1 # Drought early warning based on optimal risk forecasts in

2 # regulated river systems: application to the Jucar River Basin

3 # (Spain)

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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.

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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

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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.

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). Inother, 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

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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^2) and in volume of resources (1,548 hm^3/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^3/year and the water demand for irrigated agriculture

142   reaches 1034.3 hm^3/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

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147   in the management of these basins. The total amount of available groundwater resources in

148   the basin is 1,225 hm^3/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.

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)[1].

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

$$If \ V_i \geq V_{av} \ \rightarrow \ \mathrm{SI} = \frac{1}{2} \cdot \left[1 + \frac{V_i - V_{av}}{V_{max} - V_{av}} \right] \hspace{3cm} \text{Eq. 1}$$

$$If \ V_i < V_{av} \ \rightarrow \ \mathrm{SI} = \frac{1}{2} \cdot \frac{V_i - V_{min}}{V_{av} - V_{min}} \hspace{3cm} \text{Eq. 2}$$

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

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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≥0.5); Pre-alert

210 (0.5>SI≥0.3); Alert (0.3>SI≥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

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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

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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 is 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:

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

263   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

264      $n \, x \, n$ matrix of coefficients that multiplies the random $N(0,1)$ values vector represented by ε.

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

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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

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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.

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

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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

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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.

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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

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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.

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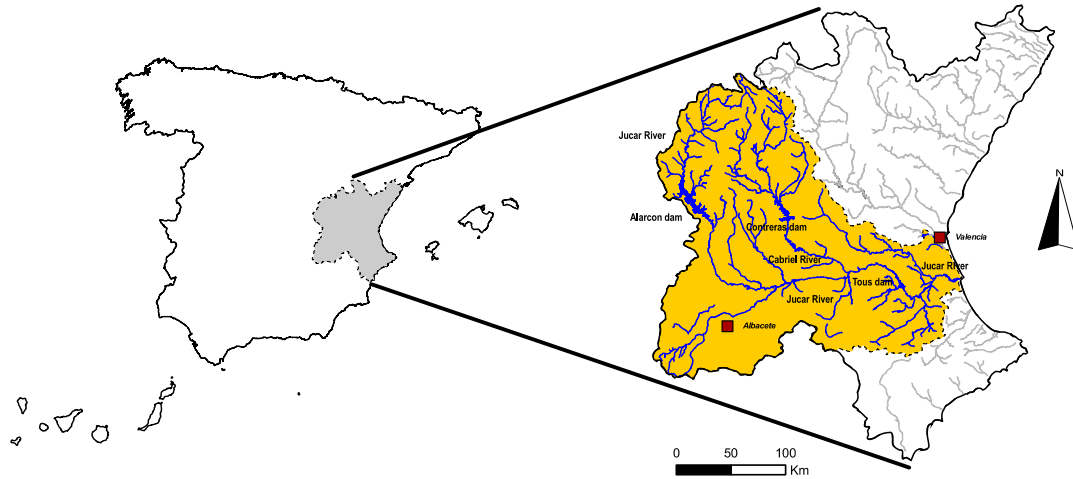
Figure 1. Location of the Jucar River Basin in Iberian Peninsula and within the other systems in CHJ
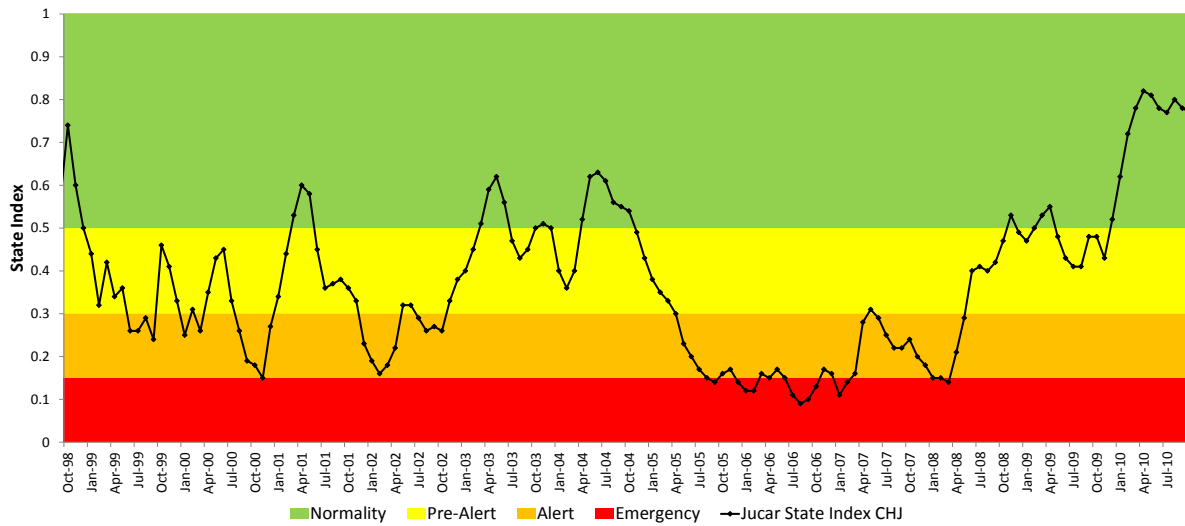
Figure 2. Evolution of the Jucar River Drought State Index with drought scenario thresholds between years 1998 to 2010
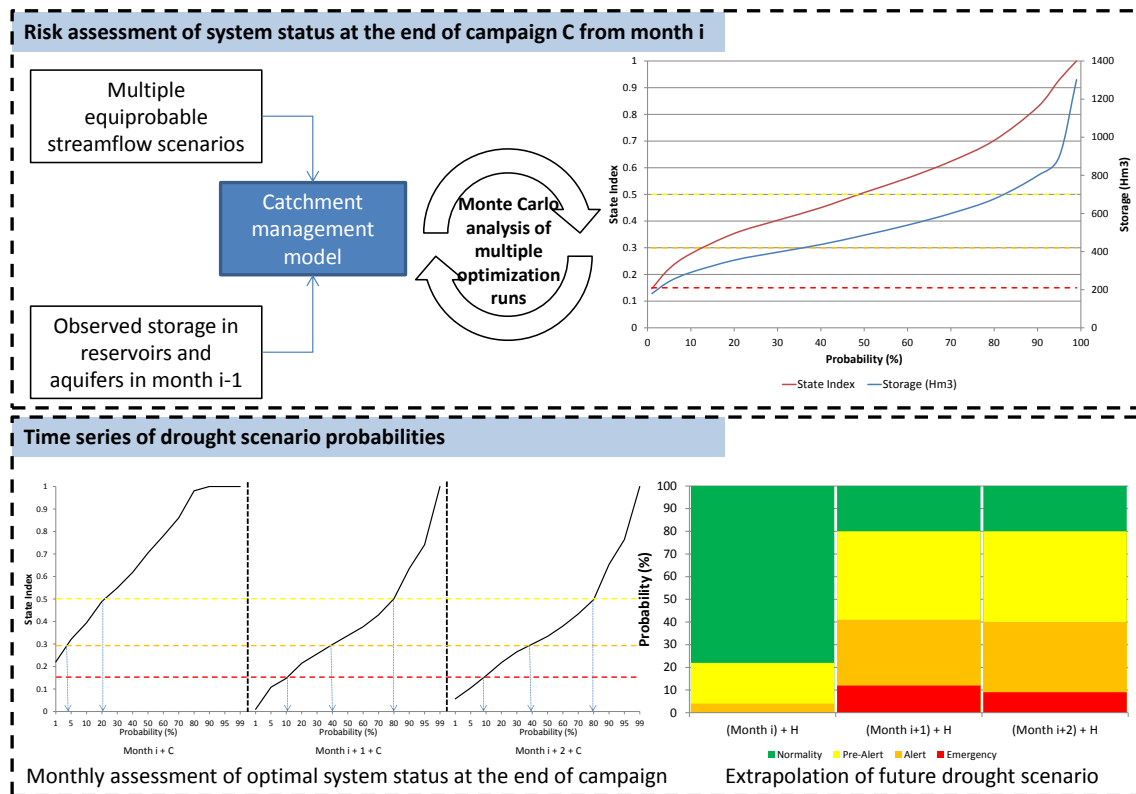
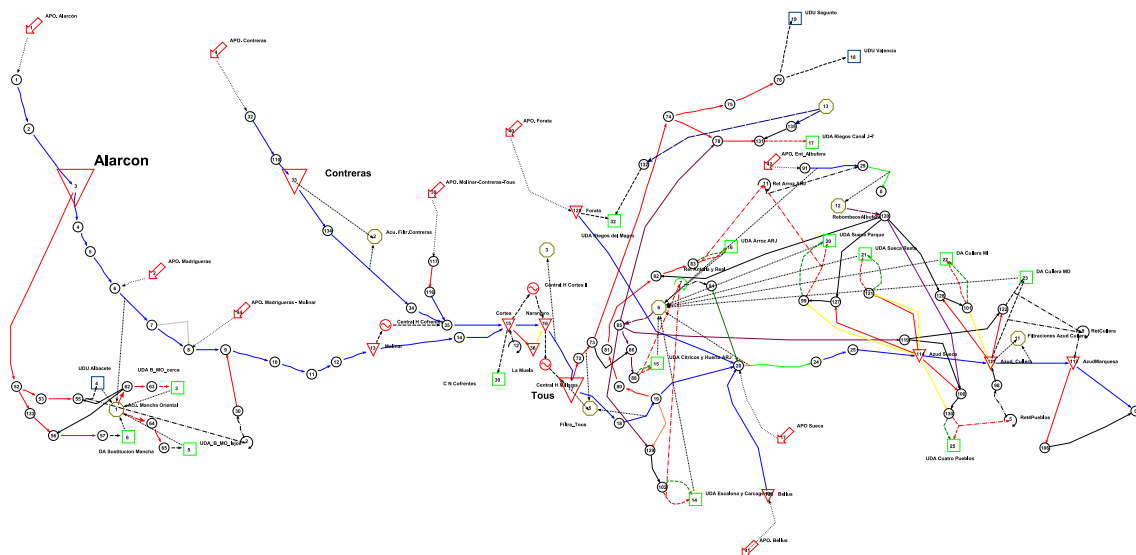Figure 3. Schematic of the methodology for the definition of future drought scenarios
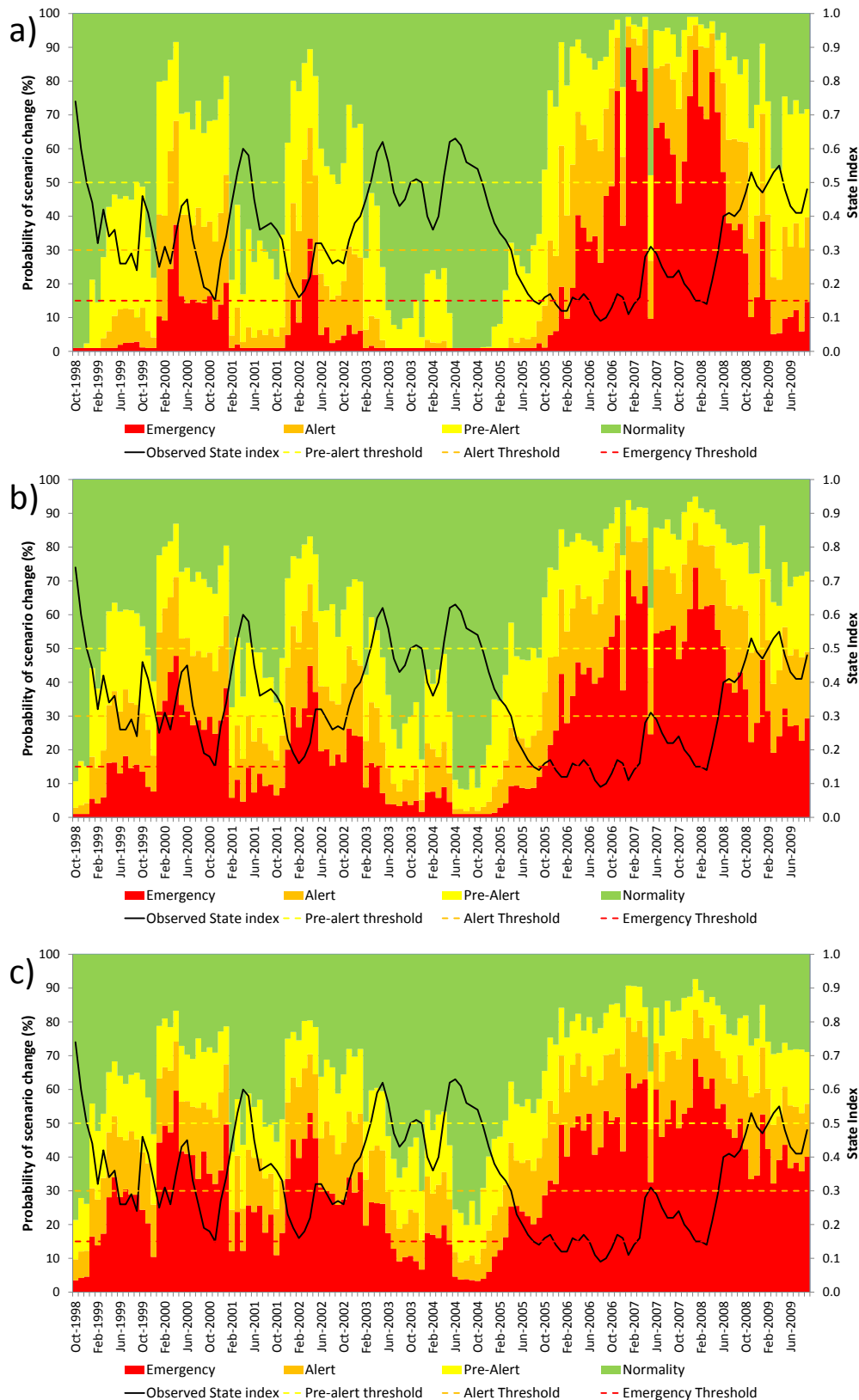

Figure 4. Scheme of the Jucar River Management Model

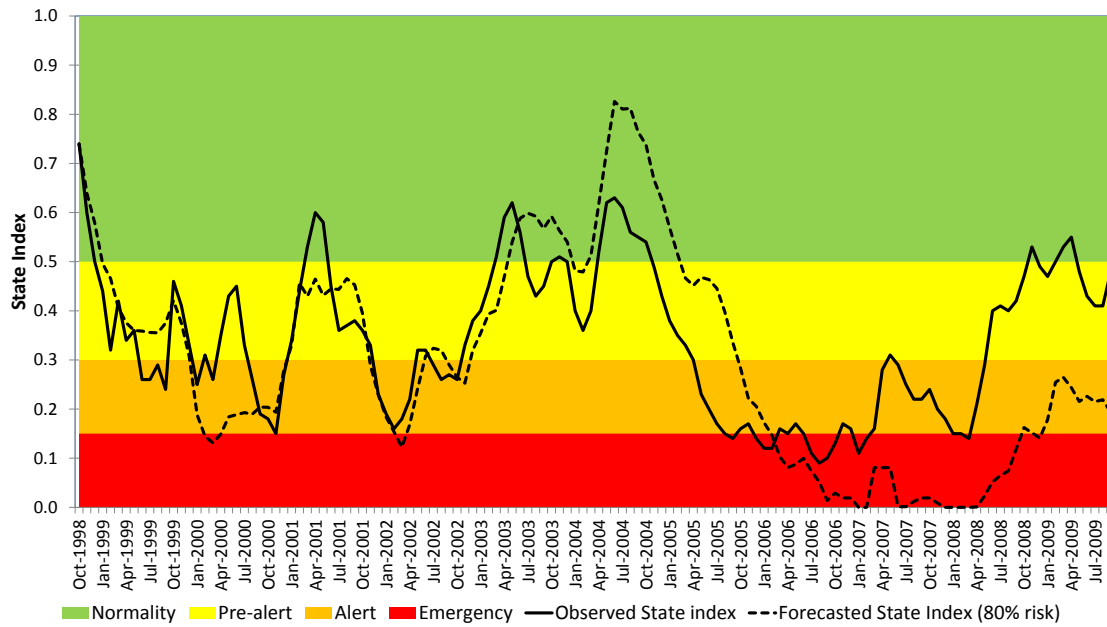Figure 5. Probabilistic risk scenario definition vs Observed State Index in the Jucar River Basin at the end of (a) one, (b) two, and (c) three campaigns

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

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

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