

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

4 David Haro-Monteagudo<sup>a,b</sup>, Abel Solera<sup>a</sup>, Joaquín Andreu<sup>a</sup>

5 <sup>a</sup>Water and Environmental Engineering Institute, Universitat Politècnica de València, Camino  
6 de Vera s/n, 46022, Valencia, Spain

7 <sup>b</sup>Cranfield Water Science Institute, Cranfield University, Bedford, MK43 0AL, UK

8 Corresponding author: David Haro Monteagudo, [d.haromonteagudo@cranfield.ac.uk](mailto:d.haromonteagudo@cranfield.ac.uk)

9 <https://doi.org/10.1016/j.jhydrol.2016.11.022>

10 **Abstract**

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

27

28

## 29 **Highlights**

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

## 36 **Keywords**

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

39

## 40 **1. Introduction**

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

48 The assessment of drought severity requires the use of an index which fulfils well-known  
49 criteria (Tsakiris et al. 2013): operational usefulness, physical meaning, sensitivity to a wide  
50 range of drought conditions, applicability in all parts of the globe, quick response to changes  
51 due to drought and high availability of required data. Commonly, such an index is a prime  
52 variable for assessing the effect of a drought and defining different drought parameters,  
53 which include intensity, duration, severity and spatial extent as defined by Yevjevich (1967)  
54 in his theory of runs. A time series of drought indices provides a framework for evaluating  
55 drought parameters of interest. Generally, drought indices are categorized as  
56 meteorological, hydrological, agricultural or remote sensing-based (Rossi and Cancelliere  
57 2013). Mishra and Singh (2010) and Pedro-Monzonis et al. (2015) made an extensive review  
58 of existing univariate drought indices both concluding that each index performance is region  
59 specific mostly due to the characteristics of the variables used for their calculation and the  
60 purpose of the analysis. In addition, in recent time some authors have also attempted to  
61 combine all the variables (e.g. precipitation, soil, water content) that lead to different  
62 physical forms of drought in so-called multivariate drought indices (Rajsekhar et al. 2015). In  
63 some cases, the index is built as an aggregation of variables selected according to their  
64 relation each drought type (Keyantash and Dracup 2004; Rajsekhar et al. 2015). In other, the  
65 index is constructed using copulas to derive the joint distribution of two or more variables  
66 (Kao and Govindaraju 2010; Hao and AghaKouchak 2013).

67 An indicator system is a drought monitoring system that allows the anticipation in the  
68 application of mitigation measures for the reduction of socio-economic and environmental  
69 impacts of droughts (Estrela and Vargas 2012). Such systems can also be considered early  
70 warning systems for their capacity to anticipate the effects that drought may have on the  
71 system in order to trigger necessary mitigation measures (Rossi et al. 2008). In most cases,  
72 these systems are normally formed by basic variables selected at different points in a river

73 basin that are capable of defining the current drought status. Their reliability will depend on  
74 their capacity to represent, using real-time data: 1) the relationship between significant  
75 reductions of water availability with deviations of meteorological and hydrological  
76 components from their average; 2) detecting early stages of drought development; 3)  
77 provide results that allow comparison between events both in time and space; and 4)  
78 assessing the severity of the ongoing situation in order to support decision making for  
79 triggering drought mitigation actions. Additionally, in the case of regulated water resources  
80 systems, it would be desirable that the indicator is capable of showing the evolution of  
81 management and how this would change the drought status of the system if new operation  
82 rules are envisaged.

83 Different drought early warning systems have been developed at different spatial scales, but  
84 a very small number of such systems are actually in operation (Rossi and Cancelliere 2013).  
85 This is mainly due to the low density of meteorological and hydrological gauging networks,  
86 the sharing of the data among different agencies with different objectives, and to the lack of  
87 universal standards in computing drought indices (Rossi 2003). In addition, the development  
88 of indicator systems based on observational frameworks cannot provide sufficient  
89 anticipation with regard to the event in progress in order to activate the necessary measures  
90 to mitigate its effects (Haro et al. 2014). Efforts have been made to correlate drought indices  
91 to impacts (Stagge et al. 2015), but these relationships only provide insight after the event  
92 has finished and the impacts reported. Mishra and Singh (2011) acknowledged that to  
93 develop suitable techniques for forecasting the onset and termination of droughts is still a  
94 major research challenge due to the inability to predict drought conditions accurately for  
95 months or years in advance. Due to these inaccuracies and uncertainties, drought  
96 management relies nowadays mainly on risk assessment. Risk assessment during the  
97 operation phase of a system is often referred as conditioned risk assessment. With this

98 procedure, the state of the system is usually evaluated for the short-term to explore  
99 alternative mitigation measures and policies for an ongoing drought episode. This same  
100 assessment approach can be adopted for early warning purposes (Cancelliere et al 2009).

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

116 This paper proposes a novel methodology to support drought monitoring and scenario  
117 definition in regulated water resources systems. It is based on the results of two models, an  
118 optimisation model and a stochastic streamflow generation model, both of which have been  
119 calibrated and validated in previous research (Haro et al. 2012a, 2012b, and 2014b; Ochoa-  
120 Rivera 2002). Using storage in reservoirs as a summary indicator of the future system  
121 status, we propose a combined use of the two models to generate a series of results that  
122 can support and complement drought monitoring and early warning systems currently in

123 place in a river basin. The methodology is applied to the Jucar River Basin in Spain to  
124 evaluate the probability of a scenario change several years in advance. The proposed  
125 method has the potential to enhance decision making under highly uncertain hydrological  
126 situations, and provide water resource planners and managers with new insights both  
127 regarding the behavior of the system and the development of drought episodes.

## 128 **2. Case study description**

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

137 The river is an example of a typical Mediterranean river, characterized by a semi-arid climate  
138 in most of the basin territory consisting of low precipitation rates (475mm/year) during the  
139 year combined with exceptional convective storms that can lead to flooding and seasonal  
140 summer scarcity that occurs when irrigation requirements are at their highest. Urban  
141 demand accounts for circa 143.3 hm<sup>3</sup>/year and the water demand for irrigated agriculture  
142 reaches 1034.3 hm<sup>3</sup>/year. Water supply to small urban areas comes mainly from wells and  
143 springs, but large metropolitan areas such as Albacete, Sagunto and Valencia rely on  
144 surface water (Andreu et al. 2009). According to the White Book of Groundwater (CEDEX  
145 1995), nearly three quarters (73%) of the resources in the territory of the DHJ have  
146 subterranean origin. This highlights the major importance that groundwater resources have

147 in the management of these basins. The total amount of available groundwater resources in  
148 the basin is 1,225 hm<sup>3</sup>/year. However, this only represents the estimated volume in all the  
149 groundwater bodies without accounting for their sharing between other basins or the  
150 relationship these bodies have with the surface water system.

151 With regard to droughts, the Jucar River Basin can be considered to be one of the most  
152 vulnerable areas in the western Mediterranean region, due to high water exploitation  
153 indexes, and the environmental and water quality problems that arise when droughts occur.  
154 This situation has triggered increased use of non-conventional resources in recent years,  
155 such as reuse of wastewater and drought emergency wells. Also, conjunctive use of surface-  
156 ground waters has historically been a very important option in the region to provide  
157 robustness against droughts. The integrated use of these three resource options was  
158 considered a major success in adapting to the latest drought episode between 2005 and  
159 2008 (Ortega-Reig et al 2014).

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

### 167 **3. Methodology**

168 In this section, we present the indicator system currently in use in the Jucar River basin as  
169 well as in most of Spanish river basins. Despite being a useful methodology to evaluate the  
170 actual drought conditions in the basin, it has low forecasting capacity; making preventive

171 management of droughts inefficient and/or very difficult. To complement the information  
172 provided by the indicator, we developed a methodology to derive the probability of drought  
173 scenario change for a four year planning horizon. It is based on the Monte Carlo evaluation  
174 of the results of multiple runs of an optimization model of the system. Based on this analysis,  
175 we derive distribution functions on the future state of the basin and combine them with  
176 trigger values for each drought scenario.

### 177 3.1. Current drought indicator system for Spanish river basins

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

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

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

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

---

<sup>1</sup> A partial translation of the contents in CHJ(2007) is provided in Acacio et al. (2013)



191

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

207 Spanish Drought Plans establish four different levels of drought, or scenarios, namely:  
208 normality, pre-alert, alert and emergency (CHJ 2007). These levels are determined  
209 according to the values of the SI with the following thresholds: Normality ( $SI \geq 0.5$ ); Pre-alert  
210 ( $0.5 > SI \geq 0.3$ ); Alert ( $0.3 > SI \geq 0.15$ ); and Emergency ( $0.15 > SI$ ). Figure 2 shows the evolution of  
211 the SI in the Jucar River Basin between October 1998 and September 2010. Between the  
212 end of the XX century and the beginning of the XXI century the basin experienced a short  
213 but intense period of drought that made the SI oscillate between the pre-alert and the alert  
214 levels until 2002 when the situation returned to normality after a period of intense  
215 precipitation. Between 2005 and 2008, the system suffered the worst drought event on

216 record with SI reaching emergency levels several times during that period. After that, the  
217 system gradually recovered to pre-alert in 2009 to finally reach the normality level in 2010.

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

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

231 3.2. Drought scenario definition based on the risk assessment of the system's optimal  
232 operation

233 The methodology developed is based on previous research by Sanchez-Quispe (1999),  
234 Andreu and Solera (2006), Andreu et al (2007, and 2013) and Cancelliere et al (2009). Their  
235 findings were successfully used in the management of previous drought episodes of the  
236 Jucar River Basin. Here we present a further development of existing approaches by  
237 introducing an optimisation approach that allows one to obtain the best results achievable in  
238 the system and better rules for the application of mitigation and prevention measures. This  
239 work further develops that presented by Haro et al. (2014a) by extending its application to a

240 multi-year regulated basin. In addition, we show how the risk assessment methodology  
241 presented here is applicable to forecast drought scenarios. Figure 3 provides a schematic  
242 summary of the methodology, which is briefly described below.

243 We applied a monthly Monte Carlo optimisation process to a catchment management model  
244 of the Jucar River Basin previously developed in the GUI of Aquatool DSS (Andreu et al  
245 1996) for the implementation of the European Water Framework Directive (CHJ 2004) and  
246 the development of its latest basin plan (CHJ 2015), and shown in Figure 4. The model  
247 includes the main surface storage facilities ('Alarcon', 'Contreras', and 'Tous' reservoirs) as  
248 well as the main aquifers in the basin that have a crucial role in the management of the  
249 system ('Mancha Oriental' and 'Plana de Valencia'). The most important demands are also  
250 represented, namely: traditional irrigation in 'Plana de Valencia'; groundwater irrigation from  
251 'La Mancha Oriental' aquifer; conjunctive irrigation from the newer developments along the  
252 'Jucar-Turia' canal; and the urban demands of Valencia, Sagunto and Albacete, which is  
253 minor in quantity but more sensitive to failures in the supply. Haro et al. (2012a and 2012b)  
254 and Haro Monteagudo (2014) provide a detailed description of the optimization technique,  
255 equations and constraints utilised by the model, as well as the input data it needs. A  
256 previous application can also be found in Haro et al (2014b). The model runs on a monthly  
257 time step fed by synthetic streamflow series generated stochastically from historically  
258 observed monthly values between 1980 to 2012. There are 16 streamflow input nodes along  
259 the model network, represented as thick red arrows in Figure 4. The synthetic series were  
260 generated with the stochastic analysis and modelling module in Aquatool (Ochoa-Rivera  
261 2002). The 16 observed streamflow time series were normalised and standardised to  
262 calibrate the autoregressive model, AR(1), shown in equation 3:

$$X_t = \boldsymbol{\varphi}_1 \cdot X_{t-1} + \boldsymbol{\theta}_0 \cdot \varepsilon \quad \text{Eq. 3}$$

263 where  $X_t$  and  $X_{t-1}$  are  $n$  variables vectors;  $\varphi_1$  is an  $n \times n$  autocorrelation matrix;  $\theta_0$  is an  
264  $n \times n$  matrix of coefficients that multiplies the random  $N(0,1)$  values vector represented by  $\varepsilon$ .  
265 For this case,  $n$  has a value of 16. For the stochastic generation of synthetic streamflow  
266 series from observed values, the last monthly observed value is used as a seed after  
267 normalisation and standardisation. The generated time series of standardised values are  
268 converted to streamflow values following the inverse path. The validation of the model  
269 against the long term characteristics of the historic series (average, standard deviation,  
270 number of dry years), makes it suitable to explore a large range of events.

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

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

283 Based on the previous consideration, we use the storage probability in the different  
284 reservoirs in the basin as the basis to determine the risk level and the change of scenario  
285 probability at the end of a number of campaigns for each month. It must be noted that  
286 reservoirs levels is an important element in the Jucar River Basin drought indicator system,  
287 representing almost 50% of the indicators value. We transform the reservoir levels

288 probability distribution into state index distributions following the calculation method above  
289 by comparing the results to the historic series of observed levels. Afterwards, we determine  
290 the probability of scenario change for each month by crossing each state index distribution  
291 by the threshold levels defined by the state index methodology.

292 We applied this methodology in the Jucar River Basin for the period between hydrologic  
293 years 1998-1999 and 2008-2009. During these 10 years, two of the most important drought  
294 episodes for the Jucar River Basin in history took place (CHJ 2007; van Lanen et al. 2013):  
295 the short but intense drought of 1999-2000 and the long drought episode between 2005 and  
296 2008.

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

## 304 **4. Results**

### 305 4.1. State Index complementation with scenario change probability

306 Figure 5 shows the result of applying the proposed methodology together with the evolution  
307 of the Jucar River observed state index for the three first years of the optimisation period  
308 considered in each run. The fourth year is disregarded because it coincides with the end of  
309 the optimisation period, when the algorithm uses all the available water. For each month, we  
310 have the actual drought scenario as defined by the thresholds and the probability of each

311 scenario occurring one to three years later corresponding to Figures 5a to 5c, respectively.  
312 In Figure 5a, the probability of a scenario change in the next year is low, with a general  
313 tendency to remain at the same level. In Figures 5b and 5c, the probabilities of a scenario  
314 change increase after two and three years and how this provides a better insight of what can  
315 be expected in the system. With these results, the methodology proposed adds value to the  
316 actual State Index by showing the probability that the current situation might change in the  
317 future, hence providing additional support for decision makers in terms of activating  
318 mitigation measures, which normally require some time to start operating appropriately.

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

#### 330 4.2. Approximation of SI values with risk results

331 Previous stakeholder participation experiences in the Jucar River with risk assessment tools  
332 have shown that, in general, risk results obtained for an 80% probability of exceedance level  
333 and one year in advance are trusted as good approximations of the future state of the  
334 system. These results can be easily extracted from the tools used to perform the proposed

335 methodology, as well as any other risk level results. Hence, we explored the ability of the  
336 proposed methodology to approximate SI from a probabilistic perspective.

337 Figure 6 shows the evolution of SI approximated as the 80% risk level one year in advance  
338 versus the actually observed SI in the Jucar River for the period October 1998 through  
339 September 2009. Both indices reflect accurately the drought events occurred in the Jucar  
340 River basin for the period of study. However, while the risk based SI follows the observed  
341 one during the first part of the period, there is a six months delay disconnection right before  
342 the beginning of the 2004-2008 drought episode. This is due to the operation of the  
343 optimisation process. The objective function in the optimisation model works tries to  
344 maximise the stored volume in reservoirs while meeting all the demands and environmental  
345 flows, minimising water loses from the system. First, during the wet period prior to the 2004-  
346 2008 event, the optimisation model achieves better storage levels before the episode starts  
347 because all the demands are met and there is water that would be lost instead at a high cost  
348 for the objective function. Since the optimisation process implies perfect forecast, the model  
349 is capable of storing that water. Second, when reservoirs are near to empty, like during the  
350 drought period, the objective function benefits more from supplying the demands than from  
351 storing water. Hence, despite the risk based SI drops below the observed one, the demands  
352 still have a better level of supply than in the real situation. Therefore, the risk based results  
353 offer an envelope of the actual situation, providing managers with an idea of how the system  
354 can be expected to respond at different levels of risk.

## 355 **5. Discussion**

356 The predictions of the methodology presented improve with respect to the combined use of  
357 storage, streamflow and precipitation to define a drought state index because they include  
358 both previous precipitation and storage data, as well as information regarding the physical

359 system what allows obtaining its best management options. It also includes up to date  
360 information of the human influence on the system by means of water demands for the  
361 different sectors, and allows considering the environmental needs of the riverine ecosystems  
362 in the form of environmental flows definition. In addition, the presented methodology can be  
363 used afterwards to assess the risk level with the existing management rules to evaluate the  
364 changes introduced by the mitigation measures. Since the methodology is meant to be used  
365 every month to monitor the state of the system, any new measures could be implemented in  
366 the model in real time. In this way, it is possible to select the best measures for each case  
367 and their optimal application.

### 368 5.1. Methodological limitations

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

381 Secondly, optimisation is a highly resources consuming process. This means that complex  
382 models of the system under study will require longer calculation periods than more simple  
383 ones. The creation of models capable of representing the reality of the system while



384 maintaining a low degree of computational complexity requires a high level of knowledge  
385 and understanding about the system. The Jucar River Basin has been extensively studied by  
386 researchers for many years, and the methodology presented here was relatively easily  
387 applicable. However, it will not be of immediate use in river basins where water level is  
388 scarce and/or the relationships between the individual hydrological processes are not clear.

389 Finally, in order to be effective, the methodology and its results must be trusted, but also  
390 understood, by those that will be later affected by the decisions derived from its use. The  
391 model used in this study was developed conjunctively with the managers and water users of  
392 the basin within a participatory process that required reaching agreements for everyone. In  
393 the same way, the triggers that define each drought situation and the corresponding  
394 measures are the results of negotiations between the different actors in the system. This  
395 trust building process is achieved over time and thus, methods such as the one presented  
396 here are unlikely to be successful at the beginning of participative management processes.

397 Anyway, as observed in Andreu et al. (2009) and Andreu et al. (2013), the very process of  
398 implementing similar methodologies finally resulted in better knowledge of the system and  
399 understanding of stakeholders needs with an overall improvement of management.

#### 400 5.2. Implications for drought management

401 Existing drought monitoring systems are normally limited to measure a series of climatic and  
402 hydrologic variables and calculating various indices that allow determining what is the state  
403 of the system compared to the past. Such is the case of the state index used in Spanish  
404 drought management plans shown above. This approach may be useful, if not the only one  
405 possible in some cases, but has been revealed insufficient for its use in some systems,  
406 especially regulated water resources systems (Haro et al. 2014). Using indicators based on  
407 observation of hydrologic variables, and comparison with past data in systems where human  
408 activities take place, are unable to represent the changes occurring in the system along time.

409 Anthropogenic actions influence not only river flows themselves with extractions and returns  
410 but also runoff production and groundwater recharge, delaying or preventing water from  
411 reaching the streams. Accounting for all of this and translating observed flows in one point to  
412 natural regime is often an arduous task that is not always rewarded with appropriate results.  
413 In addition, the parameters used for drought indices calculation are variable with time. This  
414 causes that new maximum and minimum observed values have the chance to change  
415 dramatically the shape of the indicator evolution. For example, if an exceptionally wet, or dry,  
416 period occurred, several hydrological variables (precipitation, streamflow, reservoir storage  
417 levels, etc.) could reach unprecedented levels that might change the values of the state  
418 index resulting in completely erroneous impressions regarding past drought events, as well  
419 as influencing the perception of future ones.

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

433 knowledge that managers and users have of the system as well as building common  
434 understanding on the needs and concerns of the different actors involved.

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

## 446 **6. Conclusions**

447 This paper has proposed a new methodology to support drought monitoring and scenario  
448 definition in regulated water resources systems. It allows approaching droughts risk  
449 assessment and early warning from a new perspective with regard to previous approaches,  
450 adding value to the existing monitoring methods currently in use. The use of optimisation  
451 modelling to obtain the best management of the system during uncertain hydrologic periods  
452 such as droughts permits anticipating the possible outcomes of these situations without the  
453 need of considering the operation rules in place that might result ineffective in these cases.  
454 An important advantage of the method developed is its capacity for dealing with complex  
455 systems, providing a general picture of the situation in the basin while most of the previously  
456 developed indices are applicable only to a demand or to a group of demands. Thus, the

457 proposed method constitutes a step forward in the definition of drought early warning  
458 systems in regulated basins. The application of the methodology in the Jucar River shows its  
459 potential for supporting the definition of drought scenarios and hence improving the overall  
460 drought management process in the basin. Furthermore, the methodology proposed is easily  
461 exportable to other cases of study since it makes use of generalized modelling tools freely  
462 available online, although it is important to keep in mind that it is necessary a good  
463 knowledge of the system in order it to be effective.

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

## 472 **Acknowledgements**

473 The authors thank the Confederación Hidrográfica del Jucar for providing data and support  
474 to build the models. We also thank the comments and language revision of Dr Jerry Knox  
475 that helped improving the overall quality of the article.

476 This work was supported by the Spanish Ministry of Economy and Competitivity (CGL2009-  
477 11798, CGL2012-34978, and CSD2009-00065), and the European Commission FP7  
478 programme (FP7-ENV-2011-282769 and FP7-ENV-2012- 308438).

## 479 **References**

- 480 Acacio, V., Andreu, J., Assimacopoulos, D., Bifulco, C., di Carli, A., Dias, S., Kampragou, E.,  
481 Haro Monteagudo, D., Rego, F., Seidl, I., Vasiliou, E., Wolters, W., 2013. Drought monitoring  
482 systems. DROUGHT&R-SPI Technical Report No. 6. [http://www.eu-](http://www.eu-drought.org/media/default.aspx/emma/org/10825941/DROUGHT-)  
483 [drought.org/media/default.aspx/emma/org/10825941/DROUGHT-](http://www.eu-drought.org/media/default.aspx/emma/org/10825941/DROUGHT-)  
484 [RSPI+Technical+Report+No.+6+--+Drought+Monitoring+systems.pdf](http://www.eu-drought.org/media/default.aspx/emma/org/10825941/DROUGHT-RSPI+Technical+Report+No.+6+--+Drought+Monitoring+systems.pdf)
- 485 Alecci, S., Reitano, B., Rossi, G., 1986. Evaluation of alternatives in management of water  
486 resources systems through performance indices. In Proceedings of the International  
487 Conference on water Resources Needs and Planning in Drought Prone Areas, Khartoum  
488 (Sudan), December 15–17
- 489 Andreu, J., Capilla, J., Sanchís, E., 1996. AQUATOOL, a generalized decision-support  
490 system for water-resources planning and operational management. *J Hydrol* 177, 269-291  
491 DOI 10.1016/0022-1694(95)02963-X
- 492 Andreu, J., Ferrer-Polo, J., Perez, M.A., Solera, A., 2009. Decision Support System for  
493 Drought Planning and Management in the Jucar River Basin, Spain. 18th World  
494 IMACS/MODSIM Congress, Cairns, Australia
- 495 Andreu, J., Ferrer-Polo, J., Perez, M.A., Solera, A., Paredes-Arquiola, J., 2013. Drought  
496 Planning and Management in the Júcar River Basin, Spain. In: K. Schwabe et al (eds)  
497 Drought in Arid and Semi-Arid Regions, 237-249, Springer Science+Business Media,  
498 Dordrecht DOI: 10.1007/978-94-007-6636-5\_13
- 499 Andreu, J., Pérez, M.A., Ferrer, J., Villalobos, A., Paredes, J., 2007. Drought Management  
500 Decision Support System by Means or Risk Analysis Models. In: G. Rossi et al. (eds)

- 501 Methods and Tools for Drought Analysis and Management, 195-216, Springer, Utrecht,  
502 Netherlands DOI 10.1007/978-1-4020-5924-7\_10
- 503 Andreu, J., Solera, A., 2006. Methodology for the analysis of drought mitigation measures in  
504 water resources systems. In: J. Andreu et al (eds) Drought Management and Planning for  
505 Water Resources, 133-168, CRC Taylor & Francis, Boca Raton
- 506 Cancelliere, A., Nicolosi, V., Rossi, G., 2009. Assessment of drought risk in water supply  
507 systems. In: A. Iglesias et al. (eds) Coping with drought risk in agriculture and water supply  
508 systems, 93-109, Springer, Utrecht, Netherlands DOI 10.1007/978-1-4020-9045-5\_8
- 509 CEDEX, 1995. Libro Blanco de las Aguas Subterranas. Ministerio de Industria y Energia,  
510 Ministerio de Obras Publicas, Transportes y Medio Ambiente. Madrid
- 511 CHJ, 2004. Jucar Pilot River Basin. Article 5 report pursuant to the Water Framework  
512 Directive
- 513 CHJ, 2007. Plan especial de alerta y eventual sequia en la Confederacion Hidrografica del  
514 Jucar
- 515 CHJ, 2015. Plan hidrológico de la demarcación hidrográfica del Jucar. Memoria – Anejo 6:  
516 Sistemas de explotación y balances. Pages 286-392
- 517 Estrela, T., Vargas, E., 2012. Drought Management Plans in the European Union. The Case  
518 of Spain. Water Resour Manag 26, 1537-1553 DOI 10.1007/s11269-011-9971-2
- 519 Hao, Z., & AghaKouchak, A. (2013). Multivariate standardized drought index: a parametric  
520 multi-index model. Adv Water Resour, 57, 12-18. DOI 10.1016/j.advwatres.2013.03.009

- 521 Haro, D., Paredes, J., Solera, A., Andreu, J., 2012a. A model for solving the optimal water  
522 allocation problem in river basins with network flow programming when introducing non-  
523 linearities. *Water Resour Manag* 26, 4059–4071 DOI 10.1007/s11269-012-0129-7
- 524 Haro, D., Solera, A., Paredes, J., & Andreu, J. 2012b. Incorporating aquifer modeling into a  
525 multi-period network flow programming optimization model for water resources  
526 management. In *Understanding Changing Climate and Environment and Finding Solutions*,  
527 *Proc. of 10th International Conference on Hydroinformatics–HIC*.
- 528 Haro, D., Solera, S., Paredes, J., Andreu, J., 2014a. Methodology for drought risk  
529 assessment in within-year regulated reservoir systems. Application to the Orbigo River  
530 system (Spain). *Water Resour Manag* 28, 3801-3814 DOI 10.1007/s11269-014-0710-3
- 531 Haro, D., Solera, A., Pedro-Monzonís, M., Andreu, J., 2014b. Optimal Management of the  
532 Jucar River and Turia River Basins under Uncertain Drought Conditions. *Procedia*  
533 *Engineering* 89, 1260-1267 DOI 10.1016/j.proeng.2014.11.432
- 534 Haro Monteagudo, D., 2014. Methodology for the optimal management design of water  
535 resources systems under hydrologic uncertainty. PhD thesis. Universitat Politècnica de  
536 Valencia, Spain
- 537 Hashimoto, T., Stedinger, J.R., Loucks, D.P., 1982. Reliability, resiliency, and vulnerability  
538 criteria for water resource system performance evaluation. *Water resour res* 18, 14-20 DOI  
539 10.1029/WR018i001p00014
- 540 Kao, S. C., & Govindaraju, R. S. (2010). A copula-based joint deficit index for droughts. *J*  
541 *Hydrol*, 380(1), 121-134. DOI 10.1016/j.jhydrol.2009.10.029

- 542 Keyantash, J. A., & Dracup, J. A. (2004). An aggregate drought index: Assessing drought  
543 severity based on fluctuations in the hydrologic cycle and surface water storage. *Water*  
544 *Resour Res*, 40(9). DOI 10.1029/2003WR002610
- 545 Mishra, A.K., Singh, V.P., 2010. A Review of drought concepts. *J Hydrol* 391, 202-216 DOI  
546 10.1016/j.jhydrol.2010.07.012
- 547 Mishra, A.K., Singh, V.P., 2011. Drought Modeling: A Review. *J Hydrol* 403, 157-175 DOI  
548 10.1016/j.jhydrol.2011.03.049
- 549 Ochoa-Rivera, J.C., 2002. Modelo estocastico de redes neuronales para la sintesis de  
550 caudales aplicados a la gestion probabilistica de sequias. PhD Thesis. Universitat  
551 Politecnica de Valencia, Spain
- 552 Ochoa-Rivera, J., Andreu, J., García-Bartual, R., 2007. Influence of Inflows Modeling on  
553 Management Simulation of Water Resources System. *J. Water Resour Plan Manag* 133 (2),  
554 106-116 DOI 10.1061/(ASCE)0733-9496(2007)133:2(106)
- 555 Ortega-Reig, M., Palau-Salvador, G., Cascant, M.J., Benítez-Buelga, J., Badiella, D.,  
556 Trawick, P., 2014. The integrated use of surface, ground and recycled waste water in  
557 adapting to drought in the traditional irrigation system of Valencia, *Agr Water Manage*, 133;  
558 55-64 DOI 10.1016/j.agwat.2013.11.004
- 559 Pedro-Monzonís, M., Solera, A., Ferrer, J., Estrela, T., Paredes-Arquiola, J., 2015. A review  
560 of water scarcity and drought indexes in water resources planning and management. *J*  
561 *Hydrol* 527, 482-493 DOI 10.1016/j.jhydrol.2015.05.003.
- 562 Rajsekhar, D., Singh, V. P., & Mishra, A. K. (2015). Multivariate drought index: An  
563 information theory based approach for integrated drought assessment. *J Hydrol*, 526, 164-  
564 182. DOI 10.1016/j.jhydrol.2014.11.031



565 Rossi, G., 2003. Requisites for a drought watch system. In: G. Rossi et al. (eds) Tools for  
566 drought mitigation in Mediterranean Regions, 147-157, Springer Netherlands. DOI  
567 10.1007/978-94-010-0129-8\_9

568 Rossi, G., Cancelliere, A., 2013. Managing drought risk in water supply systems in Europe: a  
569 review, *Int J Water Resour D* 29, 272-289 DOI 10.1080/07900627.2012.713848

570 Rossi G., Nicolosi V., Cancelliere A., 2008. Recent methods and techniques for managing  
571 hydrological droughts. In : López-Francos A. (ed.). Drought management: scientific and  
572 technological innovations. Zaragoza : CIHEAM, 2008. p. 251-266. (Options  
573 Méditerranéennes : Série A. Séminaires Méditerranéens; n. 80). 1. International Conference  
574 Drought Management: Scientific and Technological Innovations, 2008/06/12-14, Zaragoza  
575 (Spain). <http://om.ciheam.org/om/pdf/a80/00800450.pdf> Sanchez-Quispe, S. (1999) Gestión  
576 de Sistemas de Recursos Hídricos con Toma de Decisión Basada en Riesgo. PhD Thesis,  
577 Universitat Politecnica de Valencia, Spain

578 Sánchez-Quispe, S. (1999). Gestión de Sistemas de recursos Hídricos con Toma de  
579 Decisión Basada en Riesgo (Doctoral dissertation, Tesis Doctoral. Universidad Politécnica  
580 de Valencia).

581 Stagge, J.H., Kohn, I., Tallaksen, L.M., Stahl, K., 2015. Modeling drought impact occurrence  
582 based on meteorological drought indices in Europe, *J Hydrol* 530, 37-50 DOI  
583 10.1016/j.jhydrol.2015.09.039.

584 Tsakiris, G., Nalbantis, I., Vangelis, H., Verbeiren, B., Huysmans, M., Tychon, B.,  
585 Jacquemin, I., Batelaan, O., 2013. A system-based paradigm of drought analysis for  
586 operational management. *Water Resour Manag*, 27, 5281-5297 DOI 10.1007/s11269-013-  
587 0471-4

588 Van Lanen, H., Alderlieste, M.A.A., Acacio, V., Andreu, J., Garnier, E., Gudmundsson, L.,  
589 Haro Monteagudo, D., Lekkas, D., Paredes, J., Solera, A., Assimacopoulos, D., Rego, F.,  
590 Seneviratne, S., Stahl, K., Tallaksen, L., 2013. Quantitative analysis of historic droughts in  
591 selected European case study areas. DROUGHT-R&SPI Technical Report No.8,  
592 <http://www.eu-drought.org/media/default.aspx/emma/org/10827335/DROUGHT->  
593 [RSPI+Technical+Report+No.+8+-](http://www.eu-drought.org/media/default.aspx/emma/org/10827335/DROUGHT-RSPI+Technical+Report+No.+8+-+Quantitative+analysis+of+historic+droughts+in+selected+European+case+study+areas.pdf)  
594 [+Quantitative+analysis+of+historic+droughts+in+selected+European+case+study+areas.pdf](http://www.eu-drought.org/media/default.aspx/emma/org/10827335/DROUGHT-RSPI+Technical+Report+No.+8+-+Quantitative+analysis+of+historic+droughts+in+selected+European+case+study+areas.pdf)  
595 Yevjevich, V., 1967. The application of surplus, deficit and range in hydrology. Colorado  
596 State University, Fort Collins, Colorado <http://hdl.handle.net/10217/61287>  
597

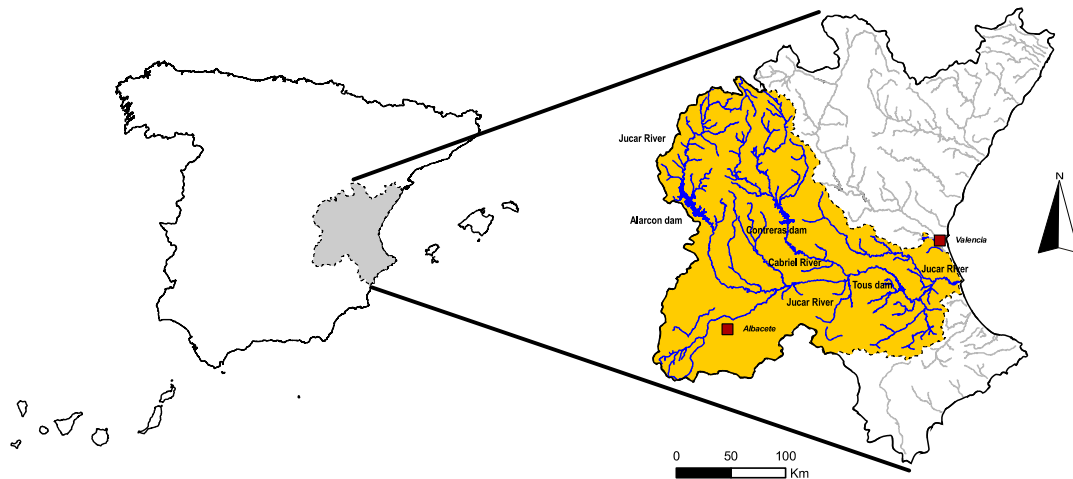


Figure 1. Location of the Jucar River Basin in Iberian Peninsula and within the other systems in CHJ

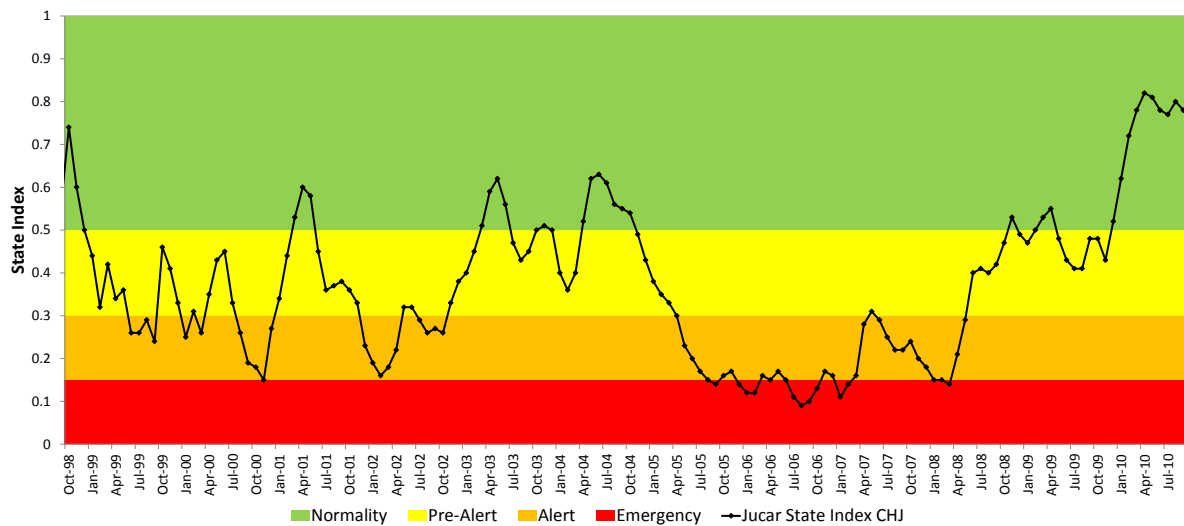


Figure 2. Evolution of the Jucar River Drought State Index with drought scenario thresholds between years 1998 to 2010

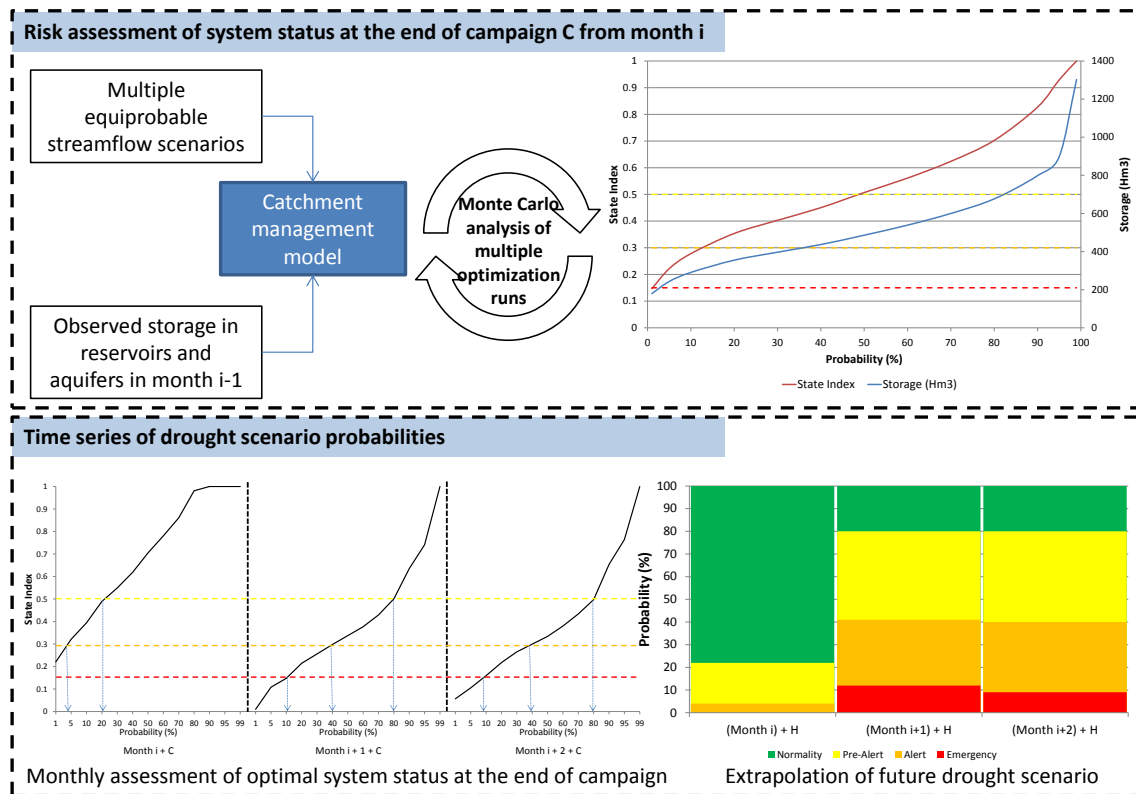


Figure 3. Schematic of the methodology for the definition of future drought scenarios

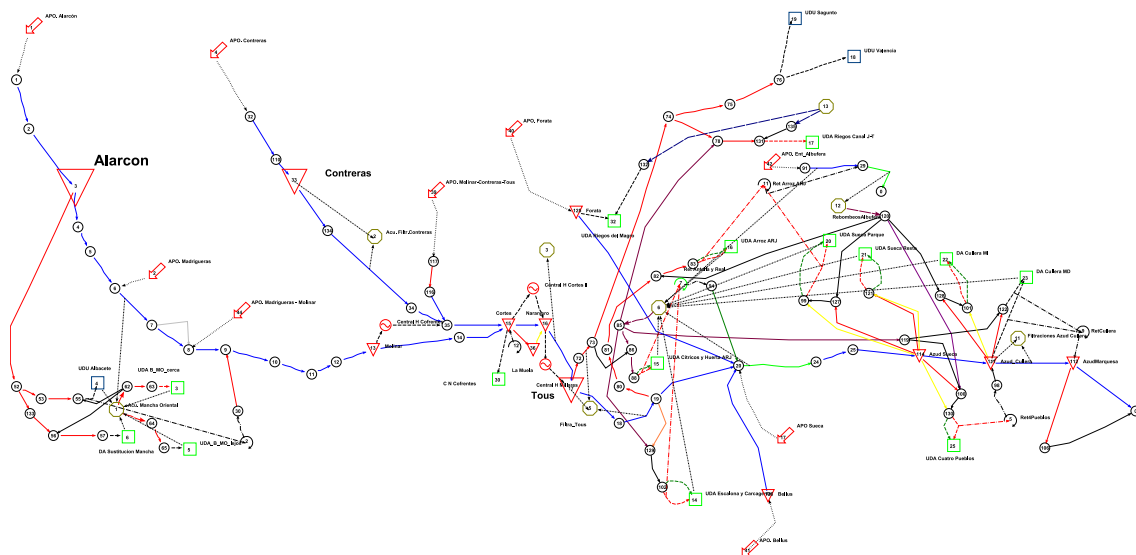


Figure 4. Scheme of the Jucar River Management Model



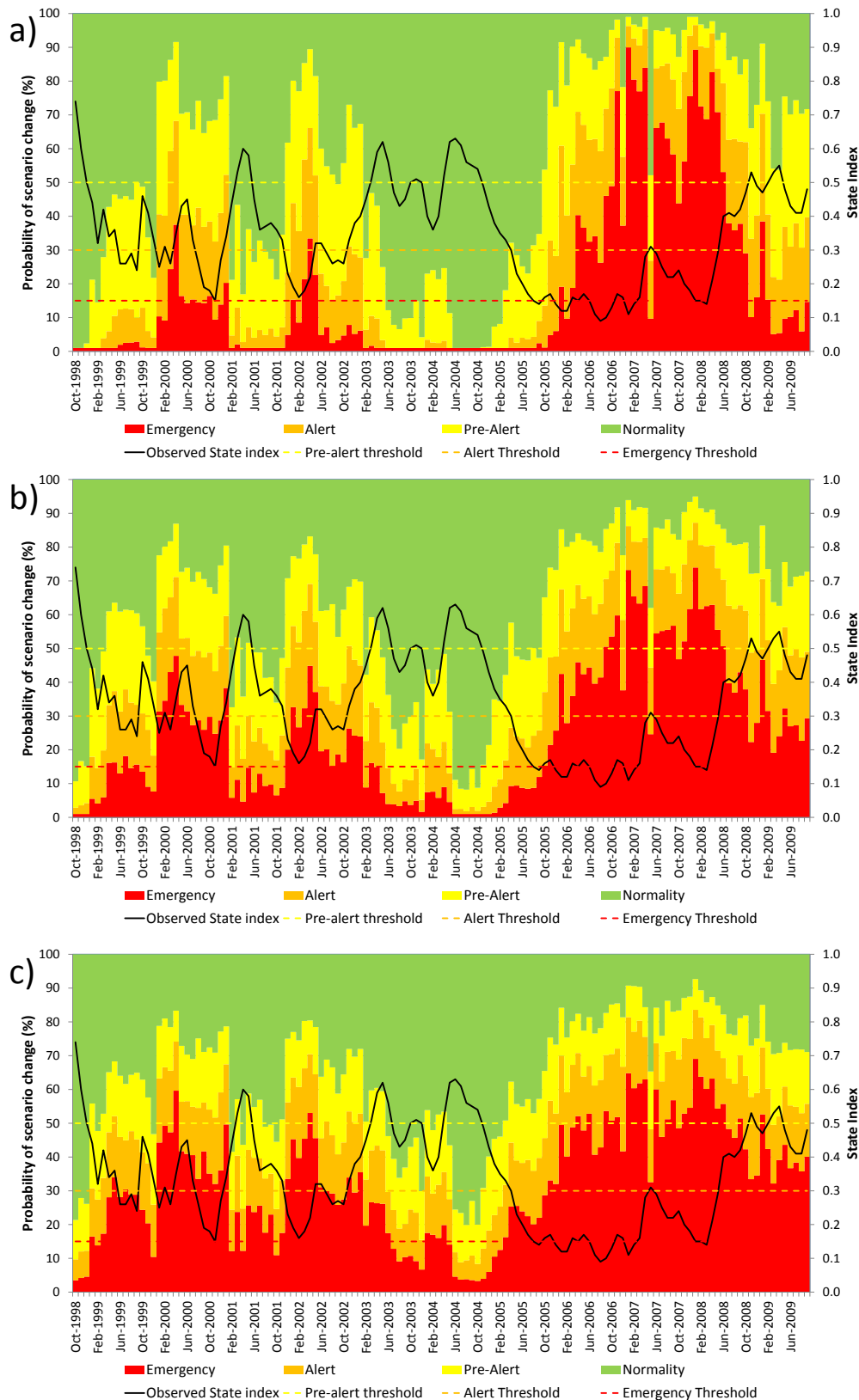


Figure 5. Probabilistic risk scenario definition vs Observed State Index in the Jucar River Basin at the end of (a) one, (b) two, and (c) three campaigns

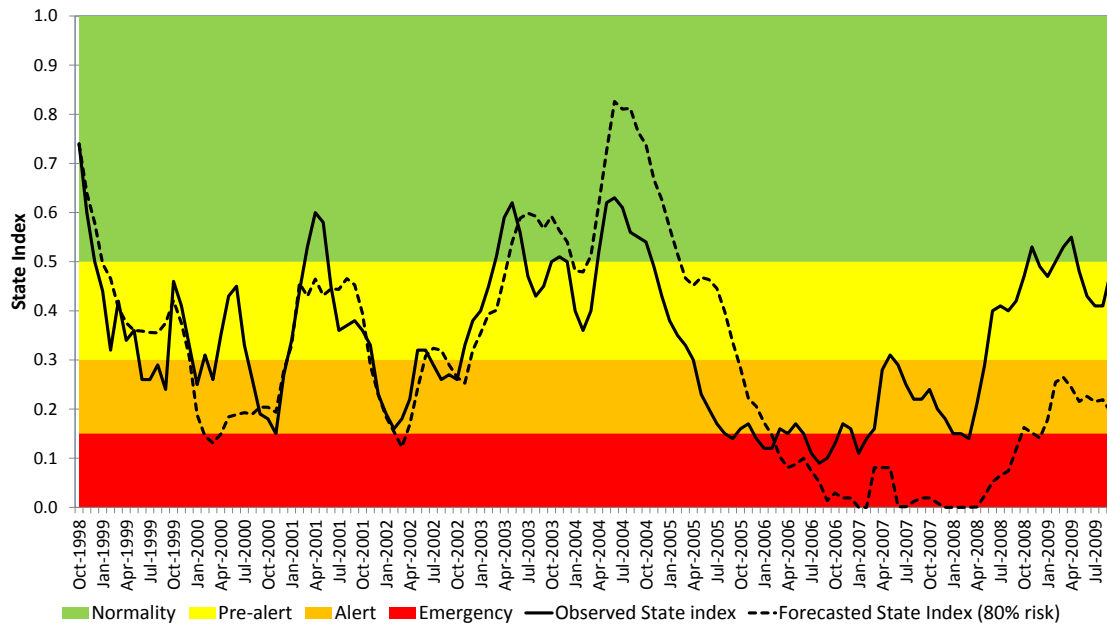


Figure 6. Observed state index values at the Jucar River versus calculated state index at 80% risk level