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2014

Weather and Climate Extremes 4 (2014) 11–18

Contents lists available at ScienceDirect

Weather and Climate Extremes

journal homepage: www.elsevier.com/locate/wace

Drought management plans and water availability in agriculture: A risk assessment model for a Southern European basin

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ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form
17 January 2014
Accepted 28 February 2014
Available online 18 March 2014

Keywords:
Agricultural economics
Water economics
Risk management
Mediterranean river basin

ABSTRACT

The Drought Management Plans (DMPs) are regulatory instruments that establish priorities among the different water uses and define more stringent constraints to access to publicly provided water during droughts, especially for non-priority uses such as agriculture. These plans have recently become widespread across EU southern basins. However, in some of these basins the plans were approved without an assessment of the potential impacts that they may have on the economic activities exposed to water restrictions. This paper develops a stochastic methodology to estimate the expected water availability in agriculture that results from the decision rules of the recently approved DMPs. The methodology is applied to the particular case of the Guadalquivir River Basin in southern Spain. Results show that if DMPs are successfully enforced, available water will satisfy in average 62.2% of current demand, and this figure may drop to 50.2% by the end of the century as a result of climate change. This is much below the minimum threshold of 90% that has been guaranteed to irrigators so far.

1. Introduction

Population growth and the improvement of living standards have increased water demand worldwide and, along with decreasing water supply as a result of climate change, the vulnerability to drought events. This situation is to a great extent attributable to agriculture, which is the world's largest water consumer and is often believed to be wasteful (OECD, 2013; Ward and Pulido-Velazquez, 2008). Consequently, policy makers in drought prone areas have called for measures to save water in this sector and thus guarantee the provision of water for priority uses, namely, drinking water and minimum environmental flows. However, the effectiveness of these measures has been burdened so far by the prevailing paradigm, which considers water demand as an exogenous variable outside the field of water policy. As a result, water policy has been mostly based on expensive supply oriented policies, such as the construction of major infrastructures or the modernization of irrigation devices, that paradoxically have ended up increasing water demand, reducing water availability and undermining the robustness and resiliency of the system and its ability to cope with future droughts (Anderies et al., 2004; Ruttan, 2002).

The high financial costs of these policies in a time of crisis and especially the limits of water supply have forced water authorities to alter their policy action. In the EU, some important legal restrictions over agricultural water use have recently been approved to address the problem of recurrent droughts. This is the case of the Drought Management Plans (DMPs). DMPs are inspired in the drought contingency plans implemented in the US since the '80s and thus follow similar rules (NDMC, 2013). Basically, DMPs define the precise thresholds of possible drought situations and set the water constraints that will come into force in each of these cases, with the aim of guaranteeing priority uses. The drought thresholds are obtained from the historical assessment of water supply, while the extent of the water constraints varies from one basin to other and depends largely on the ratio between water demand and water supply, being more restrictive in the more exploited basins and focusing on agricultural uses (the water use with the lowest priority) (EC, 2008). As a result, the declaration of a drought will automatically reduce, in a predictable amount, the quantity of water delivered to the irrigation system from publicly controlled water sources.

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http://dx.doi.org/10.1016/j.wace.2014.02.003

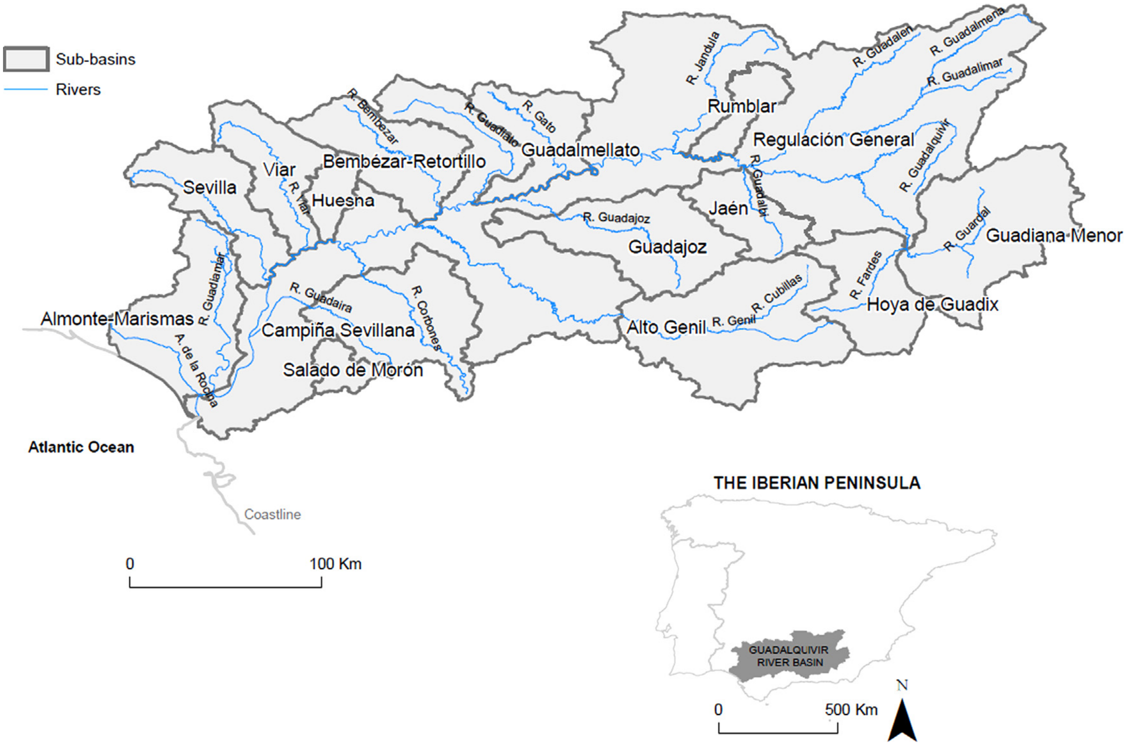

Fig. 1. Location of the Guadalquivir River Basin in the Iberian Peninsula and detail of its sub-basins.

In spite of being relatively new and voluntary, DMPs have rapidly spread across EU southern countries, such as France, Italy, Portugal and Spain[2] (EC, 2008). In particular, Spain has pioneered the adoption of DMPs and every river basin comprising more than two regions (NUTS 2[3]) has already approved its DMP. However, there are no assessments available on the potential impact of DMPs on the economic activities exposed to water restrictions. As a result, the effects of DMPs over water availability in sectors such as agriculture are basically unknown. This paper wants to help bridge this gap. We develop a stochastic methodology to estimate the expected water availability in agriculture resulting from the decision rules of the recently approved DMPs. Then we apply this method to the particular case of the Guadalquivir River Basin (GRB) in Spain, using historical data and official climate change scenarios. Results show that after the implementation of the basin's DMP expected water availability drops to 62.2% of the annual demand, with relevant spatial disparities among sub-basins. According to the previous legislation, River Basin Management Plans (RBMPs) had to guarantee irrigators a water access reliability of 90%. This has happened since the implementation of the first wave of RBMPs in 1998 (Berbel et al., 2012). However, if DMPs are successfully enforced, it will not be possible to guarantee a failure rate below the target of 10% -rather the contrary, this failure rate will be close to 40%.

This paper is structured as follows: in Section 2, we introduce the area where the case study is applied, the Guadalquivir River Basin in southern Spain. Section 3 presents the methodology used to estimate expected water availability in agriculture, and Section 4 presents the results obtained. Section 5 discusses the results and concludes.

2. Background to the case study: the Guadalquivir river basin (Spain)

Because most of the variables involved in the design of the DMPs are site-specific, such as water supply and risk exposure, we illustrate each step of the model with the results for the particular case of the GRB in Southern Spain.

The GRB is a large basin (57,071 km^2) located in the south of Spain (see Fig. 1). 90.2% of its territory is located in the region (NUTS 2) of Andalusia (ES61), with less relevant shares in the regions of Castile-La Mancha (ES42) (7.1%), Extremadura (ES43) (2.5%) and Murcia (ES62) (0.2%)[4]. The GRB has a semi-arid Mediterranean climate, with an average temperature of 16.8 °C, warm summers and mild winters. Rainfall is scarce (548 mm/year in average) and unevenly distributed along time, with peak monthly values between 70 and 80 mm/month from November to February and values below 25 mm/month during the summer (June to September). Due to relatively high temperatures potential evapotranspiration is high, and during the summer months higher than rainfall, resulting in a low runoff with an average value of 128 mm/year (GRBA, 2013).

In spite of water scarcity and recurrent droughts, past economic growth in the GRB has been closely coupled to increases in water demand. As a result, average water demand amounts to 4016 hm^3/year, while renewable resources are estimated to be 3028 hm^3/year,

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[2] Unlike other water management instruments such as River Basin Management Plans, DMPs are not prescriptive, although they are already available in several Southern European basins in Spain, Italy, Portugal and France, and also in Finland, Netherlands and UK.

[3] The NUTS classification (for French *Nomenclature des unités territoriales statistiques*, Nomenclature of territorial units for statistics in English) is a hierarchical system for dividing up the economic territory of the EU. For each EU member country, a hierarchy of three NUTS levels is established, which do not necessarily correspond to administrative divisions within the country. A NUTS code begins with a two-letter code referencing the country, followed by up to three numbers indicating the three possible levels of disaggregation. The three NUTS levels are: NUTS 3, usually working at a local level (parish/canton/oblast/city and regency/county/municipality); NUTS 2, which is a set of NUTS 3 and usually works at a level of region/province/state/prefecture (including: autonomous type); and NUTS 1, working at different levels and defined as a set of NUTS 2 (EC, 2003).

[4] ES61: ESpaña (Spain), NUTS 1 number 6, NUTS 2 number 61; ES42: ESpaña (Spain), NUTS 1 number 4, NUTS 2 number 42; ES 43: ESpaña (Spain), NUTS 1 number 4, NUTS 2 number 43; ES62: ESpaña (Spain), NUTS 1 number 6, NUTS 2 number 62.

resulting in an overexploitation of almost 1000 hm^3/year and a water exploitation index (ratio of total freshwater abstraction over total renewable resources) of 1.22 (GRBA, 2007). More recent estimations set this ratio at 1.64 (EEA, 2009). Consequently, the GRB is regarded as a severely overexploited and drought exposed basin and its recurrent drought events may have particularly harmful effects over the economy (GRBA, 2013). In addition, strong evidence suggests that the existing water supply deficit of the last decades has been effectively covered with non-renewable groundwater resources, thus reducing the resiliency of the system to droughts and worsening the water crisis (GRBA, 2013; WWF, 2006).

Overexploitation is not homogeneously distributed among the 14 sub-basins that constitute the GRB. The Regulación General Sub-basin, which is the largest sub-basin and supplies most of the water in the GRB, is also the most deteriorated system. The remaining sub-basins, including Salado de Morón, Campiña Sevillana, Alto Genil, Hoya de Guadix, Alto Guadiana Menor, Bembézar-Retortillo, Viar, Almonte-Marismas, Jaén, Rumblar, Guadalmellato, Huesna and Sevilla are less overexploited (GRBA, 2013).

Agriculture is the main water user in the GRB and demands 87% of the total water consumption. Given the structural water deficit of the basin, this sector is highly vulnerable to drought events. Agriculture is a traditional activity in the GRB, of relevance in terms of employment and income generation (agriculture represents 5.5% of the Gross Value Added and 7% of the employment in the GRB, as compared to 3.1% and 4% in Spain, respectively) (GRBA, 2013). In order to avoid financial losses in this strategic sector, during droughts water authorities have traditionally prioritized water supply to agriculture over environmental uses (EEA, 2009), thus leading to further overexploitation. Although this goes against the principles of the EU Water Framework Directive (EC, 2000), it has been possible because water restrictions during drought events until a few years ago were based on a crisis-management approach that allowed water authorities to take discretionary (and often unpredictable) decisions. All this has changed after the implementation of the DMPs.

3. Methodology

DMPs quantify the particular situation at hand and the severity of the problem by using an objective and publicly observable drought index. This drought index is an objective monthly value that is estimated at a sub-basin level using a combination of site-relevant hydrogeological variables, which include rainfall, runoff, groundwater stock and/or water stored in reservoirs (BOE, 2001). The drought index value ranges between 0 and 1 depending on the severity of the drought. A value close to 1 denotes a situation of normality, while a value close to 0 denotes an extreme drought event. In the case of Spain, the severity of the drought is divided into four categories: normality, pre-alert, alert and emergency. Each one of these drought thresholds specifies the water restrictions that will come into force for every water use, being particularly severe in the case of agriculture. In the GRB, water restrictions for the whole irrigation campaign are adopted in accordance to the drought index calculated at the beginning of the irrigation campaign in April[5] (GRBA, 2007).

The model presented in this paper estimates the probability density functions (PDFs) of the site-relevant hydrogeological variables. Then it uses these PDFs to obtain the probability of every drought index value in every sub-basin and aggregates these probabilities to obtain the probability of each drought threshold (i.e., the probability of being under normality, pre-alert, alert and emergency). Every drought threshold has a pre-established water restriction associated, and from these water restrictions and their corresponding probabilities the model obtains the expected water availability for irrigated agriculture.

3.1. Probability Density Functions (PDFs)

DMPs use hydrogeological variables to calculate drought indices that assess the drought severity in a sub-basin. Drought indices are made up of one or a combination of the following hydrogeological variables: rainfall, runoff, water stored in reservoirs and the stock of groundwater (see for example the DMPs of SRBA, 2008; GRBA, 2007; JRBA, 2005). There are large data series of these variables (covering from 47 to 67 years) available in official databases (AEMET, 2013; MAGRAMA, 2013a, 2013b). We use these data series to estimate the PDF for all the relevant variables in the GRB's sub-basins. This way we obtain the probability of every possible state of nature. We use a Gamma PDF for the rainfall (Martin et al., 2001), runoff (Gómez and Pérez-Blanco, 2012) and groundwater (Pérez-Blanco and Gómez, 2013) and a Weibull PDF for the water stored in reservoirs (Martínez et al., 2002).

3.1.1. Gamma PDF

The Gamma PDF is defined by a scale parameter (a) and a shape parameter (b) that we estimate by maximum likelihood. The function reaches a maximum for intermediate values, decreases according to its scale parameter and converges to a normal distribution function as the shape parameter increases. The Gamma PDF allows us to assign a probability density p_i ($i=1,\ldots,3$) for the variable y_i ($i=1,\ldots,3$):

$$p_i(y_i) = z(y_i|a,b) = \frac{1}{b^a \Gamma(a)} y_i^{a-1} \exp\left(\frac{-y_i}{b}\right) \tag{1}$$

Where y_1 is rainfall, y_2 the groundwater stock and y_3 the runoff, expressed as the ratio (in %) of the average value of the variable for the last 12 months (in the case of groundwater stock, we consider the last observed value) to the maximum value in the historical data series, and p_1, p_2 and p_3 are their corresponding probability densities. Rainfall is used in the calculation of the drought index in the sub-basins of Campiña Sevillana, Alto Guadiana Menor and Almonte Marismas and the corresponding Gamma PDFs are calibrated with data from AEMET (2013) for the time period 1944–2011. Runoff data is used in the calculation of the drought index in the Viar and Huesna sub-basins and the corresponding Gamma PDFs are calibrated with data from MAGRAMA (2013a) for the time period 1943–2009. Data on groundwater levels is used in the calculation of the drought index in the Alto Genil Sub-basin and the corresponding Gamma PDF is calibrated with data from MAGRAMA (2013b) [6] for the time period 1965–2012.

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[5] The GRB has a ratio of reservoir storage capacity to average annual water use of 2.38 (GRBA, 2013; MAGRAMA, 2013a). Since hydrological droughts lag behind meteorological droughts, DMPs assume that this large storage capacity is enough to prevent further water restrictions along the irrigation campaign, even if the meteorological drought is aggravated (GRBA, 2007). Therefore, water restrictions are not revised until the following campaign, although in the past water authorities have imposed extraordinary measures during particularly severe drought events (nonetheless, these measures are part of a crisis response out of the scope of DMPs and of this work) (BOE, 2005, 2006). In theory, this rigidity also applies if the declaration of a drought is followed by a series of rainy months, until the hydrological drought is overcome. However, in practice, water restrictions may be softened in the latter case.

[6] Drought indices in the Alto Genil, Viar and Huesna sub-basins are obtained from the aggregated data on water stored in one or more reservoirs. However, some of the data series required in these cases were not sufficiently large to adjust robust PDFs. We selected then proxy variables based on the more significant water sources for irrigation (with available large data series) in these sub-basins. Drought thresholds and water restrictions were defined in accordance to the rules of the GRB DMP (GRBA, 2007).

Table 1
Gamma function. The dependent variable is the percentage of rainfall (y_1), groundwater (y_2) or runoff (y_3) over their maximum value in the historical data.
Source: Authors' elaboration from AEMET (2013) and MAGRAMA (2013a, 2013b).

Sub-basin	Variable type	Time period	Coefficient	
			a (Scale)	b (Shape)
Campiña Sevillana	y_1	1944–2011	10.699[a] (0.764)	0.057[a] (0.005)
Alto Guadiana Menor	y_1	1944–2011	11.327[a] (0.755)	0.049[a] (0.004)
Almonte-Marismas	y_1	1944–2011	16.452[a] (1.371)	0.032[a] (0.003)
Alto Genil	y_2	1965–2012	7.719[a] (0.858)	0.062[a] (0.010)
Viar	y_3	1943–2009	1.679[a] (0.316)	0.193[a] (0.025)
Huesna	y_3	1943–2009	1.263[a]	0.324[a]

Estimated by maximum likelihood. Standard errors in parentheses.

[a] Significant at the 1% level.

Table 2
Weibull function. The dependent variable is the percentage of dam-stored water over dam storage capacity (y_4).
Source: Authors' elaboration from MAGRAMA (2013a).

Sub-basin	Time period	Coefficient	
		a (Scale)	b (Shape)
Salado de Morón	1943–2009	0.500[a] (0.036)	1.684[a] (0.153)
Alto Genil	1943–2009	0.597[a] (0.040)	1.683[a] (0.129)
Hoya de Guadix	1943–2009	0.818[a] (0.068)	5.109[a] (0.426)
Alto Guadiana Menor	1943–2009	0.720[a] (0.080)	3.062[a] (0.510)
Bembézar-Retortillo	1943–2009	0.711[a] (0.178)	2.397[a] (0.184)
Jaén	1943–2009	0.549[a] (0.110)	1.698[a] (0.170)
Rumblar	1943–2009	0.743[a] (0.106)	2.538[a] (0.195)
Guadalmellato	1943–2009	0.589[a] (0.059)	1.924[a] (0.275)
Sevilla	1943–2009	0.731[a] (0.061)	2.137[a] (0.194)
Regulación General	1943–2009	0.347[a] (0.035)	1.484[a] (0.212)

Estimated maximum likelihood. Standard errors in parentheses.

[a] Significant at the 1% level.

Table 1 shows the best fit parameters for these variables in their corresponding sub-basins using a Gamma function.

3.1.2. Weibull PDF

The Weibull distribution is a continuous probability distribution with a scale parameter (c) and a shape parameter (d) that we estimate by maximum likelihood. The Weibull PDF assigns a probability density p_i ($i=4$) for the water stored in reservoirs y_i ($i=4$), expressed as a percentage over the maximum value in the historical data:

$$p_4(y_4)=j(y_4|c,d)=\frac{d}{c}\left(\frac{y_4}{c}\right)^{d-1}\exp\left(-\left(\frac{y_4}{c}\right)^{d}\right) \tag{2}$$

The water stored in reservoirs is the most relevant variable in the calculation of the drought index in the GRB's sub-basins. We use it in the calculation of the drought index in the sub-basins of Regulación General, Salado de Morón, Alto Genil, Hoya de Guadix, Alto Guadiana Menor, Bembézar-Retortillo, Jaén, Rumblar, Guadalmellato and Sevilla. Data series from MAGRAMA (2013a) that span the time period 1943–2009 are used to calibrate the corresponding Weibull PDFs.

Table 2 shows the best fit parameters for the water stored in reservoirs in these sub-basins using a Weibull function.

3.2. Drought indices

Now we obtain the probability of every drought index value (I_e) using the PDFs obtained above. For the simplest case in which only one variable is used, the drought index is obtained as follows[7] (GRBA, 2007):

$$I_{e,y_i}=\begin{cases}\left[\frac{y_i-y_{imin}}{2(y_{iav}-y_{imin})}\right] & , \quad \text{if } y_i<y_{iav}\\ \frac{1}{2}\left[1+\frac{y_i-y_{iav}}{1-y_{iav}}\right] & , \quad \text{if } y_i\geq y_{iav}\end{cases} \tag{3}$$

Where y_i is the variable's observed value in the month of reference (April in the GRB) and y_{iav} and y_{imin} are the average and minimum values in the historical data series of that variable, respectively (all of them as a percentage over their maximum value in the historical data). The corresponding probability of this drought index would be thus p_i ($i=1,\ldots,4$).

In the case where the drought index is made up of a combination of hydrological variables (combined drought index), it is obtained as follows:

$$I_e=\sum_{i=1}^{4} b_i * I_{e,y_i} \tag{4}$$

where b_i is a weighting coefficient predetermined by the river basin authority that ranges from 0 (the variable is not relevant in the calculation of the index) to 1 (the same situation as in (3)), with $\sum_{i=1}^{4} b_i=1$. The probability of the combined drought index (q_{I_e}) is

$$q_{I_e}=\prod_{i=1}^{4} h(y_i) \tag{5}$$

where:

$$h(y_i)=\begin{cases}1 & , \quad \text{if } b_i=0\\ p_i(y_i) & , \quad \text{if } b_i>0\end{cases} \tag{6}$$

3.3. Drought thresholds and expected water availability

We finally aggregate the probabilities of all the feasible index values into the four drought stages (normality; pre-alert; alert; and emergency) to obtain the aggregated probability of every drought stage. First we define a set of dummy variables that are used to signal the drought severity (normality, n_{I_e}; pre-alert, z_{I_e}; alert, a_{I_e}; and emergency, e_{I_e}):

$$n_{I_e}=\begin{cases}1 & , \quad \text{if } I_e>I_{e,z}\\ 0 & , \quad \text{if } I_e\leq I_{e,z}\end{cases} \tag{7}$$

$$z_{I_e}=\begin{cases}1 & , \quad \text{if } I_{e,a}<I_e\leq I_{e,z}\\ 0 & , \quad \text{otherwise}\end{cases} \tag{8}$$

$$a_{I_e}=\begin{cases}1 & , \quad \text{if } I_{e,e}<I_e\leq I_{e,a}\\ 0 & , \quad \text{otherwise}\end{cases} \tag{9}$$

$$e_{I_e}=\begin{cases}1 & , \quad \text{if } I_e\leq I_{e,e}\\ 0 & , \quad \text{if } I_e>I_{e,e}\end{cases} \tag{10}$$

where $I_{e,z}$, $I_{e,a}$ and $I_{e,e}$ are the pre-alert, alert and emergency thresholds, respectively, which in the case of the GRB adopt a value of 0.5, 0.3 and 0.15, respectively (GRBA, 2007).

Next we obtain the probability of every drought stage k ($q_{I_e,k}$) in the sub-basins of the GRB. For example, the probability for the

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[7] Drought indices are obtained in the same way in all the Spanish basins.

stage of *normality* ($q_{I_e,n}$) is obtained as follows:

$$q_{I_e,n} = \int_{y_1=0}^{max_{y_1}} \int_{y_2=0}^{max_{y_2}} \int_{y_3=0}^{max_{y_3}} \int_{y_4=0}^{max_{y_4}} (n_{I_e} * \prod_{i=1}^{4} h(y_i)\, dy_i) \tag{11}$$

where max_{y_i} is the value of the variable y_i that makes the cumulative density function equal to 1 (i.e., the probability of having a value above this limit is zero[8]). $\prod_{i=1}^{4} h(y_i)$ is defined in (6).

Similarly, the probability for the stages of *pre-alert* ($q_{I_e,z}$), *alert* ($q_{I_e,a}$) and *emergency* ($q_{I_e,e}$) is obtained as follows:

$$q_{I_e,z} = \int_{y_1=0}^{max_{y_1}} \int_{y_1=2}^{max_{y_2}} \int_{y_3=0}^{max_{y_3}} \int_{y_4=0}^{max_{y_4}} (z_{I_e} * \prod_{i=1}^{4} h(y_i)\, dy_i) \tag{12}$$

$$q_{I_e,a} = \int_{y_1=0}^{max_{y_1}} \int_{y_2=0}^{max_{y_2}} \int_{y_3=0}^{max_{y_3}} \int_{y_4=0}^{max_{y_4}} (a_{I_e} * \prod_{i=1}^{4} h(y_i)\, dy_i) \tag{13}$$

$$q_{I_e,e} = \int_{y_1=0}^{max_{y_1}} \int_{y_2=0}^{max_{y_2}} \int_{y_3=0}^{max_{y_3}} \int_{max_{y_4}}^{max_{y_4}} (e_{I_e} * \prod_{i=1}^{4} h(y_i)\, dy_i) \tag{14}$$

Finally we use the water availability specified in the DMP for every drought stage k ($R_{I_e,k}$) to estimate the expected water availability in agriculture ($EWirr$). In the GRB the DMP establishes the following four drought thresholds and their corresponding water availability (GRBA, 2007): (i) when water levels are regarded as normal ($I_e > I_{e,z}$), there are no restrictions ($R_{I_e,n} = 1$); (ii) water availability for irrigation is reduced by 5% ($R_{I_e,z} = 0.95$) when available water falls below the prealert threshold ($I_{e,a} < I_e \le I_{e,z}$); (iii) if the alert limits are exceeded ($I_{e,e} < I_e \le I_{e,a}$), water availability for irrigation is reduced by 30% ($R_{I_e,a} = 0.7$); and (iv) in emergency situations ($I_e \le I_{e,e}$), water availability for irrigation is reduced by 70% ($R_{I_e,e} = 0.3$). $EWirr$ is obtained for every sub-basin in the GRB as follows:

$$EWirr = \sum_k q_{I_e,k} * R_{I_e,k} \tag{15}$$

3.4. Climate change scenarios

So far we are assuming that the dynamics of the renewable water resources are stable and endogenous. However, there is evidence that renewable water resources worldwide (OECD, 2013) and also in Spanish basins (MAGRAMA, 2013b, 2011) have been decreasing during the last years. Climate change is regarded as the main cause and consequently has become a matter of concern, especially in overexploited and drought exposed southern basins such as the GRB (GRBA, 2013, 2007). Accordingly, national and regional authorities have commissioned several reports on the effects of climate change over water supply in the GRB.

The most extensive and up to date assessment on the availability of water resources under different climatic scenarios is that of MAGRAMA (2011). This report develops water availability scenarios at a river basin level based on the climate change scenario families A2 and B2 designed by the Intergovernmental Panel on Climate Change (IPCC, 2007). The simulations by MAGRAMA (2011) load temperature and rainfall forecasts by IPCC (2007) into the SIMPA hydrogeological model[9] in order to estimate water availability in different water sources for the time periods 2011–2040, 2041–2070 and 2071–2100, and then compare the results to the average water availability in the control period 1961–1990.

Instead of using all the possible water availability scenarios in MAGRAMA (2011), this paper summarizes the information in the report in *synthetic indices* that are obtained as the average of the alternative water availability scenarios for every water source and time period in the GRB. Then we use these *synthetic indices* to adjust the historical data series of the hydrogeological variables used to obtain the drought indices, and we repeat the methodology above (Sections 3.1–3.3) to assess the impact of climate change on water availability in agriculture in the medium-long term considering climate change. The three time periods considered (2011–2040, 2041–2070 and 2071–2100) show a decrease in water supply in every water source as compared to the control period 1961–1990. Rainfall decreases 7.5% in the time period 2011–2040, 12.5% in 2041–2070 and 19% in 2071–2100 (MAGRAMA, 2011, p. 116), runoff decreases 12%, 20% and 33.5% (MAGRAMA, 2011, p. 192), respectively, and groundwater decreases 14%, 21.5% and 33.5%, respectively (MAGRAMA, 2011, p. 168). There is no information regarding the impact of climate change on water availability in reservoirs, which is assumed to evolve in the same way as runoff.

4. Results

4.1. Baseline scenario

According to our model, after the implementation of the DMP in the GRB a drought is declared almost one in two years and the probability of suffering an extreme drought (with water restrictions for agriculture of 70%) is approximately 14%. Consequently, the implementation of the DMP results in an expected water availability for agriculture ($EWirr$) of 62.2%[10] of the water allotment in a normal hydrological year without drought (much lower than the 90% specified in the previous legislation).

Expected water availability varies significantly among sub-basins. Regulación General is the largest sub-basin in the GRB and represents 66% of agricultural water demand, and it is also the most affected sub-basin by the water restrictions specified in the DMP, with an expected water availability of 51%. The Jaén Sub-basin (3.3% of the agricultural water demand) also has a low expected water availability of 67%. On the other hand, the sub-basins of Campiña Sevillana, Alto Genil, Hoya de Guadix, Alto Guadiana, Bembézar-Retortillo, Viar, Almonte Marismas and Sevilla, which together represent 26.8% of the agricultural water demand in the GRB, have an expected water availability over 80%. The remaining sub-basins show similar results, with expected water availability values above 75%, although most of these sub-basins are located upstream and have a marginal relevance for irrigation (3.8% of the agricultural water demand) (GRBA, 2013) (Fig. 2).

4.2. Climate change scenarios

In this section we use climate projections to assess possible future reductions in renewable water resources (see Section 3.4). Our results show that expected water availability for agriculture in the GRB is reduced in average by 4.5% in 2012–2040 ($EWirr = 57.7\%$), by 7.7% in 2041–2070 ($EWirr = 54.5\%$) and by 13% in 2071–2100 ($EWirr = 49.2\%$) as compared to the values in the simulation with no climate change (Section 4.1).

As before, there are relevant differences among sub-basins. In the Regulación General Sub-Basin the expected water availability

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[8] If we adjust a PDF to y_i in a given sub-basin, max_{y_i} is the value at the end of the tail of the PDF, i.e., the value above which the probability of y_i is zero.

[9] The SIMPA model (*Sistema Integrado de Simulación Precipitación Aportación*) estimates real evapotranspiration, soil humidity, runoff and groundwater recharge at a spatial detail of 1 km^2 on a monthly basis (Ministry of Public Works, 2013).

[10] This value is obtained as the weighted average of the expected water availability for agriculture in every sub-basin. Weights are assigned in accordance to the share of agricultural water demand in every sub-basin (see Table 3).

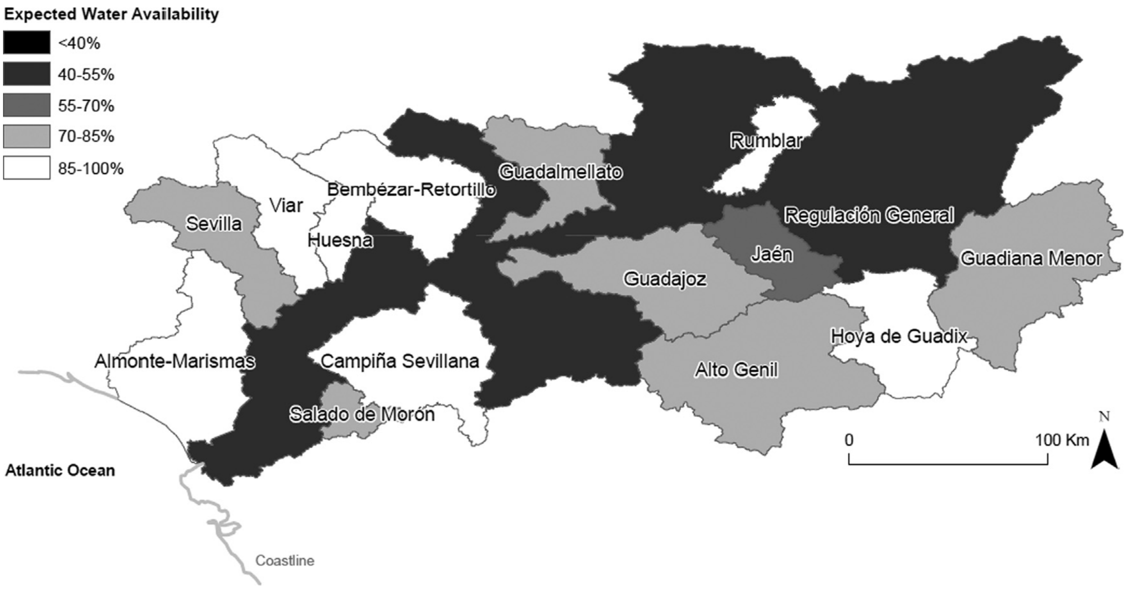

Fig. 2. Expected water availability for agriculture (*EWirr*), GRB. Baseline scenario.

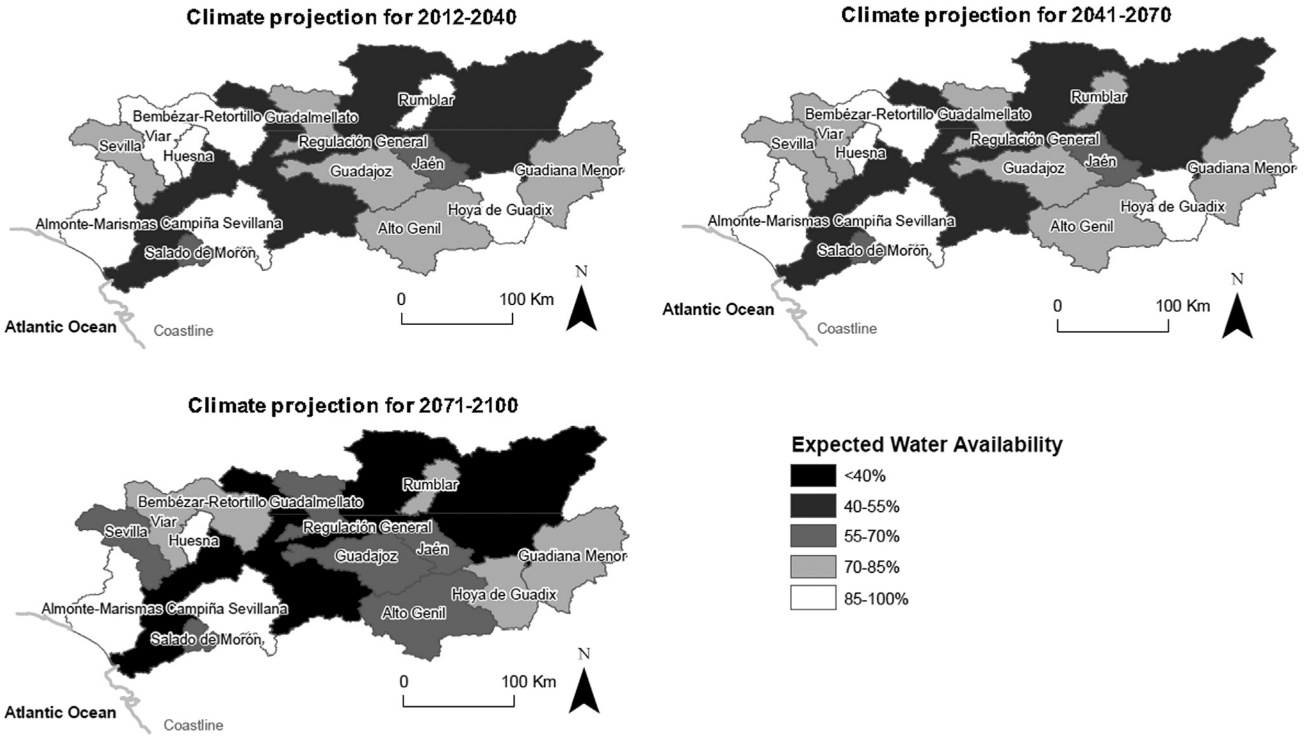

Fig. 3. Expected water availability for agriculture (*EWirr*), GRB. Climate change scenarios 2012–2040, 2041–2070 and 2071–2100.

for agriculture is reduced by 12.7% throughout the century, from 51% to 38.3%, revealing a scenario in which a large share of the irrigated land in the GRB would be unsustainable. Expected water availability in the Alto Genil Sub-Basin, which supplies 9% of the agricultural water demand, is reduced by 17.1% in the period 2011–2100, from 84% to 66%. Also the Alto Guadiana (from 84.1% to 69.8%), Guadalmellato (from 78.3% to 67.2%) and Sevilla (from 80.1% to 61.5%) sub-basins show expected water availability values for agriculture below 70% in the end of the century. Finally the Salado de Morón (from 74.5% to 58.4%) and Jaén (from 67.1% to 55.7%) sub-basins show expected water availability values for agriculture below 60% in 2100. These results are displayed in Fig. 3. All the results of the baseline and climate change scenarios simulations are displayed jointly in Table 3.

5. Discussion and conclusions

In this paper we develop a model to assess the impact of Drought Management Plans (DMPs) on water availability for agriculture. The methodology aims to be general and implementable in any basin with a DMP in force. We apply this methodology to the particular case of the overexploited Guadalquivir River Basin (GRB) in Spain. Results show that, provided that the DMP is

Table 3
Agricultural water demand and expected water availability for agriculture (*EWirr*) in the GRB, all scenarios.
Source: Authors' elaboration. Agricultural water demand was obtained from GRBA (2013).

Sub-basin	Agricultural water demand (%)	*EWirr*			
		Baseline (%)	2011–2040 (%)	2041–2070 (%)	2071–2100 (%)
Salado de Morón	0.5	74.5	66.6	65.3	58.4
Campiña Sevillana	2.3	97.5	93.2	91.3	89.7
Alto Genil	9.0	83.9	76.8	73.1	66.7
Hoya de Guadix	1.7	96.0	94.9	91.1	84.9
Alto Guadiana Menor	4.0	84.1	80.8	75.6	69.8
Bembézar-Retortillo	4.2	90.8	90.1	87.3	83.4
Viar	1.5	92.2	86.4	83.0	78.3
Almonte-Marismas	0.0	97.3	93.3	92.0	90.6
Jaén	3.3	67.1	66.7	64.0	55.7
Rumblar	0.2	88.0	85.0	81.1	73.1
Guadalmellato	2.8	78.3	77.7	74.5	67.2
Huesna	0.3	95.8	93.1	92.4	87.3
Sevilla	4.1	80.1	73.0	70.7	61.5
Regulación General	66.0	51.0	46.2	43.2	38.3
Guadalquivir River Basin	100.0	62.2	57.7	54.5	49.2

effectively enforced, the effects over water availability in agriculture are significant. Water availability is reduced in average to 62.5% of the water demand, a much lower figure than the water availability of 90% that the previous legislation aimed to guarantee. In some areas, the impact may be even larger. For example, expected water availability is halved in the Regulación General Sub-basin, which comprises most of the irrigated lands in the GRB. If we introduce climate change simulations in our model, water restrictions become more intense and frequent.

In basins suffering a severe water deficit, such as the GRB, water restrictions are tighter and thus have more impact on non-priority uses such as agriculture. Climate change is expected to further reduce water availability and increase the gap between water supply and demand. Therefore, complementary policies aimed towards reducing and adapting agricultural water demand to existing water supply are needed. This policy mix would have the potential to improve the environmental status of water bodies and make agriculture a sustainable activity in the medium-long run. However, unlike the US contingency plans, EU DMPs do not include the use of complementary policies to curb water demand, such as voluntary agreements, water markets or water pricing. As a result, water demand in the GRB is expected to remain in similar levels (GRBA, 2013), although expected water availability will be reduced throughout the century (OECD, 2013; MAGRAMA, 2011).

It is also important to consider that in this model we have assumed a perfect enforcement of DMPs. However, experience shows that moral hazard abounds in water use. Water demand may remain higher than water supply during droughts even if we control for minimum environmental flows, at the expense of loosely controlled groundwater bodies. This has already happened in other Mediterranean basins such as the Segura River Basin in Spain (Gómez and Pérez-Blanco, 2012) and the Murray Darling Basin in Australia (Crase, 2012). The substitution of the publicly allotted water by illegal groundwater abstractions may create environmental as well as inequality concerns, as those who have no access to groundwater would be the ones actually facing the consequences of water restrictions.

In order to avoid a sudden and disproportionate impact of droughts on agriculture and at the same time guarantee water demand for priority uses, water policy needs to balance water supply and demand. Without complementary policies, DMPs may regulate water availability but not agents' incentives to use water. Water demand needs to be addressed as well.

Therefore, DMPs should not be regarded as a panacea, but rather as a part of an institutional change towards a sustainable water management. A comprehensive policy mix can find the way to make the reduction of water scarcity and drought exposure compatible with the maintenance of a sustainable agricultural sector. DMPs are a first step and an opportunity, but the transition towards a sustainable water use relies on building better institutions and putting the effective incentives in place in order to keep water demand under control.

Acknowledgments

The research leading to these results has received funding from the EU Seventh Framework Program (FP7/2007–2013) under Grant agreements n° 265213 (EPI-WATER – Evaluating Economic Policy Instruments for Sustainable Water Management in Europe) and n° 308438 (ENHANCE – Enhancing risk management partnerships for catastrophic natural disasters in Europe). The authors also acknowledge the support of the Spanish Association of Agrarian Insuring Firms (Agroseguro S.A.). We would like to thank two anonymous referees for their interest in our paper and for the comments, which allowed us to improve the original version of the manuscript.

References

AEMET, 2013. AEMET Climatological Series (Password Required) [WWW Document]. Agencia Española de Meteorología – Database. URL ⟨http://ftpdatos.aemet.es/series_climatologicas/⟩ (accessed 20.10.13).

Anderies, J., Janssen, M., Ostrom, E., 2004. Framework to analyze the robustness of social-ecological systems from an institutional perspective. Presented at the The Commons in an Age of Global Transition: Challenges, Risks and Opportunities, the Tenth Biennial Conference of the International Association for the Study of Common Property, Oaxaca, Mexico.

Berbel, J., Kolberg, S., Martin-Ortega, J., 2012. Assessment of the draft hydrological basin plan of the Guadalquivir River Basin (Spain). Int. J. Water Resour. Dev. 28, 43–55.

BOE, 2001. Ley 10/2001, de 5 de julio, del Plan Hidrológico Nacional, Law.

BOE, 2005. Real Decreto-Ley 15/2005, de 16 de diciembre, de medidas urgentes para la regulación de las transacciones de derechos al aprovechamiento de agua (Vigente hasta el 30 de Noviembre de 2009), Royal Decree.

BOE, 2006. Real Decreto-Ley 9/2006, de 15 de septiembre, por el que se adoptan medidas urgentes para paliar los efectos producidos por la sequía en las poblaciones y en las explotaciones agrarias de regadío en determinadas cuencas hidrográficas, Royal Decree.

Crase, L., 2012. Water markets, property rights and managing environmental water reserves. In: Water Policy Reform. Edward Elgar Publishing, Cheltenham, pp. 37–48.

EC, 2000. Water Framework Directive 2000/60/EC, Council Directive.

EC, 2003. Regulation No 1059/2003, Regulation.

EC, 2008. Drought Management Plan Report (Report no. 23). European Commission, Brussels (Belgium).

EEA, 2009. Water Resources Across Europe – confronting Water Scarcity and Drought (Report No. 2/2009). European Environment Agency, Copenhagen, Denmark.

Gómez, C.M., Pérez-Blanco, C.D., 2012. Do drought management plans reduce drought risk? A risk assessment model for a Mediterranean river basin. Ecol. Econ. 76, 42–48.

GRBA, 2007. Plan de Actuación en Situaciones de Alerta y Eventual Sequía de la Cuenca del Guadalquivir (Report). Guadalquivir River Basin Authority.

GRBA, 2013. Plan Hidrológico de la Demarcación Hidrográfica del Guadalquivir (River Basin Management Plan). Guadalquivir River Basin Authority.

IPCC, 2007. IPCC Fourth Assessment Report (AR4). Intergovernmental Panel on Climate Change, Geneva, Switzerland.

JRBA, 2005. Protocolo de actuación en situación de alerta y eventual sequía (Report). Júcar River Basin Authority, Valencia.

MAGRAMA, 2011. Evaluación del impacto del cambio climático en los recursos hídricos en régimen natural (Report). Ministerio de Agricultura, Alimentación y Medio Ambiente.

MAGRAMA, 2013a. Anuario de Aforos [WWW Document]. Anuario de Aforos del Ministerio de Agricultura, Alimentación y Medio Ambiente. URL ⟨http://hercules.cedex.es/anuarioaforos/default.asp⟩ (accessed 20.10.13).

MAGRAMA, 2013b. Sistema de Información del Agua (SIA) [WWW Document]. Ministerio de Agricultura, Alimentación y Medio Ambiente. URL ⟨http://servicios2.MAGRAMA.es/sia/visualizacion/lda/recursos/superficiales_escorrentia.jsp⟩.

Martin, S.W., Barnett, B.J., Coble, K.H., 2001. Developing and pricing precipitation insurance. J. Agric. Resour. Econ. 26, 261–274.

Martínez, E.I., Garrido, A., Gómez-Ramos, A., 2002. Evaluación de la garantía de suministro de agua a la agricultura. Una aplicación a la cuenca del Guadalquivir. Ingeniería del agua. vol. 9, pp. 279–294.

Ministry of Public Works, 2013. Sistema Integrado para la Modelación del proceso Precipitación Aportación (SIMPA) [WWW Document]. URL ⟨http://hercules.cedex.es/hidrologia/pub/proyectos/simpa.htm⟩ (accessed 20.10.13).

NDMC, 2013. Directory of Drought and Management Plans [WWW Document]. National Drought Mitigation Centre. URL ⟨http://drought.unl.edu/Planning/PlanningInfobyState/DroughtandManagementPlans.aspx⟩ (accessed 30.09.13).

OECD, 2013. Water Security for Better Lives (Report), OECD Studies on Water. Organisation for Economic Co-operation and Development, Paris, France.

Pérez-Blanco, C.D., Gómez, C.M., 2013. Designing optimum insurance schemes to reduce water overexploitation during drought events: a case study of La Campiña, Guadalquivir River Basin, Spain. J. Environ. Econ. Policy 2, 1–15.

Ruttan, V.W., 2002. Productivity growth in world agriculture: sources and constraints. J. Econ. Perspect. 16, 161–184.

SRBA, 2008. Plan de Actuación en Situaciones de Alerta y Eventual Sequía de la Cuenca del Segura (Report). Segura River Basin Authority.

Ward, F.A., Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. Proc. Natl. Acad. Sci. 105, 18215–18220.

WWF, 2006. Illegal Water Use in Spain. WWF, Madrid. Spain (Causes Effects and Solutions (Report))