An Economic Drought Management Index to Evaluate Water Institutions' Performance

Eva Iglesias
Alberto Garrido
Almudena Gómez

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AN ECONOMIC DROUGHT MANAGEMENT INDEX TO EVALUATE WATER INSTITUTIONS' PERFORMANCE [1]

Eva Iglesias[2], Alberto Garrido and Almudena Gómez

Department of Agricultural Economics
E.T.S. Ingenieros Agrónomos. Univ. Politénica de Madrid
Ciudad Universitaria
28040 Madrid- SPAIN
e-mail: eiglesias@eco.etsia.upm.es

Abstract

This paper proposes an 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. Results for one district show that the region's vulnerability to drought could be reduced following the interpretation of the EDMIs. For the other district, the index shows that water stocks are managed under nearly optimal criteria. This last result shows that there is an efficient level of drought vulnerability, and that increasing supply security levels would result in welfare losses.

Keywords: Water Resources, Irrigation, Stocks management

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[2] Corresponding author

Introduction

Hydrological or operational droughts occur when water supply systems fail to meet their demands. They originate from persistent periods of abnormally low precipitation, but are not entirely naturally-induced events (Tate and Gustard, 2000; Wilhite, 1993). In addition to low discharges, water demand behaviour and the criteria with which reservoirs are operated are also at the root of the water shortages that societies suffer occasionally.

Although water supply systems must accept certain levels of risk of not being able to service all its customers (Owen *et al.,* 1997), determining whether water shortages can be avoided, or at least mitigated and at what cost, is of paramount importance to deciding whether project expansions should or should not be developed. The literature seeking to explain why water shortages originate cross-cuts several scientific fields. Institutionalists (Bakker *et al*.,1998; Kenney, 1995; O'Riordian and Jordan, 1999; Ostrom, 1990); economists (Lise *et al.* 2001; Beare *et al.,* 1998; ; Howe and Smith, 1994); modellers (Dudle y and Hearn, 1993; Garrido and Gómez-Ramos, 2000; Garrido et al. 2000); geographers (Emel and Roberts, 1995), hydrologists (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. Some authors associate weak governance capacity to implement risk-reducing strategies, with poor law enforcement (Ray and Willians, 1999;del Moral, 1998; Riesco 1998). This would suggest that optimised decision support systems are difficult to apply in its fullest extent in many real contexts. Another explanation is proposed by Giansante *et al*., (2002), pointing to the divergence between individual groups' and collective's interests, and the political pressure exerted by strong stakeholders, whose power originates from the priority allocation mechanisms that are present in most Mediterranean countries (Iglesias *et al*., 2000).

In view of the abundant evidence emphasising the influence of institutions in the magnitude of risks imposed by natural events, 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 is documented. To exploit its efficiency properties, 'Capacity sharing' requires that users be given tradable water rights as well as tradable rights attached to the reservoir storage capacity, which in the eyes of water policy reformers may be seen as the privatisation of multiple-use infrastructures.

Water markets established under extremely diverse institutional settings may promote efficient allocation among consumptive users within periods (Easter et al, 1998), but whether or not they may help reduce society's vulnerability to operational droughts remains unresolved, as the prospects for scarcity losers may worsened in a market setting. As Miller (1996) contends, water banking in California and Idaho is promoted only when drought conditions are already in place, a strategy followed also by the water law reform in Spain. 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.

To date, little effort has been made to develop and apply new indices to judge water institutions' outcomes and operations based on economic efficiency and performance. It is surprising that among the drought indices encountered in the literature (Vogt and Somma, 2000), none incorporates economic variables that translate the supply and demand forecasts into costs and benefits. Recently Griffin and Mjelde (2000) provided valuations of consumers' preferences for different water supply reliability values, adding to previous evaluations reported by Howe *et al.* (1994).

This paper attempts to contribute to the literature both in the methodological and the empirical strands, expanding previous attempts in the area of operational droughts and storage yield analysis (Tase, 1976; Guerrero-Salazar and Yevjevich, 1975, Marsh and Lees, 1985; Marsh *et al.* 1994). First, it develops 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 guidelines. 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), including storage capacities; (2) the stochastic nature of discharges; (3) the institutional rules used to manage reservoirs, as deduced from the historical records; and (4) the economic value of agricultural users. Since EDMIs are based on users' shadow values of water, they avoid the need to obtain direct measures of their willingness to pay for various reliability levels. Because the index's formulation results from the solution of an optimal control problem, it provides the means to judge observed reservoirs' management on economic efficiency grounds and infer whether or not such behaviour may or may not suboptimally risky.

In this sense, 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, taking the Guadalquivir River Basin (South Spain) as the area of study. 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 lay down the theoretical foundations 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 total productivity and provide alternative storage management guidelines. 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. Defining an Economic Drought Management Index

In this section, we develop an optimisation model that represents the stochastic and dynamic problem of running a reservoir. Our objective is to derive and propose an index that embodies the problem's optimality conditions and provides reference conditions against which actual and observed behaviour of reservoirs' managers can be judged on economic efficiency grounds.

Lets consider the most simple case of a risk-neutral agent in charge of running a single reservoir that supplies water to a well defined group of agricultural users. At the beginning of any given period t, the agent observes the stock of water in the reservoir, S_t, and takes a crucial decision on how much water, W_t, should be released to service its customer users. This decision leads to an immediate reward $F(W_t)$ that represents the benefits derived from the use of water in irrigation. Function F is assumed to be twice continuously differentiable with 0 and 0. Clearly, this action affects future benefits, since it also determines how much water is left in the reservoir for future uses to confront the possibility of a future drought.

We consider that the state of the reservoir follows a controlled Markovian probability law given by 0, where R_t is a random variable that represents water discharges filling the reservoir during period t. We assume that this stochastic variable is time independent and identically distributed over time.

The state transition function is defined as:

0 (1)

Where S_k represents the maximum water stock that can be held at the reservoir to observe the reservoir flood prevention security threshold.

The problem faced by the agent can be stated as a discrete time Markov decision process with state space 0, where the objective is to seek a state-contingent water releasing policy 0 that maximizes the present value of current and expected agricultural benefits from water use.

0 (2)

subject to the state transition equation given by (1) and the obvious constraint that states that releases must be less than or equal to the reservoir stock:

0 (3)

Assuming 0 sufficiently large, the non negativity constraints, $S_t>0$ and $W_t>0$, will not be binding at an optimal solution and the shadow price of water will satisfy the Euler equilibrium conditions.

Applying the Bellman´s Optimality Principle to this particular case yields the value function that denotes the maximum attainable sum of current and expected benefits for given initial conditions at the reservoir.

0 (4)

where 0 if 0, and 0 if 0

and where E_R represents the expectations operator over future benefits subject to the stochastic discharges R_t entering the reservoir. As we are dealing with an autonomous infinite horizon problem, we can drop the time subscript from equation and denote the value function as solely dependent on the initial conditions of the reservoir $S_0=S_i$.

0 (5)

Since the discount factor is bounded, 0, the mapping underlying Bellman's equation is a strong contraction on the space of bounded continuous functions and, thus, by the Contraction Mapping Theorem, will possess an unique solution.

Characterizing the solution via its equilibrium conditions, the so-called Euler conditions, involves the derivative of the value function 0 and provides an intertemporal arbitrage interpretation that helps to understand the essential dynamic features of the optimal water releasing problem.

We apply the Karush-Kuhn-Tucker condition and the Envelope Theorem to the Bellman recursive equation and get that an optimal state contingent water releasing policy must meet the following first order necessary conditions (Miranda and Fackler, 2001):

0 (6)

0 (7)

Equation (7) states that when $\mu=0$ ($W(S_i)<S_i$), the present value of one additional unit of water released today should be equal to its expected value when left in stock one year ahead. Equation (8) states that the present value of one additional unit in the initial stock today should be equal to its expected value when left in stock one year ahead.

Deriving the state transition equation given by (1), we get that for this particular case: 0

Substituting this result and rearranging terms, we can rewrite the previous equilibrium condition in (6) as:

0 (8)

From (8) and (7), it is straight forward that:

0 (9)

Multiplying by 0 and taking expectations on both sides of equation (8), we obtain:

0 (10)

substituting this expression in (7), results in:

0 (11)

This equation captures the essential problem faced by a dynamically optimising manager: the need to optimally balance immediate certain benefits against expected future benefits. The left hand side of this equation represents the current marginal value of the water released to irrigation uses and can be interpreted as the cost of leaving one more unit of water in the reservoir or the marginal cost of reducing the risk of drought. The first term in the right hand side represents the expected marginal value of leaving one more unit of water in the reservoir for next period. It can be interpreted as the marginal benefit of reducing the risk of drought. The second term in the right hand side μ takes a positive value when $W(S_i)=S_i$, that is, when all available water in the reservoir has already been released.

Thus, this optimality rule states that the present marginal value of the water released must be equal (when $W(S_i)<S_i$) or larger (when $W(S_i)=S_i$) than the expected marginal value of leaving one more unit in the reservoir.

Now, consider a realistic case of a water supply system that is managed with a water releasing rule $W(S_i)$ that either exists in an explicit form, or at least can be observed from the responsible agent's actual or past behaviour. Using equation (1) that describes the dynamics of the reservoir together with a known distribution of the stochastic water inflows that enter the reservoir, we can build the markovian transition probability matrix **P** with elements P_{ij} that represent the probability of jumping from initial state S_i to a final state S_j, where i = 1,...,n and j = 1,...,n, respectively, represent all possible initial and final states of the reservoir. Each element P_{ij} of the transition matrix **P** is denoted as:

0

Taking into account that $g_w=1$ when $S_j<S_k$ and $g_w=0$ when $S_j=S_k$, we can compute the expected marginal value of water that results from the actual water releasing rule $W(S_i)$ as:

0 (12)

With this result, we make use of the optimality condition in (11) to derive and propose an Economic Drought Management Index to test the intertemporal efficiency of actual water releasing policy operating in a reservoir system.

0 (13)

According to the economic interpretation given for equation (11), the EDMI reveals the implicit trade-off between present benefit from last unit of water released from the reservoir and future expected benefits that could have been obtained if one more unit would have been stocked in the reservoir. Thus, the EDMI can be interpreted as the cost-benefit ratio of reducing the risk of drought that results from a given water releasing rule. The application of the EDMI to water releasing rules actually operating a reservoir will reveal how efficient are water institutions or responsible agents in managing inter-temporally their water storage facilities.

The interpretation of EDMI values is quite straight forward. Deviations of the EDMI from one will give a measure of the economic inefficiency of the explicit or implicit rules used to supply water to end users. In particular, EDMI values below one provide an indication that water institutions may be "too risky" and that the economic costs imposed by hydrological droughts may be reduced through a more conservative water releasing policy

EDMI values in the vicinity of one reveals that institutions are using efficient inter-temporal management criteria. This is because the shadow value of the water released approximately equals its future expected benefit. EDMI values higher than one will be signalling that the actual cost of marginally reducing the risk of drought is higher than its expected benefit. It has to be noted from equation (11) that EDMI values for low stocks, when all water is already being released, should be higher than one.

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 inflows, 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.

However, 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 W(S). 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 dynamic process that govern the transition from S_i to S_j in a systematic and reliable way.

3. Background of the area of study

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

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.

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. In addition, all water quality parameters deteriorated significantly causing unvalued damage in riverine ecosystems and natural life (EMASESA, 1997; MIMAM, 1998).

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

Two water management systems coexist in the Guadalquivir basin. 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 this 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. In normal circumstances, no other consumptive users are served from the GRS. The resources and the civil works associated with the GRS are managed by the RBA.

The second management system operates in smaller projects which serve clearly identified groups of users. Although they are predominantly managed by these users' representatives, their operations are constraint by general basin security rules and subordinated to the GRS's emergency plans. The legal system recognises these users 'special' water rights, based on historical uses, which means that they have preferential access to the resources stored in their system. Central to the paper's analysis is the fact that, within wide binding limits, the water storage facilities are managed independently from the RBA. The paper's empirical contexts are illustrative of these two management systems— which hereafter are referred to as centrally-managed and self-managed — and provide distinguishable institutional examples of water stock management.

A number of common features and rules apply to both case studies' irrigators. 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 expressed in the water right, but is often set at a lower level. Before 1999, right-holders were not allowed to sell or lease their water rights, but after the inception of the water law reform right-holders will be allowed to exchange their rights. 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. In the centrally-managed case, the RBA sets farmers' allowances for tens of districts based on the state of the reservoirs in the supply system and taking into account priority criteria among users. Thus, if the GRS reservoirs are too low, the RBA may need to 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.

For this empirical application, we have selected 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 homogeneous irrigators, who farm similar land plots, grow almost the same crops and use similar technological packages. Small differences are found in the acreage farmers devote to cotton within their rotations, and whether or not they use sprinklers to make the water applications during the initial growing stages. 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 and provides an average of 1.9 billion cubic meters to more than 200,000 hectares. 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.

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)[2]	78	1,895

[1] Based on the total reservoirs' capacity;

[2] In the BG case, agricultural demand refers to total acreage served from the GRS, which amounts to 200,000 ha.

<u>Source</u>: Iglesias et al. (2000) and (MIMAM 2000)

4. Empirical application

In order to obtain the EDMI for each management system, we need previous estimation of three basic elements:

Irrigators' shadow values
The reservoirs' management models $W_t=W(S_t)$
The transition probabilities matrix from stock level S_i to S_{tj}.

Estimating the EDMIs for BG supply system 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. By contrast, 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. The fact that BG system serves other purposes besides irrigation implies that the storage capacity of the system that can be effectively used to manage irrigation water is more restricting than the system's storage capacity.

Estimation of irrigators' shadow value

Shadow values of irrigation water are based on the results of a mathematical programming model applied to a set of representative farms in both water irrigation districts. We have modified the original model of Varela et al. (1998), developed to analyse the impact of a water pricing policy, to simulate in this case farmers' behaviour under a water allotment constraint. The modelling technique ensures that a broad scope of farming alternatives are properly simulated and includes rigidities caused by permanent crops as well as the possibility to combine surface water and groundwater using small pumping sets. The model is calibrated to each representative farm of each district under normal and drought conditions. By simulating a range of water allotments, the model generates individual farms' shadow values based on the dual value associated to the water availability constraint.

The following equations represent the demand functions obtained for each irrigation districts:

0 for BG

0 for EV

Estimation of the water releasing rules $W(S_i)$

In the absence of statute or explicit rules that establish guidelines about how reservoirs are managed, saving flood prevention and other environmental constraints, the functions $W_t=W(S_t)$ have been elicited from the historical records of each district taking the stock of water in the reservoir at the beginning of the period as the explanatory variable. Iglesias *et al.* (2000) screened alternative model specifications, and found that annual farmers' allotments were best fit with a quadratic relationship of the stock level measured at the beginning of the season. Regression results are reported on Table 3.

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	BG
a (Stock)	Values recorded at Febr 1st measured as of storage capacity	194 (11.33)	216 (14.84)
b $(Stock)^2$	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 dummyHStock)			-443 (-4.15)
E (Drought dummyH$(stock)^2$)	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.

The estimated functions explain at least 88% percent of the allotment variations and all coefficients are significant at a 99% confidence level. These functions are meant to be interpreted as observed behavioural relationships between stocks and water supply, and do not imply nor deny the existence of operational rules governing each of the analysed systems[1]. Note that in BG, the model's curvature switches when stocks fall below 25%, making negative both the linear and quadratic coefficients. This indicates that BG's water allotments are very rapidly reduced when stocks get below 25%. This curvature might be explained by the priority criteria that operate in this reservoir system: under drought conditions -when stocks are low-, water releases are reserved for urban uses

Estimation of the transition probability matrix

The transition probability matrix can be obtained from the estimation of equation (1) that reproduces the dynamics of the reservoir and the statistical characterisation of the natural discharges into both storage systems. Discharges into reservoirs follow stochastic processes that result from hydrological phenomena that are largely driven by the rainfall regime. In our model, we treat natural discharges (*R*) as a time independent 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 discharge's distribution function.

Because the EV district is supplied by a self-managed single reservoir, its annual discharge is much easier to characterise. The statistical tests carried out using 50 annual observations of discharge into the EV's reservoir are best modelled by a gamma distribution[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 discharges 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 discharges, 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 discharges, as a percentage of total storage capacity. As before, a gamma distribution function was selected among alternative functions, with a 99% significance level (see footnote 4).

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[3] The reader will note that both functions reach global maxima at 76% and 82% of stock, respectively for EV and BG systems. Since stocks are usually below those levels, it does not represent a serious limitation to the use of these functions.

[4] In longer version of the paper we provide the statistical characterisation of discharges.

The estimation of equation (1), that captures the specific dynamic features of each supply system, was carried out following slightly different procedures. In Viar water allotments represent total releases from the reservoir since they are exclusive users. In the BG system, allotments only represent a small part of total water releases since there are also other users that are supplied from this system. In a longer version of this paper, we provide a detailed description of the estimation of each district's equations. Figures 1 and 2 show that the discrepancies between the projected stock levels –using our estimation of equation (1)- and the actual levels are not very significant. These regressions provide quite a trustworthy and stable representation of each system's equation [1].

Figure 1: Actual and projected stock levels in BG. Figure 2: Actual and projected stock levels in EV

Based on the discharges' statistical characterisation and the estimated functions $W=W(S_i)$, we can estimate each element of the transition probabilities matrix linking stock states S_i to S_j. Let $S=(S_1,S_2,...S_{15})$ represent all possible stock levels in the reservoir. Assume that at the beginning of the season, stock level happens to be S_i ($I,j=1,...,15$), define p_{ij} as a generic element of the transition probability matrix, representing the probability of reaching S_j at the end of the season. The value of p_{ij} results from:

$$0 \qquad [14]$$

These p_{ij} can be directly computed from the gamma distributio3n that characterise stochastic water discharges. Each element in matrix ***P*** provides the probability of moving from one initial state (a row) to a final state (a column). It is worth recalling the assumptions that have been made to calculate it: (1) behavioural function $W(S_t)$ exists and exhibits time stability, in the sense that the recorded history can be used to elicit current or future behaviour; (2) the dynamics governing each system can be confidently characterised by the parametric versions of equation [1], and (3) the statistical characterisation of discharges, based on historical record, is presently valid.

5. Results and discussion

EDMI has been evaluated for the water supply systems that service EV and BG irrigation districts. The values of the EDMI in each district supply system are reported in Table 4 for the 15 possible initial state levels, S*ᵢ*, and plotted on figure 6 for comparison purposes.

The comparison of EDMI values reveals that the self-managed supply system follows much more efficient inter-temporal water allocation rules than the centrally-managed system. EDMI values obtained for BG display large deviations below the optimal one-value and indicate that water managers may be following rather inefficient water releasing rules, assuming excessive risks of drought. From Figure 3, we can observe that when the initial stock level is in between 76% and 34% of reservoir capacity, EDMI values sharply drop below the one-value.

Erreur ! Argument de commutateur inconnu.

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 subsequent reduction in drought risk. This finding supports the recommendation that more conservative strategies should be implemented and that inter-temporal water allocation rules should be more responsive when such initial conditions are observed at the reservoir.

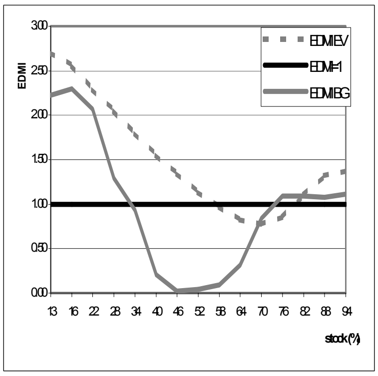
When stocks are at relative low levels, below 30%, EDMI values cross the one-value line indicating that it is too late to avoid drought impacts. The cost of saving water under such situation is already larger than the expected benefits. The sharp change in EDMI values is partly due to the pattern followed 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%.

Table 4. Economic drought management indices (EDMIs) for EV and BG water supply systems

EV district					**BG district**				
			Current	**Expected**				**Current**	**Expected**
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.37	0.67
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.36	0.158
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.28	0.135
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.14	0.109
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.08	0.081
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.01	0.054
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.031
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.015
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.006
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.002
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.001
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.001
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.001
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.001
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	0.00	0.001

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

Figure 3. EDMIs for EV and BG



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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 46%, water managers still release large water allotments to BG farmers despite the risk of drought is considerably increasing. In this case, EDMI is 0.02, revealing that the cost of saving water is only 2% of the expected value of one more unit of water at storage. The finding that EDMI hits the one-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 nearly full probability.

The EDMIs for EV portray a widely different situation. EDMI values in this case display moderate departures from the one-value and even stay above it for an ample range of possible water stock at the beginning of the season, suggesting that water managers follow quite a conservative strategy. Given the climate conditions as well as structural and hydrological constraints they face, self-managed managers exhibit quasi-efficient levels of drought risks. This implies that there would be efficiency losses resulting from running the supply system at a lower drought vulnerability level. This result partly answers the question raised by Griffin and Mjelde (2000) about the costs of deviating from optimal drought vulnerability levels. Only for initial stocks around 70% of capacity, the EDMI slightly deviates below the one-value and suggests that in this case the risk of drought could be slightly reduced through moderate reductions in water allotments when such initial conditions are observed at the reservoir.

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) and the results obtained show remarkable differences in the performance of these water supply management systems. The estimated EDMI indicate that centrally-managed water supply systems seem to display riskier strategies since deviations below optimum value are much larger than in the self-managed system. It comes out that the BG supply system is failing to spread the hydrological risks, falling short of the possibilities available from their present storing capacity. EDMI values suggest in this case that the economic risk of drought could be reduced and significant efficiency gains could be achieved by pursuing a more conservative releasing strategy. On the contrary, EDMI for the Viar supply management system demonstrates that a conservative releasing strategy is being performed and show that vulnerability to drought can not be further reduced in this system without incurring in efficiency losses.

While in the empirical application we showed how EDMI can be used to evaluate and establish guidelines to improve the actual releasing patterns operating in different reservoir supply systems, other applications of the EDMI are possible. For example, the EDMI could be used to assist water managers of a given supply system in comparing the economic efficiency of alternative management patterns. We also suggest that EDMI may be an useful tool in simulation exercises providing guidelines for the adaptation of the actual management patterns to changing conditions such as climate change scenarios.

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 different 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.

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