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Irrigation Water: Alternative Pricing Schemes Under Uncertain Climatic Conditions

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1. Introduction

The European Water Framework Directive (European Union, 2000; herein, WFD) aims to protect the environmental quality of water and encourage its efficient use. The EU member states are required to implement effective water-management systems and appropriate pricing methods that ensure the adequate recovery of water costs. These directive also relates to the pricing of water for agriculture. However, a general framework specific methodologies used by each country to establish water tariffs is not yet available.

Furthermore, it appears that numerous exceptional rules of contexts prevent the adoption of uniform pricing guidelines even within individual countries (OECD, 2010).

In the past decade, various studies have focussed on the pricing of irrigation water. Albiac and Dinar (Albiac & Dinar, 2009) published an up-to-date review of approaches to the regulation of non-point-source pollution and irrigation technology as a means of achieving water conservation, and Molle and Berkoff (2007) performed a thorough analysis of pricing policies worldwide, touching on multiple aspects related to water policy reform, primarily in developing countries. Tsur and others (Tsur et al., 2004) presented a similarly wide-ranging analysis. Most of these studies based their conclusions on the results of numerical modelling and generally did not consider the uncertainties that farmers face in making decisions (Bazzani et al., 2005; Riesgo & Gómez-Limón, 2006; Bartolini et al., 2007; Berbel et al., 2007; Semaan et al., 2007; Dono, et al., 2010). However, uncertainty related to climate change is an important aspect of decision-making in the context of the management of agro-ecosystems and agricultural production. In this regard, process-based crop models, such as Environmental Policy Integrated Climate (EPIC) (Williams et al., 1989), have been widely used to simulate crop response to changing climate, addressing the problem of assessing the reliability of model-based estimates (Niu et al., 2009).

Climate change related to the atmospheric accumulation of greenhouse gases has the potential to affect regional water supplies (IPCC, 2007). In particular, the long-term scenarios calculated by most global and regional climate models depict a greater reduction in precipitation with decreasing latitude in the Mediterranean area (Meehl et al., 2007). This result is important because reduced water availability could result in heavily reduced net returns for farmers (Elbakidze, 2006).

There are various sources of uncertainty in climate change simulations (Raisanen, 2007), including those associated with the nature of the direct relationships between climate variability and water resources, given the strong influence on such relationships of land cover (Beguería et al., 2003; García-Ruiz et al., 2008) and water-management strategies (López-Moreno et al., 2007). The main problems for irrigation reservoirs are that they must be filled at the beginning of the irrigation season, whereas the filling season is characterized by a large uncertainty. Consequently, the management regimen of the reservoir, and even the pricing of its water resources, must be adjusted to the variable conditions of inflow.

2. Aim of the study

The present study assesses the economic effects and influence on water usage of two different methods for pricing irrigation water under conditions of uncertainty regarding the accumulation of water in a reservoir used for irrigation. For this purpose, several simulations are performed using a Discrete Stochastic Programming (DSP) model (Cocks, 1968; Rae, 1971a, 1971b; Apland et al., 1993; Calatrava et al., 2005; Iglesias et al., 2007). This type of model can be used to analyse some of the uncertainty aspects related to climate change (CC) because it describes the choices open to farmers during periods (stages) in which uncertainty regarding the state of nature influences their economic outcomes. The DSP model employed in this study represents a decision-making process based on two decisional stages and three states of nature, reflecting different levels of water accumulation in the reservoir (Jacquet et al., 1997; Hardaker et al., 2007; Dono & Mazzapicchio, 2010).

The model describes the irrigated agriculture of an area in North-Western Sardinia where water stored in a local reservoir is distributed to farmers by a water user association (WUA). Simulations are executed to evaluate the performances of the different water-pricing methods when the conditions of uncertainty regarding water accumulation in the dam are exacerbated by the effect of climate change on winter rainfall[1]. In fact, the model simulations are first executed in a present-day scenario that reproduces the conditions of rainfall and water accumulation in the dam during 2004[2]. The model is then run in a scenario of the near future, which is obtained by projecting to 2015 the rainfall trends of the last 40 years[3].

Among the various productive and economic impacts of the methods for water pricing that the WUA may apply, particular attention is paid to examining the changes in the extraction of groundwater from private wells in the various scenarios. This resource is used by farmers

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[1] Rainfall is most abundant in winter, making this season the most important in determining the level of water accumulation in the dam.

[2] The present-day scenario focuses on 2004 because a detailed sequence of aerial photographs, showing land use in northwest Sardinia throughout the agricultural season, is available for this year, courtesy of the MONIDRI research project (Dono et al. 2008). These photographs enable us to evaluate the ability of the model to replicate the choices of farmers in terms of soil cultivation.

[3] We chose a near-term future scenario because the Italian agricultural policy barely extends beyond 2013, given the upcoming implementation of the Common Agricultural Policy. The climate scenario for this period will be crucial for farmers in terms of deciding to adhere to the RDP measures that support adaptation strategies to climate change. In addition, extrapolating trends to a longer-term climate results in greater uncertain regarding the quality of the climate scenario. Finally, a longer-term scenario would increase the likelihood that the farm typologies and production technologies considered in this study would have become completely obsolete.

to supplement dam water, and its over-extraction is a key issue of environmental protection in the Mediterranean context.

3. Background

3.1 Payment schemes

In Italy, irrigation water is distributed by local associations of farmers (WUA) that 'water storage and distribution facilities developed mainly using public funding. In line with the guidelines of the WFD, Italian WUAs charge the associated farmers for the operating costs of water distribution, the maintenance costs of water networks, and the fees paid to local authorities, representing the opportunity costs of water and the environmental costs of providing the water. This set of items is herein referred to as the cost of water distribution (WDC, Water Distribution Cost). In most cases, the water storage and distribution facilities were built with public money, meaning that their long-term costs (depreciation and interest) are not included in the budgets of the WUAs, which only manage the water distribution service. Consequently, these costs are not included in farmers' payments to the WUA for irrigation costs. Note that there is a recent trend for farmers to co-finance investments in irrigation infrastructure, in which case the farmers also bear the long-term costs in proportion to their participation.

WUAs adopt various methods for charging WDC, with the most widely used being a fee that is paid per irrigated hectare. Some WUAs levy a two-stage fee (binomial system).

The per-hectare fee has traditionally been the most widely adopted method in Italy because it is the simplest to manage in terms of charging farmers. In fact, WUAs compute WDC at the end of the irrigation campaign and divide it by the amount of farmland that water was supplied to by the collective irrigation network, regardless of whether the land was irrigated; consequently, this approach bears no relation to the amount of water used by farmers.

The two-stage system comprises a *basic payment* and a *water payment*. The *water payment*, directly or indirectly linked to water use, is computed by multiplying the unit price of water by the amount of water used by farms. *Water payments* that are directly linked to water use are calculated based on readings from water meters installed at farm gates, while those that are indirectly linked to water use are calculated by estimating the water needs (per hectare) for each irrigated crop. The unit price of water is usually defined before the beginning of the irrigation season and is generally set below the expected average WDC. Farmers are then asked for a *basic payment* which covers general and maintenance costs and that is usually charged to individual farms according to the area of land equipped with the collective irrigation network. The *water payment* component of this two-stage system can be calculated using two different methods.

A VPM (Volumetric Payment Method) approach is used in the case that water meters are installed and functioning on every farm (as this enables water use to be monitored). This approach does not usually apply when water is delivered to the farm gate by gravity-fed canal networks. National and Regional Governments commonly provide financial support to encourage a switch from canal to pipeline systems and to install farm-gate meters as part of collective networks. This financial support aims at reducing water losses from the network and providing a better service to farmers, but also at metering water supplied to farms and encouraging the switch to VPMs.

Alternatively, *water payments* are calculated using an Area-Based Pricing Method (ABM), which estimates the unitary irrigation requirements for each irrigated crop (i.e., crop-based charges). Some WUAs calculate large, accurate sets of estimates that vary according to crop type, irrigation technology, soil characteristics and climatic conditions. In contrast, other WUAs refer to broad groups of crops with different unitary irrigation requirements, although this approach yields only a rough estimate of farm water use. In the case that an ABM is employed, farmers must apply to the WUA for water by reporting their irrigation plan at the beginning of the season. The WUA then checks if the actual extent of irrigated crops is consistent with the irrigation plan (to prevent the avoidance of payments in the case that the plans show fewer crops than actually cultivated). In the event of severe drought, during which time farmers are forced to leave fields fallow, payments are calculated based on the actual extent of irrigated crops, not solely on the cultivation plan presented beforehand.

ABMs are based on irrigated acreage and the water needs of crops, irrespective of whether the water comes from a WUA network or from farm wells, thereby generating an indirect charging effect on groundwater. VPM is widely supported in technical and political debates because it directly links water payments to the amount of water delivered to farmers. However, for both pricing models, water charges are set by WUAs in order to recover the WDC. The use of the average cost in these calculations deviates from the prescription that a fully *efficient* allocation scheme for a scarce resource such as water should be based on balancing the marginal net benefits of its uses (Perman *et al.*, 2003). However, these methods of charging farmers, even if economically imperfect, are easily manageable by WUAs.

3.2 Study area

The study area covers the Cuga River basin in the Sassari district, northwest Sardinia (Italy), comprising 34,492 ha of farmland (Figure 1). On 21,043 ha of this area, around 2,900 farms receive water from the Nurra WUA, distributing the surface water stored in two man-made lakes, Cuga (30 million m^3) and Temo (54 million m^3).

The WUA distributes only surface water: groundwater is managed by farmers as a private asset. In this system, the water stored in the two lakes is shared between urban and farm uses. In the case of a water shortage, urban uses are given priority and farmers respond by using water from private wells, if available.

Surface water is distributed via two interconnected network systems that differ in altitude (i.e., for low and high land). For lowland areas, water from the two lakes is directly introduced into pipelines and distributed by gravity. For highland areas, water is first pumped into gathering basins located at a relatively high altitude, from where it flows downward under gravity through a network of pipelines. In 2004, the two systems carried similar volumes of water. The water fees paid by farmers are aimed at recovering the WDC incurred by the WUA. Since 2001, the pricing method has been VPM, whereby farmers pay 0.0301 €/m^3 (in 2004) as a *water payment* for the water they use, measured via farm-gate meters installed at each farm of the WUA. Before 2001, the Nurra WUA adopted an ABM based on per-hectare estimated water use for three different groups of crops (Table 1)[4].

[4] In the study area, water meters were installed at farm gates with a financial contribution from National and Regional Governments.

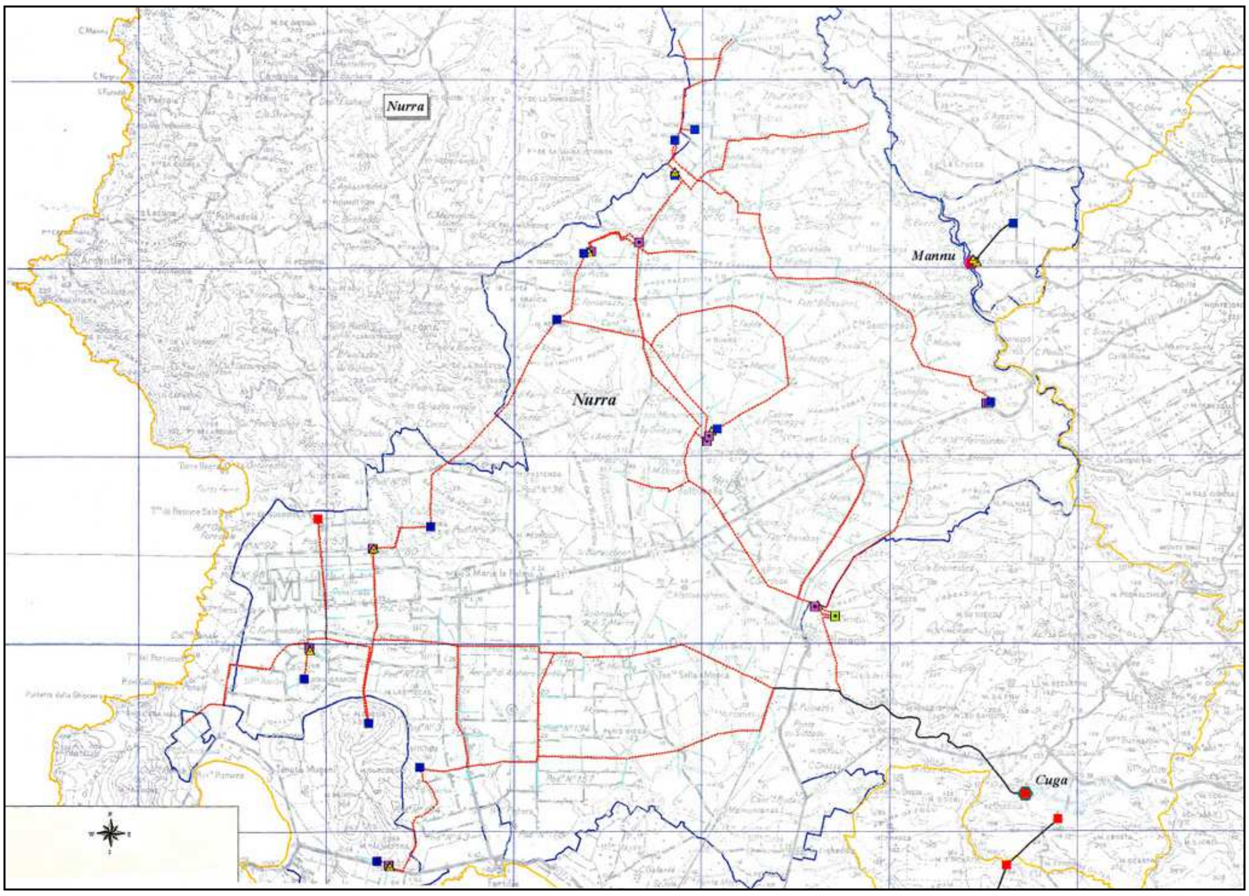

Fig. 1. WUA area of Nurra, North-Western Sardinia (Italy). Blue lines are the WUA boundaries; black line is the main channel from the reservoir to the pipeline network; redis the pipeline network.

	Areas served by the WUA					Areas ***not*** served by the WUA				
	Well	No. of farms	Ha per farm	Cattle (heads)	Sheep (heads)	Well	No. of farms	Ha per farm	Cattle (heads)	Sheep (heads)
Cattle, L**		2	532.4	1,558	-			-	-	-
Cattle, S		5	37.6	280	-	w	27	12.6	1,026	-
Crops, L	w*	139	66.1	-	-	w	52	55.8	-	-
Crops, M	w	28	10.2	-	-	w	148	7.7	-	-
Crops, S		1,509	0.7	-	-	w	540	0.9	-	-
Olive, M	w	33	12.3	-	-	w	25	13.4	-	-
Olive, S		543	0.8	-	-	w	542	1.0	-	-
Horticultural, M	w	41	14.8	-	-	w	8	8.7	-	-
Horticultural, S	w	49	2.8	-	-	w	10	2.1	-	-
Sheep, M	w	34	64.1	-	57,578	w	33	76.3	-	14,398
Sheep, S	w	94	26.1	-	40,353	w	45	34.4	-	21,273
Vineyards, L	w	1	693.0	-	-			-	-	-
Vineyards, M	w	136	2.7	-	-	w	44	2.0	-	-

** Farm possesses a private well.*
*** L, Large; M, Medium; S, Small.*

Table 1. Farm typologies in the areas served and not served by the Nurra WUA.

There are no official data on the extraction of water from wells; however, the WUA's engineers have estimated that the annual withdrawal of groundwater is between 2.5 and 4 million m^3, depending on how much water from the dams is provided for agricultural use. The number of wells owned by farms, as well as their location and technical features, has been identified from Agricultural Census data and from data compiled as part of the RIADE Research Project, jointly run by ENEA (National Agency for New Technology, Energy and Sustainable Economic Development, Italy) and the University of Sassari (Italy) (Dono et al., 2008). These data reveal that farms use approximately 107 wells in the area.

The agricultural sector of this territory is represented by a regional DSP model consisting of 24 blocks describing the most relevant farming systems. Each farming system, called a macro-farm (with reference to the block in the model), represents a group of farms that are homogeneous in terms of size (cultivated land and number of livestock head), production patterns, labour availability, presence of wells and location within the study area (Table 1). These macro-farms are defined using data from field surveys, the 2001 Agricultural Census and records of the European FADN (Farm Accountancy Data Network). The availability of multiple sources of farm data enabled us to consider economic characteristics (e.g., budget, net profit and performance indexes) in defining macro-farms. Thirteen of the macro-farms are located in the zone to which the WUA delivers water; 11 are located outside of this zone, where farms rely solely on water from privately owned wells or practice rain-fed agriculture. Note that the production of some of these typologies is not considered as typically Mediterranean, such as intensive dairy production and the associated cultivation of irrigated crops as forage.

In the mathematical programming model, production technologies for crops and livestock breeding are accurately defined based on the main activities observed in the study area. In particular, the use of water by crops is defined according to the employed irrigation techniques. Drip irrigation techniques, used for horticultural and tree crops, are represented in the model, whereas flood irrigation is not because this technology is not employed in the area. Farm typologies and production technologies that characterize the agricultural sector of the area were reconstructed as part of the MONIDRI Research Project, run by INEA (National Institute for Agricultural Economics, Italy) (Dono et al., 2008).

4. Methods

4.1 DSP models (general characteristics)

Discrete Stochastic Programming models (Cocks, 1968; Rae, 1971a, 1971b; Apland et al., 1993; Calatrava et al., 2005; Iglesias et al., 2007) can be used to analyse some of the uncertainty aspects related to CC. DSP models describe choices made by farmers during periods (stages) of uncertainty regarding conditions. Therefore, such models represent the decision process that prevails under typical agricultural conditions, where farmers are uncertain regarding which state of nature will prevail in the cropping season that is being planned, and it is only possible to estimate the probability distributions of the various states of nature. In this study, the DSP model represents a decision-making process based on two decisional stages and three states of nature (Jacquet et al., 1997; Hardaker et al., 2007), where farmers face uncertainty regarding the wintertime accumulation of water in a dam. In the literature, two-stage DSP models have considered various states of nature in the second stage. Jacquet and others (Jacquet et al., 1997) used four states of nature associated with annual rainfall, and Hardaker and others (Hardaker et al., 2004) represented the planning problems in dairy farming by referring to three levels of milk production. However, these authors did not justify the number of stages or the number of states of nature employed in the analyses, except for the need to simplify the problem as much as possible.

The first of the two stages of the DSP model proposed in this paper represents an autumnal period of choice, when farmers establish fields for winter crops. The limited irrigation needs of these cultivations can be satisfied by extraction from farm wells, and hence they are not directly influenced by uncertainty about water availability from the dam. However, when defining the area for winter crops, farmers also establish the surface to be left for spring crops. In contrast to winter crops, the irrigation needs of spring crops are substantial and can only be met by using water accumulated in the dam, whose availability is uncertain. In this way, uncertainty about water availability during the spring period influences the farmers' choices in the autumn period.

The second stage of the DSP model concerns the spring–summer period of choice. At that time, winter accumulation of water in the dam has already occurred, and farms can choose the area to be allocated to each spring crop with certainty. However, during this period farmers can only cultivate the area left unused from the first stage, when uncertainty about water levels in the dam might have produced choices that, in spring, turn out to be sub-optimal. This uncertainty is expressed by a probability distribution function of the level of water accumulation in the dam. The distribution is then discretized to yield three states of water accumulation (high, medium and low) along with their associated probability of realization.

The DSP model represents the influence of this uncertainty on the decision-making processes of farmers. According to this model, the farmer knows that different results may arise in planning the use of resources based on a certain state of nature. In particular, with three states of nature, three different results may occur. One is optimal, when the state of nature assumed by the farmer occurs as expected. The other two results are sub-optimal, where the farmer plans resource allocation based on a certain state of nature, but one of the other two states occurs, resulting in reduced income compared with the optimal outcome. The probabilities of these three results are the probabilities of the respective states of nature. The DSP represents the decision-making processes of the farmer who, based on these data, calculates the expected income of all the various outcomes (obtained by weighting the incomes from the three results with the probabilities of the respective states of nature) and adopts the solution that yields the higher expected income. Accordingly, the farmer adopts the use of resources generated by a weighted average of the three solutions.

Note that a solution that also weights the sub-optimal results may represent the outcome of precautionary behaviour of farmers who try to counter programming errors generated by relying on a given state of nature that ultimately does not occur. Also note that this average of DSP outcomes is different from the average of LP (Linear Programming) model outcomes under low, medium and high water-availability scenarios. Indeed, LP results are optimal to the relative water-availability state, considered in the LP model to be known with certainty. In contrast, DSP outcomes are sub-optimal when a state is planned but does not eventuate, meaning that average income levels are smaller than the analogous income levels in the LP model. This difference can be considered as the cost of uncertainty.

A major limitation of this approach may be that the farmer represented by the DSP model is risk-neutral; thus, the lower resulting income represents the cost of making optimal choices under conditions of uncertainty, but does not consider the cost of the farmer's attitude towards risk (risk aversion). Another limitation may be that we considered only one factor of uncertainty, whereas the farmer's decision-making process is affected by multiple uncertain factors that overlap. The future development of this analysis would be as a multi-stage DSP model with a larger number of uncertainty factors. However, with increasing number of stages and factors, the model becomes difficult to handle; consequently, it is crucial to identify the most relevant elements.

4.2 DSP model (technical characteristics)

As mentioned above, the DSP model used in this analysis is articulated in blocks of farm typologies. Each block refers to a macro-farm that represents a group of farms in the study area. The macro-farms differ in terms of structural characteristics (quality and availability of fixed resources in the short term), farming system and location. The optimisation problem involves maximising the sum of the stochastic objective functions of single macro-farms (expected gross margins), subject to all of the farming restraints (specific as well as territorial). Expected gross margins for each state of nature are given by the sum of two elements: one obtained from activities started in the first stage, and the other obtained from activities of the second stage. This DSP model can be mathematically formalised as follows:

Objective function:

$$\underset{X}{Max} \quad Z = GI_1 * X_1 + P_K * GI_2 * X_{2,K} \tag{1}$$

Subject to:

$$A_1 * X_1 + A_2 * X_{2,K} \le b_K \quad \forall \mathrm{K} \tag{2}$$

$$X_1, \ldots, X_{2,K} \ge 0 \quad \forall \mathrm{K} \tag{3}$$

where Z is the total gross margin, X_1 is the vector of first-stage activities, $X_{2,K}$ is the matrix of second-stage activities for each state of nature occurring in the second stage, P_K is the probability of occurrence of each state of nature, GI_1 and GI_2 are the vectors of unitary gross margins, A_1 and A_2 are the matrixes of technical coefficients, b_K is the vector of resource availability for each state of nature (here, only the availability of water has a different value for each state of nature; other resources have the same value), K is the state, and 1 and 2 are the stages. The variables of the model can be divided into three groups: crop, breeding and animal feeding; acquisition of external work; and activity related to the water resource.

Several groups of model constraints are defined. The first group refers to the expected availability of labour, land and water. Labour constraints are specified with reference to family labour and hired labour, permanent or temporary. Water constraints apply to both the reservoir water supplied by the WUA, as well as the groundwater, which can only be utilised based on the presence and technical characteristics of wells on the farms. The constraints on the expected availabilities of labour, land and water are specified for each month. Another set of constraints is concerned with agronomical practices as commonly adopted in the area to avoid declines in crop yields. Other constraints refer to Common Agricultural Policy systems to control production, such as production quotas and set-asides. Moreover, livestock breeding requires a balance between animal feeding needs and feed from crops or purchased on the market. In addition, constraints are imposed for specific farm typologies on the number of hectares of various trees growing and on the number of raised cattle or heads of sheep. These constraints are applied at different levels: some are specified at the farm level, such as the constraints on land use and on family and permanent labour, which cannot exceed the farm availability of these resources; others act at the area level, such as the constraint on the total irrigation water provided to farms, which cannot exceed the total water resources available to the WUA. Similarly, a constraint on temporary hired labour is specified at the area level. Finally, constraints on water availability are specified for each state of nature, for each of three scenarios regarding the distribution of water accumulation. Input and Produce Prices are defined as values that could be expected in 2004, based on the average of actualised values in the 3 preceding years. Similarly, agricultural policy conditions in 2004 are applied (Dono et al., 2008).

In essence, the basic approach of this study is to use a regional DSP model to estimate the impact of CC on production activity and income of farms in the area and to assess the performances of the various water-pricing methods under different climatic conditions. The stochastic expectations of water accumulation in the dam, which are included in the DSP model, are considered to be altered by CC that modifies the rainfall regime. The present-day (2004) probability distribution of water accumulation in the reservoir is estimated and used as a proxy for the stochastic expectation in the DSP model that reproduces the present conditions. This distribution is replaced with a future scenario probability function for rainfall and, hence, for the level of water accumulation in the dam. This future scenario is obtained by projecting historical rainfall data.

The next section describes the criteria used to reconstruct climate scenarios of winter precipitation and the resulting probability distributions for the accumulation of water in the dam, in the present and future.

4.3 Climatic scenarios

The present and future scenarios for water accumulation in the reservoir were reconstructed using the statistical correlation between rainfall amount and water storage in the dam, and by extending to the 2015 year the estimated trend of a 40-year rainfall series.

Estimation of the probability distribution for water accumulation in the reservoir was complicated by the fact that the Nurra WUA was only able to provide accurate monthly data for short periods in recent years. At the time of the MONIDRI research project, accurate records were only available for the years 1992–2003. Table 2 lists the annual values of water allocation obtained from these monthly data, showing that on average, potable use accounted for 40% of the available resource. In the years 1995, 2000 and 2002, the total amount of water available was insufficient to meet all the needs, and the Commissioner for Water Emergency limited the amount withdrawn for irrigation in favour of domestic usage, which had a major impact on farm incomes. During these years, the withdrawal for domestic use exceeded that for irrigation.

Water uses	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Irrigation	*43.5*	*33.4*	*31.6*	*2.3*	*23.2*	*39.1*	*10.4*	*17.6*	*2.4*	*27.8*	*12.4*	*26.6*
Potable	*10.3*	*11.2*	*11.3*	*10.9*	*12.8*	*12.7*	*13.2*	*14*	*14.3*	*20.4*	*19.7*	*8.1*

Table 2. Amount of water (million m^3) from Cuga Dam allocated to different uses in the period 1992–2003 (source: Nurra WUA).

The limited temporal coverage of this record of water use makes it statistically insufficient for estimating the probability distribution of states of water storage for the present scenario, and even more so for the future. In addition, hydrological models had not been developed for the study area for the appropriate transformation of long-period rainfall data in terms of water accumulation in the Cuga Dam. To overcome these limitations, a statistical relationship was estimated between rainfall amount and water accumulation level, and the parameters of this relationship were used to generate the probability distributions of water collection states. The following section describes the procedure for estimating the statistical relationship between rainfall regime and level of water accumulation in the reservoir. These estimated values are used to obtain the probability distribution of water level in the reservoir, for which low, medium and high states of accumulation were defined.

4.4 Assessment of climate change

The first step in the analysis was to examine the long-term trends in the rainfall regime that are believed to have influenced the accumulation of water in the Cuga Dam. Rainfall in the area was analysed using a 43-year series of monthly data (1961–2003) comprising a total of 516 observations. This analysis assumed an additive or multiplicative relationship between the components. The choice between additive or multiplicative decomposition methods was based on the degree of success achieved by their application (Spiegel, 1973). In this study, the multiplicative method yielded slightly better results than the additive decomposition. The analysis was therefore based on the assumption that the following multiplicative link exists among components:

$$X = T * S * C * \varepsilon \tag{4}$$

where X is the observed rainfall data as generated by trend T, seasonality S, cycle C and residual elements ε. The influence of these elements was decomposed. To estimate the trend, a linear function was used as follows:

$$\text{Rain} = \delta_0 + \delta_1 \text{T} + \varepsilon \tag{5}$$

where Rain is rainfall, T is time and δ_0 and δ_1 are the parameters of the function. Quadratic or exponential functions can also be used for estimating trends; the choice among the different structures is generally based on their statistical adaptation to the analysed series (Levine et al., 2000).

Seasonality (S), as a specific characteristic of each individual month, was obtained by first normalising the monthly data to the average for that year, and then computing from these values the median for each month in the observed range. We assumed the absence of a cycle (C) in climatic events of the study area, given the lack of clear physical phenomenon (e.g., a dominant atmospheric circulation pattern) linked to cyclic behaviour in the study area.

Finally, residuals were calculated by isolating the observed data from the climatic components of trend and seasonality, given that any cycle is assumed to be absent. Residuals usually depend solely on random and uncertain factors; i.e., they are stochastic elements that represent the variability of climate phenomena. Analysing the standard deviation of residuals can highlight the existence of temporal changes in the variability of climate phenomena, which is an important part of CC. This analysis can be developed by estimating a linear trend of the standard deviation of residuals, as follows:

$$\mathrm{SDR} = \gamma_0 + \gamma_1 \mathrm{T} + \varepsilon \tag{6}$$

where SDR is the standard deviation of residuals and γ_0 and γ_1 are the parameters of the function.

4.5 Statistical relation between rainfall regime and water accumulation in the Cuga Dam

Once the rainfall data had been examined and the presence of relevant trends highlighted, a statistical relationship was estimated to define the on water accumulation in the Cuga Dam. A linear regression model between rainfall (Rain) and water amount in the dam (Wa) was constructed based on the 144 monthly observations for the period 1992–2003. The estimated coefficients of this regression and the observed rainfall data were used to reproduce the entire series of data on water amount in the dam for the period 1961–2003. This procedure generated a sufficiently long series of data on water accumulation in the dam to be used when estimating the probability distribution of this variable.

In more detail, when estimating the statistical relationship between rainfall data and water accumulation level, a preliminary analysis of the data was performed to reveal (and eventually correct) the possible non-normality and non-stationarity characteristics of the series. A series is considered normal when the characteristics of symmetry and unimodality make it similar to the realisations of a normal random variable. A stationary process is a stochastic process whose joint density distribution does not change when shifted in time or space; as a result, parameters such as mean and variance (if they exist) also do not change over time or space. To satisfy the regression model hypothesis, data that do not show normality or stationarity characteristics must be standardised to obtain a stationary series, as follows:

standardisation:

$$X_{SAV_{i,j}} = \frac{X_{OBS_{i,j}} - \mu_i}{\sigma_i} \tag{7}$$

where $X_{SAVi,j}$ is the series of seasonally adjusted values, $X_{OBSi,j}$ is the series of observed values, μ_i is the monthly average of the values of the observed series, σ_i is the monthly standard deviation of the observed series, and i and j indicate the month and year, respectively.

Therefore, the standardised data were normalised by using a Box–Cox transformation:

normalisation:

$$X_{tras_{i,j}} = \begin{cases} \dfrac{(X_{SAV_{i,j}})^{\lambda} - 1}{\lambda} & for\ \lambda \neq 0 \\ \log(X_{SAV_{i,j}}) & for\ \lambda = 0 \end{cases} \tag{8}$$

where λ is determined by maximising the following log-likelihood function:

$$\ln L(\lambda, \bar{x}_{SAV}) = -\frac{n \cdot m}{2} \ln\left[\sum_{i=1}^{n}\sum_{j=1}^{m} \frac{(x_{SAV\,i,j}(\lambda) - \bar{x}_{SAV}(\lambda))^2}{n \cdot m}\right] + (\lambda - 1)\sum_{n}^{i=1}\sum_{j=1}^{m} \ln(x_{SAV\,i,j}) \tag{9}$$

and

$$\bar{x}_{SAV}(\lambda) = \begin{cases} \dfrac{1}{n \cdot m}\displaystyle\sum_{i=1}^{n}\sum_{j=1}^{m}(x_{SAV\,i,j})^{\lambda} & for\ \lambda \neq 0 \\ \dfrac{1}{n \cdot m}\displaystyle\sum_{i=1}^{n}\sum_{j=1}^{m}\ln(x_{SAV\,i,j}) & for\ \lambda = 0 \end{cases} \tag{10}$$

where n and m are respectively the number of months and years.

Hence, making use of standardised and normalised data on water amount in the dam (Wa_{tras}) and on rainfall ($Rain_{tras}$), we constructed the following model:

$$Wa_{tras} = \beta_0 + \beta_1 Rain_{tras\ (-1)} + \beta_2 Wa_{tras\ (-1)} + \varepsilon \tag{11}$$

Based on the coefficients of this model, Wa_{tras} values were first calculated for the period 1961–1991 and then transformed into water availability data (Wa) by applying the inverse Box–Cox transformation (inverse of normalisation) and the inverse standardisation adjustment.

4.6 Probability distribution of water accumulation in the dam

The inferred data on water accumulation levels for individual months during the period 1961–2003 were used to estimate density functions related to sub-periods within this interval. These functions were estimated on the basis of a dataset restricted to March values, because this month is the last before the start of the irrigation campaign. Consequently, the level of water accumulation in March is crucial for decisions made by farmers regarding the cultivation of irrigated and non-irrigated crops, and for decisions made by WUAs regarding water allocation to farms. The parameters of these density functions are estimated using the software @Risk, which uses a chi-square value (Goodness of Fit index) to select the function that best approximates the dataset. These parameters are the basic input for generating the stochastic expectations of farmers in the DSP model.

Probability values can be computed and incorporated into DSP models only for states of nature expressed as intervals and not as single values (Piccolo, 2000). To this end, based on water management in the area of interest, three accumulation states are considered as relevant to the use of reservoir water in the farm sector: high, medium and low. The first state is recognised as occurring in years when the dam contains abundant water, when no limits are imposed on water use for irrigation or other purposes. A state of medium accumulation is identified for years when the amount of collected water necessitates careful use, even if explicit measures of public rationing are not required. A state of low accumulation is recognised when major water emergencies occur and irrigation is limited by public authorities to ensure the availability of water for potable use. The boundaries between these states are defined based on their occurrence in 1992–2003. Specifically, the lower limit of the low accumulation state is taken as the minimum value of the series: 5.6 million cubic meters (Mm^3). The upper bound of this state is taken as the maximum value at which irrigation was publicly rationed to guarantee potable use (42.6 Mm^3). This latter value is also the lower bound of the medium state, whose upper limit (64.0 Mm^3) is defined based on symmetry about the average value of accumulation (53.3 Mm^3). The value of 64.0 Mm^3 is also the lower bound of the high accumulation state, whose upper limit is the maximum value of the series, 89.9 Mm^3. Different sub-periods during the interval 1961–2003 yield different distributions of water accumulation states, with different probabilities and average values for the three states. The parameters of these different functions can be used to generate stochastic expectations of water accumulation in the dam, as represented by the regional DSP model.

The dataset obtained using this adjustment to the regression results was used to estimate a first probability distribution function for the continuous, stochastic variable of water accumulation in the dam, based on data for the years 1984–2003; this represents the expectations of the present period. Similarly, 21 distributions were computed by progressively shifting the 20-year period forward, by 1 year at a time, from the period 1964–1983 to the period 1984–2003. The probability values for low, medium and high levels of water accumulation in the dam were computed for each of these distributions. Based on the result, linear trends of probability values for the three states of nature were estimated and projected to estimate data for the years 2004–2015 and to compute an analogous probability distribution for the 20-year period 1996–2015. The probability distributions obtained in this way for the years 1984–2003 and 1996–2015 were used to represent the stochastic expectations in the present and future, respectively.

4.7 Simulation scenarios

The baseline model of this study refers to the VPM, as applied by the Nurra WUA in 2004, when the *water payment* was set at 0.0301 €/m^3 for water delivered by the WUA distribution network and the *complementary payment* was charged to fully cover the WDC. With this pricing method, only the *water payment* directly affects farmers' water use. No charge for the use of groundwater is applied by the WUA.

Two other scenarios refer to ABM. In these cases, the farm payment for water consists of two components: the *water payment* is charged according to *estimates* of the water requirements of crops, multiplied by the water unitary price (0.0301 €/m^3), and the *complementary payment* is again charged to ensure that the WDC is fully recovered.

Two ABM scenarios are simulated (ABM-1 and ABM-2), referring to two different methods of estimating the water applied to each crop. In ABM-1, these estimates accurately reflect the irrigation requirements of every crop, whereas in ABM-2 the crops are clustered into classes that consider their *average* irrigation requirements[5]. This latter scenario considers the ABM practiced by the Nurra WUA until 2001, where the estimates of unitary irrigation requirements used in calculating the payments are not always consistent with the actual requirements of crops (Table 3)[6]. The main feature of ABMs is that the payment is charged regardless of the water source (i.e., surface water from the WUA or groundwater from private wells). Furthermore, all irrigated areas are supposedly charged by the WUA. Given that farmers pay according to the area under irrigation and that the price is set considering estimates of irrigation requirements, irrigation payments are affected by cropping patterns but not by the source of water.

I – (104.30€/ha)	II – (143.84 €/ha)	III – (179.77 €/ha)
Tomatoes in glasshouses	Ryegrass	Artichoke
Watermelon	Alfalfa	
Melon	Clover	
Olive trees	Corn	
Vineyard	Open field Tomatoes	
Peach trees		

Table 3. Payment classes in the Nurra WUA (based on the parameters applied in 2001)

5. Results

First, we present the temporal changes in rainfall patterns over the past 40 years, and then describe the outcomes obtained by estimating a statistical relationship between the rainfall regime and level of water accumulation in the dam. Subsequently, the levels and respective probability values for states of water accumulation in the dam are reported for each of the three scenarios. Finally, we present the economic and productive outcomes of the DSP models.

5.1 Precipitation time series

The linear trend of monthly rainfall reveals a decrease in the area, indicated by the value of the regression coefficient in relation to time (δ_1) (Table 4). In addition, the linear trend in the monthly variability of the standard deviations of residuals reveals an increase residuals, as indicated by the regression coefficient of the same standard deviations of residuals in relation to time (γ_1).

5.2 The regression model

A preliminary analysis of the data reveals a statistically significant autocorrelation in the Wa series and cross-correlation between the Wa and Rain series. The data were then

[5] Some WUAs chose this last option to reduce their administrative burden or because of political reasons, such as considering the relative contributions of certain crops in terms of farm employment or income.

[6] For instance, clover and alfalfa in the second class (Table 3) pay less than artichoke in the third class, yet the water needs of the former are approximately twice those of the latter. This favourable treatment is justified by WUAs because alfalfa and clover crops are relevant to the cow- and sheep-milk sectors, which are considered to be important for the economy of the entire area.

standardised and normalised, and new time series of the amount of water in the dam (Wa_{tras}) and rainfall ($Rain_{tras}$) were used to estimate the model (11).

	Coefficient	Estimate	T-stat	P value
Rainfall	δ_0	55.645	13.6477	0.000
	δ_1	-0.0381	-2.7904	0.000
Standard deviation of residuals	γ_0	131.07	3.2885	0.000
	γ_1	2.74	1.6568	0.100

Table 4. General trends of rainfall and of the standard deviation of residuals.

Good statistical results were obtained from the regression: the coefficients have the expected signs and are statistically significant, and high R^2 values indicate that more than 95% of the variability in Wa_{tras} is explained by the model (see Table 5).

Coefficient	Estimate	T-stat	P-value
$\beta 0$	-0.3149	4.5442	0.000
β 1	0.5828	5.3247	0.000
β 2	0.9694	54.6706	0.000
R^2	0.9555	F	1501.44
Adj-R^2	0.9548	p (F≤f)	0.000

Table 5. Results of the regression model for the dependent variable Wa_{tras}.

Based on these coefficients, Wa_{tras} values were calculated for the period 1961–1991 and were then transformed to water availability data (Wa) by applying the inverse Box–Cox transformation (inverse of normalisation) and the inverse standardisation adjustment.

5.3 The density distribution of water accumulation

The dataset obtained from this adjustment of the regression results was used to estimate the density functions of water accumulation in the dam for the period 1984–2003. The best estimate was a triangular function with a chi-square value of 0.400 and a p-value of 0.9402. With k (number of bins) = 4 (3 degrees of freedom), the null hypothesis is accepted (i.e., that this is the best possible function for representing the data). Once the boundaries of the low, medium and high accumulation states were defined based on data for the period 1992–2003, the respective probabilities were computed, yielding values of 27.3%, 40.7% and 32.0%, respectively.

Next, the density distribution values for the future scenario were determined. To this end, 21 distributions were computed by progressively shifting the 20-year window, 1 year at a time, from 1964–1983 to 1984–2003. The probability values for low, medium and high levels of water accumulation in the dam were computed, yielding a progressive increase in the degree of variability, especially for periods more recent than 1976–1995. Based on these data, linear trends of probability values for the three states of nature were estimated and projected to obtain an analogous distribution for 1996–2015, yielding values of 38.8%, 13.7% and 47.5% for the states of low, medium and high water accumulation in the dam, respectively.

Once the total accumulation levels and respective probabilities had been defined for the two scenarios, the respective availabilities of water for irrigation were also defined. To this end, the data supplied by the WUA for the years 1992–2003 were used to infer the level of water accumulation in the dam and the percentage of water allocated to irrigation for each of the three states of nature. These percentages were used to define the amount of water accumulated in the dam that farmers could expect to be allocated to agriculture in each state of nature.

As a side analysis, an analogous distribution based on data for the period 1964–1983 was computed with the same boundaries for water collection states, yielding probability values of 0.0%, 99.7% and 0.3% for the low, medium and high levels, respectively. Compared with the previous scenario, these outcomes reveal that water accumulation in the dam during the 1960s and 1970s was characterised by a smaller variability than in present scenario. This result is consistent with the finding of a temporal increase in rainfall variability, as obtained by analysing the standard deviation of residuals (see Table 4).

5.4 The DSP models

The DSP simulation models employed in this study were solved using the program GAMS (General Algebraic Modelling System; Brooke et al., 1996). The baseline of this study is the average of the outcomes related to the three states of nature in the present scenario, weighted by the respective probabilities. The baseline is evaluated by comparing its average weighted outcome regarding land use to the actual pattern determined from remote sensing data and field data approved by the WUA (Dono et al., 2008). The similarity between the patterns is assessed by the Finger–Kreinin index, which compares the respective percentages of total land occupied by each group of crops, selects the lower value among them and sums the figures (Finger and Kreinin, 1979). The more similar that two series are, the higher the sum of the lower values, which yields a value of 100% for identical series. A high degree of similarity is obtained in this study between DSP outcome and the actual land use, with the value of the similarity index being 91.9%. The baseline model is therefore considered to adequately reproduce the observed choices of farmers and is therefore useful for providing insights into farmers' possible adjustments in the case of changing economic or climatic conditions[7].

At this point, we can discuss the results obtained with different pricing methods for the water distributed by the WUA, in the context of the present and future climate. Table 6 lists

[7] An analogous linear programming model (LP) was constructed, differing only in the condition of irrigation water availability, which was defined as the average water level in the dam over the previous 5 years. By considering uncertainty, the DSP model yields better results in reproducing agricultural activities; in fact, the Finger–Kreinin similarity index has a lower value (90.2) in the LP model.

the key financial results for the entire area in which the WUA distributes water from the reservoir.

Outside of this area, agriculture is not irrigated and is not affected by the water pricing system of the dam or changes in the volume of water in the reservoir. Table 6 lists the total revenues, indicating the portion of product sales, the main items of variable costs and gross margin. Fixed costs have been estimated for the various farm typologies, enabling the calculation of their net incomes; these are aggregated to yield the entire area value. Table 6 lists all of these values, expressed in thousands of euros and in percentage change from the baseline (in this VPM).

	Absolute value ('000 €)						% variations from the Baseline				
	present	Present		future			present		future		
	VPM	ABM		VPM	ABM		ABM		VPM	ABM	
	Baseline	1	2		1	2	1	2		1	2
Revenue	73,892	73,892	73,906	73,713	73,713	73,644	0.0	0.0	-0.2	-0.2	-0.3
Sales	64,667	64,667	64,68	64,557	64,557	64,478	0.0	0.0	-0.2	-0.2	-0.3
Costs	19,109	19,151	19,218	19,431	19,483	19,505	0.6	0.2	1.7	2.0	2.1
Feeding cost	*430*	*430*	*430*	*723*	*723*	*723*	*0.0*	*0.0*	*68.2*	*68.2*	*68.2*
Labour cost	*2,133*	*2,133*	*2,134*	*2,34*	*2,34*	*2,321*	*0.1*	*0.0*	*9.7*	*9.7*	*8.8*
WUA cost	*341*	*407*	*461*	*289*	*362*	*450*	*19*	*35*	*-15*	*6*	*32*
Drawing cost	*82*	*58*	*58*	*88*	*67*	*66*	*-29.7*	*-29.7*	*6.8*	*-18.7*	*-19.1*
Irrigation Equip.	*1,381*	*1,381*	*1,381*	*1,379*	*1,379*	*1,365*	*0.0*	*0.0*	*-0.1*	*-0.1*	*-1.2*
Other costs	*14,06*	*13,928*	*13,831*	*14,034*	*13,888*	*13,681*	*-0.9*	*-1.6*	*-0.2*	*-1.2*	*-2.7*
Gross Margin	54,783	54,742	54,688	54,283	54,231	54,139	-0.2	-0.1	-0.9	-1.0	-1.2
Net Income[8]	32,627	32,532	32,586	32,127	31,983	32,075	-0.3	-0.1	-1.5	-2.0	-1.7

Table 6. Economic results for the entire area.

These data show that the transition from VPM to the ABMs generates a very small change in income in the present climate scenario. However, a significant change in cost structure emerges, with a strong reduction in expenses for the extraction of water from wells and an increase in the irrigation payments to the WUA. This change occurs because the two ABMs are based on irrigated acreage and the water needs of crops, irrespective of whether the water is derived from the WUA network or from farm wells, thereby generating an indirect pricing of groundwater. Consequently, the two ABMs encourage farmers to reduce the use of groundwater that is only applied in cases where irrigation is necessary but the WUA irrigation season has yet to open, or during the summer periods when the water resources of the WUA do not meet the general water demand of the area.

[8] Net income is obtained based on estimates of fixed costs coming from European FADN database.

The transition to the future climate scenario results in a more pronounced change in cost structure. The greater variability in water accumulation in the reservoir generates a greater reduction in total income, which also affects the system based on VPM. With this method of charging, there is an increase in the cost of drawing groundwater and a reduction in irrigation payments to the WUA. At the same time, there is an increase in the cost of purchasing feed and forage that can no longer be sufficiently produced locally under the new scenario of expectations regarding the availability of water in the reservoir. Of note, the use of ABMs yields the same increase in costs as when using VPM. However, these last two methods of water pricing are completely different from VPM in terms of the effect on other cost items. As in the present scenario, a reduction in expenses occurs with the extraction of water from wells, with a parallel increase in irrigation payments to the WUA. These variations are less pronounced than in the present scenario because the expectation of a greater variability in the future accumulation of water in the reservoir prevents a more significant reduction in the use of groundwater.

Table 8 lists the net incomes of the farm typologies in the study area for each scenario, grouped by product specialization. These data show that the farms involved mainly in the production of crops (cereals, oilseeds and protein crops, and also forage and pasture) make the greatest contribution (30%) to the agricultural income of the territory, followed by vineyards and to a much lesser degree the sheep farms and the other typologies.

In the case of ABM-2, the horticultural farms show a marked increase in income, which is not seen in the case of ABM-1. This result indicates that estimates of the water needs of the WUA in ABM-2 favour some vegetables grown by horticultural farms.

Farm Typology	Absolute value ('000 €)						% variations on the baseline				
	present	Present		future			present		future		
	VPM	ABM		VPM	ABM		ABM		VPM	ABM	
	Baseline	1	2		1	2	1	2		1	2
Cattle	1,363	1,364	1,365	1,207	1,208	1,206	0.1	0.1	-11.5	-11.4	-11.5
Arable	13,738	13,691	13,634	13,381	13,339	13,322	-0.3	-0.8	-2.6	-2.9	-3
Olive	3,525	3,54	3,545	3,511	3,511	3,529	0.4	0.6	-0.4	-0.4	0.1
Vegetable	982	982	1,048	1,050	1,050	1,029	0	6.7	6.9	6.9	4.7
Sheep	2,691	2,683	2,684	2,657	2,65	2,649	-0.3	-0.2	-1.2	-1.5	-1.5
Vineyard	9,36	9,356	9,287	9,353	9,348	9,279	0	-0.8	-0.1	-0.1	-0.9
Total	31,658	31,617	31,563	31,158	31,106	31,014	-0.1	-0.3	-1.6	-1.7	-2

Table 7. Net income of farming typologies.

However, the most interesting aspect of this table is the effect of the transition to the future scenario. The mean changes emerge as the result of very different changes among the typologies, with a collapse in the incomes of dairy farms and an appreciable increase in the income of vegetable growers. The choice of pricing system of irrigation water has little influence on the effect of increased variability in water accumulation in the dam.

The VPM scheme encourages farmers to meet their water requirements with minimum cost. Consequently, farmers with wells tend to draw water until it remains cheaper than the WUA *water payment*. Thus, the VPM scheme results in increased groundwater extraction. Under the ABM scenarios for the present, in contrast, farmers only draw groundwater from wells if the WUA is unable to supply water, either because of a demand pick or a request coming off the irrigation season. Otherwise, farmers are inclined to use the WUA water as much as possible, because such behaviour does not affect the *water payment*. When these pricing method are simulated in the future climate scenario, the amount of groundwater extraction is lower than that of the present in the case of the ABMs; moreover, the use of VPM results in increased extraction in the case of increasing uncertainty regarding the availability of WUA water.

	Absolute value (ha)						% variations on the baseline				
	present	Present		future			present		future		
Cultivation	VPM	ABM		VPM	ABM		ABM		VPM	ABM	
	Baseline	1	2		1	2	1	2		1	2
Forage	*8,935*	*8,935*	*8,925*	*9,050*	*9,050*	*9,016*	*0*	*-0.1*	*1.3*	*1.3*	*0.9*
Wheat	*3,679*	*3,679*	*3,679*	*3,771*	*3,771*	*3,771*	*0*	*0*	*2.5*	*2.5*	*2.5*
Barley/Oat	*850*	*850*	*850*	*869*	*869*	*888*	*0*	*0*	*2.2*	*2.2*	*4.5*
Pasture	*3,209*	*3,209*	*3,209*	*3,205*	*3,205*	*3,233*	*0*	*0*	*-0.1*	*-0.1*	*0.7*
Silage corn	*216*	*216*	*216*	*133*	*133*	*133*	*0*	*0*	*-38.6*	*-38.6*	*-38.6*
Grain corn	*867*	*867*	*867*	*660*	*660*	*660*	*0*	*0*	*-23.9*	*-23.9*	*-23.9*
Tomato	*21*	*21*	*21*	*21*	*21*	*21*	*0*	*0*	*0.0*	*0*	*0*
Artichoke	*243*	*243*	*253*	*83*	*83*	*85*	*0*	*4*	*-65.9*	*-65.9*	*-65*
Melons	*1,061*	*1,061*	*1,061*	*1,148*	*1,148*	*1,133*	*0*	*0*	*8.2*	*8.2*	*6.8*
Olive	*754*	*754*	*754*	*754*	*754*	*754*	*0*	*0*	*0.0*	*0*	*0*
Wine	*1,336*	*1,336*	*1,336*	*1,336*	*1,336*	*1,336*	*0*	*0*	*0.0*	*0*	*0*
Peach	*587*	*587*	*587*	*587*	*587*	*587*	*0*	*0*	*0.0*	*0*	*0*
	208	*208*	*211*	*190*	*190*	*191*	*0*	*1.6*	*-8.3*	*-8.3*	*-8*
Total	**21,966**	**21,966**	**21,970**	**21,807**	**21,808**	**21,807**	**0**	**0**	**-0.7**	**-0.7**	**-0.7**
Water sourcing											
Total	**16,821**	**17,007**	**17,040**	**14,841**	**15,005**	**14,939**	**1.1**	**1.3**	**-11.8**	**-10.8**	**-11.2**
WUA	13,925	14,928	14,960	11,792	12,673	12,620	7.2	7.4	-15.3	-9	-9.4
Wells	2,896	2,080	2,080	3,050	2,332	2,319	-28.2	-28.2	5.3	-19.5	-19.9

Table 8. Farming activities and water sourcing.

6. Discussion

The consequences of using different water-pricing systems for irrigation water were estimated by applying the systems under various climate scenarios (i.e., level of water accumulation in the reservoir). The first system is the one currently applied by the WUA, the Volumetric Pricing Method (VPM), based on the metered use of water by farms. The second system is an Area-Based Pricing Method (ABM), whereby fees are charged per hectare according to the estimated average water use for each crop. This system was applied in two versions: (1) employing water use coefficients that strictly reflect the actual irrigation requirements of the various crops in the area, and (2) employing the estimated average levels of water use prescribed by the WUA prior to 2001, when the switch was made to VPM. We used a DSP model to examine the application of these pricing methods in a future scenario in terms of their impacts on the use of agricultural land, on inputs (e.g., water and labour), and on the income of the agricultural sector, for the entire area and for representative farms.

The results of DSP modelling suggest that the farm sector overall is well placed to adapt to CC in the present and in the near future, particularly with respect to water accumulation in the dam. Indeed, the model predicts that increased variability in water accumulation in the reservoir would have a negligible effect on the economy of the entire agricultural sector in the study area. However, the economic impact of this increased variability shows marked differences among the farm typologies: some suffer marked reductions of income, particularly dairy farms that depend on the use of large volumes of water for the irrigation of corn.

Furthermore, the general adaptation path followed by the agricultural sector of the Nurra area is predicted to result in an increase in the environmental impact of agricultural activities, including the excessive extraction of groundwater. In this regard, the use of VPM poses problems when individual farmers have direct access to uncontrolled water sources such as groundwater, as is the case in the present study area and in many other Mediterranean areas. This problem arises because wells are generally a private asset of the farm and because there is a lack of information and legislation regarding this source of water, which would be required to control its level of exploitation. These results are consistent with the findings of other studies regarding the use of volumetric pricing (Cornish et al., 2004; Dinar et al., 1989). Furthermore, the application of ABM pricing, unlike VPM, is able to restrict the extraction of groundwater even in a scenario of increased uncertainty regarding water availability from collective, surface sources. This restriction arises because ABMs charge for the irrigation of crops regardless of the water source. Therefore, groundwater under VPM is a substitute for water distributed by the WUA, whereas under ABM it is complementary to the water distributed by the WUA, as its extraction generates extra pumping costs but does not save on other irrigation costs. This eliminates cost competition between the two water sources and results in a marked reduction in groundwater use.

These findings demonstrate that the introduction of VPMs is, in many regards, contradictory to the basic goal of environmental protection advanced by the WFD, since over-extraction could lead to increased salinization of groundwater. The pricing method can be considered a relevant strategy for adapting to the challenges of foreseen climate scenarios; hence, the adoption of a unique *a priori* strategy for water conservation may yield unsatisfactory results.

7. Conclusion

The contribution of this study is of interest primarily because it examines different pricing methods of irrigation water in a state of uncertainty, which is typical of the decision-making framework in the agricultural sector. Moreover, this condition of uncertainty is likely to become accentuated in the near future because of ongoing climate change (CC); this work sought to evaluate the impact of this change on the economics and the water management of the Nurra area . The model used for this analysis could be improved by considering the impact of additional aspects of CC (e.g., temperature, evapotranspiration and atmospheric CO_2) on crop cycles, and by considering the interactions among irrigation practices, network losses and groundwater recharging, which affect the water balance of the entire watershed.

Indeed, a reduction in the amount of water applied to crops does not necessarily correspond to increased water conservation, as farmers may respond to increased uncertainty regarding water availability by using improved irrigation technologies. These technologies generally enable reduced water application for a given level of crop consumption, or an increase in the area under irrigation for a given quantity of water applied. Neither outcome is a real saving of water; indeed, the latter would result in increased water consumption at the watershed level and less water availability downstream. However, in the present study area there exists little scope for improving the available irrigation technology; instead, farmers must consider making changes to cropping patterns.

Therefore, even considering the limitations of the model, the results indicate an advantage in adopting ABMs rather than VPM. The ABMs protect the groundwater resource and are consistent with the goal of setting prices that encourage farmers to use water efficiently, with the purpose of protecting the environmental quality of the resource.

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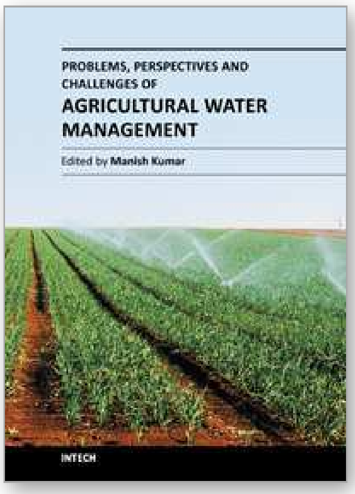

Problems, Perspectives and Challenges of Agricultural Water Management

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Food security emerged as an issue in the first decade of the 21st Century, questioning the sustainability of the human race, which is inevitably related directly to the agricultural water management that has multifaceted dimensions and requires interdisciplinary expertise in order to be dealt with. The purpose of this book is to bring together and integrate the subject matter that deals with the equity, profitability and irrigation water pricing; modelling, monitoring and assessment techniques; sustainable irrigation development and management, and strategies for irrigation water supply and conservation in a single text. The book is divided into four sections and is intended to be a comprehensive reference for students, professionals and researchers working on various aspects of agricultural water management. The book seeks its impact from the diverse nature of content revealing situations from different continents (Australia, USA, Asia, Europe and Africa). Various case studies have been discussed in the chapters to present a general scenario of the problem, perspective and challenges of irrigation water use.