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Evaluation of drought management in irrigated areas

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Abstract

This paper focuses on the economic consequences of droughts for the irrigation sector. We develop a dynamic-recursive mathematical programming farm model that assumes imperfect mobility of capital and labour as well as rational expectations about future water availability. The model is calibrated to 12 representative farms belonging to three irrigation communities of the Guadalquivir Basin (south Spain) and used to simulate the 1991–1997 period, which included 3 years of intense drought. Results indicate that the drought imposed significant costs on farmers, but show also that water managers partly exacerbated these costs by allocating excessive amounts of water to irrigators in the abundant years. The model is also used to evaluate the benefits of a perfect water supply forecast and to simulate the economic gains of a voluntary water banking scheme. Results show that the benefits resulting from the perfect forecast of water supply 1 year ahead would represent a relative gain of 5%. However, a voluntary banking system would allow farmers to increase their benefits by 32–82% depending on the supply system.

JEL classification: Q12; Q25; Q21

Keywords: Dynamic farm models; Irrigation; Droughts; Banking systems

1. Introduction

In times of water scarcity, the irrigation sector is often the first to suffer water supply cuts, but ecological flows and environmental standards are relaxed as well if urban supply is also threatened (MIMAM, 1998; Giansante et al., 2002; Chavez, 1999; Hernández, 1999). Irrigation is the major water consumer in most of the regions that are prone to water shortages, especially in Mediterranean countries. The dual nature of irrigators as victims and originators of droughts justifies the need to gain more insight into irrigators' costs and benefits. Commonly, the decision about how much water is granted to farmers is taken by public agencies that take reservoir levels, other users' demand and environmental constraints into account. As Grigg (1996) reports for the US Federal reservoirs, drought vulnerability has increased not only because water uses have increased in most multi-purpose reservoirs, but because of poor co-ordination among differing data analysis programs "due to the multi-agency nature of drought concern" (p. 538). However, in setting farmers' allotments, it is essential to bring into the decision support systems evaluations of benefits and costs of alternative actions.

Attempts to ascertain the costs to irrigators of water shortages revolve around issues such as adaptation possibilities, unavoidable costs, differing degrees of flexibility of farm input allocation, and the

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expectations farmers can build about future water supplies based on experience with previous scarcity episodes. Keplinger et al. (1998) show that public programs aimed at reducing groundwater pumping with payments to suspend irrigation in dry years are sensitive to the moment at which the program is announced, suggesting differing degrees of farmers' adaptability. Isé and Sunding (1998) explore the personal and financial characteristics of irrigators who volunteer to sell their water rights to the environment, finding that temporary lease-out contracts would add greater flexibility to potential sellers than permanent sales. Howitt and Lund (1999), among many others, provide overwhelming evidence of Californian farmers' ability to respond to water price differences, either fallowing land or substituting crops.

Beare et al. (1998) develop a stochastic reduced-form model to evaluate optimal seasonal water prices and measure various institutional and structural constraints. Their findings show that in presence of uncertain supply, farmers' valuation of water is two to four times higher than would be calculated from their marginal returns under certainty conditions. Venema et al. (1997) develop a dynamic program to optimise the Manantali reservoir in the Senegal river, which serves irrigation and provides hydropower, and evaluate alternative farm policies with large impacts of farmers' water demand. Seminal work by Yaron and Dinar (1982), followed by Bryant et al. (1993) and Ward and Lynch (1996), develops optimisation models that incorporate the marginal values of competing strategies to guide the allocation of water within seasons. Dudley and Hearn (1993) develop a dynamic optimisation model combining a farm model and a reservoir model to manage irrigation water intra-seasonally. To ease the computational load, these papers are based on farms that grow one or two annual crops, are not affected by agricultural policies, do not face the opportunity costs of fixed or semi-fixed farm inputs, and do not make investments in productive assets. However, recent work suggests the importance in modelling farmers' decisions of incorporating tactical adjustments based on updated information (Pannell et al., 2000). Farmers' adaptability to water scarcity is based on more complex cropping patterns that include permanent crops, on their financial situation and on their flexibility to allocate their permanent labour resources. In short, farmers' adaptation to droughts is primarily dependent on the timing of water supply cuts. This conclusion is supported by the findings of Moore et al. (1994) exploring water price response differences across Western irrigation districts. They find that water demand becomes more elastic moving from a short- to a long-run framework, and suggest that land-allocation decisions are more important than crop-level adjustments. Schaible (1997) develops a static multi-output, primal–dual optimisation model to analyse irrigators' behaviour in the presence of alternative and interrelated water sources. The model is used to evaluate agricultural water conservation and the economic impacts of various public water pricing policies under the assumption that farmers' can resort to groundwater or other private sources.

The difficulty of measuring the effects of intra-season and season to season rigidities of farming operations goes beyond testing standard formulations of the Le Châtelier principle. Because drought relief programs aim to compensate farmers' financial losses, it is critical to count on tools that permit economic evaluations of various socio-economic indicators. Moreover, water managers in charge of setting farmers' allotments can be better assisted with optimisation models that make more realistic assumptions about the farmers' adaptation and the financial impacts for differing degrees of water scarcity. However, to provide valid and applicable results, models must make realistic assumptions about three issues that the literature has not explicitly addressed. The first issue is the rigidity of key productive factors such as family labour and capital, which hinders the adaptive capacity of irrigators in periods of low water availability. The second is the way expectations about future water availability are generated, and how irrigators can develop strategic responses to allocate fixed and semi-fixed farm inputs in a dynamic and uncertain environment. And the third issue is the dynamic-recursive framework that characterises farmers' most crucial decisions when operating under uncertain water supply.

This paper has two objectives: first, it attempts to contribute to the literature on farm models used to analyse the economics of irrigation and water use. We propose an original modelling approach featuring a dynamic-recursive structure, in which adaptive expectations about future water supply, as well as imperfect mobility of labour and farm capital assets are assumed. This modelling framework allows for consideration of drought adaptation costs, providing insight into the economic implications of alternative managing criteria of irrigation water when storage facilities permit inter-annual management plans. The second objective is to characterise an actual period of drought and evaluate its economic effects in a Spanish region whose agriculture is highly dependent on irrigation water and is prone to drought cycles and torrential rains. The paper aims to show how farm models can be used to provide valuable inputs into the decision-making processes that are in place in all highly controlled river basin systems. In view of the recently passed European Union Water Framework Directive (European Union, 2000), the paper's main contribution in this area is to highlight the critical issues that the correct measure of the 'resource cost' implies for water management in Mediterranean countries. The model is used in two further applications. In the first, we evaluate the economic benefits of a perfect water supply forecast. In the second, we simulate the results of a simple water banking system in which farmers would be permitted to voluntarily save part of their allotments across seasons.

2. The Guadalquivir Basin, its water institutions and the 1992–1995 drought

The Guadalquivir River Basin (GRB) is located in the southern part of Spain and drains into 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 predominantly agricultural use (about 75% of water use in normal years).

Constitutionally, all water bodies and flows belong to the public domain and are administrated by state basin agencies. To become water users, individuals, companies and official agencies must file an application to the basin agency. Agencies grant corresponding water rights provided water is available in normal years and the applicant shows evidence that the water will be used beneficially with no anticipated impact on senior right-holders, the riverine environment or water quality. A water right is a temporal permit to use a nominal flow for a specific purpose. The basin agency has legal capacity to impose restrictions on the flows or volumes that users can use, based on the allocative criteria laid down in the water Law and the availability of resources stored in the reservoirs (Ley, 46/1999). Effectively, this is the most powerful mechanism in place to facilitate inter-temporal management of water reserves, and develop drought prevention strategies.

The GRB water managers are responsible of developing an inter-temporal strategy that involves deciding how much water is released at a given time, and how much should be stored for future consumption. Ecological flows must be guaranteed year round at levels established in the basin hydrological plans for all river tracts. But as will be explained in detail, water release decisions result from negotiations between authorities, users, stakeholders and other government branches. 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. While the reformed 1999 Water Law made water rights tradable among right-holders, farmers are not permitted to bank their water rights in the reservoirs to sell or use them in later periods (Garrido, 2000). The absence of incentives for users to defer water consumption when scarcity is anticipated places all the responsibility of inter-temporal management of water stocks in the hands of the water agencies.

The GRB encompasses two different management levels, which can overlap in extreme situations. First is the General Regulation System (GRS), which consists of a set of eight main 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 storage capacity is 4046 billion cubic meters. An irrigated acreage of about 200,000 ha 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 urban supply, flood control, hydropower and water quality upgrading. The resources and the civil works associated with the GRS are managed by the RBA. The second management level is typically characterised by a dam which serves a single group of users, who have 'special' rights over its water resources. These dams are placed in tributaries to the Guadalquivir and were erected decades ago—a fact that explains the 'special' nature of the water rights. What is crucial to our analysis, they are managed by users independently of the RBA.

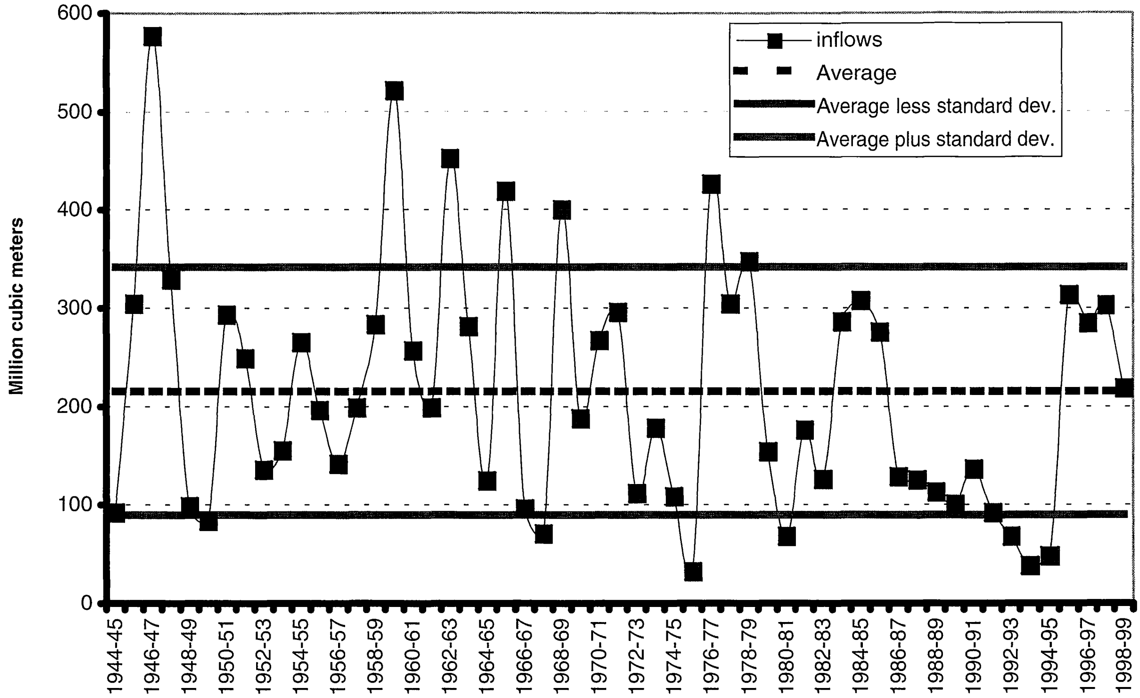

Fig. 1. Annual inflows into the Tranco de Beas Reservoir (Guadalquivir Basin). *Source*: Confederación Hidrográfica del Guadalquivir.

Of course, type two must follow a few general guidelines dictated by the RBA, but unless extreme droughts occur, they simply inform RBA of their operations. Although the Water Law is in principle applicable to both management levels, under normal circumstances they operate independently. Under stressful conditions, such as the 1992–1995 period, intense discussions within key decision bodies in the Basin Agency were reported (Giansante et al., 2002). Fig. 1 shows the records of the inflows into the basin's head reservoir during the last 50 years, and shows that the 1992–1995 was the most severe of the series, as no other dry interval in the series lasted three consecutive years. Nearly 5 million people in the GRB, including cities such as Seville and Cordoba, suffered water service cuts of various duration ranging from 6 h per day to 14 h per day over more than 100 days (EMASESA, 1997). In addition to the service cuts, quality standards were reduced below drinking requirements as a result of the insufficient chemicals dissolution capacity and the high degree of eutrophication in the upstream reservoirs. Losses to the farming sector were evaluated in the range of 3–4.2 billion Euros. About 20,000 jobs were lost in agriculture due to the fallowing of irrigated acreage (EMASESA, 1997).

3. Modelling framework

This model is the third generation of the dynamic model initially developed by Varela-Ortega et al. (1998) to analyse the impact of water pricing policies and updated by Garrido and Gómez-Ramos (2000) to study the economic effects of droughts in a non-recursive manner with perfect mobility of labour and capital and perfect information regarding the occurrence of droughts. The model presented here expands the previous efforts of Iglesias et al. (2000) to simulate more realistically the nature of farmers' decisions in the presence of uncertainty about future water availability, learning capacity about water managers' behaviour, and imperfect mobility of farm permanent labour and capital assets. In a real context, farmers decide on cropping patterns, investments in fixed or semi-fixed productive assets, and family and permanent labour allocation based on the current and expected future values of key parameters, such as water availability or product prices. Most variables that influence the strategies that farmers develop to optimise their resources in an uncertain water environment are dynamic. For instance, farmers can install water saving irrigation technologies to expand the value of their resources, but the resulting benefits will depend on the amount of water that is used. In addition, farmers must anticipate future family/permanent labour necessities in order to manage their farming operations and find alternative work opportunities in case of redundant time availability. When water supply unexpectedly falls, family labour will not have time to adapt and search for alternative occupations. Technically, farmers operate in a dynamic and recursive time-dimension. The decisions made in one season depend on decisions taken in previous seasons, which in turn were based on past knowledge and supported by the then current expectations. However, season to season adaptation is limited by the fact that most farm capital assets are not mobile, and family labour is imperfectly mobile. In mathematical jargon, farmers solve a recursive sequence of dynamic problems in which some choice variables can be revised flexibly, others can only be altered after incurring in high adaptation costs, and a third group of variables are rigidly inherited from previous periods.

3.1. The model

In any given year, say 1990, a farmer is assumed to maximise the discounted flow of net revenues over a planning horizon of J years. We define farmer's net revenues, π_t, for period t as follows:

$$\pi_t = \sum_{i=1}^{I}\sum_{r=1}^{R}(\alpha_{ir}p_{it} - c_{irt} + s_{it})X_{irt} - \sum_{r=1}^{R}\sum_{t=t-P}^{t} g(I_{rt}) + \sum_{r=1}^{R} f_r(EQ_{tr}) + p_L L_t \quad (1)$$

where α_{ir} represents the yield of crop i grown with technology r; p_{it} is the price of crop i in period t; c_{irt} represents the variable costs, including seasonal labour costs, of crop i under technology r in period t; s_{it} is the per hectare subsidy for crop i and period t;[1] X_{irt} the area devoted to crop i, technology r in period t; $g(I_{rt})$—with $g' > 0$; $g'' = 0$—is the function that yields the annual instalments that result from the investment (I_{rt}) made in period t on technology r and previous investments whose debt remain outstanding, which date back at most to period $t - P$; $f_r(EQ_{rt})$—with $f'_r > 0$; $f''_r = 0$—denotes the capital operation and maintenance costs of irrigation technique r, of which the farm has an acreage equal to EQ_{rt}; and L_t is an integer variable representing the number of family/permanent workers required to manage farming operations in period t, whereas p_L represents its opportunity cost.

In each period t the farmer is assumed to optimise the following expression:

$$\Phi_t = \max_{\{X_t, I_t L_t\}} \left\{ \pi_t(X_t, I_t, L_t; \omega_t, \theta_t) + \sum_{j=1}^{J-1} \pi_{t+j}(X^{e}_{t+j}, I^{e}_{t+j}, L^{e}_{t+j}; \omega^{e}_{t+j}, \theta^{e}_{t+j}) \times (1+\gamma)^{-(t+j)} \right\} \quad (2)$$

where γ is the discount rate; $j = 1, \ldots, J-1$ the planning horizon, with J equal to 8 years; X_t is a vector whose elements are the X_{irt}. To ease presentation, we only make explicit the parameter ω_t, which denotes the actual amount of per hectare water available for irrigation; the rest of the parameters are included in the vector θ_t. Eq. (2) makes a distinction between variables and parameters from period t planned decision variables from those indexed by $t + j$, all labelled with a superscript 'e' expected parameter values for future periods. Hence, the farmer, in each period t, is assumed to solve a dynamic problem, the solution to which comprises two groups of variables. The first group, indexed by t, includes decision variables that will be carried out within the current period, while

[1] The 1992 reform of the CAP established crop payments per hectare based on historical yields and partially decoupled from actual production. On average, these subsidies represent about 50% of net income in a normal year in the study area. For a more comprehensive discussion on the CAP reform, see Ritson and Harvey (1997).

the second group, indexed by $t + j$, includes decision variables for the planning horizon J. Φ_t is maximised subject to a set of constraints, of which only the most relevant are explained in the following.[2]

3.2. Water allotment and irrigation technology constraints

$$\sum_{i=1}^{I}\sum_{r=1}^{R}\beta_{ir}X_{irt} \leq S\omega_t, \quad \forall r, t \tag{3}$$

$$\sum_{i=1}^{I}\sum_{r=1}^{R}\beta_{ir}X^{e}_{irt+j} \leq S\omega^{e}_{t+j}, \quad \forall r, t+j \tag{4}$$

$$\sum_{i=1}^{I}X^{e}_{irt+j} \leq EQ^{e}_{rt+j}, \quad \forall r, t+j \tag{5}$$

where β_{ir} represents the water requirements of crop i grown with technology r; S is the farm's irrigated acreage; ω_t the water allowance for the current period; and ω^{e}_{t+j} are the expected values of water availability in subsequent periods. Thus, for any j the ω^{e}_{t+j} represent the expected water allotments in future periods based on the inferred allocation rules, the reservoir's historical inflows and the actual stock levels (see below for details). Constraint (5) limits the acreage of crops irrigated with technology r to the size of the farm section on which r technology is available.

3.3. Modelling the rigidity of productive assets and labour

The irrigation equipment available at the beginning of each period results from the investments made in previous periods plus the newly invested irrigation equipment. Therefore, for period t the availability of equipment of technology r results from:

$$EQ_{rt} = \sum_{t-Q}^{t} I_{rl}, \quad \forall r, t \tag{6}$$

[2] The structure of the model includes a number of equations to make it complete in agronomic, financial and technical aspects of importance to irrigated agriculture. These constraints, added to the dynamic structure of the model, avoid the need to develop further calibration procedures, such as those proposed or reviewed by Howitt (1995). Appendix A includes the complete model specification.

$$EQ^{e}_{rt+j} = \sum_{t-(Q-j)}^{t} I^{e}_{rt} + \sum_{j-Q}^{j} I^{e}_{rt+j}, \quad \forall r, t+j \tag{7}$$

With Eq. (6), in which parameter Q denotes the number of operative seasons of irrigation technology r, we assume that the acreage available of irrigation technology in period t results from previous periods' investments and the new investment made in the same period; Eq. (7) models the fact that planned investments are accumulative. The rigidity stems from the fact that optimal investment decisions must accommodate those taken in previous periods under differing conditions.

With regard to the number of permanent workers, the following equations constrain the choice values for L_t:

$$\sum_{i=1}^{I}\sum_{r=1}^{R}\eta_{ir}X_{irt} \leq L^{S}_{t} \tag{8}$$

$$L^{S}_{t} \leq \delta L_t \tag{9}$$

$$L_t \geq L^{e}_{t-1+j}, \quad \text{for } j = 1 \tag{10}$$

Constraint (8) sums the amount of seasonal labour L^{S}_{t} that results from the product of workers–day per hectare required for each crop i and technique r, denoted by η_{ir}, times the surface devoted to each crop and technique. Constraint (9) translates the amount of seasonal workers into permanent farm workers through the labour supervision coefficient, δ. While constraints (8) and (9) do not impose limits on the amount of contracted seasonal labour, Eq. (10) forces the farm to accommodate the number of permanent workers that was planned the period before in the problem that solves Φ_{t-1}. Intuitively, what Eq. (10) models is the inability to fire permanent workers in the year for which actual plans are being made. In other words, in year t the farmer must meet the opportunity cost of all the permanent workers that were planned in year $t-1$ for year t. The direction of the inequality means that farmers can contract as many new permanent workers or add family members to the farm as necessary.

3.4. Dynamic-recursive structure

The above dynamic model provides the basic structure of a recursive model which incorporates a sequential series of dynamic models. This is where the index t becomes meaningful. The sequence $(t_1, t_2, \ldots, t_8)$ denotes a sequence of actual years, say 1990–1997. In period t_1 the farmer solves the dynamic problem formulated above for a planning horizon of J years taking into account what he knows about the actual water allotment for the current year and his expectations of future allotments, and given some initial conditions of labour, L_0, capital resources, EQ_{r0}, and the cropping pattern, $\boldsymbol{X}_0$.

Let Z_1^* be the solution of the dynamic model in t_1, defined as follows:

$$Z_1^* = [\boldsymbol{X}_1^*, \boldsymbol{X}_2^{*e}, \ldots, \boldsymbol{X}_{J-1}^{*e}, I_1^*, I_2^{*e}, \ldots, I_{J-1}^{*e}, L_1^*, L_2^{*e}, \ldots, L_{J-1}^{*e}] \qquad (11)$$

In Z_1^* the variables with subscript 1 are actual, in the sense that they express actions and farm strategies that will be carried out. The optimal variables with superscript 'e' indicate the actions and strategies that the farmer plans ahead of time for subsequent periods. These differ from the ones with subscript 1 in that those for $j \geq 1$ may be partly revised in future periods. Note, however, that all components of matrix Z_1^* result from a one-shot optimising strategy. Essentially, the matrix Z_1^* represents the best strategy the farmer can develop taking into account the parameters he knows and his expectations regarding parameters in future periods.

When period t_1 is over, the farmer faces the next one, denoted by t_2, and will solve a new dynamic problem that is similar to the one that yielded Z_1^*. However, the conditions prevailing in t_1 will not apply any more because new information becomes available and both current and planned decisions in t_1 will impose some adjustment costs. First, the amount of capital inherited from t_1 results from $EQ_{r0}+I_1^*$; if the farmer has anticipated guessed conditions in t_2 correctly, that amount of capital may be a good starting point; conversely, if his expectations about conditions in t_2 have proven incorrect then he will have to cope with $EQ_{r0}+I_1^*$. In both cases, he must meet the financial liabilities generated from previous investment decisions. Second, the amount of permanent labour will be constraint by L_2^{*e}. This means that in t_2 the farmer must cope with the amount of permanent labour that was planned in t_1 for period $j = 1$. Furthermore, while the model allows irrigators to hire more labour than L_2^{*e}, it assumes that farmers cannot set L_2^{*e} below that level. In period t_{2+j}, for any j, permanent labour will be optimised based on the best information available. With this, we model permanent labour variables in such a manner which allows for an increasing degree of flexibility as the farmer makes plans for longer periods. Also, the model reproduces the lower flexibility imposed by tree crops by allowing increases but not decreases in the acreage that farmers aim to devote to tree crops. If tree crops are planted in t_1, the model carries this decision forward to the initial conditions of the subsequent dynamic problem whose initial period is t_2. Initial conditions are based on the records of the irrigation communities in 1991. Third, in t_2 the farmer will have certain information on his water allotment in t_2, and he will also have updated information on the state of the reservoir, which means that expectations about irrigation water availability in subsequent years will now be revised.

Let Z_2^* denote the matrix of optimal vectors that maximise Φ_2:

$$Z_2^* = [\boldsymbol{X}_2^*, \boldsymbol{X}_3^{*e}, \ldots, \boldsymbol{X}_{2+J-1}^{*e}, I_2^*, I_3^{*e}, \ldots, I_{2+J-1}^{*e}, L_2^*, L_3^{*e}, \ldots, L_{2+J-1}^{*e}] \qquad (12)$$

Generalising to any t, the matrix of optimal values Z_2^* is given by

$$Z_t^* = [\boldsymbol{X}_t^*, \boldsymbol{X}_{t+1}^{*e}, \ldots, \boldsymbol{X}_{t+J-1}^{*e}, I_t^*, I_{t+1}^{*e}, \ldots, I_{t+J-1}^{*e}, L_t^*, L_{t+1}^{*e}, \ldots, L_{t+J-1}^{*e}] \qquad (13)$$

The actual socio-economic effects of a drought during a real sequence of periods $t \in (1, T)$ can be evaluated from the optimum values of the choice variables indexed by subscripts $t = 1, \ldots, T$ selected from the matrices $(Z_1^*, Z_2^*, \ldots, Z_T^*)$. From these, we look strictly at the optimised values that are actually carried out. Hence, what we would observe from the farmers' strategies along a period of normal or drought years is expressed by the following matrix:

$$\Omega^* = [\boldsymbol{X}_1^*, \boldsymbol{X}_2^*, \ldots, \boldsymbol{X}_T^*, I_1^*, I_2^*, \ldots, I_T^*, L_1^*, L_2^*, \ldots, L_T^*] \qquad (14)$$

The components of Ω^* have been generated from a recursive sequence of T dynamic problems, representing a real series of T years, along which drought effects are identified and measured.

3.5. The value of a precise water supply forecast

Several assumptions can be made regarding the way in which farmers formulate expectations about future water availability (ω^{e}_{t+j} in Eq. (4)). Here, we assume farmers can (1) learn from the past, eliciting their water managers' criteria, and (2) make realistic projections about their water allotments, based on the recent historical records of the supply system they are served from and the managers' criteria. The question of whether managers' criteria are systematic and consistent is empirically tested with actual data for each water supply system. Although farmers may build rational hypotheses about their supply system, their projections may nevertheless turn out to be wrong, reducing farm profitability as a result of the rigidities outlined above. Under Mediterranean climatic patterns, the probability of erring is non-negligible.

Let the economic value of a perfect water supply forecast be defined by the following difference:

$$\pi_t(X^{**}_t, I^{**}_t, L^{**}_t; \omega^{p}_t, \theta^{e}_t, X^{**}_{t-1}, I^{**}_{t-1}, L^{**}_{t-1}) \\ -\pi_t(X^{*}_t, I^{*}_t, L^{*}_t; \omega^{e}_t, \theta^{e}_t, X^{*}_{t-1}, I^{*}_{t-1}, L^{*}_{t-1}) \qquad (15)$$

where the ω^{p}_t represents a perfect forecast of each farm's water allotment, the double asterisk label denotes the optimal variables given this forecast. Note that in the value of a perfect supply forecast, no anticipation of other parameters, θ^{e}_t, is made. Thus, if expression (15) is positive, the difference should exclusively be attributed to the fact that water allotments are perfectly forecasted.

3.6. A water banking scheme

The above model allows us to simulate farmers behaviour within a given hydrological sequence of periods under the current institutional context in which water consumption is restricted to the annual water allotment set by water managers on a year by year basis. In this section, we now introduce several modifications to simulate what would have been the drought mitigation impact of a water banking system where by farmers would be allowed to 'bank' part of their water allotment and use it in the following period.

Based on the water banking model developed by Iglesias (2001) for the case of groundwater, we now introduce new decision variables B_t and B^{e}_{t+j} that represent water savings in the current period t and planned periods $t+j$, respectively. Thus, constraints (3) and (4) of the previous model are now substituted by Eq. (3a) that indicates that actual water consumption is now restricted by the water allotment set by the water manager plus the water savings inherited from the previous period, and Eq. (4a) that states that planned water consumption in any future period $t+j$ of the planning horizon will be limited by the expected water allotment plus the expected water savings inherited from the previous period.

$$\sum_{i=1}^{I}\sum_{r=1}^{R}\beta_{ir}X_{irt} \le S\omega_t + B_t, \quad \forall r, t \qquad (3a)$$

$$\sum_{i=1}^{I}\sum_{r=1}^{R}\beta_{ir}X^{e}_{irt+j} \le S\omega^{e}_{t+j} + B^{e}_{t+j}, \quad \forall r, t+j \qquad (4a)$$

Two additional constraints are needed to reflect the dynamics of water savings through periods. Eq. (4b) reproduces the dynamics of water savings across the planning horizon J within each period t, while Eq. (4c), that is introduced in the recursive sequence, reflects water savings dynamics across the actual sequence of periods.

$$B^{e}_{t+j} - B^{e}_{t+j-1} = S\omega^{e}_{t+j-1} - \sum_{i=1}^{I}\sum_{r=1}^{R}\beta_{ir}X^{e}_{irt+j-1} \qquad (4b)$$

$$B_t - B_{t-1} = S\omega_{t-1} - \sum_{i=1}^{I}\sum_{r=1}^{R}\beta_{ir}X_{irt-1} \qquad (4c)$$

Note that since the water banking option will be simulated within a pre-drought and drought sequence of periods, when water stock at the reservoir is at low or very low levels, we may consider negligible the probability of water releases and thus we assume that all the water saved in one period will be inherited in the following period. Also, no evaporation losses are considered.[3]

According to this model structure, farmers now decide, within each hydrological period t, their actual water consumption and water savings that will be available in the following period, based on their

[3] Due to the characteristics of the reservoir, evaporation losses are considered to be relatively low and will not significantly affect the model results.

Table 1
Regression results for the functional relation between farmers' allotments and water stock levels for the *EV* and *BG* districts [$W_t = aS_t + b(S_t)^2 + cD_t^{st} + d(S_t D^{DR}) + e(S_t^2 D^{DR})$]

Coefficient	Definition	EV (1974–1998; $n = 25$)	BG (1977–1998; $n = 21$)
Stock	Values recorded on 1st February measured as percentage of storage capacity	194 (11.33)	216 (14.84)
(Stock)^2	Values recorded on 1st February measured as percentage of storage capacity	−1.27 (−7.26)	−1.35 (−7.23)
Structural dummy[a]	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)
Drought dummy × stock	BG: drought dummy $D_t^{DR} = 1$, for stock <25%, $D_t^{DR} = 0$ otherwise		−443 (−4.15)
Drought dummy × (stock)^2	BG: drought dummy $D_t^{DR} = 1$, for stock <25%, $D_t^{DR} = 0$ otherwise		17.5 (3.41)
Adjusted R^2		0.88	0.95
F-statistics		81.77	82.26
Durbin–Watson		2.01	1.91

Source: Own calculations; t-ratios are in parenthesis.
[a] 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.

actual water allotment for the current period and their expected water allotments in the following period.

4. Empirical application

The above model is used to evaluate the effects of the severe drought that occurred in Spain during the years 1991–1997. Three representative irrigation water districts have been selected for the empirical application. The first, called *El Viar* (*EV*), operates since 1949, has about 500 farmers, encompasses about 12,000 ha and its water supply depends on just one reservoir that is managed by the water users association. The second is *Bajo Guadalquivir* (*BG*), operates since 1974 with about 800 farmers, has an acreage of 15,000 ha and its water supply originates from the pool of resources that can be stored in eight large reservoirs centrally managed by the GRS. The third, called *Genil Cabra* (*GC*) operates since 1989, has 1637 farmers, irrigates a surface of 15,134 ha and uses water originating from the Iznajar reservoir which is one of the eight reservoirs managed by GRS. Districts *BG* and *GC* are illustrative of type one basin management, referred to as centrally managed, while *EV* is an example of type two or self-management, following the terminology described in Section 2. Field work carried out by Sumpsi et al. (1998) permitted the definition of six, two and three representative farms in the *EV*, *BG* and *GC* districts, respectively. Agronomic, financial and technical parameters have been obtained from Sumpsi et al. (1998), and revised field work done by the authors.[4]

4.1. Inferring the rules followed to set farmers' water allotments

About 200,000 ha of irrigated acreage are supplied from the system of reservoirs that is called the GRS of the GRB. The allotment given to each irrigator is set by the basin agency taking into account the reservoir stocks and basic agronomic and technical parameters. Districts *BG* and *GC* are supplied by this management system. In contrast, *EV* is served from an independently managed reservoir with no competing users.

In order to identify the variables that enter the decision rule of the basin agency, we have run two regressions in which the per hectare allotment given to the farmers is the dependent variable. Results for irrigation districts *EV* and *BG* are reported in Table 1.

The results reported in Table 1 for *EV* show that the volume stored, measured as a percentage of total storage capacity at the beginning of the irrigation season—

[4] Appendix A completes the description of the model specification and provides all data sources and documentation. The models have been written in GAMS code and can be obtained from the authors upon request.

1st February—has a key influence on farmers' water allotments. A relative measure of stock was needed for *BG* case because in the last 25 years, a few new dams have been erected adding further storage capacity to the system Of course, new water right-holders have been added as well. We used a relative stock measure in the *EV* model as well to make the results comparable with the *BG* model. The structural dummy variable (D_t^{st}) captures the fact that starting in 1991 farmers shifted their cropping patterns to less consuming crops and that many farmers installed drip irrigation technologies. The absence of lagged values of the February water stock may come as a surprise. Various specifications were tested, adding lagged variables and water inflows, but all led to worse statistical results. The implications of the statistical findings are that: (1) water allotments in a given season are largely explained by the known stock levels at a date prior to the start of the season; (2) regular allotment is given as long as the reservoir reaches about 70–80 mill. cubic meter, irrespective of whether the previous Fall and Winter were dry or wet; (3) allotments have been reduced by about 1000 m^3/ha due to the structural change discussed above.

The implications for the *BG* district are applicable to any other district within the 200,000 ha whose water supply depends on the general regulation of the GRB. Another dummy variable was also included in the model: D_{DROUGHT} is a binary variable that takes value 1 when the stored volume falls below 25% of the total reservoirs' capacity. The model captures 95% of the dependent variable variation, and all coefficients are significant. Figs. 2 and 3 plot the regression results depicting the actual and the fitted values for allocation, measured in m^3/ha, for *EV* and *BG*.

4.2. Modelling rational expectations about future farmers' water allotments

Eqs. (3) and (4) in the model include three types of parameters. First, the average water requirements for each crop i and irrigation technique r specific to each irrigation district, which is denoted by β_{ir}. Second, the farm's acreage entitled to water supply, S. These two parameters are based on the Annual Reports of each district and on personal interviews with agronomists and district managers. Third, the expected water availability in the future, $\omega_{t+j}^{\mathrm{e}}$.

To evaluate $\omega_{t+1}^{\mathrm{e}}$ for each district, three steps were needed. First, we formulate a water balance equation for each water supply system as follows:

$$\tilde{S}_{t+1} = S_t - WR_t + I\tilde{F}_t \qquad (16)$$

where $\tilde{S}_{t+1}$ and $I\tilde{F}_t$ are stochastic variables. $\tilde{S}_{t+1}$ is the state level in year $t+1$ and $I\tilde{F}_t$ are the reservoir net inflows (once security water releases have been accounted for) needed to reach a final state S_{t+1}. WR_t is the annual water release taken from supply system records. Using the historical records of the three water supply systems, we estimate the distribution function

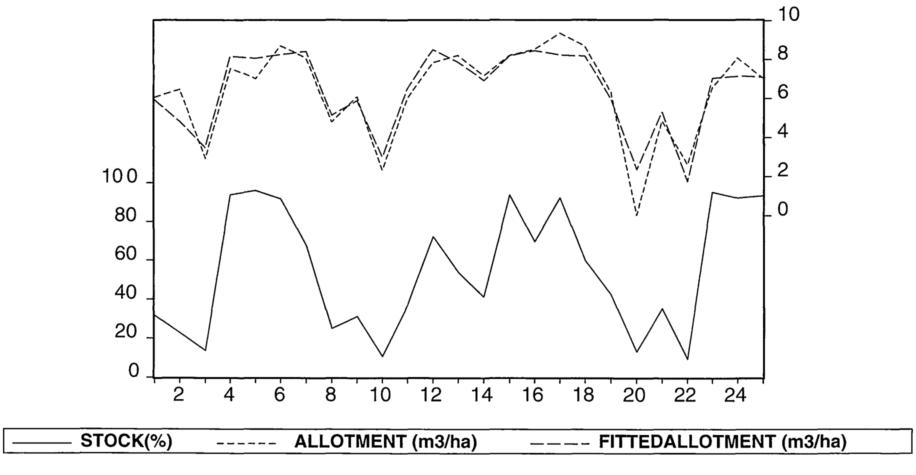

Fig. 2. Water allocation rules in EV (Table 1 provides the statistical results). *Source*: Own calculation.

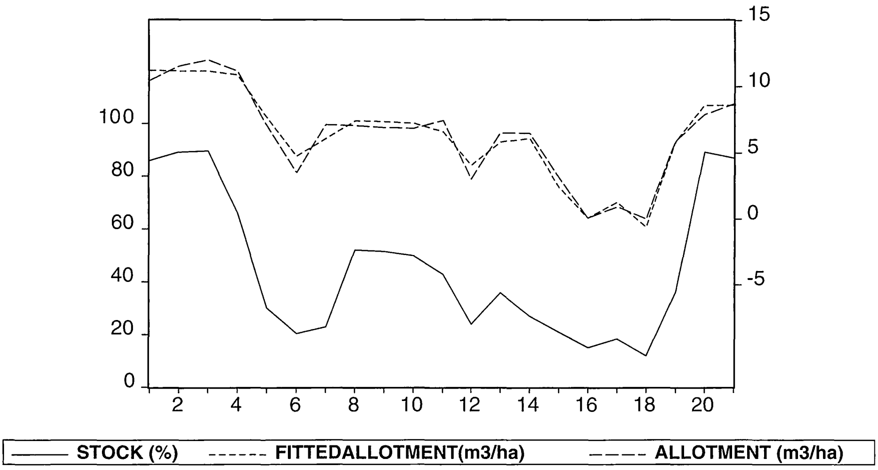

Fig. 3. Water allocation rules in BG (Table 1 provides the statistical results). *Source*: Own calculation.

that provided the best fit for $I\tilde{F}_t$. In all three cases, a gamma distribution provide the best approximation to the recorded data (see Table 2).

In a second step, we conduct a Monte Carlo experiment using the estimated gamma distributions to generate 200 observations of inflows for each supply system and year (from 1991 to 1997). Taking the stock level at the beginning of each year into account, the 200 observations are then inserted in Eq. (16) to obtain an equal number of S_{t+1} values. In the final, we apply the water managers' rules (modelled by the regression results shown in Table 1) to the S_{t+1} values and generate 200 water allotment values. These three steps are carried out for each of the 7 years (1991–1997) in each water supply system. Lastly, the allotment expectations result from

$$\omega^{\mathrm{e}}_{t+1,k} = \bar{\omega}_{t+1,k} - \sigma_{\omega_{t+1}} \tag{17}$$

where k stands for a district and $\bar{\omega}_{t+1,k}$ is the average of the 200 observations and $\sigma_{\omega_{t+1}}$ the standard deviation.

Table 2
Estimation gamma distribution of IF_t

Parameter	GC ($n = 27$)	BG ($n = 37$)	EV ($n = 50$)
Gamma: shape	3.18085	1.836	1.285
Gamma: scale	0.007183	0.0370	0.0102
P-value	0.98	0.311	0.160

Source: Own calculations.

The expectations for more than one period ahead are

$$\omega^{\mathrm{e}}_{t+2,k} = \omega^{\mathrm{e}}_{t+3,k} = \cdots = \omega^{\mathrm{e}}_{t+T,k} = \underline{\omega}_k$$

where $\underline{\omega}_k$ are the average allotments given to farmers since each district became operative. Thus, it is assumed that the initial stock level in year t does not influence more than 1 year ahead.

5. Results and discussion

Table 3 reports the weighted average results for *EV*, *GC* and *BG* districts from 1991 to 1997, where all variables are expressed in Euros per hectare, except for *stock* (which is the stored volume as a percentage of, storage capacity at the beginning of February in the reservoir(s) that service each district) and *allotment* (which is the per hectare irrigation water supplied). For these two variables we report actual values that illustrate the decisions made by water managers between 1991 and 1997 in the GRB. *Shadow price* represents the dual value associated with the water availability constraint (see Eq. (3) above); *gross margin* is the difference between total revenues and variable costs; *net benefits* is gross margin minus fixed costs and financial costs. *VPROD* is the market value of farm output, and provides an indicator of the off-farm social consequences of the drought. All these variables are computed as the weighted averages of

Table 3
Aggregate results for *El Viar* (*EV*), *Bajo Guadalquivir* (*BG*) and *Genil-Cabra* (*GC*)

	1991	1992	1993	1994	1995	1996	1997
El Viar (EV)							
Stock (%)	60	43	13	35	10	96	93
Allotment (m^3/ha)	8600	6310	260	4820	0	6550	8070
Shadow price (Euros/m^3)	0.00	0.08	0.52	0.13	1.24	0.05	0.00
Gross margin (Euros/ha)	1150	601	−350	966	−64	947	1177
Net benefits (Euros/ha)	1002	442	−508	771	−222	764	935
VPROD (Euros/ha)	4111	3521	1434	3777	1654	3943	4334
Hired labour (man–day/ha)	16	16	6	16	5	16	17
Financial costs (Euros/ha)	148	159	159	196	159	183	241
Bajo Guadalquivir (*BG*)							
Stock (%)	27	21	15	18	12	36	89
Allotment (m^3/ha)	6400	3100	70	900	0.0	5900	7900
Shadow price (Euros/m^3)	0.00	0.19	0.54	0.31	0.92	0.02	0.02
Gross margin (Euros/ha)	1536	1218	−48	551	159	513	876
Net benefits (Euros/ha)	1394	1075	−19	396	8	370	604
VPROD (Euros/ha)	3996	3049	756	1674	1006	1964	3459
Hired labour (man–day/ha)	14	8	0.3	2	0	5	13
Financial costs (Euros/ha)	142	143	143	155	152	143	272
Genil-Cabra (*GC*)							
Stock (%)	29	26	15	18	11	29	91
Allotment (m^3/ha)	3600	2020	0	740	0	1580	2740
Shadow price (Euros/m^3)	0.00	0.34	1.32	0.35	1.61	0.11	0.04
Gross margin (Euros/ha)	858	679	−141	428	316	1752	2085
Net benefits (Euros/ha)	661	520	−292	274	165	1580	1749
VPROD (Euros/ha)	3643	2796	964	2160	1444	4122	5085
Hired labour (man–day/ha)	17	10	3	12	3	14	16
Financial costs (Euros/ha)	197	160	151	154	151	172	337

Source: Own calculations.

the representative farms' model results. Finally, *hired labour* is the amount of person–days per hectare of hired workers, and serves as an indication of social performance since Andalusia is the region with the highest unemployment rate in the European Union.

Three stages can be identified in the 1991–1997 period: the first coincides with the inception of the meteorological drought in 1991 and 1992; the second, corresponding with the most severe hydrological drought, runs from 1993 to 1995; and the third, beginning in 1996, represents a very wet period resulting from abnormally high rains in the fall of 1995.

The drought had severe consequences in the farming sector although impacts were larger for *EV* and *GC*, than for *BG*. As expected, the drought had different impacts on farmers, workers and society as whole. For instance, in *EV* farmers' benefits diminished more in relative terms in 1993 and 1995 than the amount of hired labour and the market value of production, which experienced a maximum reduction of about 60% in the worst season (1993). In *BG* farmers experienced lower net losses in 1993 than *EV* and *GC*, although farm workers remained completely idled 1995. However, the reduction of the production value was less than the reductions experienced in farmers' benefits and farm labour demand. The results for *GC* show that farmers experienced more difficulties than their farm workers, who on average worked 60% less than in normal years. This result is explained by the significant acreage devoted to olive trees under irrigation by most *GC*'s farmers. While the trees do tolerate soil dryness, they still bear some production that must be harvested at low labour efficiency rates.

These differences arise because farming systems have evolved differently in each irrigation community, not only due to different natural endowments such as soils and climate, but also because the conditions under which irrigators can make use of their water allowances vary across districts. *GC* is a modern district compared to the other two, but has worse soils and lower allotments. Many farmers grow olive trees, which adapt well to drip irrigation technologies and to low quality soils, and bear production even in conditions of soil moisture stress. The shadow prices in *GC* indicate that its farmers have adapted well to low water allowances. For instance, in 1991 the shadow price is zero with an allowance of just 3600 m^3/ha, which is about half the allowance needed in the *EV* and *BG* districts to reach a zero shadow price. The other districts are used to larger allotments and their preparedness for scarcity is poorer due to low water conveyance efficiency and the tendency to grow water-consuming crops such as corn (*EV*) and cotton (*EV* and *BG*).

The results for 1994, when all districts got some irrigation water, merit specific discussion. While in *BG* farmers got one seventh of their regular allotment, their net revenues went down by a maximum of 50%, the market value of production experienced a 25% reduction, and labour demand contracted by 45%, all measured against the average of the 8-year period. As a result of a more conservative behaviour in the previous years, *EV* was able to enjoy a lower allotment reduction. This explains why *EV*'s results were similar to those achieved in normal seasons. Also its farmers were favoured by high product prices, particularly cotton, that prevailed in 1994 as a result of the contraction of cotton supply caused by the drought. *GC* had slightly worse results in 1994 than in 1991 and 1992, although its farmers used only one third of the water they did in pre-drought years.

Although of similar qualitative importance, water scarcity's effects on farmers were more severe in 1993 than in 1995. There are two explanations for this result. First, the European Union switched its farm income support mechanisms from minimum prices to partially decoupled direct payments per hectare, providing farmers with a revenue cushion which was not in place prior to the 1994 marketing season. Second, since stocks were very low in the in-between 1994 season, farmers may have anticipated the occurrence of the 1995 drought 1 year in advance, giving them some flexibility to adjust their permanent labour resources and their savings and consumption pat-

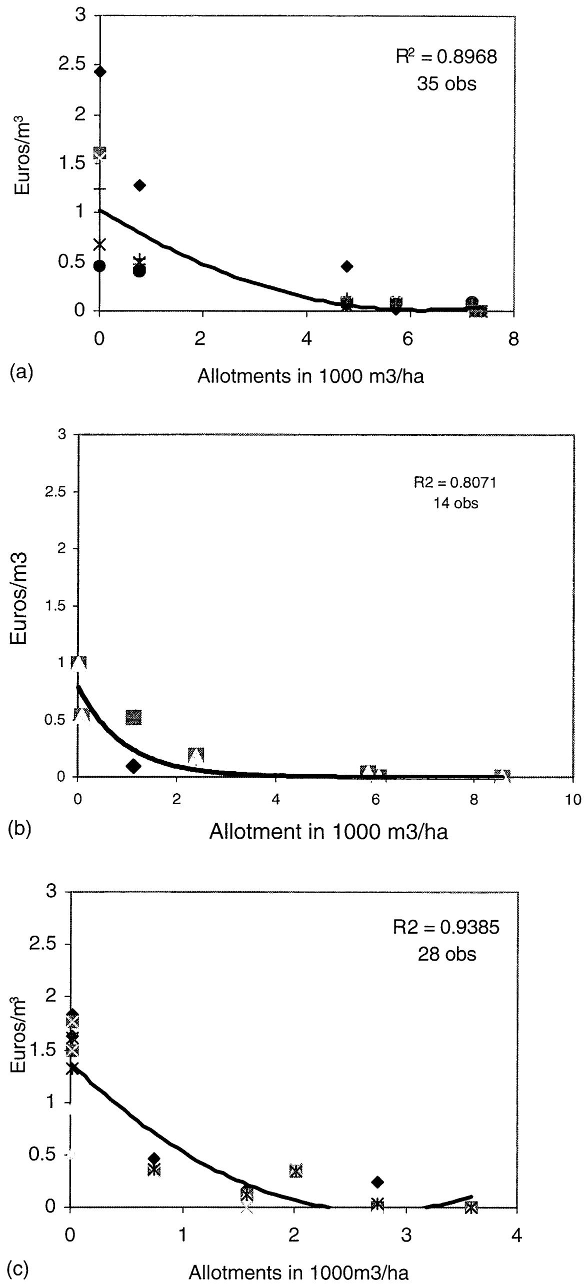

Fig. 4. (a) Shadow prices vs. allotments (EV). *Source*: Own calculation. (b) Shadow prices vs. allotments (BG). *Source*: Own calculation. (c) Shadow prices vs. allotments (GC). *Source*: Own calculation.

terns. This second effect is picked up by the model's dynamic-recursive structure and the way rational expectations about the understanding of each district's institutional rules were modelled.

Fig. 4a–c display the relationship between the shadow price of water and the water allotment for each farm in EV, BG and GC, respectively, for each of the seven seasons. Since market conditions change across seasons—the ceteris paribus clause does not hold—these figures do not represent water demand schedules. Despite the limited number of observations and the limited variation of x-axis values, in all three districts the clusters of points describe convex curves that cut the horizontal axis at allotments that correspond to normal years.

These curves demonstrate that significant benefits are foregone as a result of excessive deliveries when water saving possibilities are present. Because a unit of water that is not conveyed during a wet year has a shadow price of almost zero, the opportunity cost of keeping it in the reservoir is conditioned by the probability that torrential rains will fill up the reservoir, making it necessary to release water for flood prevention. This is a very unlikely event when reservoirs are at 27% capacity as was the case for *BG* and *GC* in February 1991.

In Table 3, the rows reporting the value of 'stock' and 'allotment' show that despite the fact that the stocks below 30% should have signalled increased risk of drought, BG's water allotments were set at almost normal levels in 1991. Even more striking is the fact that the shadow prices of water at these levels suggest that the cost of reducing the risk of suffering a drought would have been virtually zero. The high probability of experiencing a dry year and the high shadow prices during drought seasons, i.e. 1993 and 1994, show that the opportunity cost of this rather risky behaviour in previous years was considerably high. For instance, one cubic meter saved in season 1991 had no value at the margin in *BG* and *GC*, while having this water available during the 1992 season would have provided 0.18 and 0.34 Euros in BG and GC, respectively, and about three times more in 1993.

In an attempt to evaluate the benefits that would result from perfect water supply forecasts, we run the farm models with actual values for the right-hand side of Eq. (4) for $j = 1$. Hence, instead of running the model with $\omega_{t+1}^{\mathrm{e}}$, we inserted the real value, denoted by $\omega_{t+1}^{\mathrm{p}}$. With this change, the model allows us to simulate the strategies that irrigators would pursue in year $t - 1$ if they could anticipate the water supply cuts imposed in year t. Table 4 reports the resulting gross margins (in Euros/ha) for representative farms in 1993 and 1995. The results show that for some farms a perfect water supply forecast would not change their economic results. This is the case for irrigators who

Table 4
Change in gross margin (Euro/ha) resulting from a perfect water supply forecast

Representative farms	1993			1995		
	Expected water supply	Perfect forecast	Change in gross margin	Expected water supply	Perfect forecast	Change in gross margin
EV-1	−1118	−1118	0	−595	−595	0
EV-2	−986	−397	589	−781	−337	445
EV-3	36	150	114	481	715	234
EV-4	48	198	150	96	397	301
EV-5	118	433	314	397	697	301
EV-6	120	421	301	493	787	294
GC-1	−745	−745	0	−222	−222	0
GC-2	−48	192	240	463	697	234
GC-3	−30	204	234	288	517	228
GC-4	36	276	240	391	739	349
BG-1	−230	224	454	39	533	494
BG-2	224	224	0	339	533	194
Average			219.7			256.2
Standard deviation			183.1			148.7

Source: Own calculations.

have very limited flexibility to change their cropping patterns and their labour force, for instance, irrigators with large acreages devoted tree crops. However, as shown in Table 4, most irrigators would have been able to reduce their costs and adapt their cropping patterns if they had known that they were going to experience severe water supply cuts in 1993 and 1995. A rough estimate of the economic gains from perfect forecasts for the 400,000 ha of irrigated land in the GRB is between 73 and 109 million Euros per year (taking as reference points the averages for 1993 and 1995). This corresponds to about 5% of the average annual gross margin. Of course, these estimates represent an upper bound as perfect forecasts are inherently impossible.

The model is used to simulate a simple banking system in which each farmer is allowed to voluntarily store part of his allotment in the reservoirs and use it in following years. Table 5 reports water allotments, water consumption and water savings left is the reservoirs for the next period. The last column reports the resulting changes to the gross margin compared with the current situation with no banking option. The results indicate that irrigators facing uncertain water supplies would probably be interested in using the banking option as a strategic response to reduce their vulnerability to drought periods. In quantitative terms, the banking system would be used more intensively by irrigators in EV and GC than in BG. This is because their managers already mandated in 1992 severe allotment cuts, eliminating the incentives to save water for the following years.

The results show that the water banking option would have considerably mitigated the severe 1993 drought impact at a relative low cost. While water saving efforts in periods 1991 and 1992 represent approximately 2–10% of the annual gross margin, much better economic results would have been obtained in the 1993 drought period, as it is reported in Table 5. On the other hand, it is shown that little could have been done to mitigate the persistent 1995 meteorological drought, even with a water banking scheme.

The accumulated gains for the 7-year period resulting from the banking system follow the same pattern. They represent about 66 and 88% of the average annual gross margin without banking in EV and GC, respectively, and 32% in BG. The comparison of the reduction in gross margins in the saving years and the gains accrued in the drought years clearly demonstrates that the criteria by which allotments have been set in the GRB result in welfare losses.

Table 5
A water banking scheme

	Water measurements (m^3/ha)			Gains/loses: change in gross margin (Euros/ha)
	Allotment	Water savings	Used water	
El Viar (EV)				
1991	8.60	2.72	5.63	−75.24
1992	6.31	3.40	5.33	−67.86
1993	0.26	0.03	3.14	821.47
1994	4.81	0.53	4.67	−37.42
1995	0.01	0.00	0.09	146.74
1996	6.56	0.72	6.51	−0.29
1997	8.07	3.71	5.08	−53.63
Net gains				734
Bajo Guadalquivir (BG)				
1991	6.40	1.09	5.31	−108.16
1992	3.10	1.11	3.08	−7.10
1993	0.07	0.00	1.19	417.26
1994	0.90	0.00	0.90	−0.79
1995	0.01	0.00	0.01	−33.20
1996	5.89	0.00	5.89	−1.15
1997	7.87	3.09	4.79	0
Net gains				267
Genil-Cabra (GC)				
1991	3.60	1.99	1.61	−106.09
1992	2.02	2.10	1.90	−15.81
1993	0.00	0.58	1.53	890.38
1994	0.74	0.12	1.21	122.03
1995	0.00	0.00	0.13	156.23
1996	1.58	0.00	1.58	−55.62
1997	2.74	1.14	1.60	−128.33
Net gains				863

Source: Own calculation.

6. Concluding remarks

A dynamic-recursive mathematical programming model is developed to analyse the economic effects of hydrological droughts in three Spanish irrigated districts. Results illustrate the strategic value of water to irrigators under the influence of Mediterranean climate, and demonstrate the extent to which their economic performance depends on the criteria applied by the water managers to run the storage facilities.

A farm's vulnerability to drought partly depends on its ability to overcome the rigidities imposed by imperfectly mobile labour and capital. The results show that the farmers who exhibit the highest adaptation capacity to severe drought episodes are not those who operate under tight water supply regimes. Adaptation capacity is rather driven by natural factors, such as soil productivity under rain fed conditions, and farms' flexibility to respond with appropriate crop rotations. Since farmers subject to tight water supply regimes tend to rely on precision farming techniques, they are financially more vulnerable than less capitalised farmers. The same applies to farms with permanent crops and to small farms overstaffed by permanent workers or family members.

The literature suggests that adaptation capacity is also driven by the timing of allotment reduction announcements. We have adapted the modelling approach to estimate the gains that would result if farmers had perfect forecasts of their allotments 1 year ahead. The results indicate that the gains are non-negligible but relatively modest at about 5% of the gross margin in a normal hydrological year. This suggests that farmers' guesses of future availability, based on rational calculus and learning capacity, has helped them develop anticipatory strategies.

Two pieces of evidence suggest that the supply systems that service the three studied irrigation districts could be more efficiently managed. First, large differences in water shadow prices across periods are found for the three districts. These differences indicate that lower allotments during meteorological droughts when reservoirs are at medium capacity could ensure a higher economic returns in subsequent periods. The opportunity costs incurred in pursuing more prudent strategies are largely overshadowed by the likely benefits in ensuing seasons, even given the highly unstable rainfall regimes that prevail in the region of study. This result also shows that 'taking the resource cost into account, as is suggested in the Water Framework Directive becomes a more complex issue when water storage infrastructure is present. Under these conditions, reservoir management plays a crucial role and the current shadow value of water demand with a man-made water supply does not necessarily provide the correct measure of resource cost.

The second piece of evidence is provided by the simulation of a voluntary water banking scheme. Results indicate that the incentives to save water across periods would result in lower consumption rates when stocks are at medium capacity and signalling an increasing likelihood of future supply cuts. Farmers would occasionally decide to bank part of their water rights following simple expectations in response to the opportunity cost of water. Over a 7-year period the accumulated gains from a voluntary savings scheme are in the range of 32–88% of the average annual gross margin. This finding supports the recommendation that prior to establishing water markets, which are complex institutions and not always very active, water institutions should begin by defining special types of water rights which promote voluntary water savings across seasons. Determining to what extent this represents a significant departure from the way water rights have been traditionally defined in the GRB constitutes a promising research area of interest to other water-stressed regions as well.

This research suggests two further lines of work. First is the translation of key hydrological variables into economic and social indicators. If the water volumes stored in reservoirs at different times span a real-time vector of socio-economic indexes, the decisions on how to manage stocks inter-temporally would be more efficient from both private and social perspectives. More sophisticated analysis using risk measurements and financial management methods jointly with hydrological methods could provide valuable services to regions whose economy depend on surface waters. Second, linked to the economic evaluation of pro-active and re-active strategies for mitigating the effect of drought, our model could easily be extended to accommodate palliative financial loans, deterrent irrigation water charges and other options identified in the literature.Funds supporting this research come from a European Project Research Project titled: *Societal and Institutional Responses to Climate Change and Climatic Hazards: Managing Flood and Drought Risks* (*SIRCH*). Contract no. ENV4-CT97-0447, 1998–2000. Previous versions of this paper were presented at the XXIV International Conference of Agricultural Economists, Berlin, 13–18 August 2000 and at the Tenth Annual Conference of the European Association of Environmental and Resource Economists, June 2000, Crete. We appreciate the comments made by discussants, chairpersons and the members of the audience. We also benefited from comments made by Tom Downing, Karen Bakker, Richard Tol, Yacob Tsur and Wietze Lise.

Appendix A

In addition to the equations outlined in the text, the empirical model is completed by the following constraints:

(i) Crop rotation constraints:

$$\sum_{r=1}^{R} X_{irt} \le \sum_{r=1}^{R}\sum_{m=1}^{M} X_{mrt-1}\mathrm{ROT}_{ii}, \quad \forall i \qquad \text{(A.1)}$$

where ROT_{ii} is a $i \times i$ matrix of binary elements that represent rotation constraints among crops. Initial conditions are X_{mr0} for each representative farm, based on field work carried out by Sumpsi et al. (1998) and revised by the authors.

(ii) Financial constraints:

$$\pi_t + \pi_{t-1} + \mathrm{SRL}_t - \rho\mathrm{SRL}_{t-1} \ge \mathrm{MIN} \qquad \text{(A.2)}$$

where π_t is defined by Eq. (1) in the text; SRL_t is a endogenous variable representing the farm's short-term indedtedness; ρ is the interest rate for short-term loans; and MIN denotes minimum survival income (a parameter representing the annual cash needed by the family farm to cover basic living costs). In Eq. (1), the liabilities resulting from investment in irrigation equipment are included in π_t.

(iii) Calibration and agricultural policy constraints:

Set aside constraint:

$$\varphi\sum_{r=1}^{R}\sum_{i'\in I}^{I} X_{i'rt} \le \mathrm{SETASIDE} \qquad \text{(A.3)}$$

This constraint ensures that the area devoted to crops indexed by i' meets the set aside requirements imposed by the Common Agricultural Policy of the European Union. SETASIDE is thus an activity that occupies a fraction of the land devoted to crops that are entitled to CAP direct payments.

Calibration constraints:

$$\sum_{r=1}^{R}\sum_{i''\in I}^{I} X_{i''rt} \le \xi_{i''}S, \quad \forall i'',\ i'' = 1\text{–}4 \qquad \text{(A.4)}$$

This constraint binds the area that each representative farm can allocate to different groups of crops. Four crops groups have been defined for all districts' representative farms: industrial crops (including cotton and sugar beets), CAP crops (corresponding with the group i defined above), horticultural crops (including tomato, asparagus, melon, water melon, onions and so on) and tree crops (including orange, peach and olive trees). The coefficients $\xi_{i''}$ represent limits to the land that can be allocated to each group of crops. These coefficients are based on: the crops grown in each district during each of the seven seasons between 1991 and 1997 (as recorded by the districts' data bases), field work including interviews with the districts' managers, and previous work in the same districts carried out by Sumpsi et al. (1998). In all cases, the values for $\xi_{i''}$ that are specific for each representative farm have been augmented by 20% to provide a reasonable degree of flexibility. No lower bounds are imposed, except for tree crops. This last constraint is justified by the field work findings which provide no evidence of farmers cutting down their trees as a result of water supply cuts, even in the most acute drought situations.

(iv) Parameters and initial conditions for each representative farm model:

Fixed parameters	Representative farms											
	EV-1	EV-2	EV-3	EV-4	EV-5	EV-6	BG-1	BG-2	GC-1	GC-2	GC-3	GC-4
S (ha)	5	5	40	40	100	100	12	30	5	25	50	50
φ (set aside) (%)												
MIN	0	0	10	10	10	10	10	10	0	10	10	10
MAX	0	0	15	15	15	15	15	15	0	15	15	15
$\xi_{\text{industrial}}$ (%)	15	50	50	50	50	50	80	80	80	80	80	80
ξ_{CAP} (%)	12	100	60	60	60	60	100	100	100	100	100	100

Appendix A (*Continued*)

Fixed parameters	Representative farms											
	EV-1	EV-2	EV-3	EV-4	EV-5	EV-6	BG-1	BG-2	GC-1	GC-2	GC-3	GC-4
$\xi_{\text{horticult}}$ (%)	15	2.5	2.5	2.5	5	4	10	10	10	10	10	10
ξ_{trees} (%)	100	100	12	0	20	10	0	0	20	20	20	20
ρ (interest rate)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Initial conditions												
L_0 (permanent labour)	0	0	1	2	2	2	1	2	0	1	2	2
π_0 (initial cash) (1000 Euros)	6	6	120	120	300	360	36	84	12	48	150	120
$EQ_{0,\text{sprinklers}}$ (%)	0	0	0	0	0	0	0	0	100	100	100	100
$EQ_{0,\text{dripping techn}}$ (%)	0	0	0	0	0	0	0	0	0	0	0	0

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