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Drought early warning based on optimal risk forecasts in regulated river systems: application to the Jucar River Basin (Spain)

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Abstract

Droughts are a major threat to water resources systems management. Timely anticipation results crucial to defining strategies and measures to minimise their effects. Water managers make use of monitoring systems in order to characterise and assess drought risk by means of indices and indicators. However, there are few systems currently in operation that are capable of providing early warning with regard to the occurrence of a drought episode. This paper proposes a novel methodology to support and complement drought monitoring and early warning in regulated water resources systems. It is based in the combined use of two models, a water resources optimization model and a stochastic streamflow generation model, to generate a series of results that allow evaluating the future state of the system. The results for the period 1998-2009 in the Jucar River Basin (Spain) show that accounting for scenario change risk can be beneficial for basin managers by providing them with information on the current and future drought situation at any given moment. Our results show that the combination of scenario change probabilities with the current drought monitoring system can represent a major advance towards improved drought management in the future, and add a significant value to the existing national State Index (SI) approach for early warning purposes.

Highlights

- Modelling the past to anticipate future drought is an ineffective and risky approach
- A new method for continuous drought monitoring and early warning in regulated catchments is proposed
- Reservoir storage probability is a reliable indicator for drought status in regulated catchments
- New approach adds value to existing monitoring and early warning methods

Keywords

Monitoring; Early Warning System; Optimisation Modelling; Water Resources Systems Analysis; Aquatool

1. Introduction

Droughts are a major threat to the sound operation and management of water resources systems. Developing new approaches to anticipate them will help in defining strategies and measures to minimise their effects. The use of monitoring systems to calculate drought indices and indicators can help water managers characterize droughts and define risk scenarios. The activation of a drought scenario in a system will trigger a number of measures addressed to minimise the possibilities of developing into a worse scenario and minimizing the possible effects of the current situation.

The assessment of drought severity requires the use of an index which fulfils well-known criteria (Tsakiris et al. 2013): operational usefulness, physical meaning, sensitivity to a wide range of drought conditions, applicability in all parts of the globe, quick response to changes due to drought and high availability of required data. Commonly, such an index is a prime variable for assessing the effect of a drought and defining different drought parameters, which include intensity, duration, severity and spatial extent as defined by Yevjevich (1967) in his theory of runs. A time series of drought indices provides a framework for evaluating drought parameters of interest. Generally, drought indices are categorized as meteorological, hydrological, agricultural or remote sensing–based (Rossi and Cancelliere 2013). Mishra and Singh (2010) and Pedro-Monzonis et al. (2015) made an extensive review of existing univariate drought indices both concluding that each index performance is region specific mostly due to the characteristics of the variables used for their calculation and the purpose of the analysis. In addition, in recent time some authors have also attempted to combine all the variables (e.g. precipitation, soil, water content) that lead to different physical forms of drought in so-called multivariate drought indices (Rajsekhar et al. 2015). In some cases, the index is built as an aggregation of variables selected according to their relation each drought type (Keyantash and Dracup 2004; Rajsekhar et al. 2015). Inother, the index is constructed using copulas to derive the joint distribution of two or more variables (Kao and Govindaraju 2010; Hao and AghaKouchak 2013).

An indicator system is a drought monitoring system that allows the anticipation in the application of mitigation measures for the reduction of socio-economic and environmental impacts of droughts (Estrela and Vargas 2012). Such systems can also be considered early warning systems for their capacity to anticipate the effects that drought may have on the system in order to trigger necessary mitigation measures (Rossi et al. 2008). In most cases, these systems are normally formed by basic variables selected at different points in a river basin that are capable of defining the current drought status. Their reliability will depend on their capacity to represent, using real-time data: 1) the relationship between significant reductions of water availability with deviations of meteorological and hydrological components from their average; 2) detecting early stages of drought development; 3) provide results that allow comparison between events both in time and space; and 4) assessing the severity of the ongoing situation in order to support decision making for triggering drought mitigation actions. Additionally, in the case of regulated water resources systems, it would be desirable that the indicator is capable of showing the evolution of management and how this would change the drought status of the system if new operation rules are envisaged.

Different drought early warning systems have been developed at different spatial scales, but a very small number of such systems are actually in operation (Rossi and Cancelliere 2013). This is mainly due to the low density of meteorological and hydrological gauging networks, the sharing of the data among different agencies with different objectives, and to the lack of universal standards in computing drought indices (Rossi 2003). In addition, the development of indicator systems based on observational frameworks cannot provide sufficient anticipation with regard to the event in progress in order to activate the necessary measures to mitigate its effects (Haro et al. 2014). Efforts have been made to correlate drought indices to impacts (Stagge et al. 2015), but these relationships only provide insight after the event has finished and the impacts reported. Mishra and Singh (2011) acknowledged that to develop suitable techniques for forecasting the onset and termination of droughts is still a major research challenge due to the inability to predict drought conditions accurately for months or years in advance. Due to these inaccuracies and uncertainties, drought management relies nowadays mainly on risk assessment. Risk assessment during the operation phase of a system is often referred as conditioned risk assessment. With this procedure, the state of the system is usually evaluated for the short-term to explore alternative mitigation measures and policies for an ongoing drought episode. This same assessment approach can be adopted for early warning purposes (Cancelliere et al 2009).

Alecci et al. (1986) considered that the risk assessment of a water supply system is a problem that is better approached through a set of several indices and analysing the probability of suffering shortages of different entities. This is due to the many complexities existing within a water resources system such as the stochastic nature of inflows, the high interconnection that exists between different components of the system, the competition for water by conflicting demands, the definition of what elements are at risk, and the uncertain character of the impacts in different drought episodes. Traditionally, reliability, resiliency and vulnerability have been the indices used to capture the different performance aspects of water supply systems (Hashimoto et al. 1982). However, these indices are normally representative of just one particular use, defining the state of the system with regard to the probability of a failure for such index. Since all drought events are unique, so too are their effects both temporally and spatially. Therefore, it is necessary to have an indicator that is capable of summarising the state of the system for any given situation. In regulated systems, it will be the volume stored in reservoirs since it provides an overview of the previous management of the system and is the basis for future resources allocation.

This paper proposes a novel methodology to support drought monitoring and scenario definition in regulated water resources systems. It is based on the results of two models, an optimisation model and a stochastic streamflow generation model, both of which have been calibrated and validated in previous research (Haro et al. 2012a, 2012b, and 2014b; Ochoa-Rivera 2002). Using storage in reservoirs as a summary indicator of the future system status, we propose a combined use of the two models to generate a series of results that can support and complement drought monitoring and early warning systems currently in place in a river basin. The methodology is applied to the Jucar River Basin in Spain to evaluate the probability of a scenario change several years in advance. The proposed method has the potential to enhance decision making under highly uncertain hydrological situations, and provide water resource planners and managers with new insights both regarding the behavior of the system and the development of drought episodes.

2. Case study description

The Jucar River Basin is located in the eastern part of the Iberian Peninsula in Spain (Figure 1). This basin is the most important of the 9 water exploitation systems in the Jucar River Basin Demarcation (Demarcacion Hidrografica del Jucar – DHJ in Spanish). In the Valencia coastal plain, where the Jucar River has its mouth, there is a shallow lake called Albufera, with an associated wetland. Both, the lake and the wetland depend on return flows from irrigated areas in the basin, and also on groundwater flows from the coastal aquifer beneath the plain (Andreu et al. 2009). It is the largest system of the DHJ both in surface (22,261 km^2) and in volume of resources (1,548 hm^3/year).

The river is an example of a typical Mediterranean river, characterized by a semi-arid climate in most of the basin territory consisting of low precipitation rates (475mm/year) during the year combined with exceptional convective storms that can lead to flooding and seasonal summer scarcity that occurs when irrigation requirements are at their highest. Urban demand accounts for circa 143.3 hm^3/year and the water demand for irrigated agriculture reaches 1034.3 hm^3/year. Water supply to small urban areas comes mainly from wells and springs, but large metropolitan areas such as Albacete, Sagunto and Valencia rely on surface water (Andreu et al. 2009). According to the White Book of Groundwater (CEDEX 1995), nearly three quarters (73%) of the resources in the territory of the DHJ have subterranean origin. This highlights the major importance that groundwater resources have in the management of these basins. The total amount of available groundwater resources in the basin is 1,225 hm^3/year. However, this only represents the estimated volume in all the groundwater bodies without accounting for their sharing between other basins or the relationship these bodies have with the surface water system.

With regard to droughts, the Jucar River Basin can be considered to be one of the most vulnerable areas in the western Mediterranean region, due to high water exploitation indexes, and the environmental and water quality problems that arise when droughts occur. This situation has triggered 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 historically been a very important option in the region to provide robustness against droughts. The integrated use of these three resource options was considered a major success in adapting to the latest drought episode between 2005 and 2008 (Ortega-Reig et al 2014).

The operation of the system is mainly multi-year. The Alarcon and Contreras reservoirs, at the headwaters of the system, are capable of storing the highly variable streamflow coming from their upstream sub-basins. The third most important reservoir in the system, the Tous, is operated on an annual basis. Before the summer season it stores incoming mid-basin streamflow and upstream reservoirs releases to supply the different demands within the Valencia Plain. By the end of the summer, the reservoir is emptied in order to prevent floods originated from often intense autumn rainfall events.

3. Methodology

In this section, we present the indicator system currently in use in the Jucar River basin as well as in most of Spanish river basins. Despite being a useful methodology to evaluate the actual drought conditions in the basin, it has low forecasting capacity; making preventive management of droughts inefficient and/or very difficult. To complement the information provided by the indicator, we developed a methodology to derive the probability of drought scenario change for a four year planning horizon. It is based on the Monte Carlo evaluation of the results of multiple runs of an optimization model of the system. Based on this analysis, we derive distribution functions on the future state of the basin and combine them with trigger values for each drought scenario.

3.1. Current drought indicator system for Spanish river basins

One of the objectives of Spanish Drought Plans is providing means for anticipating drought events. To do this, it is necessary to establish an early warning system that allows forecasting drought characteristics and assessing their effects on the system. Spanish basin operators have adopted a method of drought indicators based on the analysis of historic data that reflect the availability of water in the system. This indicator is known as State Index (SI) and it is the result of combining several hydro-meteorological variables obtained from a monitoring system. The SI has a hydrologic character since its practical interest lays on its ability to serve as decision-making instrument regarding water resources management in the basin. For each catchment, managers select a set of variables that best represent the water resources for different demand units in the basin using values of reservoirs storage, piezometric levels, natural streamflow and areal precipitation. In the case of the Jucar River, the selected variables are detailed in CHJ (2007)[1].

For each selected variable, the value of the SI has the following expression (CHJ 2007):

$$If\ V_i \geq V_{av} \ \rightarrow \ \mathrm{SI} = \frac{1}{2} \cdot \left[1 + \frac{V_i - V_{av}}{V_{max} - V_{av}}\right] \qquad \text{Eq. 1}$$

$$If\ V_i < V_{av} \ \rightarrow \ \mathrm{SI} = \frac{1}{2} \cdot \frac{V_i - V_{min}}{V_{av} - V_{min}} \qquad \text{Eq. 2}$$

Where V_i is the value of the variable in month i; V_{av} is the average monthly value of the variable in the historic series considered; and V_{max} and V_{min} are the maximum and minimum monthly values of the variable in the historic series considered respectively. The main reason to follow this calculation approach is that the arithmetic average is a robust statistic, as well as simple; so a comparison of the current variable value with the average of the historic series considered will adjust better to the real situation of the studied region. Additionally, taking into account the maximum and the minimum historic values allows homogenising the different variables into a dimensionless numeric value capable of quantifying the current situation with regard to the historic. This also permits to quantitatively compare the different variables selected between them. Finally, the overall SI of the basin and hence its drought level is defined as the weighted sum of the SI values of each of the selected hydro-meteorological variables. The weight assigned to each variable depends on the level of demand served. For the Jucar River, the SI consists of a combination of 12 different variables including precipitation, streamflow, piezometric levels and storage in reservoirs at different strategic points within the basin (CHJ 2007).

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[1] A partial translation of the contents in CHJ(2007) is provided in Acacio et al. (2013)

Spanish Drought Plans establish four different levels of drought, or scenarios, namely: normality, pre-alert, alert and emergency (CHJ 2007). These levels are determined according to the values of the SI with the following thresholds: Normality (SI≥0.5); Pre-alert (0.5>SI≥0.3); Alert (0.3>SI≥0.15); and Emergency (0.15>SI). Figure 2 shows the evolution of the SI in the Jucar River Basin between October 1998 and September 2010. Between the end of the XX century and the beginning of the XXI century the basin experienced a short but intense period of drought that made the SI oscillate between the pre-alert and the alert levels until 2002 when the situation returned to normality after a period of intense precipitation. Between 2005 and 2008, the system suffered the worst drought event on record with SI reaching emergency levels several times during that period. After that, the system gradually recovered to pre-alert in 2009 to finally reach the normality level in 2010.

Haro et al. (2014) showed the possibility that an indicator such as the SI might be insufficient in order to set and trigger the most appropriate drought mitigation measures early enough to be efficient. This method is limited to determine the current drought situation based on the comparison of present variables values with the variables occurred in the past; making its forecasting capability low, or even non-existent. Moreover, drought episodes vary between one and another. Hence, it is very unlikely that the SI is capable of working as an early warning system for droughts, advancing the real consequences of an upcoming event.

In addition, as commented above, it is important that the effects of management decisions and mitigation measures are included in the monitoring process and that their modifications are reflected in order to advance their efficacy and to better support decision-making. For this reason, the use of risk assessment methodologies in combination with indicator systems provides an interesting and novel framework to support decision making during drought situations in regulated systems.

3.2. Drought scenario definition based on the risk assessment of the system's optimal operation

The methodology developed is based on previous research by Sanchez-Quispe (1999), Andreu and Solera (2006), Andreu et al (2007, and 2013) and Cancelliere et al (2009). Their findings were successfully used in the management of previous drought episodes of the Jucar River Basin. Here we present a further development of existing approaches by introducing an optimisation approach that allows one to obtain the best results achievable in the system and better rules for the application of mitigation and prevention measures. This work further develops that presented by Haro et al. (2014a) by extending its application to a multi-year regulated basin. In addition, we show how the risk assessment methodology presented here is applicable to forecast drought scenarios. Figure 3 provides a schematic summary of the methodology, which is briefly described below.

We applied a monthly Monte Carlo optimisation process to a catchment management model of the Jucar River Basin previously developed in the GUI of Aquatool DSS (Andreu et al 1996) for the implementation of the European Water Framework Directive (CHJ 2004) and the development of is latest basin plan (CHJ 2015), and shown in Figure 4. The model includes the main surface storage facilities (‘Alarcon’, ‘Contreras’, and ‘Tous’ reservoirs) as well as the main aquifers in the basin that have a crucial role in the management of the system (‘Mancha Oriental’ and ‘Plana de Valencia’). The most important demands are also represented, namely: traditional irrigation in ‘Plana de Valencia’; groundwater irrigation from ‘La Mancha Oriental’ aquifer; conjunctive irrigation from the newer developments along the ‘Jucar-Turia’ canal; and the urban demands of Valencia, Sagunto and Albacete, which is minor in quantity but more sensitive to failures in the supply. Haro et al. (2012a and 2012b) and Haro Monteagudo (2014) provide a detailed description of the optimization technique, equations and constraints utilised by the model, as well as the input data it needs. A previous application can also be found in Haro et al (2014b). The model runs on a monthly time step fed by synthetic streamflow series generated stochastically from historically observed monthly values between 1980 to 2012. There are 16 streamflow input nodes along the model network, represented as thick red arrows in Figure 4. The synthetic series were generated with the stochastic analysis and modelling module in Aquatool (Ochoa-Rivera 2002). The 16 observed streamflow time series were normalised and standardised to calibrate the autoregressive model, AR(1), shown in equation 3:

$$X_t = \boldsymbol{\varphi_1} \cdot X_{t-1} + \boldsymbol{\theta_0} \cdot \varepsilon \qquad \text{Eq. 3}$$

where X_t and X_{t-1} are *n* variables vectors; $\boldsymbol{\varphi_1}$ is an $n\ x\ n$ autocorrelation matrix; θ_0 is an $n\ x\ n$ matrix of coefficients that multiplies the random $N(0{,}1)$ values vector represented by ε. For this case, n has a value of 16. For the stochastic generation of synthetic streamflow series from observed values, the last monthly observed value is used as a seed after normalisation and standardisation. The generated time series of standardised values are converted to streamflow values following the inverse path. The validation of the model against the long term characteristics of the historic series (average, standard deviation, number of dry years), makes it suitable to explore a large range of events.

The results of each optimisation run in the Monte Carlo process are the time series of reservoirs storage and releases, surface and groundwater supply to the different demands, aquifers relative storage and recharge, and flows in river streams. The statistical analysis of all runs yields a number of indicators to assess risk.

When confronting an ongoing drought situation from a risk minimisation approach and a high level of uncertainty, it is more useful to rely on an index that summarizes the status of the basin considering all the possible events. In the case of regulated river basins, this index is the state of the reservoirs. The evolution of storage in reservoirs clearly reflects the operation of a system during previous periods of time, and their present status defines the future use possibilities. Hence, reservoir level state probability and storage probability are useful indicators with regard to drought in a regulated catchment and may support the decision making process with information about what can be expected in the future.

Based on the previous consideration, we use the storage probability in the different reservoirs in the basin as the basis to determine the risk level and the change of scenario probability at the end of a number of campaigns for each month. It must be noted that reservoirs levels is an important element in the Jucar River Basin drought indicator system, representing almost 50% of the indicators value. We transform the reservoir levels probability distribution into state index distributions following the calculation method above by comparing the results to the historic series of observed levels. Afterwards, we determine the probability of scenario change for each month by crossing each state index distribution by the threshold levels defined by the state index methodology.

We applied this methodology in the Jucar River Basin for the period between hydrologic years 1998-1999 and 2008-2009. During these 10 years, two of the most important drought episodes for the Jucar River Basin in history took place (CHJ 2007; van Lanen et al. 2013): the short but intense drought of 1999-2000 and the long drought episode between 2005 and 2008.

The optimisation process tends to empty the reservoirs by the end of the optimisation period. Thus, setting the multiple risk assessment runs for just one year would not provide adequate results since we want to make use of the perfect forecast principle of optimisation. Therefore, optimisation periods of four years were used for each run extracting the results of the first year. Three hundred series of 48 months generated with the autoregressive model from equation 3 proved sufficient to yield representative results in the Monte Carlo optimisation process for each monthly run.

4. Results

4.1. State Index complementation with scenario change probability

Figure 5 shows the result of applying the proposed methodology together with the evolution of the Jucar River observed state index for the three first years of the optimisation period considered in each run. The fourth year is disregarded because it coincides with the end of the optimisation period, when the algorithm uses all the available water. For each month, we have the actual drought scenario as defined by the thresholds and the probability of each scenario occurring one to three years later corresponding to Figures 5a to 5c, respectively. In Figure 5a, the probability of a scenario change in the next year is low, with a general tendency to remain at the same level. In Figures 5b and 5c, the probabilities of a scenario change increase after two and three years and how this provides a better insight of what can be expected in the system. With these results, the methodology proposed adds value to the actual State Index by showing the probability that the current situation might change in the future, hence providing additional support for decision makers in terms of activating mitigation measures, which normally require some time to start operating appropriately.

The probability of scenario change with one year anticipation (Figure 5a) is useful for the middle and end of drought episodes as well as for annually operated systems. For example, soft preventive measures could have been maintained in February 2001 despite the entrance in the normality scenario in order to prevent the posterior quick fall to almost emergency one year later. Conversely, the two and three year anticipation probabilities (Figures 5b and 5c) are useful in detecting the possible start of a drought situation, especially in multi-year systems. Between 2004 and 2008, the State Index dropped from the normality scenario to emergency in about one year (June 2004 to June 2005) and then remained in that situation for two years. This situation is captured in Figures 5b and 5c, where the probabilities of being in a scenario worse than normality two and three years after June 2004 exceeded 50%.

4.2. Approximation of SI values with risk results

Previous stakeholder participation experiences in the Jucar River with risk assessment tools have shown that, in general, risk results obtained for an 80% probability of exceedance level and one year in advance are trusted as good approximations of the future state of the system. These results can be easily extracted from the tools used to perform the proposed methodology, as well as any other risk level results. Hence, we explored the ability of the proposed methodology to approximate SI from a probabilistic perspective.

Figure 6 shows the evolution of SI approximated as the 80% risk level one year in advance versus the actually observed SI in the Jucar River for the period October 1998 through September 2009. Both indices reflect accurately the drought events occurred in the Jucar River basin for the period of study. However, while the risk based SI follows the observed one during the first part of the period, there is a six months delay disconnection right before the beginning of the 2004-2008 drought episode. This is due to the operation of the optimisation process. The objective function in the optimisation model works tries to maximise the stored volume in reservoirs while meeting all the demands and environmental flows, minimising water loses from the system. First, during the wet period prior to the 2004-2008 event, the optimisation model achieves better storage levels before the episode starts because all the demands are met and there is water that would be lost instead at a high cost for the objective function. Since the optimisation process implies perfect forecast, the model is capable of storing that water. Second, when reservoirs are near to empty, like during the drought period, the objective function benefits more from supplying the demands than from storing water. Hence, despite the risk based SI drops below the observed one, the demands still have a better level of supply than in the real situation. Therefore, the risk based results offer an envelope of the actual situation, providing managers with an idea of how the system can be expected to respond at different levels of risk.

5. Discussion

The predictions of the methodology presented improve with respect to the combined use of storage, streamflow and precipitation to define a drought state index because they include both previous precipitation and storage data, as well as information regarding the physical system what allows obtaining its best management options. It also includes up to date information of the human influence on the system by means of water demands for the different sectors, and allows considering the environmental needs of the riverine ecosystems in the form of environmental flows definition. In addition, the presented methodology can be used afterwards to assess the risk level with the existing management rules to evaluate the changes introduced by the mitigation measures. Since the methodology is meant to be used every month to monitor the state of the system, any new measures could be implemented in the model in real time. In this way, it is possible to select the best measures for each case and their optimal application.

5.1. Methodological limitations

The methodology has a number of inherent limitations. Firstly, it was limited by the quality of the stochastic streamflow series used to drive the whole process. The definition of a good stochastic model requires an amount of previously observed data that is not always going to be available. In addition, depending on the stochastic model used, the generated streamflow series will have a different capacity of capturing the dynamics of hydrology in the system. This, together with the tendency of stochastic series to reach values around the historic average after a number of generations, will limit the risk forecasting ability of the method. In this paper, an autoregressive AR(1) stochastic model was used. Despite being capable of capturing the basic statistical parameters of the observed series, Ochoa-Rivera et al. (2007) showed that the approach to streamflow modelling has a significant influence in the final results. Hence, different modelling methodologies should be explored before implementing the proposed methodology.

Secondly, optimisation is a highly resources consuming process. This means that complex models of the system under study will require longer calculation periods than more simple ones. The creation of models capable of representing the reality of the system while maintaining a low degree of computational complexity requires a high level of knowledge and understanding about the system. The Jucar River Basin has been extensively studied by researchers for many years, and the methodology presented here was relatively easily applicable. However, it will not be of immediate use in river basins where water level is scarce and/or the relationships between the individual hydrological processes are not clear.

Finally, in order to be effective, the methodology and its results must be trusted, but also understood, by those that will be later affected by the decisions derived from its use. The model used in this study was developed conjunctively with the managers and water users of the basin within a participatory process that required reaching agreements for everyone. In the same way, the triggers that define each drought situation and the corresponding measures are the results of negotiations between the different actors in the system. This trust building process is achieved over time and thus, methods such as the one presented here are unlikely to be successful at the beginning of participative management processes. Anyway, as observed in Andreu et al. (2009) and Andreu et al. (2013), the very process of implementing similar methodologies finally resulted in better knowledge of the system and understanding of stakeholders needs with an overall improvement of management.

5.2. Implications for drought management

Existing drought monitoring systems are normally limited to measure a series of climatic and hydrologic variables and calculating various indices that allow determining what is the state of the system compared to the past. Such is the case of the state index used in Spanish drought management plans shown above. This approach may be useful, if not the only one possible in some cases, but has been revealed insufficient for its use in some systems, especially regulated water resources systems (Haro et al. 2014). Using indicators based on observation of hydrologic variables, and comparison with past data in systems where human activities take place, are unable to represent the changes occurring in the system along time. Anthropogenic actions influence not only river flows themselves with extractions and returns but also runoff production and groundwater recharge, delaying or preventing water from reaching the streams. Accounting for all of this and translating observed flows in one point to natural regime is often an arduous task that is not always rewarded with appropriate results. In addition, the parameters used for drought indices calculation are variable with time. This causes that new maximum and minimum observed values have the chance to change dramatically the shape of the indicator evolution. For example, if an exceptionally wet, or dry, period occurred, several hydrological variables (precipitation, streamflow, reservoir storage levels, etc.) could reach unprecedented levels that might change the values of the state index resulting in completely erroneous impressions regarding past drought events, as well as influencing the perception of future ones.

In regulated systems, the volume stored in the different reservoirs of the system, especially the regulation reservoirs, is normally regarded as a good approximation of the actual status of the whole system. Moreover, the comparison between the storage levels at the beginning and the end of the hydrologic year are commonly accepted as a summary of how the management of the system has been. However, the volumes stored nowadays are not comparable with the volumes stored, for example, ten years ago since water uses in the system change over time. This makes that the behaviour of the system, and thus the storage in reservoirs is different should the new demands were considered and indicators such as the one used by river basin districts in Spain cannot reflect that. In addition, the existence of high risk levels of developing drought scenarios during normality situations raise concern about the need for a more appropriate definition of what is considered to be normality in a water resources system. For this, it is undoubtedly necessary to have a deep knowledge about the system. The use of both simulation and optimisation models allow enhancing the knowledge that managers and users have of the system as well as building common understanding on the needs and concerns of the different actors involved.

Finally, following a drought preventive strategy in a water resources system needs maintaining a continuous state of vigilance. Hence, drought monitoring systems should warn of the risk that a certain situation, that is considered to involve risk, develops into a worse scenario instead of just informing about the current state of the system. In this way, the measures addressed to minimise the risk or mitigating the effects of a fully developed drought episode would have enough time to operate and be efficient, and they could even be less severe than when applied with urgency. Water resources systems management involves some bureaucracy and it is necessary to take into account that the activation of measures normally will take some time after the declaration of a new drought scenario. Thus, being able to anticipate the state of the system in a way like the one presented in this work can definitely help improving the performance of drought plans.

6. Conclusions

This paper has proposed a new methodology to support drought monitoring and scenario definition in regulated water resources systems. It allows approaching droughts risk assessment and early warning from a new perspective with regard to previous approaches, adding value to the existing monitoring methods currently in use. The use of optimisation modelling to obtain the best management of the system during uncertain hydrologic periods such as droughts permits anticipating the possible outcomes of these situations without the need of considering the operation rules in place that might result ineffective in these cases. An important advantage of the method developed is its capacity for dealing with complex systems, providing a general picture of the situation in the basin while most of the previously developed indices are applicable only to a demand or to a group of demands. Thus, the proposed method constitutes a step forward in the definition of drought early warning systems in regulated basins. The application of the methodology in the Jucar River shows its potential for supporting the definition of drought scenarios and hence improving the overall drought management process in the basin. Furthermore, the methodology proposed is easily exportable to other cases of study since it makes use of generalized modelling tools freely available online, although it is important to keep in mind that it is necessary a good knowledge of the system in order it to be effective.

Since no drought is identical to another, especially given a changing climate, modelling the past to anticipate future drought is an ineffective and risky approach. Including future changes in climate and hydrology is essential, but also future water demands and operation policies must be considered in order to attain useful and reliable results for an efficient anticipation to future drought events. Different operation policies may also require different approaches with regard to drought management, both in the definition of scenario thresholds for measures activation and the variables monitored, and the tools necessary to support decision making.

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