventional resources in recent years, such as reuse of wastewater and drought emergency wells. Also, conjunctive use of surface-ground waters has been historically a very important option in the district to provide robustness against droughts. The integrated use of those three kinds of resources was crucial in adapting to the recent drought occurring between 2005 and 2008 [10]. This situation is especially important in Turia River Basin where Valencian farmers have been able to integrate groundwater, recycled and traditional surface water use in a single system.

From the above, the Albufera Lake represents the nexus of union between both river basins (see Fig. 2). Their natural and anthropogenic inputs correspond to [11]: freshwaters, groundwater contributions through a series of springs called "ullals", direct precipitation on the lake, return flows from irrigation areas belonging to both basins and urban or industrial wastewater treatment outflows. It is noteworthy that agricultural activity, contribute to near 60% of inputs to the Albufera [11].

2.2. The SIMRISK-OPTIRISK methodology

The SIMRISK-OPTIRISK methodology is based in previous works presented in [12], [13] and [14]. Their results were successfully used in the management of previous drought episodes in the two systems studied. We now present an evolution of the previous ones introducing an optimization approach what will allow obtaining the best results achievable in the system and the better rules for the application of the mitigation and prevention measures.

This methodology is summarized in Fig. 2 and allows evaluating the propensity of the WRS to operative droughts, both on a short and a long-term time scale (from a single campaign to some years depending on the memory of the system). It requires, on a first stage, the identification of the water resources system and its characteristics, both hydrological and physical. From hydrologic characteristics, principally stream flow series, it will be possible to formulate and calibrate a stochastic model with which generating multiple stream flow series equiprobable with the historic series. From the physical characteristics of the system it is possible to develop a scheme that can be later used to run a simulation or an optimization model of the system management. The previously generated series can be used to feed the desired model in multiple runs so multiple different management results of the system are obtained depending on the hydrologic conditions introduced.

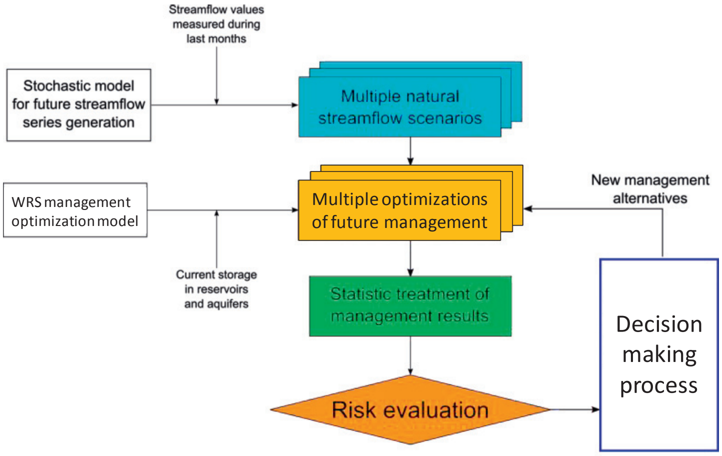

Fig. 2. Flow chart of the OPTIRISK methodology

After the multiple runs are completed, it is possible to calculate several indicators for short-term management, such as: the probability of suffering a monthly shortfall in the supply to a demand or environmental flow; or the probability of being in a certain storage level at a reservoir in one month.

These values provide an estimation of the risk of operative drought in the forthcoming months. If this risk is high, it will be necessary to take measures to mitigate the effects of the possible drought.

If the model of the system used is a simulation model, then the results obtained are with regard to the existing, or newly proposed, management rules of the system. On the other hand, by using an optimization model, like we propose now, the results yielded by the analysis will be with regard to the best achievable management of the system resources. This may help decision makers to know what is the best situation they may encounter after the considered period (for example at the end of the irrigation campaign in the summer), and thus to better define operation rules of the system during drought episodes. It will also allow optimizing the timing for additional measures to mitigate drought effects, saving money from their setting and operation costs.

Therefore, to apply this methodology we need a stochastic model for multiple stream flow series generation, an optimization model of the system to study and tools to carry out the probability analyses to obtain management indicators.

2.2.1. Stochastic generation of stream flow series

For the studied case, we adjusted a multivariate ARMA(1,1) model using the monthly stream flow series from 1980 to 2008. With the calibrated model we are now capable of generating any number of time series equiprobable with the historic series. Following the proposed methodology, we generated a high number of series (1000) with initial analysis month April 2014, which corresponds to the beginning of the irrigation campaign, and 18 months length in order to reach the end of the next year irrigation campaign (irrigation campaign normally ends in September).

2.2.2. Water resources system management optimization model OPTIGES

OPTIGES is a program of general use that allows optimizing a scheme of water resources. It is integrated in the DSS AQUATOOL [15].

For its use, the user must previously create a simplified scheme of the water resources system with the elements considered by the model that are, namely, channels (natural and artificial), nodes (forks, junctions or reservoirs), hydrological inflows and demands (zones where water is used). The user supplies the program with the configuration data of the scheme together with the physical data of the elements (for example maximum capacities of channels, or maximum volume stored in reservoirs), the demands data as well as the data used for fixing priorities between scheme elements and for defining guarantee criteria of demands satisfaction and environmental requirements. Fig. 3 shows the scheme of the Jucar and Turia water resources system developed for this study.

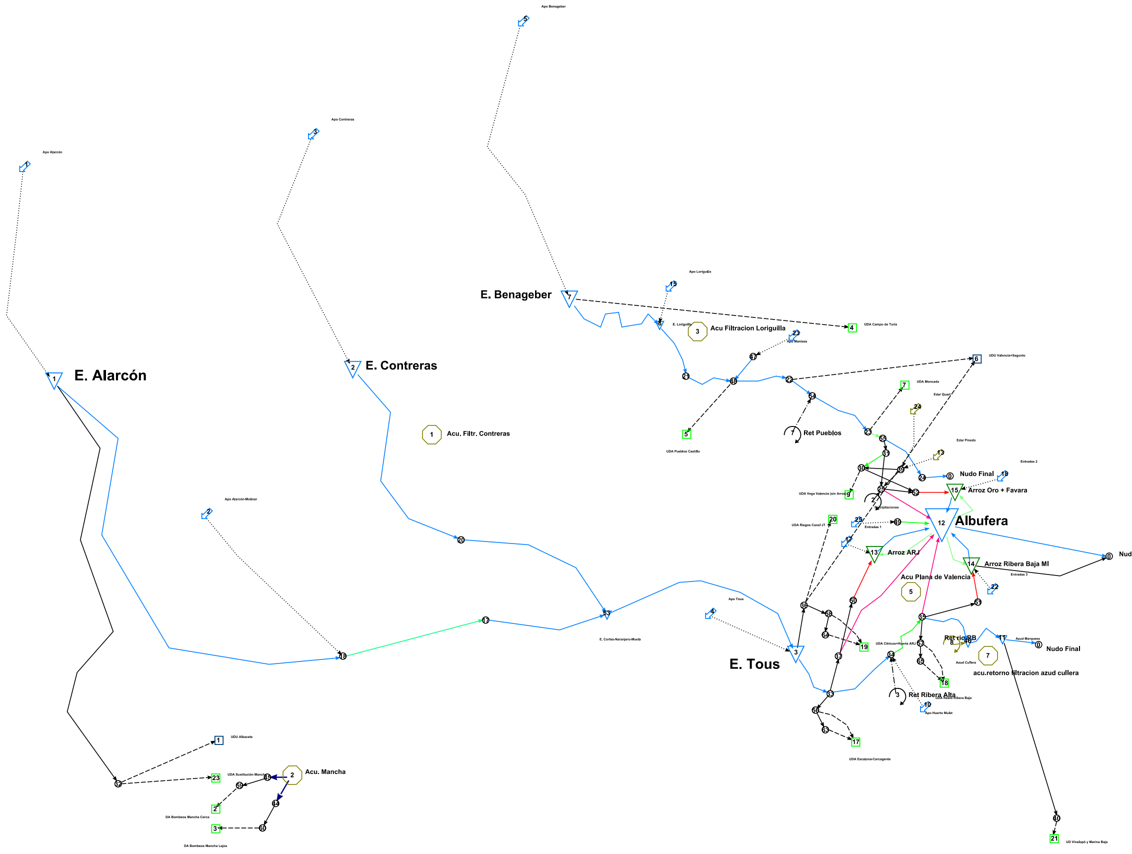

Fig. 3. AQUATOOL scheme of the Jucar and Turia water resources systems

The program works with monthly values and allows optimization periods of at least one year, with a number of periods also fixed by the user. The model results include the values of the stored volumes in reservoirs, circulating flows and supply deficits for each month, as well as a final summary of the whole optimization horizon including average, monthly and yearly values of all variables.

To solve the optimization problem, OPTIGES converts the user scheme with all the introduced data into a minimum cost network flow problem which is afterwards solved with a high performance algorithm.

OPTIGES is also capable to deal with evaporation from reservoirs and water returns from demands. Additionally, it is also capable of considering, to a certain extent, the relation between the surface system and groundwater [16]. The user can make use of several aquifer models and connecting them to the surface system via infiltration losses from conductions and reservoirs, hydraulic connected river stretches, pumping from demands and artificial groundwater recharges. All these aspects represent non-linearity that are, a priori, impossible to solve directly with network flow programming, since it is a form of linear programming. What it is done instead is solving iteratively the minimum cost network flow problem, changing the characteristics of the arcs in the network associated to each of the non-linear elements, after each iteration, until convergence is reached. The iteration routine calculates the flows associated to the solution obtained with the network flow algorithm and compares these values with the ones obtained in the corresponding arcs of the network; if there is a difference between them, the routine modifies the flow limits of the arcs and runs again the algorithm. This is done until the difference between the calculated values and the ones obtained from the algorithm is minimal, or the maximum number of iterations is reached.

3. Results and discussion

During the last large drought episode suffered in the basin, CHJ developed a Standardized Operative Drought Monitoring Indicators system (SODMI) [17]. In essence, the SODMI uses real-time information provided by the Automatic Data Acquisition System of CHJ on the state of reservoirs, aquifers, rivers, and precipitation to produce standardized indexes for some selected elements in the basin. These indexes then are combined into a single standardized index for each basin. Fig. 4 shows the evolution of this index along time for the Jucar and Turia Rivers basins.

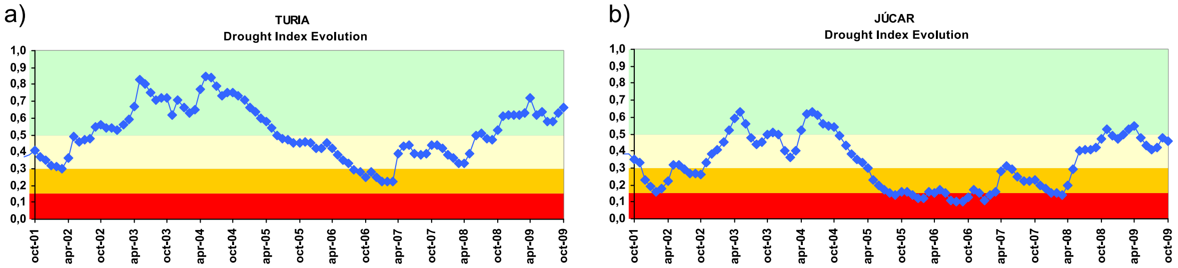

Fig. 4. Evolution of the standardized drought index in the a) Turia and b) Jucar Rivers basins

SODMI has provided useful information for early warning and action against drought, as well as for risk perception by the public. Yet, in order to manage droughts, a more elaborate and detailed information system is needed to better assess the risk and the effectiveness of the measures that can be used to modify the risks, and to mitigate the effects of the drought on both the established uses and on the environment.

The predictions of OPTIRISK improve with regard the combined indicators of storage and stream flow because they include both previous precipitation and storage data. Additionally, they include the information regarding the physical system what allows obtaining its best management options.

A very important issue with regard to drought risk in a regulated system is the storage level of reservoirs, especially at the end of the irrigation campaign, which coincides with the beginning of the hydrologic year, and thus representing the available volume to confront the next management period. Fig. 5 shows the probability of non-exceedance of storage in the reservoirs of the Turia and Jucar Rivers at the end of the two campaigns considered when generating stream flow series. It is possible to observe that there are high chances the Turia River basin ends the current campaign with low storage levels, below 100 hm3, while for the end of the second campaign the situation improves notably.

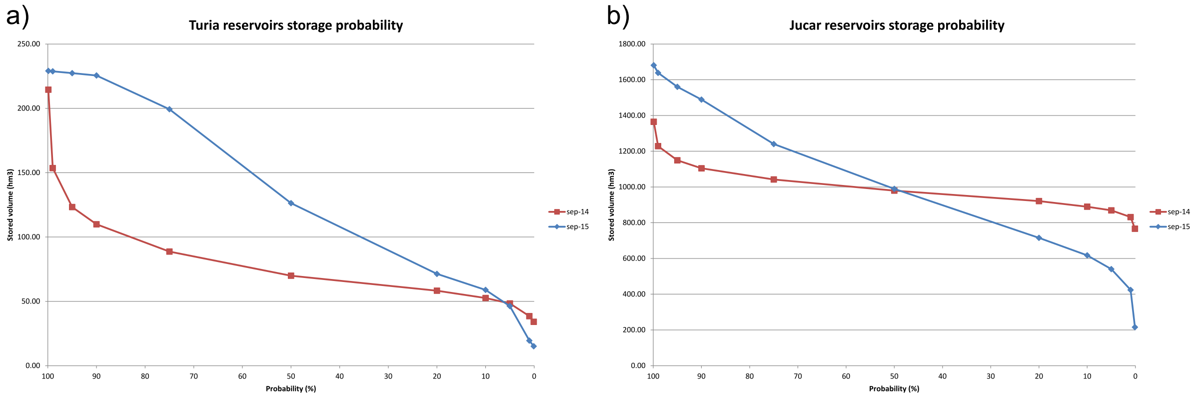

Fig. 5. Probability of non-exceedance of storage in the reservoirs of the a) Turia and b) Jucar Rivers at the end of the 2013-14 and 2014-15 campaigns, calculated in May 2014

This is due to Turia River basin is regulated in a within-year basis what means its management is mostly driven by hydrology. On the other hand, the Jucar River basin will probably end the current campaign with intermediate-high storage levels and, since it is an over-year operated, the chances that it ends the next campaign with levels above average. The decisions made by the water managers will depend on how serious they consider the risk of shortages, especially in the Turia River basin.

4. Conclusions

We have presented a methodology for drought risk assessment based on the probabilistic aggregation of optimal management results of a water resources system model when fed with multiple stochastic generated stream flow series. We have applied it to the water resources system of the Jucar and Turia River basins and shown how this analysis improves the quality of the information on the actual situation at the time, since it provides estimations of probability that are not obtainable from the more classical indicators described above, complementing them.

The methodology we presented has a broad range of applications with regard to drought management and preparation, for example: identification and definition of both measures to reduce the propensity to operative droughts (pro-active measures) and short-term operative drought mitigation measures (reactive measures); design of emergency plans against drought; definition of better indicators to identify the risk of suffering an operative drought; and optimizing the implantation of the measures considered to be the most appropriate.

One of the main advantages of the proposed methodology is its capacity for dealing with complex systems, giving an overall picture of the situation in the basin as well as of the individual uses, while most of the previously developed indices are applicable only to a demand or to a group of demands. Thus, the proposed method constitutes an authentic early warning system on the arrival of an operative drought.

Acknowledgements

The authors wish to thank the Confederación Hidrográfica del Júcar (Spanish Ministry of the Environment) for the data provided in developing this study and the Spanish Ministry of Economy and Competitiveness for its financial support through the projects SCARCE (Consolider-Ingenio 2010 CSD2009-00065) and NUTEGES (CGL2012-34978). We also value the support provided by the European Community’s Seventh Framework Program in financing the projects DROUGHT-R&SPI (FP7-ENV-2011, 282769), ENHANCE (FP7-ENV-2012, 308438), WAMCD (EC-DG Environment No. 07.0329/2013/671291/SUB/ENV.C.1) and LIFE ALBUFERA (LIFE12 ENV/ES/000685).

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