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AN ECONOMIC DROUGHT MANAGEMENT INDEX TO EVALUATE WATER INSTITUTIONS' PERFORMANCE UNDER UNCERTAINTY AND CLIMATE CHANGE[1]

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Abstract

This paper proposes a new Economic Drought Management Index (EDMI) that could assist water managers to inter-temporally manage water reservoirs. The index's main appeal is that it can be easily interpreted and that encompasses in a single number hydrological processes, structural constraints, water institutions' rules and the economic benefits of the customers served from the supply system. An empirical application of EDMIs is performed for two irrigation districts in Andalusia (Southern Spain), that are managed under different institutional arrangements. EDMIs are then re-evaluated and estimated for various scenarios of climate change, and for a 8-year real period, which includes three consecutive drought years. Results show that the region's vulnerability to drought could be reduced following the interpretation of the EDMIs. EDMIs under climate change scenarios suggest that the water stocks management criteria should be vastly reformed. Lastly, EDMIs evaluated for the actual period of 1990-98 indicated that the severe drought suffered by the region could have been partially avoided, or at least delayed, if water managers had followed the recommendations that are warranted by the EDMIs evaluated for those years.

Keywords: Water Resources, Irrigation, Stocks management, Climate Change

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1. Introduction

Virtually all world water supply systems experience occasional difficulties to meet their demands (Tate *et al.,* 1999; Wilhite, 1993). Water works are built to secure water supply to different users, expanding the resource base and reducing the variability caused by unstable climatic patterns. Hydrological droughts occur when supply systems fail to meet their demands and originate from persistent periods of abnormally low precipitation. Most river basins' water works are operated by single agencies that take decisions regarding the operation of dams and storage facilities, that have large economic impacts on the economy. Generally, water supply systems assume tolerable levels of risk of not being able to service all its customers (Owen *et al.,* 1997). However, in view of the number of people and thousands of farmers that suffer water shortages – not to mention the damage of wildlife and riverine ecosystems--, the fundamental question to address is whether water shortages could have been avoided, or at least mitigated, and at what costs. Not a single answer exists for such a question. Institutionalists (Bakker *et al.*,1998; Kenney, 1995; O´Riordian and A.Jordan, 1999; Ostrom, 1990); economists (Beare *et al.,* 1998; Howe and Smith, 1994); modellers (Dudley and Hearn, 1993; Garrido and Gómez-Ramos, 2000); geographers (Emel and Roberts, 1995), engineers (Harding *et al.*, 1995); sociologists (Keenan and Krannich, 1997); and statisticians (Tarboton, 1995; Hobbs, 1997), among others, contribute with alternative and non-exclusive explanations of why societies experience periods of water shortages. Several authors argue that attenuated property rights over State-managed water bodies are conducive to dominant non-cooperative strategies pursued by rights-holders in their game with water managers to secure water access in uncertain hydrological conditions (Lise *et al.*, 2000). Others have looked at users' incentives to deviate from statute rules resulting from poor law enforcement, that leads to insufficient governance capacity to implement risk-reducing strategies (Ray and Willians, 1999;del Moral, 1998; Riesco 1998). Giansante *et al.*, (2000) point to the divergence between individual groups' and collective's interests, and the political pressure exerted by strong stakeholders to show evidence of institutional failure in reducing social vulnerability to droughts. Some other reasons are based on economic disincentives on right-holders to reduce water use as a result of the priority allocation mechanisms that are present in most Mediterranean countries (Iglesias *et al.*, 2000).

In view of the abundant evidence pointing out to poor institutional performance, several authors have proposed alternative institutional arrangements to improve the efficiency of water stocks management. Holistic approaches, such as the one proposed by Dudley et al. (1998) , attempt to comprise in a model environmental and commercial values to guide water allocation in highly variable hydrological systems. The introduction of the concept of 'capacity sharing' is an example that allows different users acquire a portfolio of guarantee-graded rights accordingly with their tolerable level of risk (Dudley, 1992;Alaouze, 1991; Easterling, 1993), although to date no real application of it has been documented in the literature. Venema et al. (1997) showed that alternative and viable management criteria would reduce the impacts of low run-off in the Senegal river, suggesting an agricultural development policy which is based on the optimisation of the storage capacity and the statistical properties of the river's flow. Contingency plans to reduce drought's vulnerability have been developed and applied by numerous urban suppliers. However, none of them use economic drought indices that translate the supply and demand forecasts into costs and benefits. Griffin and Mjelde (2000) argued that "[water managers] are not judged by their ability to deliver water that has value in excess of its costs, [...] but simply by their ability to deliver a dependable, steady, and problem-free water supply" (p.414). Their paper provides valuations of consumers' preferences for different water supply reliability values, adding to previous evaluations reported by Howe *et al.* (1994). Surprisingly, analogous efforts to obtain commercial users' willingness to pay for various supply reliability levels have not been found in the literature. Hurd *et al.* (1999) have simulated the impacts of climate change on a few major US river basins under alternative institutional scenarios. They concluded that, unless significant institutional changes are introduced in the way resources are allocated among competing users, the environment will suffer most of the costs of global warming.

Water markets have been proposed by many authors to increase water use efficiency (Easter *et al*, 1998). While there is ample evidence that markets promote efficient allocation among consumptive users within periods, no evidence has been found to support the contention that water markets reduce society's vulnerability to drought (for instance, although Chile is at the forefront of water decentralisation, Santiago experienced in 1998 daily power cuts resulting from a drought). Recent work by Rosegrant et al. (2000) provides evidence of intra-season gains from trade in the Chilean Maipo basin under several scenarios of water availability. In a similar vein, Murphy et al. (2000) provide experimental evidence of quasi-efficient "smart" market outcomes with alternative double-auction systems to allocate scarce water. But their subjects' rights for each trading period are set proportional to the available supply – which in all their experimental treatments follow exactly the same pattern of three high, two medium, three low and two medium supply periods. None of these papers investigate why right holders face periods of high or low water availability. Even under liberalised allocation systems and prior to the initialisation of trading, a public agency must decide how much water should be given in the form of tradable entitlements to the individual rights holders. Hence, irrespective of whether or not water rights are tradable, gaining insight into public agencies' performance and efficiency measurements should be at least as important as designing market systems.

This paper attempts to contribute to the literature both in the methodological and the empirical strands. First, it proposes a new and simple index that conveys information about the economic efficiency of the decision rules followed by water managers to inter-temporally manage water stocks. We call this index Economic Drought Management Index (EDMI, hereafter), and claim its validity to be jointly used with engineering and hydrological indices to support water stock management criteria. EDMI's main appeal is that it combines in an easily interpretable index four key pieces of information: (1) the structural constraints of a supply system based on reservoir(s); (2) the stochastic nature of natural run-offs flowing into the storage facilities; (3) the institutional rules that have been followed by water managers, as deduced from the historical records; and (4) the economics benefits accruable on the consumptive users. EDMIs can assist water managers conveying them information about the economic risks associated with their strategies and the costs of reducing them. The paper's empirical dimension shows how the EDMIs can be estimated and interpreted for current hydrological conditions and under various climate change scenarios, taking the Guadalquivir River Basin (South Spain) as the area of study. We also show how EDMIs evaluated to the specific conditions that prevailed in the 1990-97 period may improve our understanding of the origin and inception of severe drought situations, such as 1993-95 severe drought episode. While the scope of the paper is limited to agricultural water uses, it could easily be expanded to incorporate any other type of commercial uses as well as any environmental indicator related to the magnitude of the water stocks. By focusing in just one category of uses, we reflect the notion of use priorities enshrined in the Spanish Water Code and look strictly at farmers' water rights, assuming that both environmental uses and higher rank users always enjoy preferential access to the available resources.

In the paper's second section, we define the concept of EDMI and discuss how different values of EDMIs should be interpreted. In section three, we briefly describe the area of study and the institutions involved in water management. Section four describes the empirical steps required to evaluate the EDMIs and apply them to two institutionally different situations encountered in the Guadalquivir river basin. In the fifth section we report the results and offer several interpretations that hinge on institutional issues and suggest alternative strategies to increase water use efficiency. Section five covers two further applications of EDMIs: in the first, we modify the indices to account for various climate change scenarios and examine the performance of current management rules under more severe hydrological regimes; in the second, EDMIs are evaluated for the 1990-1997 period and suggest strategies based on these indices that would have reduced the economic impacts suffered during the 1992-95 drought. The last and sixth section summarises the paper's main conclusions and suggests further lines of work that may improve the understanding of droughts.

2. EDMI's definition

Let's begin with the most simple case of a reservoir of a given capacity, which receives annual inflows generated by the catchment's run-off. At the beginning of the year, users are informed on the amount of water they can count on to plan their cropping patterns and take planting decisions. Denote W_t as the per hectare water allotments that farmers will be announced in that specific date. The value of W_t is claimed to depend on the known level of water stock before the season starts, denoted by S_t, such that,

$$[1] \qquad W_t = f\,(S_t,\ \theta)$$

with $f' > 0$; $W_t = 0$ for $S_t < S^{min}$ and $W_t = W^R$ for $S_t > S^{max}$.

Where S^{min} is minimum stock level, below which no consumptive uses can be supplied; W^R is the per hectare maximum allotment given to irrigators, and S^{max} is the stock level above which maximum allotments are always granted; θ represents a set of parameters that are specific to the irrigation district and the supply system. We take up below the discussion of what form of institutional arrangement could fit with the management criterium modelled by equation 1. For the moment, it suffices to say that function $f(.)$ conveys an idea of how W_t

varies with S_t, but later on we will analyse its properties and what interpretations can be made from its second-order curvature.

2.1. The economic value of the water sitting in the reservoirs

Irrigators convert their individual water allotments into marketable products following a profit-maximizing behaviour. Consider an irrigator k ($k=1,...,K$), whose production possibilities are dependent on the amount of water available for irrigation, so that:

$$[2] \qquad \pi_{kt} = \pi_k^*(W_t, \phi_k)$$

where $\pi_k^*(.)$ is the per hectare profit function, W_t is the per hectare allotment and ϕ_k is a vector of parameters with influence in the irrigator's economic returns. Associated to each W_t there is shadow value of water, denoted by λ_{kt} such that:

$$[3] \qquad \lambda_{kt}=\partial\pi_k^*(W_t, \phi_k)/\partial W= \lambda_k^*(W_t, \phi_k), \quad \text{with} \quad \partial\lambda_k^*(W_t, \phi_k)/\partial W\leq 0$$

Combining [1] and [2], irrigator's profits can be expressed by:

$$[4] \qquad \pi_{kt} = \pi_k^*(f(S_t, \theta),\phi_k))$$

The function of the shadow value can also be made dependent on the stock level:

$$[5] \qquad \lambda_{kt}= \lambda_k^*(f(S_t, \theta),\phi_k))$$

According to [4] and [5], the irrigators' profits and shadow value of water depend on the known stock of water at the beginning of the season. However, both functions can be postulated based on the assumption that the function $f(S_t, \phi_k)$ exists, is estimable and exhibits certain curvature properties, among which the most important is that it is monotonically increasing. Otherwise, equation [4] may exhibit multiple maxima for the range of relevant S_t values.

Define λ_t as the weighed average of shadow price of the heterogeneous set of K irrigators who are served from the reservoir. Its value is defined as follows:

$$[6] \qquad \lambda_t = \Sigma_k \beta_k \lambda_k^*(f(S_t, \theta), \phi_k)) \qquad k=1,\ldots, K$$

where β_k is the weighting coefficient of irrigator k. Thus, λ_t is a measurement of the average shadow value of water assigned to the set of irrigators, referred to the water stock level at the beginning of the season. It is convenient to assimilate equation 6 to a correspondence of stock levels, S_t, into water's shadow values, λ_t, such that:

$$[8] \qquad \lambda_t = \Gamma(S_t)$$

which implies that for any stock level, managed accordingly with [1], there is a unique average shadow value of water allocated to the irrigators. Although we assume that correspondence [8] does not change from season to season, there are several reasons to believe that irrigators' shadow values may not be stable. We make this limiting assumption to ease the presentation, but relax it in the empirical application.

2.2. Definition of the *E*conomic *D*rought *M*anagement *I*ndex (EDMI)

Prior to the beginning of the irrigation season, the reservoir manager is in charge of fixing the irrigators' allotments based on the water stock level. Let S_t^i any given and known stock level at the beginning of a given season, and S^j_{t+1} any possible state of the stock at the beginning of the next season. We define the Economic Drought Management Index (EDMI) for stock level S_t^i, as the following ratio:

$$EDMI(S_t^i) = \frac{\Gamma(S_t^i)}{\sum_{j=1}^{n}(p^{ij}\Gamma(S_{t+1}{}^j))} \qquad [9]$$

where n represents the number of possible stock states, and p^{ij} is the conditional probability of reaching stock j, denoted by S^j_{t+1}, originating from a stock of S^i_t. While $EDMI(S^i_t)$ can take any positive value, below we show that a meaningful comparison reference is 1.

According to [9], EDMI's numerator represents the actual shadow value of the water stock S_t^i at the beginning of season t. Since irrigators' allotments are assumed to depend on the stock level by [1], what $\Gamma(S_t^i)$ denotes is the shadow price of water allotments granted from S_t^i accordingly with equation [1]. EDMI's denominator represents the expected shadow value of the water stock at the beginning of season $t+1$. The interpretation of the denominator is as follows. By the time season t starts reservoir is at level S_t^i, part of which will be released to provide farmers' allotments following equation [1]. Then the rainy period will come with new run-offs bringing the reservoir to a new state level, denoted by S^j_{t+1}, with probability p^{ij}. Note that the new state level, S^j_{t+1}, results from two opposing effects: one is how much of S_t^i is used to set irrigators' allotments, and the other is the stock levels restoration produced by reservoir inflows. Hence, condition probability, p^{ij}, depends on (1) the inflows' regime, (2) the reservoir's balance equation – including flood prevention release rules, and (3) the behavioural function $f(.)$. The application of correspondence [8] on such final stock states yields different shadow values, from which we compute its expected value using the p^{ij} conditional probabilities.

Defined as such, EDMI features four properties that makes it appealing for water managers. First, it is unique for any stock value and conveys clear information on the economic costs of reducing vulnerability to drought. Second, it coalesces into a single and adimensional number information pertaining to reservoir run-offs, irrigators' benefits, water managers' criteria and the reservoirs storage capacity. Third, one can construct different types of EDMIs. For instance, while we have focused on irrigators' benefits to obtain the shadow value, other economic or social indicators, such as employment and farmers' net returns, could easily be used to build alternative EDMIs based on exactly the same assumptions and quite similar empirical modelling. And fourth, its interpretation is simple and based on quite intuitive economic reasoning. EDMIs values provide a efficiency measurement of the management rules of reservoir(s).

To grapple EDMI's meaning, consider the three possible cases:

a) If for S^i_t , $EDMI(S^i_t) = 1$, this implies that both shadow values, the current and the expected one, are equal. This is equivalent to the following claim: considering the economics of the area's irrigation, the historical records of reservoir's inflows, and technical constraints, water managers could not improve the efficiency of their management criterion.

b) If for S^i_t , $EDMI(S^i_t) > 1$, this implies that both shadow values, the current and the expected one, are equal. This is equivalent to the following claim: considering the economics of the area's irrigation, the historical records of reservoirs and inflows, and the reservoir's technical constraints, water managers could not improve the efficiency of their management criterion.

c) If for S^i_t, $EDMI(S^i_t) < 1$, then the shadow value of water used in the current season is lower than the expected shadow value of water that would be allocated to the farmers, with the above assumptions of inflows distributions, water managing rules and structural facilities. In other words, the cost of saving one unit now is lower than its expected marginal benefit in the future. Hence, it should be saved in the reservoir for future periods.

Two key assumptions are imposed and must be checked against actual data in order to place confidence in the informative capacity of EDMIs. One is the existence and time stability of function [1]. No normative conclusions can emerge from EDMIs interpretation unless a behavioural pattern is found to be consistent and persistent. The other is whether it is possible to represent the statistical processes that govern the transition from S_t^i to S^j_{t+1} in a systematic and reliable way. These two assumptions together with the whole empirical characterisation of equations [1] through [8] are described in section four, after a description of the region's background and water institutions.

3. Background and water institutional arrangement

The Guadalquivir River Basin (GRB) sits in the Southern part of Spain and drains to the Atlantic Ocean an area of 63,240 squared kilometers. Being the home of almost 5 million people, its water resources have a predominant agricultural use, which makes up about 75% of water uses in normal year (see Table 1).

HERE TABLE 1

The GRB has suffered three severe droughts in the last 25 years, of which the one that occurred during the 1992-95 period is identified as the most severe since 1950. More than 1,2 million people faced water service cuts during the 1993 and 1995 summers, and about 200,000 hectares of irrigated land were left idled during three consecutive years with a loss of 20,000 jobs directly linked to irrigated agriculture and of 3.5 to 4 billion Euros of agricultural output. Lastly, all water quality parameters deteriorated significantly causing unvalued damage in riverine ecosystems and natural life (EMASESA, 1997; MIMAM, 1998). Figure 1 depicts key hydrological variables of one reservoir, representative of the basin.

Here Figure 1

GRB's water managers are responsible of developing an intertemporal strategy that involves deciding how much water is released at a given time, and how much should be stored for future consumption. But as will be explained below, water release decisions result from negotiations between authorities, users, stakeholders and other government branches, albeit the River Basin Authority's president will sign the final decision. In addition to the decision-making process, the nature of the water rights and other Water Law provisions impinge on the kinds of strategies that competing users can put forward to pursue their interests. The fact that only a few players, representing a large number of users, collide within the boundaries of the River Basin Authority, which in turn has a unique voice and presumably acts on behalf of the general population, provides the applied context for this paper.

The Guadalquivir basin encompasses two different management levels. First is the General Regulation System (GRS), which consists of a set of 8 reservoirs centrally managed by the River Basin Authority (RBA). The total capacity of the system has been expanded over time as new dams were erected, and its present storing capacity is about 4 billion cubic meters. An irrigated acreage of about 200,000 hectares depends annually on the water supply that originates from the pool of resources stored in the GRS. In addition to irrigation, the GRS provides other services such as flood control, hydropower, urban supply security levels and water quality upgrading. The resources and the civil works associated with the GRS are managed by the RBA.

The second level is typically characterised by a dam which serves a single group of users, who have 'special' historical rights over its water resources. These dams are placed in tributaries to the Guadalquivir, were erected decades ago – a fact that explains the 'special' nature of the water rights—and, what is key to our analysis, are managed by users independently of the RBA. The paper's empirical contexts are illustrative of these two management levels — which hereafter are referred to as centrally-managed and self-managed — and provide distinguishable institutional examples of stocks management.

In both cases, users must have water rights to make use of the assigned volumes or flows. Each user's annual allowance is based on the face value written in the water right, but often is set at a lower level. The reasons to cut down water rights vary across institutional arrangements. In the self-managed case, farmers' allowances for a given season are set by the users' association which ponders factors such as the state of the reservoir prior to the beginning of the season. Only in extreme cases will the RBA set restrictions on how the association can manage its reservoir. In the centrally-managed case, the RBA sets farmers' allowances for tens of districts based on technical factors, such as the state of districts' conveyance systems, and on the state of the reservoirs it controls. Thus, if the GRS reservoirs are too low, the RBA may reserve all resources to urban suppliers if their storage systems happen to be in a pre-emergency situation. Under these circumstances, urban water rights are given priority and irrigators may be given no water allowance. Note, however, that in both cases the probability of experiencing low stock levels, which may or may not warrant low farmers' allowances, results from the inter-temporal management criteria applied by their respective water managers.

4. Empirical application

EDMIs have been estimated for two different water supply systems located in the Guadalquivir river basin (see Table 2). The first services *Bajo Guadalquivir* (BG) irrigation sector that is located in the low tracts of the basin at sea level. It comprises a set of very homogeneous irrigators, who grow almost the same crops and use similar technological packages. Its water supply is conveyed by a canal that diverts water from the main Guadalquivir river. Thus, its supply originates from the pool of resources that are stored by the GRS's eight main reservoirs. BG district is taken as an example of central management of water supply systems.

The second case is the reservoir that supplies *El Viar* (EV) whose farmers have an almost exclusive right on water from the reservoir since the dam was erected in 1949 to provide irrigation water to the EV irrigators. This reservoir is managed by elected representatives of the water users association. EV district has been selected to illustrate the economic performance of a self-managed supply system.

As will be shown below, estimating the EDMIs for BG district is more complex than for EV for two reasons. First, EV's acreage and the dam it is serviced from have not been altered since it began to operate, whereas BG district is serviced from a system of reservoirs that has grown in storage capacity in the last decades. Second, while EV's irrigators are the only reservoir's right-holders, the 8-reservoir system that supplies BG also services many other districts and has typical non-consumptive demands to meet, such as hydropower, water quality and urban suppliers security services.

EDMIs estimation requires a number steps, including the following:

i. Estimation of the functions, $W_t=f(S_t,\theta)$
ii. Definition of the correspondence, $\lambda_t = \Gamma(S_t)$ linking shadow use values with stock levels.
iii. Estimation of the density functions of the annual run-off into reservoirs.
iv. Estimation of the transition probabilities matrix from stock level S_t^i to S^j_{t+1}.

4.1. Estimation of the function, $W_t=f(S_t,\theta)$,

In the absence of statute or explicit rules that establish guidelines about how reservoirs should be managed, saving flood prevention and other environmental constraints, the functions $W_t=f(S_t,\theta)$ must be elicited from the historical records available for each district. Iglesias *et al.* (2000) screened alternative model specifications, and found that the best fit was a quadratic relationship between annual farmers' allotments and stock levels measured at the beginning of the season. Their regression results are reported on Table 3.

HERE TABLE 3

The estimated functions explain at least 88% percent of the allotment variations and all coefficients are significant at a 99% of level confidence.

4.2. Definition of the correspondence, $\lambda_t = \Gamma(S_t)$, linking shadow values with stock levels for each supply system

The correspondence $\Gamma(S_t)$ provides a mapping of the water stock levels onto shadow values of water, and thus is specific for each irrigation district. It yields the shadow value of water released to the farmers from the available stock, accordingly with the estimated functions shown on Table 3. The shadow values of irrigation water are based on the results of a dynamic-recursive mathematical programming model applied to a set of representative farms of both water irrigation districts (see Garrido et al, 2001; Iglesias *et al.* 2000). By simulating a range of water allotments, the model generates individual farms' marginal values. Since allotments are functionally dependent on the stock levels, as shown on Table 3, there exists a monotonically decreasing correspondence between stock levels, at the beginning of the season, and the shadow value of water for the district. Figures 2 and 3 plot each district's average shadow values against the whole range of possible water stocks of the storage systems from which both districts are supplied.

HERE FIGURES 2 AND 3

These correspondences are based on two sources of information. One is the institutions' behaviour with respect to how water is released from reservoirs, which is captured by the estimated functions $W_t=f(S_t,\theta)$, shown on Table 3. The other is irrigators' marginal value of the allotments resulting from the above mentioned mathematical programming model (see details in appendix 2).

4.3. Estimation of the density functions of the annual inflows or run-off into reservoirs

Inflows into reservoirs follow stochastic processes that result from hydrological phenomena that are largely driven by the rainfall regime and the physical conditions of the catchment's soils. In our model, we treat inflows (*IF*) as a stochastic variable that fits a distribution function, whose parameters can be estimated from the data recorded since the dam became operative. In this section, we report the results of the statistical analysis carried out to characterise inflows' distribution function.

Because the EV district is supplied by a self-managed single reservoir, its annual inflows are much easier to characterise. The statistical tests carried out using 50 annual observations of inflows into the EV's reservoir are best modelled by a gamma distribution (see table 4).

By contrast, the resources conveyed to the BG district are abstracted from the main river, although its allotments are based on the reserves stored in the reservoirs of the Guadalquivir main regulation, as shown in the above regression results. We assume that the BG's supply originates from a virtual reservoir, formed by a set of various reservoirs, that have been sequentially put in operation during the last four decades. The characterisation of the variability of inflows is hindered by the fact that the storage capacity of the basin has grown in the last decades as new dams have been erected and made operative. Thus, unlike our previous case in which a single reservoir has served a fix irrigation acreage in the last fifty years, BG's supply has been served by a growing system shared by an increasing number of users.

To make the estimation tractable, we have generated a variable of annual inflows, defined as the weighted average of each reservoir's annual run-offs measured as a percentage of the storage capacity of the reservoir its feeds. The weighting coefficients for each year are based on the percentage of the capacity of each reservoir with respect to the eight-reservoir system. This assumption allowed for a representation of the stochasticity of relative inflows, as a percentage of total storage capacity. As before, a gamma distribution function was selected among alternative functions, with a 99% significance level (Table 4).

HERE TABLE 4

4.4. Estimation of the transition probabilities matrix linking stock states S_t^i to S^j_{t+1}

Let a given reservoir's stock be governed by the following stochastic equation:

$$\widetilde{S}_{t+1} = S_t - WR_t - Sp_t - L_t + \widetilde{IF}_t \qquad [10]$$

where $\widetilde{S}_{t+1}$ is a stochastic variable, WR_t denotes total water releases during period t, including farmers' allotments; Sp_t, denotes dam spills or stock losses, originating from evaporation, releases for flood prevention and ecological flows; L_t are other unaccounted release; and $\widetilde{IF}_t$ is a stochastic variable representing water inflows into the reservoir.

Let S be divided in 16 possible states, defining the complete range of possible stock levels. Assume that on the first day of year t the stock level happens to be S_t^i ($i,j=1,\ldots,16$), define p^{ij} is a generic element of the transition probability matrix, representing the probability of reaching S^j_{t+1} one year later. The value of p^{ij} results from:

$$p^{ij} = \Pr(S_{t+1}^j - S_t^i - WR_t - Sp_t - L_t = \widetilde{IF}) \qquad [11]$$

Among all variables in equations [10] and [11] only spills are subject to discontinuities that result from events such as torrential rains in times of high stock levels. We leave to the paper's Appendix the description of the estimation of each district's equation [10]. Figures 4 and 5 show that the discrepancies between the projected stock levels and the actual levels are not very significant. Thus, despite the relative simplicity of the balance equations, they provide a good representation of the reservoirs' dynamics for both water supply systems.

HERE FIGURES 4 AND 5

To calculate the p^{ij} elements of matrix the transition probabilities ***P*** of each water supply system two further steps are needed. First, using equation [11] we compute the 16x16 values of IF^{ij} that are required to hit any state final S_{t+1}, such that $S_{t+1} \geq S^{j}_{t+1}$, starting from state S^{i}_{t}. Then, the computed IF^{ij} is entered in the gamma density functions characterised by parameters shown on Table 4. Let α^{ij} be the probability of IF^{ij}, and α^{ij-1} be probability of IF^{ij-1}, then p^{ij} results from:

$$p^{ij} = \alpha^{ij} - \alpha^{ij-1}$$

Matrixes $\boldsymbol{P}=[p^{ij}]$ computed for each water supply system are reported on Tables 5 and 6. A zero element in either matrix means that reaching the corresponding final state is not possible even if inflows are zero during the 12-month period between the initial and final state.

HERE TABLES 5 AND 6

5. Results and discussion

5.1. EDMIs evaluated for the current climatic conditions

EDMIs have been evaluated for the water supply systems that service EV and BG irrigation districts. Each district's EDMIs are reported in Table 7 for the 16 possible initial state levels, S_t^i, and plotted on figure 6 for comparison purposes.

HERE TABLE 7 AND FIGURE 6

A common interpretation is valid for both series of EDMIs. At low stock levels (less than 58% in EV and 34% in BG), EDMIs grow to values in the range of 2-2.5. This is an indication that in both water supply systems the costs of saving water grow significantly when stock levels have diminished below the mentioned thresholds. With stocks above these thresholds, both districts' EDMIs fall below 1, suggesting that the benefits of using the water today are less than the forgone benefits of not using them in the current season. While EDMIs deviations from 1 provide evidence of inefficient stocks management, there are substantial differences among both districts' results.

EDMI values obtained for BG display large deviations from optimal value and indicate that water managers may be following rather inefficient water allocation rules, assuming excessive risks of drought. From Figure 6, we can observe that for stock levels below 80%, EDMI values sharply drop below 1 until stock reaches 34%. According to the interpretation of EDMI, this is an indication that the cost of implementing a more conservative strategy would be largely rewarded by the expected benefits resulting from the reduction drought risks. This finding supports the recommendation that more conservative strategies should be implemented and that water allocation rules should be more responsive to initial decreases in stock levels.

When stocks are at relative low levels, below 30%, EDMI values cross the 1-value line indicating that it is too late to avoid drought impacts. The cost of saving water under such situation is already larger than the expected benefits. The sharp change in EDMI values is partly due to the pattern followed to release water to the BG district and its associated marginal value. Water managers release very high allotments to BG even when stocks are at 40% of capacity and reduce it drastically whenever stock happen to be below 30%. This manner of setting farmers' allotments – resembling an "all or nothing" strategy – is inefficient and would be in BG farmers interests to replace it by a much smoother trend. For instance, when stocks are at 50%, EDMI is 0.1, revealing that the cost of saving water is ten times lower than the expected value of one more unit of water at storage. The finding that EDMI hits the 1-value when stocks are above 76% is equivalent to asserting that its supply system is able to secure the complete allotment of farmers for two consecutive years, at probability 1. Whether this should be associated with an optimal strategy is in part dependent on EDMI's construction, which only takes into account current shadow value and the expected shadow value of next period. While we are aware that this may be a limitation of the index, we would argue that the loss of accuracy is small as a result of two reinforcing effects. One is the short memory of a system subject to large hydrological variability, such as the one imposed by a Mediterranean climatic pattern. Secondly, since EDMIs are based on shadow values, they provide a first order approximation of the optimality conditions. Thus, stretching the planning horizon to a third year would be equivalent to modifying the expected shadow value to include the second-order effects that result from considering two instead of one transition process.

The EDMIs for EV portray a widely different situation. EDMI values in this case display moderate departures from the 1-value and stay much more closer to it than BG's. EDMI values suggest that in this case the risk of drought could be moderately reduced through slight reductions in water allotments when stock levels are in the range of 85-50%. EDMIs also cross the 1-value line at higher stock levels – 50% in this case - reaching rather high values which indicate that the present use value of water is considerably larger than the expected value of storing it in the reservoir. In principle this would suggest the convenience of increasing water allotments under this situation. However, a caveat should be made when stocks reach very low levels, as there may be quality reduction considerations and other restrictions that may prevent managers from augmenting farmers' allotments.

The comparison of EDMIs values reveal that the self-managed supply system follows much more efficient inter-temporal water allocation rules than the centrally-managed system. Given the climate conditions as well as structural and hydrological constraints they face, self-managed managers exhibit quasi-efficient levels of drought risks.

In short, any water supply system whose EDMI deviates from 1 could improve its economic performance following one of the following three strategies: (1) increasing water allotments when EDMIs are above 1; (2) decreasing the water allotments when stocks are below 1; (3) pursuing strategies (1) and (2).

Although strategies 1 and 2 could be carried out independently, both would have impacts on the values of EDMIs along the whole range of water stocks. Consider, for example, a proposal to develop strategy 2. This would have the following effects. First, farmers would be given less water when stocks are high, as a result of which the state level, that marks the switch of EDMI from less than 1 to more than 1, would be moved to a higher stock level. This implies that efficiency gains would be attained narrowing the gap between EDMIs' discrepancies between 1 and lower values. Secondly, the probability of reaching a low stock level would be reduced, decreasing in turn the need to carry out strategy 1. In this sense, strategy 2 makes strategy 1 less needed.

Consider the alternative case, under which only strategy 1 is developed. This means that under low stock situations, farmers should be given more water, emptying a bit more the reservoir. The gains accruable from strategy 1 may come from two sources. One is due to the fact that more water is given when it is scarce, taking advantage of moving along the benefit function when the marginal gains are largest. The second is due to the fact that the reservoir would be left with larger storing capacity for further periods, reducing the probability of the need to release large amounts of water to comply with the reservoir's security constraints. The extent to which strategy 1 reduces the need and impact of strategy 2 is perhaps lower than the spillover effects of the opposite direction. This implies that the efficiency losses resulting from running a supply system at a higher drought vulnerability level than the efficient one are potentially larger than managing it at a lower vulnerability level than the efficient one. This result partly answers the question raised by Griffin and Mjelde (2000) about the costs of deviating from optimal drought vulnerability levels.

5.2. EDMIs under climate change scenarios

The EDMIs discussed above are based on the historical records of reservoir inflows. The transition probabilities matrix is based on the estimated distribution function that best fits the historical records of the reservoir inflows. Each element of the ***P*** matrix denotes the probability associated with a given level of inflows needed to hit a final stock level j starting from an initial stock level i.

Using the same modelling techniques, an attempt is made to simulate the economic performance of both water supply systems under likely climate change scenarios. As of 1998, the best projections for the Guadalquivir River Basin indicated that average river run-offs may diminish between 20% and 40%. Based on these bounds we define two out of the four scenarios based on which new series of EDMIs have been evaluated (denoted by *ScAI-20%* and *ScAI-40%*). The third scenario assumes an 100% increase of the annual inflows' variance, keeping the average at the current level (denoted by *ScVc+100%*). A fourth scenario combines a 50% increase of variance and a 20% reduction of average inflows (denoted by *ScAI-20%Vc+100%*). These new EDMIs are plotted in figures 7 and 8.

Here figure 7 and 8

EDMIs in both districts display some common features. First, all EDMIs associated with climate change (CC) scenarios move downward of the current EDMIs. Under CC scenarios, EDMIs suggest that savings strategies should be developed earlier and more intensively than under current conditions. By the same token, EDMIs deviations from above 1 are reduced significantly, which means that even for low stock levels the discrepancies between current and expected shadow values are not significant. Since the EDMIs plots cross the 1-line at a lower stock level, the institutional rules that are currently been followed will become increasingly less efficient for a larger range of stock values. If CC results in larger inflows instability on top of lower average run-offs, efficiency losses will be multiplied if the allotments are not lowered for a much larger range of reservoirs' stocks.

5.3. EDMIs during the 1993-95 droughts

So far the results discussed above assume that the correspondences that link water shadow prices and stock levels ($\lambda = \Gamma(S)$) are invariant through time. There are many reasons to assume that irrigators' shadow values of water may change from season to season. In this section, we apply the notion of EDMIs to the real circumstances that prevailed in the worst drought episode in the basin in the last fifty years. In previous work, Iglesias et al. (2000) obtained the average shadow value of water, as an average of several representative farms' shadow prices, for the eight-year period between 1990 and 1997. This period provides an illustration of how EDMIs can assist water managers to take decisions about water stocks management.

Thus, we have recalculated the numerator of EDMIs equation [9] with the best available information on farmers' marginal value of water using the results of Iglesias et al. (2000), and evaluated the denominator taking into account two sources of available information. One is the actual amount of water released to farmers in each season. Hence, instead of using the estimated equations shown on Table 4, we insert actual releasing decisions and then use the inflows distribution functions to obtain the row-vector of the transition probability matrix, which is associated with the initial stock value of each particular year. The new EDMIs are reported in Table 8.

HERE TABLE 8

EDMIs reported on Table 8 are illustrative of various inefficiency losses. Note that even in this case EDMIs still assume average inflows and no anticipation of the 1993-95 severe drought is incorporated. Despite this, EDMIs in 1990 and 1991 are below one in both districts, indicating that lesser allotments would have been recommended for the those seasons. However, the 1992 EDMI in BG came close to its optimal value, granting an allotment of 3140

m^3/ha, which is 50% than in 1991 although the stock was only five percentage points lower . EV's system behaved inefficiently in 1992, with an EDMI of 0.64, but came closer to 1 in 1994 (a year between two extremely dry ones) with an EDMI of 0.80. These results reinforce our previous judgement about the reasonable good performance of EV's managers.

Once the hydrological drought set in 1992, BG's system could not do anything but wait until rains could help restore higher stock levels. Thus, although EDMIs during the drought are very high, no action could be taken to make them close to 1 because there was not any water stored in the reservoirs. Note, however, that BG's system was run in 1990 and 1991 at EDMIs quite close to zero, when stocks were respectively at 37 and 26%. Hence, had their managers reacted in those years, then the severe 1992-95 droughts could have been in part mitigated or at least deferred to the last two out of three consecutive years of meteorological drought. EDMIs from 1996 on are all below 1, which is an indication that both systems are being run at higher than optimal drought vulnerability levels when water is abundant.

6. Concluding remarks

In this paper we have proposed a new index to measure the economic performance of the management rules that govern the decisions of water supply systems operating in highly unstable climatic patterns. The proposed Economic Drought Management Index (EDMI) combines in a single number four sources of information: (1) the structural constraints of a given water supply system, (2) the characteristics of the hydrological patterns originating from purely natural processes (3) the managers' behavioural rule, elicited from their historical records; and (4) the economic benefits accruable on water users. EDMIs have been evaluated for two institutionally different water management systems in the Guadalquivir basin (South of Spain). We then look at the deviation of the EDMIs from the optimal values and interpret them in light of the stock state prevailing in each situation and the types of institutions in charge of running each supply system.

Results show that in both systems a similar set of correcting strategies are warranted to improve the water use economic efficiency. Contrary to common belief, we find that it is too costly to reduce water consumption when stocks are low, because the current marginal value of water is 2 to 5 times larger than the expected marginal value for next period. We also find that farmers' allotments should be reduced significantly when reservoir stocks are at medium or large levels. This finding supports the conclusion that both systems are failing to spread the hydrological risks, falling short of the possibilities available from their present storing capacity. While this applies to centrally managed institutions and self-managed water supply systems, the estimated EDMIs indicate that centrally-managed water supply systems seem to display riskier strategies and deviate from optimum values in larger extent than self-managed ones.

EDMIs have also been computed for various climate change scenarios to examine the economic performance of the current management rules under more adverse climate patterns. These recalculated EDMIs suggest that the current management rules are more inefficient when stocks happen to reach medium or high levels. This finding reinforces the need to change the management rules under the climate change scenarios.

Lastly, an application of EDMIs to the drought conditions suffered in the Andalusian region (Southern Spain) shows that, although the three-year drought impacts could not have been avoided, its damaging effects could have been reduced or at least delayed one year.

Two general conclusions are supported by this paper's results. First, there seems to be an optimum level of drought vulnerability for each supply system. This implies that efficiency losses result from running a system at higher or at lower levels than the efficient level of vulnerability. However, this paper has shown that larger efficiency losses may result from excessive drought vulnerability. Second, centrally managed supply systems can generate more efficient outcomes, with no need to initiate complex and costly institutional water sector reforms. For this to happen, managers must take into account the costs and benefits that result from alternative management rules. We claim that EDMI is a valid index irrespective of whether or not water right holders are allowed to trade their rights. In fact, EDMIs based on market prices instead of shadow values, as this paper does, would perhaps provide more precise guidelines to public agencies in charge of setting total tradable volumes.

EDMIs differences across institutional arrangements suggest that if users' associations were granted higher control over their water rights and the way the reservoirs are managed perhaps their system would approach their optimal level of vulnerability to droughts. This conclusion is supported by the significant efficiency differences found for the paper's two case studies, illustrative of self-managed and centrally-managed supply systems.

This paper adds to the literature on water institutions performance under uncertain natural environments proposing an index which can be easily interpreted by water managers and analysts. It conveys unambiguous information about the kind of strategies that are desirable under a large range of circumstances. We leave for further research other objectives such as finding alternative indices that convey social information such as impacts on farm employment, the value of agricultural commodities or various non-use water values.

APENDIX. MODELING WATER BALANCE EQUATIONS

The inter-anual hydrological balance is modelled by equation [10]:

$$S_{t+1} = S_t - WR_t - Sp_t - L_t + IF_t$$

Specific modelling assumptions are needed to have a realistic description of the process governing the motion equation [10]. Variable IF_t is subject to completely natural processes, due to the fact that all reservoirs included in the analysis collect water from unregulated rivers. WR_t represents total water uses and is dependent on the stock level S_t, as shown on Table 4; and L_t represent other unaccounted stock losses. By contrast, reservoir spills (denoted by Sp_t) are dependent on the values of IF_t and the state of the reservoirs, S_t. Reservoir spills originate from many different, and sometimes overlapping, reasons. For this paper's purpose, spills are conceived as stock losses resulting from inflows that cannot be accommodated in the reservoir due to insufficient capacity or because alternative non-agricultural uses must be met. Thus, the fraction of IF_t that will have to be released from the reservoir to fulfil flood prevention risks increases with IF_t and S_t. We explain below the specific assumptions made for supply system.

a.-Spills for the EV case (the single-reservoir case).

We first define total spills, Sp_t, as follows:

If $S_{t-1} - WR_t + IF_t > 190$, then $Sp_t = IF_t - (190 - S_{t-1} + WR_t)$
If $S_{t-1} - WR_t + IF_t < 190$, then $Sp_t = Sp^{spr}_t$

where 190 is the maximum observed value of the EV's reservoir stock measured in million cubic meters; and Sp^{spr}_t, denote spring spills, and are evaluated as follows:

If $S_{t-1} + 0.35 \times IF_t > 190$, then $Sp^{spr}_t = 0.35 \times IF_t - (190 - S_{t-1})$
If $S_{t-1} + 0.35 \times IF_t < 190$, then $Sp^{spr}_t = 0$

Where the parameter, 0.35, is based on the fact that on average wet years, 35% of the inflows occur during the spring time. Defined as such, spring spills arise when large inflows during the interval between February 1st and the beginning of the irrigation season result in a stock level higher than the reservoir security level, which is set at 190 million cubic meters. In this way the model recognises the possibility of spring spills prior to the beginning of the irrigation season. Reservoir losses L_t denotes other unaccounted losses and result from $L_t = 0.1\times WR_t$.

b.-Spills for the BG case (the multi-reservoir case).

Presently, BG is supplied from the pool of resources that are stored in eight reservoirs integrated in the General Regulation System (GRS) of the Guadalquivir River basin. However, some of these reservoirs became operative after the BG district started to operate. This means that GRS's capacity, inflows and customers have grown in the last decades. In view of the difficulties involved with modelling the GRS with absolute magnitudes, we opted to denominate all annual variables in percentage of the storage capacity operative at that particular moment.

Specifically, GRS's annual stocks and inflows were measured as follows:

$$S_t = \Sigma_l \gamma_{tl} \times S_{tl},$$
$$IF_t = \Sigma_l \gamma_{tl} \times IF_{tl}$$
$$\text{with } \Sigma_i \gamma_{tl} = 1,\ \forall t$$

where γ_{tl} represents the percentage of storage capacity of reservoir l over the GRS total storage capacity operative in year t; S_{tl} is the stock of reservoir l on February 1st of year t measured as the percentage of its total storage capacity, if that reservoir was operative in year t. Note that, in general, $\gamma_{tl} \neq \gamma_{t'l}$ since the percentage of the storage capacity of reservoir l over GRS's total capacity may grow (dwindle) if the GRS has grown adding smaller (larger) reservoirs than those that were operative before the expansion.

The GRS system provides wholesale water to several irrigation districts among other commercial and non-commercial services, the water balance equation governing the supply system for BG depends has been statistically estimated. The specification that provided the best fit to explain the variations of stock, S_t, is a non-linear function of the lagged stock values, formulated as follows:

$$S_t = a_1 S_{t-1} + a_2 \ln (S_{t-1}) + a_3 IF_{t-1} + a_4 D1967 + a_5 Sp_t$$

Where S_t and IF_t have already been defined; D1967 is a dummy variable that takes the value 1 for the 1967 observation and 0 otherwise -- to control for an unexplained behaviour of S_t in that year-- and Sp_t is the GRS's spills measured accordingly with:

If $S_{t-1} - WR_t + IF_t > 90$, then $Sp_t = IF_t - (90 - S_{t-1} - WR_t)$
If $S_{t-1} - WR_t + IF_t < 90$, then $Sp_t = 0$

Where the parameter 90 represents a security level, implying that the GRS cannot operate with stocks over 90% of the GRS's total storage capacity.

The estimated coefficients and the statistical properties of the model are reported below:

a_1	0.93*
a_2	-5.96*
a_3	0.806*
a_4	-0.52*
a_5	-31.44*
Adj- R^2	0.90
F-stat.	76.95
N	37
Durbin-Watson stat:	1.441

*Significant at 99% of confidence interval.

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Table 1. Background of the Guadalquivir river basin[†]

	Guadalquivir Basin	Spain	Guad.Basin /Spain (%)
Surface (km^2)	63,240	505,000	12
Available water resources (million cubic meters per annun)	4,019	47,340	8,5
Uses (m.c.m./annun):			
• Urban	532	4,667	11
• Irrigation	3,140	24,094	13
• Industrial	88	1,647	5
• Other	259	6,598	4
• Energy (MW/annun)	515	8,637	5.9
Irrigated acreage (km$^{2)}$	4,430	34,370	12.7
Population	4,753,689	39,660,000	12
Pollution[&]	20 %	48 %	

[†]Source: MIMAM (1998)

[&]Measured as the percentage of flows that are considered eutrophic or hipereutrophic.

Table 2. Main characteristics of the Guadalquivir two case studies

Name of district	El Viar (EV)	Bajo Guadalquivir (BG)
Initial date of operation	1949	1974
Number of farmers	500	800
Acreage (ha)	12000	15000
Max. allotment (c.m./ ha)	7370	8590
Institutional arrangement	Self-managed	Centrally-managed
Water Supply System	El Pintado	General Regulation
Total capacity (Mill cubic meters)	207	4,046
Average inflows (%)[1]	70	50
Standard deviation (%)[1]	53	39
Agricultural Demand (m.c.m./year)	78	1,895

[1]Based on the total reservoirs' capacity

Source: Iglesias et al. (2000) and (MIMAM 2000)

Table 3. Regression results for the functional relation between farmers' allotments and water stock levels
$[W_t = aS_t + b(S_t)^2 + cD_t^{St} + d(S_tD^{DR}) + e(S^2_tD^{DR})]$ (t-ratios in parenthesis).

Coefficient	Definition	EV (1974-98; n=25)	BG (1977-98; n=21)
a (Stock)	Values recorded at Febr 1st measured as of storage capacity	194 (11.33)	216 (14.84)
b $(\text{Stock})^2$	Idem	-1.27 (-7.26)	-1.35 (-7.23)
c (Structural dummy)[1]	EV: $D_t^{st}=0$ for $t>18$, $D_t^{st}=1$ otherwise BG: $D_t^{st}=0$ for $t>6$; $D_t^{st}=1$ otherwise	1083 (2.84)	2627 (6.06)
d (Drought dummy×Stock)	BG: Drought dummy $D_t^{DR}=1$, for stock <25%, $D_t^{DR}=0$, otherwise.		-443 (-4.15)
E (Drought dummy×$(\text{stock})^2$)	Idem		17.5 (3.41)
	Adjusted R^2	0.88	0.95
	F-Stat	81.77	82.26
	Durbin-Watson	2.01	1.91

Source: Iglesias et al. (2000)

[1] The structural dummy was added in view of the fact that farmers' allotments were reduced after t=6 in BG and t=18 in EV.

Table 4. Inflows statistical characterisation

Parameter	BG N=37	EV N=50
Gamma: shape	1.836	1.498
Gamma: scale	0.0370	0.0102
P-value	0.311	0.160

Table 5. Probability matrix **P** for EV

Initial State (%)		Final State (in % of reservoir's capacity)															
		S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*	*S11*	*S12*	*S13*	*S14*	*S15*	*S16*
		13	**16**	**22**	**28**	**34**	**40**	**46**	**52**	**58**	**64**	**70**	**76**	**82**	**88**	**94**	**100**
S1	**13**	0.11	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.25
S2	**16**	0.10	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.25
S3	**22**	0.09	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.26
S4	**28**	0.06	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.27
S5	**34**	0.04	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.28
S6	**40**	0.02	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.29
S7	**46**	0.00	0.04	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.03	0.31
S8	**52**	0.00	0.00	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.03	0.33
S9	**58**	0.00	0.00	0.02	0.06	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.03	0.35
S10	**64**	0.00	0.00	0.00	0.03	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.38
S11	**70**	0.00	0.00	0.00	0.00	0.03	0.06	0.06	0.06	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.41
S12	**76**	0.00	0.00	0.00	0.00	0.00	0.04	0.06	0.06	0.07	0.06	0.06	0.05	0.05	0.08	0.06	0.41
S13	**82**	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.06	0.07	0.06	0.07	0.09	0.08	0.08	0.06	0.41
S14	**88**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.06	0.09	0.10	0.09	0.08	0.08	0.06	0.41
S15	**94**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.10	0.10	0.09	0.08	0.08	0.06	0.41
S16	**100**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.10	0.10	0.09	0.08	0.08	0.06	0.41

Table 6. Probability matrix **P** for BG

Initial State (%)		Final State (in % of reservoirs' capacity)															
		S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*	*S11*	*S12*	*S13*	*S14*	*S15*	*S16*
		13	**16**	**22**	**28**	**34**	**40**	**46**	**52**	**58**	**64**	**70**	**76**	**82**	**88**	**94**	**100**
S1	**13**	0.21	0.11	0.10	0.09	0.08	0.07	0.06	0.05	0.04	0.04	0.04	0.03	0.02	0.01	0.01	0.02
S2	**16**	0.18	0.11	0.11	0.10	0.09	0.07	0.06	0.05	0.04	0.04	0.04	0.03	0.02	0.02	0.01	0.02
S3	**22**	0.12	0.11	0.11	0.10	0.09	0.08	0.07	0.06	0.05	0.05	0.05	0.03	0.02	0.02	0.01	0.02
S4	**28**	0.06	0.09	0.11	0.11	0.10	0.09	0.08	0.07	0.06	0.06	0.06	0.04	0.03	0.02	0.01	0.03
S5	**34**	0.01	0.07	0.10	0.11	0.11	0.10	0.09	0.07	0.06	0.07	0.06	0.05	0.03	0.02	0.02	0.03
S6	**40**	0.00	0.02	0.08	0.10	0.11	0.10	0.10	0.08	0.07	0.08	0.07	0.05	0.04	0.03	0.02	0.04
S7	**46**	0.00	0.00	0.03	0.09	0.11	0.11	0.10	0.09	0.08	0.10	0.09	0.06	0.04	0.03	0.02	0.05
S8	**52**	0.00	0.00	0.00	0.05	0.09	0.11	0.11	0.10	0.09	0.11	0.10	0.07	0.05	0.04	0.03	0.06
S9	**58**	0.00	0.00	0.00	0.00	0.06	0.10	0.11	0.11	0.10	0.12	0.11	0.09	0.06	0.04	0.03	0.07
S10	**64**	0.00	0.00	0.00	0.00	0.01	0.07	0.10	0.11	0.11	0.13	0.13	0.10	0.07	0.05	0.04	0.08
S11	**70**	0.00	0.00	0.00	0.00	0.00	0.02	0.08	0.10	0.11	0.14	0.15	0.12	0.09	0.06	0.05	0.10
S12	**76**	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.08	0.10	0.14	0.16	0.13	0.10	0.08	0.05	0.12
S13	**82**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.09	0.14	0.17	0.15	0.12	0.09	0.06	0.15
S14	**88**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.11	0.18	0.16	0.13	0.10	0.08	0.18
S15	**94**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.17	0.18	0.15	0.12	0.09	0.22
S16	**100**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.13	0.18	0.17	0.14	0.11	0.27

Table 7. Economic drought management indices (EDMIs) for EV and BG water supply systems

EV district			**BG district**		
STOCK (S^i_t)	Allotment (1000 m^3/ha)	EDI	STOCK (S^i_t)	Allotment (1000 m^3/ha)	EDI
13	2.31	2.53	13	0.00	2.22
16	2.79	2.54	16*	0.51	2.30
22*	3.67	2.20	22	2.84	2.07
28	4.45	1.91	28	4.99	1.29
34	5.15	1.66	34	5.78	0.93
40	5.75	1.42	40	6.48	0.21
46	6.26	1.22	46	7.07	0.02
52	6.68	1.04	52	7.57	0.04
58	7.01	0.90	58	7.97	0.09
64	7.25	0.79	64	8.28	0.31
70	7.39	0.74	70	8.48	0.79
76	7.45	0.77	76	8.59	1.00
82	7.41	0.84	82	8.60	1.00
88	7.28	0.91	88	8.60	1.00
94	7.06	0.96	94	8.60	1.00
100	7,06	0,96	100	8,60	1.00

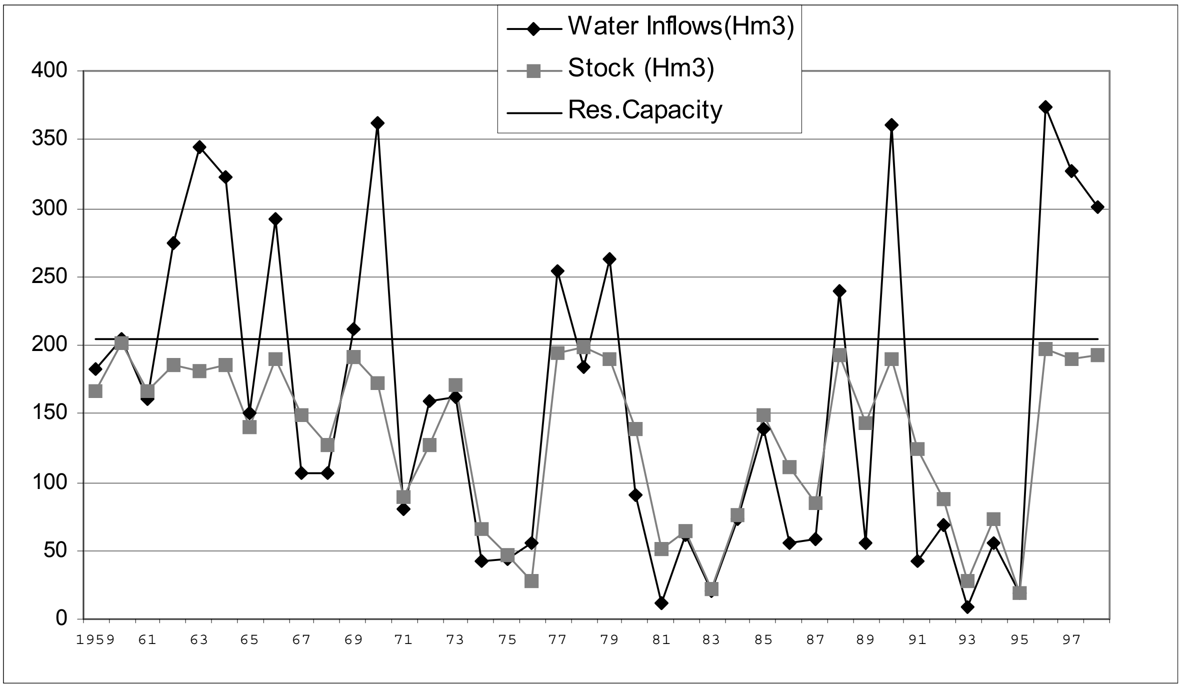
*With stocks below these levels, farmers' allotments assigned accordingly with equation [1] empty the reservoirs.

Table 8. Actual EDMIs for the EV and BG supply systems (1990-97)

	EV			BG		
Year	Stock on February 1st (% of capacity)[1]	Actual allotment (m^3/ha)[1]	EDMI	Stock on February 1st (% of capacity) [1]	Actual allotment (m^3/ha)[1]	EDMI
1990	91	9300	0.17	37	6180	0.17
1991	60	7260	0.65	26	6450	0.24
1992	42	5710	0.64	21	3140	1.35
1993	13	770	3.82	15	74	45.51
1994	35	4770	0.806	18	903	5.37
1995	9	0	9.54	11	0	9.13
1996	95	7200	0.76	36	5880	0.50
1997	92	7370	0.182	89	7890	0.15

[1] Source: Unpublished reports of the Guadalquivir River basins.

Figure 1: Annual inflows and stock of Pintado Reservoir



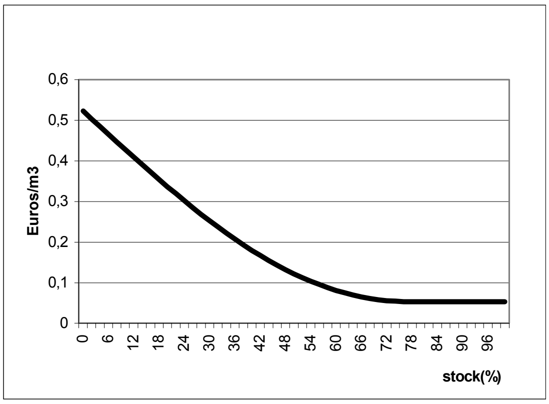


Fig.2: Correspondence $\lambda=\Gamma(S)$ in EV

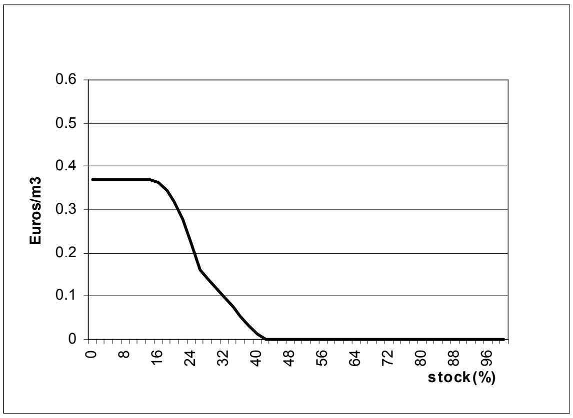


Fig. 3. Correspondence $\lambda = \Gamma(S)$ in BG

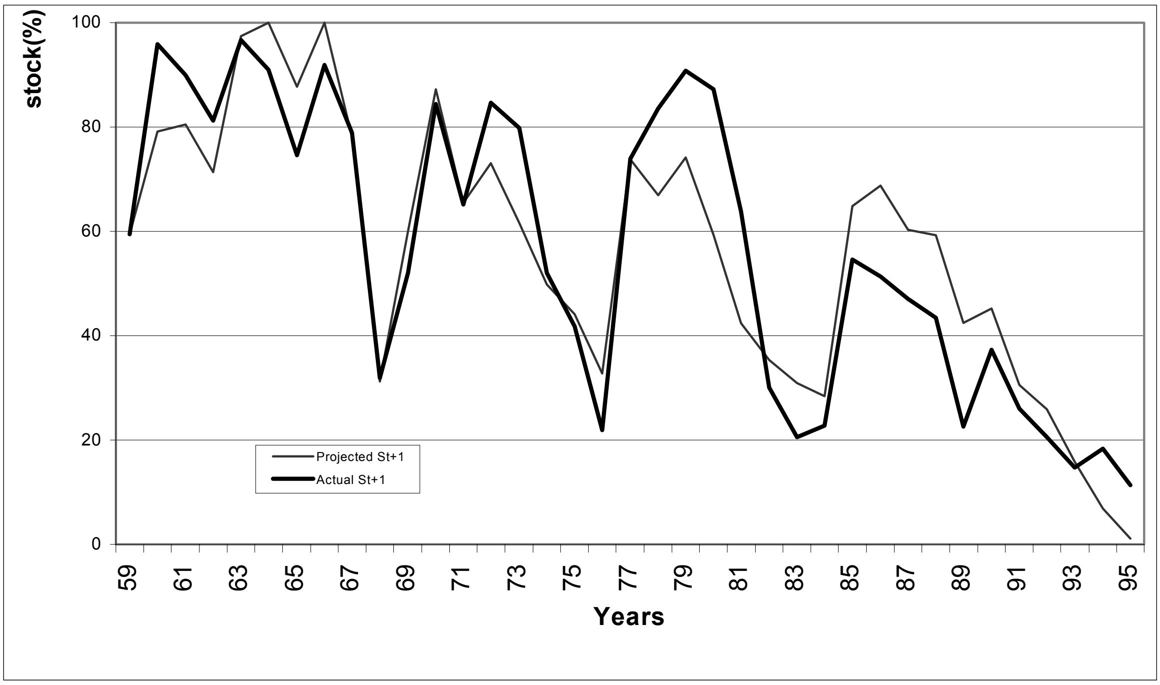


Figure 4: Actual and projected stock levels in BG.

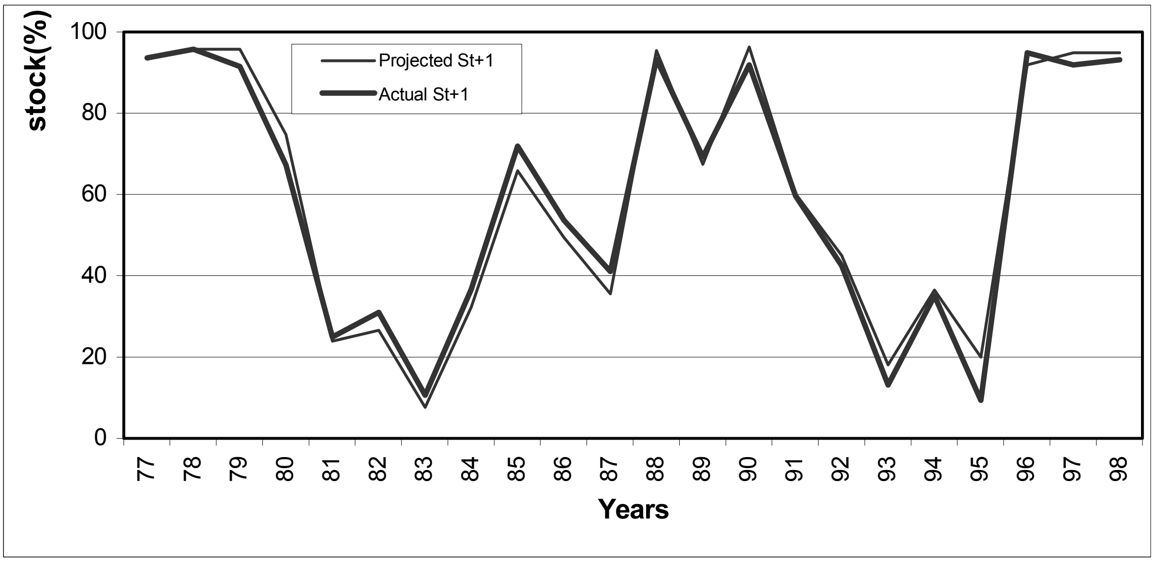


Figure 5: Actual and projected stock level in EV.

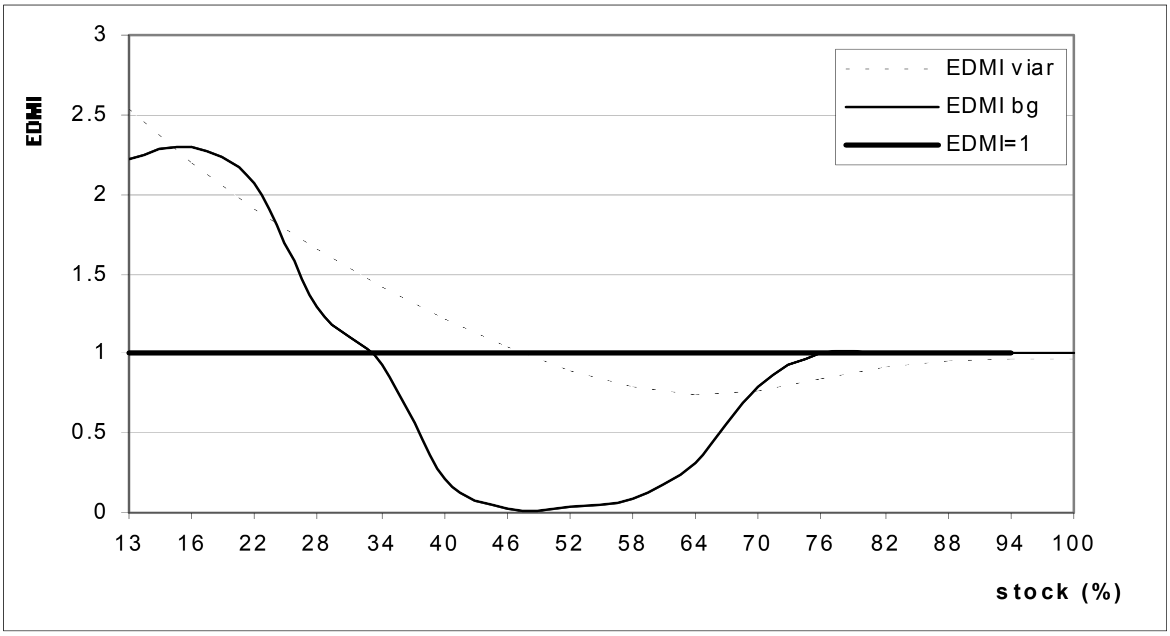


Figure 6. EDMIs for EV and BG

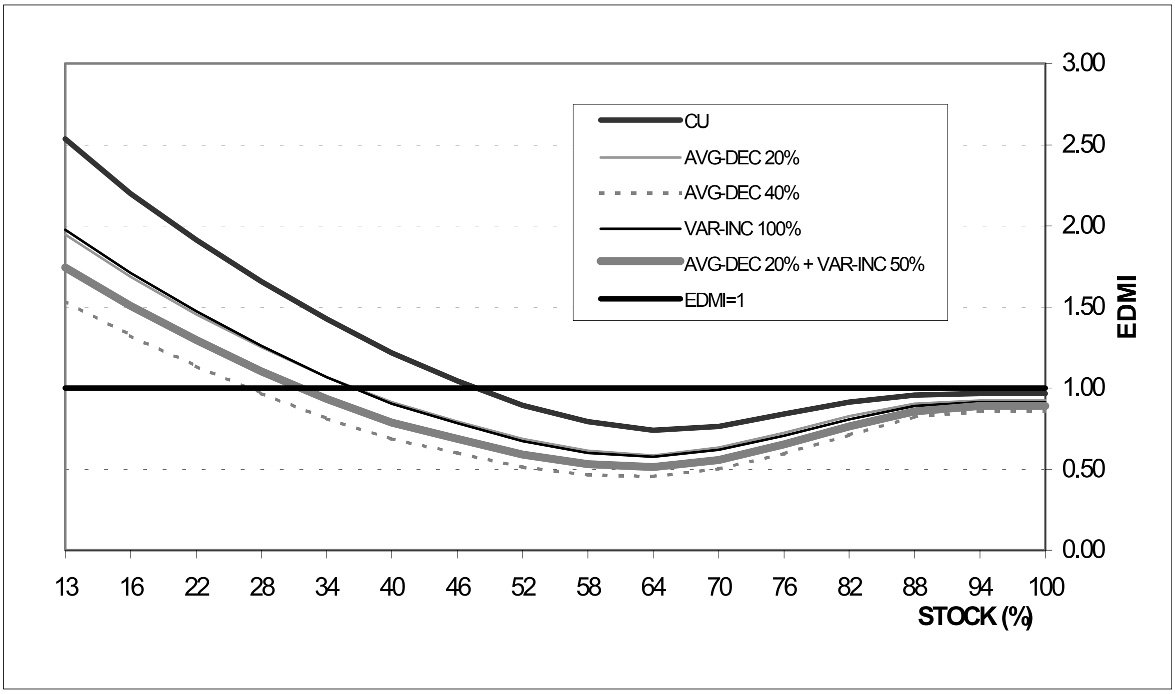


Figure 7. EDMIs for current and four climate change scenarios in EV

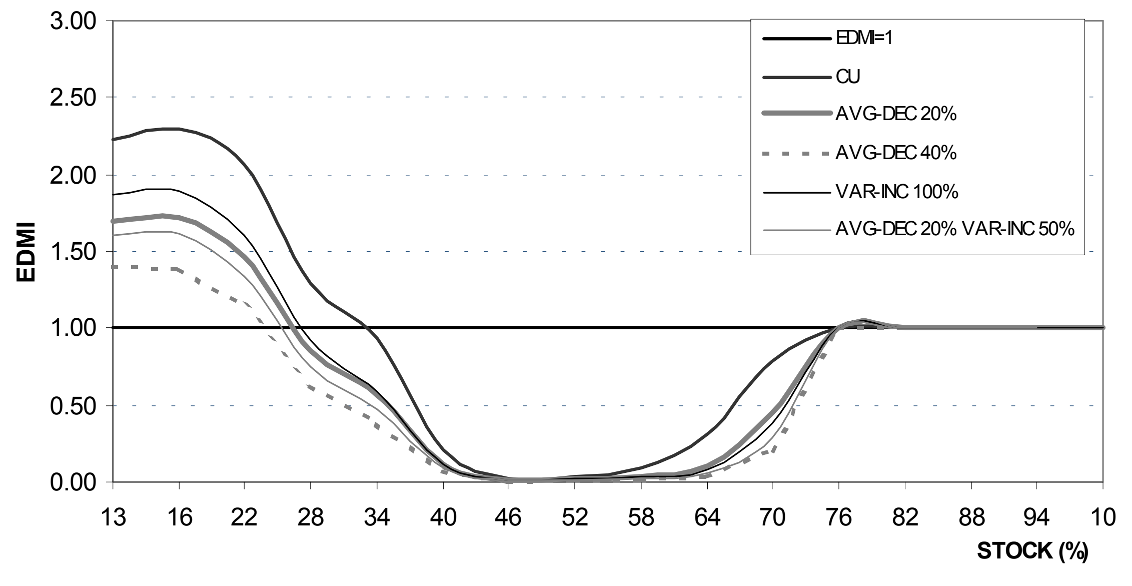


Figure 8. EDMIs for current scenario and four climate change scenarios in BG