Towards a sustainable irrigated agriculture: analysis of water pricing instruments

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ABSTRACT

The Water Framework Directive (WFD) states that all EU member states must implement water tariffs in order to recover the costs of water services. This study analyses the consequences of the hypothetical implementation of different instruments for irrigation water pricing (area, volumetric, two-part tariff and block-rate), studying their impact on the sustainability of irrigated areas. The empirical application has focused on the Campos district in the Spanish province of Palencia. To this end, we constructed simulation models based on positive mathematical programming (PMP), which enabled us to simulate farmers' behaviour in the face of the various pricing instruments analysed. Running these models for every type of farm and pricing scenario considered, we obtained a multidimensional set of sustainability indicators (economic, social and environmental). These indicators were subsequently used to construct a composite indicator (CIIA) to measure overall sustainability performance of irrigated farms in inner Spain. The results show how pricing irrigation water will have a negative impact on overall sustainability, since their economic (profitability) and social (generation of employment) sustainability will decline, while only a slight improvement in environmental sustainability will be achieved. However, it was shown that, in order to fulfil WFD requirements, block-rate pricing performance is the best in terms of the CIIA index.

Keywords: Water policy; Irrigated agriculture; Sustainability; Composite indicators; Positive mathematical programming.

JEL Classification: Q25, Q15, C61.

1. Introduction

The continued rises in water demand in Spain reflect the growing relative scarcity of this resource. This situation has led to an intense debate about efficiency in water use in the agricultural sector, which is the main consumer of water (75% of total national consumption in 2004; INE, 2008). The apparent poor management of this resource in Spanish irrigation (large water losses and its application to crops with low profitability and that require little labour) has served as an argument for requiring, as an indispensable solution, the implementation of demand policies, typical of a "mature" water economy, especially water pricing (Molle and Berkoff, 2007).

The situation of water economy maturity is not unique to Spain, but is shared by other states in the European Union (EU), which is why the EU decided to develop a common policy for water management. The result was the approval of Directive 2000/60/EC of the European Parliament and Council, which establishes a framework for community action in the field of water policy (in short, the Water Framework Directive or WFD). Following the aforementioned current of thought, the WFD has established water pricing as the European's preferred water-demand control policy (art. 9). The Directive obliges member states to apply tariffs for water use before 2010, with the aim of providing adequate incentives for users to use water resources efficiently. It thus aims to contribute to achieving the environmental objectives (the "good status" of water bodies) established in the Directive.

Although water pricing is an environmental requirement, the logic on which the instrument is based is purely economic. In this regard, irrigation farmers, according to economic theory, will respond to the increase in the price of water by reducing their consumption, following a demand curve with a negative slope, thus relieving the quantitative pressure on water bodies. In any case, pricing affects not only the demand for irrigation water, but also has other economic, social and environmental effects. The scientific community has made intensive studies of the multi-dimensional impacts of pricing irrigation water. From the extensive literature, we may highlight the studies carried out in Spain by Varela-Ortega et al. (1998), Berbel and Gómez-Limón (2000), Gómez-Limón and Riesgo (2004) and Iglesias and Blanco (2008). However, it is worth pointing out that all these studies were limited to studying the multi-dimensional impact of pricing, presenting the performance of different politically relevant indicators separately. Given this state of the art, it is relevant to point to the need to continue advancing along this line of research by applying methodologies that permit a joint analysis of the indicators analysed so far to be carried out, with the aim of establishing an overall judgement about the implications of this economic instrument on irrigation sustainability.

Similarly, a review of the current literature shows how most previous studies have considered volumetric pricing as the only means of applying the cost-recovery instrument. It would therefore appear to be just as relevant to perform a deeper analysis of other ways of applying this economic instrument, via a study of the differential effects of these alternatives.

This paper thus attempts to deal with the two aforementioned gaps in knowledge. The objective of the study was to develop a methodology to analyse *ex-ante* the impacts of the implementation of a range of alternative instruments for pricing irrigation water on the sustainability of irrigated agriculture. To achieve this goal, the innovative element of this study lies in its use of a composite sustainability index. The proposed methodology was applied, as a pilot experience, to a real irrigated agricultural system: the farming district of Campos in the Province of Palencia. The aim of the study is to demonstrate the utility of the proposed methodology as a working tool for technicians and policy decision-makers, to help them design and implement the most suitable instruments for improved governance of irrigated agricultural systems.

We have structured the paper as follows. This introductory section is followed by a description of the study area used for the empirical analysis. The third section offers a detailed description of the methodology employed. The fourth section analyses how the simulation models were formulated. The fifth section is a summary of the results, while the paper finishes with a section that discusses our main conclusions.

2. Case study

The empirical application of this research focuses on the farming district of Campos, located in the centre of the Northern Spanish plateau, in the province of Palencia. Its high altitude (between 700 and 800 m.a.s.l.) and long distance from the sea give it a clearly continental climate, with an average rainfall of around 500 mm per annum, spread heterogeneously over the year (most of the rain fall in autumn, and to a lesser degree, in spring). Under such climatic conditions, irrigated agriculture is the only means of breaking the rainfed monoculture of winter cereals typical of the area, allowing the introduction of summer crops.

Irrigated agriculture in the Campos district covers a surface of 37829 hectares, which accounts for 14.5% of its utilised agricultural area (UAA), which is distributed among 2096 farms (the average irrigated farm has 18.0 ha of irrigated land). It is important to highlight the existence of major differences in the structure of the farms, as there are both small farms (less than 5 hectares) and much larger (over 50 hectares).

These areas were transformed into irrigated land in the latter half of the 20th century, thanks to the construction of significant regulation systems for the headwaters of its main rivers (Pisuerga and Carrión) and of the corresponding irrigation channels for transporting these surface waters. These infrastructures are publicly owned and are managed by the Basin Authority (*Confederación Hidrográfica del Duero,* CHD). Besides these infrastructures, there exists a secondary distribution network. This is also publicly owned, but is managed and maintained by the communities of irrigators, as associate entities for communal management of irrigation water.

The allocation of water to the communities of irrigators by the water authorities is around 8000 m^3/ha annually. The water is measured at the entrance to the main irrigation channels. However, it is important to bear in mind that the transport efficiency through the main channels is 80.3%, while the distribution efficiency through the secondary network is 85.5% (CHD, 2007).The average amount of water which actually reaches the plots is thus about 5500 m^3/ha annually. The techniques of sprinkler irrigation and furrow irrigation occupy almost 50% of all the irrigated land each.

The most important irrigated crops in this area are winter cereals (wheat and barley) with 49.8% of the total surface, alfalfa (26.3%), sugar-beet (9.9%), maize (9.4%) and sunflower (4.6%) (data for 2008).

Irrigation water pricing is currently based on a fixed quantity depending on the irrigated area, which in turn comprises three different items. Firstly, there are two tariffs paid to the CHD: a) the *regulation fee*, for management of the infrastructures controlled by this public body (main reservoirs and channels), which is set at €24/ha per year, and b) the *water use tariff*, for use of the publicly owned secondary network, which ranges between €10 and €30/ha per year, depending on the characteristics of these networks in the various irrigated areas. On top of these fees come the *contributions* charged by the communities of irrigators themselves to cover secondary network operating and maintenance costs; these range between

€20 and €30/ha per year. Together, the total fees to be paid for irrigation water in the study area come to between €55 and €80/ha per year[1].

This area was chosen in order to study a real case both on account of its technical characteristics, in that it is representative of Spanish inland irrigated agricultural systems, where the multifunctional character of irrigated agriculture is perfectly clear (Gómez-Limón and Gómez-Ramos, 2007), and for practical reasons, i.e. the good availability of high-quality data (see section 3.5).

3. Methodology

3.1. Alternatives for irrigation water pricing

Taking into consideration the different alternative methods applicable for irrigation water pricing (Tsur and Dinar, 1997; Johansson et al., 2002; Easter and Liu, 2005; Molle and Berkoff, 2007), as well as the particular characteristics of the case study (public irrigated lands and surface water resources), we selected the following four instruments as being of greatest interest for their potential implementation in the area:

- *Pricing per unit irrigated area*. This is based on water pricing per irrigated hectare, irrespective of the crop produced. This pricing system is similar to that currently used in the area, except with the difference that the tariff is now paid per unit irrigated area (whether or not the water is used), while the proposed instrument only charges for areas which are actually irrigated. In consequence, eleven different scenarios are proposed for the simulation in our case study, in which this charge increases progressively from €0 to €500/ha per year. These values were selected bearing in mind the current average payment for water services (see above section) and the forecast for increases as a result of implementing the WFD (CHD, 2007).
- *Volumetric pricing*. This considers an irrigation water pricing scheme based on the volume of water used. For this purpose, eleven pricing levels have been selected, ranging from €0.00 to €0.10 /m^3. These values were selected for their interest as an appropriate range for the application of the cost-recovery principle required by the WFD (Gómez-Limón and Riesgo, 2004).

[1] Considering an average water allowance of 5500 m^3/ha it implies a volumetric pricing of €0.010-€0.015/m^3.

- *Two-part tariff system.* This is a combination of the two alternative pricing systems described above, which levies a fixed tariff per hectare actually irrigated and a volumetric tariff on irrigation water. Nine new different tariff levels have been generated by combining three fixed tariffs per hectare (€50, €100 and €150/ha per year) with three levels of volumetric pricing (€0.02, €0.04, €0.06/m^3).

- *Block-rate pricing*. This instrument is based on setting differentiated water prices, which increase progressively based on the band or block of water consumption (Bar-Shira et al., 2006). We found it appropriate to define three blocks of water consumption[2]: The first applies to consumption between 0 and 3000 m^3/ha, the second between 3000 and 6000 m^3/ha and the third greater than 6000 m^3/ha. Bearing in mind the price levels considered for volumetric pricing, four alternatives were generated for this pricing method. Their structure is given in Table 1.

Table 1. Water pricing alternatives for the block-rate system

Block-rate water allowance	**Water price (€/m^3)**			
	Alternative 1	Alternative 2	Alternative 3	Alternative 4
0 - 3000 m^3/ha	0.01	0.02	0.03	0.04
3000 - 6000 m^3/ha	0.02	0.04	0.06	0.08
≥ 6000 m^3/ha	0.03	0.06	0.09	0.12

To finish this section, it is important to clarify that in three of the instruments based on the water used (volumetric, two-part and block-rate), the volume of water to be paid for is that made available to the farmer on his plot of land.

3.2. Decision-making heterogeneity and cluster analysis

Modelling farming activity at agricultural system level (or at any other level that deals with a set of individual farms) implies problems of aggregation bias. Indeed, modelling a set of farms in a unique programming model overestimates the mobility of resources, allowing the modelled farms to combine resources in proportions that are impossible in the real world (Hazell and Norton, 1986). This aggregation bias can only be avoided if the farms included in

[2] The threshold value for each block is based on the crop irrigation requirement and the irrigation technology. Thus, the first threshold refers to winter cereals (wheat and barley) with sprinkler irrigation (the most efficient technique) and the second to sunflower as well with sprinkler irrigation.

the models fulfil strict homogeneity criteria (Day, 1963): technological homogeneity, pecuniary proportionality and institutional proportionality.

The irrigated area under consideration as a case study is located within a single agricultural county. Hence, bearing in mind climate and soil-quality homogeneity, and technological, institutional and market characteristics, the case study area may be regarded as a unit that fulfils the above-mentioned homogeneity criteria. It therefore seems reasonable to assume similar behaviour for all farmers in the study area, which would mean that the operation of the water pricing instruments being considered could be analysed through a single simulation model with relatively small problems of aggregation bias. However, such homogeneity in producers´ behaviour rarely exists in the real world. Thus, although they have a similar resource base, farmers in the same agricultural systems typically display significant differences in their production decisions. For this reason, in order to minimize the aggregation bias in simulation, it is necessary to classify farmers in terms of homogeneous groups with regard to their crop mixes (Berbel and Rodríguez, 1998), which include farmers with similar cost and net revenues functions (pecuniary proportionality and technological homogeneity).

In order to develop a typology of producers, we surveyed the irrigators in the area, with the aim of gathering information on crop mixes that would allow the farmers' production schemes to be characterised (see Section 3.5.). This information was used in order to apply a cluster analysis, which utilises farmers' actual crop mixes as classification criteria. This statistical technique took Euclidean squared distance as a measure of distance among actual crop mixes (vector crop area expressed in percentages). The Ward or minimum variance method was utilised as the aggregation criterion.

3.3. The simulation technique: positive mathematical programming

Positive mathematical programming (PMP), which was developed by Howitt (1995), is a mathematical modelling technique based on a calibration system, which establishes a non-linear cost function that allows the same cop-mix distribution as the one observed in the real world to be reproduced, by using the information contained in the dual values of the decision variables (crops).

The standard calibration procedure described by Howitt (1995) is based on three steps. The first step consists of building a Linear Programming (LP) model in order to obtain the dual-value variables for each of the activities (crops) considered. The following step uses these variables to calibrate the cost function of the individual crops. Finally, in the third step the cost-function parameters are used to define a non-linear objective function that will reproduce the base-year crop distribution. Once the PMP model is calibrated, it allows the productive pattern behaviour of farmers to be simulated when they face a new economic (products and/or inputs prices, subsidies, etc.) or normative (productive constraints) context that affects the agricultural sector.

However, the original method has been criticized, and some shortcomings of this technique have been identified (Heckelei and Britz, 2005; Henry de Frahan et al., 2007). This has led to further development of the PMP with the aim of mitigating the drawbacks of the original approach. In line with this, Röhm and Dabbert (2003) present an extension of the PMP which permits a higher degree of substitution between similar crops (called 'variant activities'), rather than between other less similar crops (activities). Thus, the concept of variant activities can be applied to either the same crop that is grown under different techniques (e.g. irrigated and rainfed) or crops belonging to the same family (Röhm and Dabbert, 2003). This property is very suitable for identifying relevant water-pricing scenarios since farmers would presumably substitute irrigated crops for rainfed.

The mathematical formulation of this extension of the PMP can be summarized as follows[3]. Bearing in mind the different activities (i) and the possible variants (j), the initial model takes the following formulation:

$$Max\ TGM = \sum_i \sum_j \left(p_{i,j} \cdot y_{i,j} - c_{i,j} + s_{i,j}\right) x_{i,j} + SFP \qquad [1a]$$

Subject to:

$$\sum_i \sum_j \left(x_{i,j}\right) \leq \sum_i \sum_j \left(x_{i,j}^0\right) \qquad [1b]$$

$$\sum_j \left(x_{i,j}\right) \leq \sum_j \left(x_{i,j}^0\right)\left(1+\varepsilon_1\right) \qquad \forall i \qquad [1c]$$

$$x_{i,j} \leq x_{i,j}^0 \left(1+\varepsilon_2\right) \qquad \forall i, j \qquad [1d]$$

$$\varepsilon_2 > \varepsilon_1 \qquad [1e]$$

$$x_{i,j} \geq 0 \qquad \forall i, j \qquad [1f]$$

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[3] For detailed information about the mathematical development of this PMP approach, see Röhm and Dabbert (2003).

Eq. [1a] represents the LP model objective function, where TGM is the total gross margin. The TGM is calculated as the sum of the gross margins resulting from each activity. For this reason, the objective function is logically a function of the area allocated to each crop, $x_{i,j}$ (hectares devoted to crop i, with variant j). These $x_{i,j}$ are regarded as the decision variables of the model. In order to calculate the TGM it is also necessary to have the following technical coefficient data: price ($p_{i,j}$), yield ($y_{i,j}$), variable cost ($c_{i,j}$) and Common Agricultural Policy (CAP) direct subsidies, coupled to the production per unit area ($s_{i,j}$). It also includes the single farm payment (SFP), which is based on the farmers' historical payments.

The above-mentioned model presents a set of constraints, which can be interpreted as follows: Eq. [1b] limits the total agricultural land available, where $x^0_{i,j}$ represents the crop-mix observed in the base year. Eq. [1c] represents the constraints for total activities, where ε_1 is a small positive number. Finally, Eq. [1d] represents the constraints for the variant activity, with ε_2 another small positive number that must satisfy Eq. [1e].

The addition of Eqs. [1c] and [1d] forces an optimal solution in the LP model that reproduces the activities observed in the base year ($x^0_{i,j}$). As a result of the introduction of these two constraints, the model solution generates the dual values for the different activities. Eq. [1c] produces the dual values of activities λ_i and Eq. [1d] the dual values of the variant activity $\lambda_{i,j}$.

Once the dual values have been obtained, they are used to calibrate the cost function of the individual activities. These parameters are also used to define the new objective function for the PMP model. Thus, Eq. [2] introduces the objective function of the extended version of the PMP:

$$Max\, TGM = \sum_i \sum_j \left\{ x_{i,j} \left[y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x^0_{i,j}} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \bar{x}^0_{i,j}} \bar{x}_i \right) + s_{i,j} - c_{i,j} \right] \right\} + SFP \qquad [2]$$

This PMP approach as simulation model has been previously adopted by Key and Kaplan (2007), Schmid et al. (2007), Gallego-Ayala and Gómez-Limón (2009), Henseler et al. (2009) and Cortignani and Severini (2009), among others.

3.4. Calculating the composite sustainability indicator

With the aim of calculating the Composite Indicator for Irrigated Agriculture (CIIA), we have followed the methodological guidelines suggested by the OECD-JRC (2008) regarding the creation of composite indicators. The most relevant aspects are given below.

3.4.1. Theoretical framework and selection of basic indicators

The first step was to select a set of indicators that would make it possible to quantify the sustainable performance of the irrigated farms in such a way that they would allow information to be collected about the performance of the three basic sustainability dimensions: economic, social and environmental. Bearing in mind the modelling possibilities using mathematical programming, this paper has considered 12 indicators, based on the proposed set of indicators developed by Gómez-Limón and Sanchez-Fernandez (2010) for the same agricultural system, which are shown in Table 2.

Table 2. Selected basic indicators

Sustainability dimensions	Indicators	Measurement units
Economic	Total Gross Margin (TGM)	€/ha
	Contribution to the regional GDP (CONGDP)	€/ha
Social	Farm employment (EMPLT)	Man-day labour /ha
	Seasonal labour (SEAS)	%
	Risk of farming abandonment (ABAND)	%
Environmental	Specialization (SPEC)	%
	Soil covering (SOILCOV)	%
	Nitrogen balance (BALN)	kg N/ha
	Phosphorus balance (BALP)	kg P/ha
	Pesticides risk (PESTRISK)	kg/ha
	Water consumption (WATER)	m^3/ha
	Energy balance (ENBA)	kcal/ha

Source: Based on Gómez-Limón and Sanchez-Fernandez (2010).

Each one of these indicators is briefly explained below:

- *Total gross margin*. This is the difference between revenue (sales and subsidies, both coupled and uncoupled, included in the SFP). The gross margin thus obtained can be considered as a valid estimate of the private profitability of the farming activity.
- *Contribution of agriculture to GDP*. This indicator is a proxy for the creation of wealth from farming activities for society as a whole. It is calculated by deducting all the subsidies from the previous indicator and adding the amounts paid to the authorities in the form of water tariffs.
- *Farming employment.* This indicator aims to quantify the contribution of the farming sector to rural development and to territorial balance (fixing population, income distribution, etc).
- *Labour seasonality*. The demand for labour from farming is closely related to the crop production timetable, which at certain times requires a concentration of labour requirements. Thus, this indicator quantifies the demand for farm labour at peak periods during the year, which may be regarded as a suitable estimator to measure farming's contribution to maintaining the rural population.
- *Risk of abandonment of farming*. Ongoing production in farms is linked to two factors (EEA, 2005): a) the farmer's age and b) the farm's profitability. Gómez-Limón and Sanchez-Fernandez (2010) defined an *ad hoc* index that takes values from the range between 1 (when the farm-owner is less than 55 years old and when the farm produces a higher than average income for the area) and 0 (when the owner is over 70 years old, does not have an assured successor and the income provided by the farm is less than 50% of the average income in the area).
- *Specialisation*. This indicator measures the percentage of the farm covered by the main crop, thus quantifying the tendency of the farm to monocropping. In this regard, this indicator provides information about farming biodiversity.
- *Soil coverage*. This indicator represents the percentage of days in the year on which vegetation covers the soil. This indicator can thus be regarded as a proxy for the risk of soil erosion.
- *Nitrogen/phosphorus balance.* This balance is obtained by the difference between the nitrogen/phosphorus content of the inputs used in production and that of the corresponding outputs. This difference indicates the amount of nitrogen/phosphorus

released each year into the environment, which represents an estimate of the impact of irrigated agriculture on the ecosystem through non-point pollution.

- *Pesticide risk*. This indicator is quantified by estimating the deaths of living organisms as a result of the action of the active matters present in the pesticides applied. This indicator provides information about the toxicity released into the environment through the use of agrochemicals.
- *Use of irrigation water*. The quantity of water used for irrigation the quantitative pressure that agriculture applies to bodies of water to be measured.
- *Energy balance*. This is similarly calculated via an input-output approach, by measuring the difference between the energy present in the farming inputs used in production plus the energy necessary to perform the farming works, and the energy in the crops harvested. This indicator aims to quantify the contribution of irrigation as a CO_2 sink (reduction of greenhouse effect gases), and, therefore, as a mitigator of climate change.

3.4.2. Normalisation of indicators

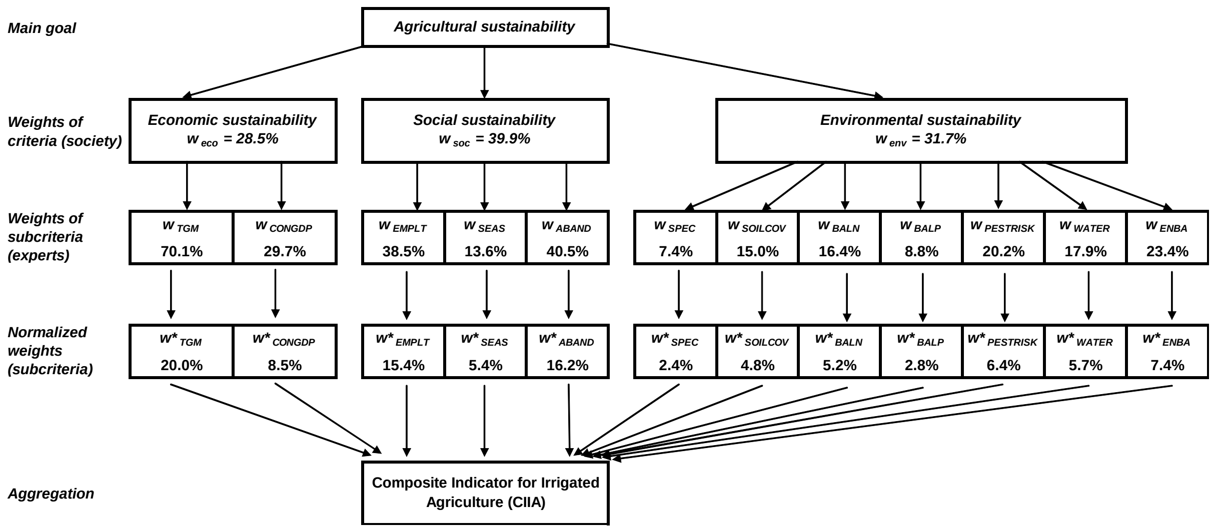
Normalisation is essential before indicators can be aggregated, since these have usually been calculated using different units of measurement. They therefore need to be expressed in homogeneous units in order to allow them to be compared and to perform arithmetical operations on them. In our case, of the various normalisation techniques available (Freudenberg, 2003), we decided to employ “min-max” normalisation, so that the values of all the normalised indicators would vary within a dimensionless range (0,1), where 0 corresponds to the worst possible value of the indicator (i.e. the least sustainable) and 1 to the best (most sustainable).

3.4.3. Indicator weighting

Once the indicators have been normalised, the next stage is to allocate weights and aggregate them. The OECD-JRC (2008) lists a number of methods for both weighting and aggregating the indicators. Our study opted for the methods most often used in this type of exercise.

Weighting makes it possible to differentiate the relative importance of the various indicators considered. We used the weights presented in Gómez-Limón and Sanchez-Fernandez (2010), calculated by means of the Analytic Hierarchy Process (AHP). This technique was first applied to a representative sample of the population of Castilla y León region (survey of 321 individuals), with the aim of obtaining the weights of the three basic components of sustainability, enabling us to calculate the relative importance of the set of economic, social and environmental indicators. The same technique was then applied to a panel of 16 technical experts from universities and research institutes, with the aim of obtaining the weightings of the base indicators contained in each of the three basic dimensions. The weight given to each of the basic sustainability components and to the different base indicators is shown in Figure 1.

Figure 1. Weights for sustainability dimensions and basic indicators



Source: Based on Gómez-Limón and Sanchez-Fernandez (2010).

3.4.4. The aggregation of the indicators

We opted to aggregate the indicators performing a weighted sum of their normalised values. The overall composite indicator for irrigated agriculture (CIIA) was first obtained by weighting the sum of the different base indicators, as shown in the following formula:

$$CIIA = \sum_{k=1}^{k=12} w^*_k \cdot I_k \qquad [3]$$

where w^*_k is the normalised weight associated with indicator *k*, and I_k is the normalised value of indicator *k*.

However, in order to analyse and differentiate the relative importance of each sustainability dimension (economic, social and environmental), partial composites indicators were also obtained for each of them, using the following expressions:

$$CIIA_{economic} = \sum_{k=1}^{k=2} w^{*}_{k} \cdot I_{k} \qquad [4]$$

$$CIIA_{social} = \sum_{k=3}^{k=5} w^{*}_{k} \cdot I_{k} \qquad [5]$$

$$CIIA_{environmental} = \sum_{k=6}^{k=12} w^{*}_{k} \cdot I_{k} \qquad [6]$$

3.5. Source of the input information for the models and indicators

The information needed as inputs for the simulation models, as well as for calculating the sustainability indicators, was collected from both primary and secondary sources.

The primary information was obtained from a survey of farmers in the study area. We drew up a questionnaire to collect information about the socioeconomic characteristics of the owners, the structural characteristics of their farms, their crop plans and the agricultural practices and techniques they employed. The sample universe was comprised farmers with irrigated land in the Campos district: 2096, according to the last Agricultural Census. Given the practical impossibility of performing a simple random sampling, we opted to use quota sampling based on affiliation of the producers to different Farmers' Unions (ASAJA, UPA and COAG). The survey was performed at the time when CAP aid applications were due to be completed (March-April 2008), as this brings farm owners to the offices of these Unions, thus easing the work of the interviewers. This procedure produced 111 valid questionnaires.

The information collected enabled us to characterise the diversity of farms in the area and to establish the farm-types in the district. The survey was also the main source of information for the building of the simulation models and calculation of the base indicators selected for the empirical application.

The sources of secondary information made it possible to collect the data needed for the models and to calculate the base indicators, especially in those cases in which this information is uniform for all the producers in the area: output and input prices, coefficients of nitrogen, phosphorus or energy contents in inputs and outputs, water requirements for irrigated crops, efficiency of irrigation systems or pesticide toxicity.

4. Modelling

4.1. Defining irrigated farm types in the study area

By employing the cluster technique described in section 3.2, four homogeneous groups of farmers with their respective farm types could be identified. The following characterisation comments on the most important variables for which statistically significant differences among the different clusters were found:

- ***Cluster A.*** This first group includes the highest percentage of farmers sampled (37.8%), and accounts for 41.5% of the total area analysed. These farmers manage mixed farms (irrigated and rainfed land) with an average size of 125 hectares, where irrigated land occupies 31% of the area. As a differentiating characteristic in comparison with the other groups of farmers, the most extensive practice is minimum tillage (75% of the total farm area). Likewise, the predominant irrigation technology is furrow irrigation (62% of the irrigated area). The most important irrigated crops in this group's crop-mix are winter cereals and alfalfa, which are sown to 51% and 26% respectively of the irrigated area. The group has been called "*minimum tillage cereal growers*".
- ***Cluster B.*** The second group comprises 19.8% of the sample of farmers, and accounts for 17.5% of the total irrigated area under study. The farms managed by these farmers average 101 hectares, of which 42% are irrigated. The farmers in this group employ conventional tillage (100% of the surface), and employ furrow irrigation (59% of the irrigated area). Their main irrigated crops are winter cereals (46%) and alfalfa (23%), followed by sunflower (12%) and maize (10%). For these reasons, we labelled this group "*conventional farmers with diversified production*".
- ***Cluster C.*** The third group includes 31.5% of the farmers, accounting for 29.4% of the total irrigated area. This group operate farms of 105 hectares, of which 48% is irrigated land. As in *Cluster A*, minimum tillage predominates (74% of the total surface); however, sprinkler irrigation is most widely employed (66% of the irrigated area). Irrigated production is oriented towards cereals and alfalfa (44% and 30%, respectively), although the group also devoted a significant area to sugar-beet (12%). We named this group "*minimum tillage and sprinkler irrigation cereal-sugar-beet growers*".
- ***Cluster D.*** The final cluster comprises the lowest number of farmers in the sample (10.8%), and likewise accounts for the lowest surface area in the area under study

(11.6%). These farmers manage farms that average 122 hectares, with 40% of the area irrigated. This group has adopted direct sowing as the dominant tillage system (80% of the total surface), and its favoured irrigation technique is furrow irrigation (71% of the irrigated area). The main irrigated crops in this farm-type are winter cereals, which cover almost 70% of the irrigated area. This group was labelled "*direct sowing cereal growers*".

Based on the results obtained in defining the farm types, it is worth pointing out how these homogeneous groups of farmers are characterised by their crop plans, as well as the tillage techniques and irrigation techniques used[4].

The above farm-types made up the basic units of analysis used construct the simulation models. Our aim was to minimise the aggregation bias discussed in section 3.2. A different model was therefore built for each group of farmers, in order to be able to simulate independently for each conglomerate the effects of the alternative irrigation water pricing methods. The results obtained for each group of producers were subsequently aggregated at district level by weighting the sum of the results for each farm-type, based on the area represented by each of them.

4.2. Decision variables

The decision variables considered for building the simulation models were the areas devoted to each of the most common crops in the study area ($x_{i,j}$). However, due to the differences in cost and existing yields, we found it most appropriate to characterise these activities on the basis of three factors: crop, irrigation technology and tillage techniques. Thus, bearing in mind only the combinations actually used by the farmers in the area, a total of 34 decision variables were selected, as shown in Table 3.

[4] The ANOVA and chi-squared tests of significance of farmers' socio-economic characteristics and farms' structural characteristics on clusters revealed no statistical relationships among them.

Table 3. Decision variables for the study area

Irrigation technology	Furrow			Sprinkler			Rainfed		
Tillage technology	CT	MT	DS	CT	MT	DS	CT	MT	DS
Wheat	**X**	**X**	**X**	**X**	**X**		**X**	**X**	**X**
Barley	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Oat							**X**	**X**	
Green peas								**X**	**X**
Sunflower	**X**						**X**	**X**	
Alfalfa	**X**	**X**		**X**	**X**		**X**		
Grain maize	**X**								
Green maize	**X**			**X**					
Sugar-beet				**X**	**X**				

CT: Conventional Tillage; MT: Minimum Tillage; DS: Direct Sowing.

In this regard, it is worth pointing out that the models developed were designed with the aim of simulating the productive behaviour of the set of farm-types analysed, including both their irrigated areas, whether these were used for irrigated or rainfed crops, and those which are purely rainfed (with no possibility of irrigation)[5].

With the aim of making the simulation models more flexible and allowing a greater level of substitution among various activities when faced with changes in water pricing policy (substitution of irrigated crops for rainfed crops), three groups of activities were defined, following the extension of the PMP developed by Röhm and Dabbert (2003). These groups are: a) *winter cereals*, comprising the variant activities wheat, barley and oats, both irrigated and rainfed, b) *sunflower*, made up of the variant activities irrigated sunflower and rainfed sunflower, and c) *alfalfa*, with the variant activities irrigated alfalfa and rainfed alfalfa.

4.3. Modelling of pricing per unit irrigated area

The model built for simulating implementation of a fixed fee over the irrigated area appears below:

[5] The modelling of irrigated and non-irrigated plots of the farm as a whole management unit represents a novelty in this study, compared with the previous literature, in which only irrigated farm plots are modelled. This approach may prove to be more suitable for explaining the farmers' behaviour, since their decisions are probably based on an overall assessment of their farms, rather than focusing exclusively on the irrigated part of the farm.

$$Max \sum_i \sum_j \left\{ x_{i,j} \left[y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x^0_{i,j}} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \bar{x}^0_{i,j}} \bar{x}_i \right) + s_{i,j} - c_{i,j} \right] \right\} + \\ + SFP - t_s \cdot \sum_{i^r} \sum_{j^r} x_{i,j} \quad [7a]$$

Subject to:

Total area constraint: $$\sum_i \sum_j x_{i,j} \leq AREA \quad [7b]$$

Total irrigated area constraint: $$\sum_{i^r} \sum_{j^r} x_{i,j} \leq AREA_{irrigated} \quad [7c]$$

Sprinkler irrigation area constraint: $$\sum_{i^{rs}} \sum_{j^{rs}} x_{i,j} \leq AREA_{sprinkler} \quad [7d]$$

Alfalfa rotation constraint: $$\sum_j x_{alf-CT,j} + \sum_j x_{alf-MT,j} \leq 0.55 \times AREA \quad [7e]$$

Sugar-beet CAP constraint: $$x_{sug-CT} + x_{sug-MT} \leq 50\% \frac{\text{Sugar beet quota}}{\text{Sugar beet yield}} \quad [7f]$$

Alfalfa market constraint:

$$\sum_j y_{alf-CT,j} x_{alf-CT,j} + \sum_j y_{alf-MT,j} x_{alf-MT,j} \leq \text{Production}_{time\ series\ maximum} \quad [7g]$$

Non-negativity constraint: $$x_{i,j} \geq 0 \qquad \forall i, j \quad [7h]$$

Equation [7a] represents the objective function, which is adjusted to the expression [2] already explained above. This includes the fee per irrigated area t_s, that would be charged for the crops and variants actually irrigated (indicated by the sub-indices i^r and j^r). The parameters of this fee was set taking values ranging from €0/ha to €500/ha.

The first constraint [7b] limits the crop area to the total area (irrigated plus rainfed) actually available on the farm (*AREA*). Constraint [7c] limits the irrigated area to the available irrigated area ($AREA_{irrigated}$). Indeed, as this is a short and medium-term model, transformation of rainfed lands into irrigated ones is not permitted. For the same reason, the possibility of introducing innovations in irrigation technology was not included. Therefore, the area using sprinkler irrigation (crops and variants indicated by indices i^{rs} and j^{rs}) is limited to the area currently irrigated using that technique ($AREA_{sprinkler}$), as established in expression [7d].

The constraint [7e] was included so that the optimum crop plans resulting from the model would respect the agronomic restrictions of alfalfa growing. Expression [7f] was incorporated in order to permit appropriate simulation to be made of the restructuring of the sugar-beet market following the latest reform of the Common Market Organization (CMO) for sugar. In accordance with this reform, sugar-beet growers are obliged to abandon 50% of the production of this crop from the 2008/2009 season, for which they will be compensated with €40 for each tonne that they had delivered on average during the four-year period 2004-2008 (quantity which is included, duly annualised, within the SFP). Finally, expression [7g] is the market constraint relating to alfalfa, conditioned by the amount of livestock in the surrounding areas.

The set of constraints [7b], [7c], [7d], [7e], [7f], [7g] and [7h], which was common to all simulations, is referred to below as $A\vec{X} \leq \vec{B}$.

4.4. Modelling of volumetric pricing

The model for simulating the implementation of volumetric water pricing is as follows:

$$Max \sum_i \sum_j \left\{ x_{i,j} \left[y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x_{i,j}^0} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \bar{x}_{i,j}^0} \bar{x}_i \right) + s_{i,j} - c_{i,j} - t_w \cdot \frac{WR_{i,j}}{Efic_{i,j}} \right] \right\} + SFP \qquad [8a]$$

Subject to:

General constraint: $A\vec{X} \leq \vec{B}$ [8b]

where t_w is the volumetric irrigation water tariff, $WR_{i,j}$ are the water requirements of the crop *i,j* and $Efic_{i,j}$ is the efficiency associated with the irrigation technique used for that crop. The parameters for t_w were also set between €0.00 and €0.10/m^3.

4.5. Modelling of the two-part tariff system

The application of a two-part irrigation water pricing system was simulated using the following model:

$$\begin{aligned} Max \sum_i \sum_j \left\{ x_{i,j} \left[y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x_{i,j}^0} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \bar{x}_{i,j}^0} \bar{x}_i \right) + s_{i,j} - c_{i,j} - t_w \cdot \frac{WR_{i,j}}{Efic_{i,j}} \right] \right\} + \\ + SFP - t_s \cdot \sum_{i^r} \sum_{j^r} x_{i,j} \end{aligned} \qquad [9a]$$

Subject to:

General constraint: $A\vec{X} \leq \vec{B}$ [9b]

In this case the values of t_s vary between €50 and €150/ha and t_w takes values which range between €0.00 and €0.06/m^3.

4.6. Modelling of block-rate pricing

Equation [10a] defines the objective function used to simulate the productive behaviour of the farm-types under a system of block-rate pricing for irrigation water:

$$Max \sum_i \sum_j \left\{ x_{i,j} \left[\begin{array}{l} y_{i,j} p_{i,j} \left(1 + \frac{\lambda_i + \lambda_{i,j}}{y_{i,j} p_{i,j}} - \frac{\lambda_{i,j}}{y_{i,j} p_{i,j} x_{i,j}^0} x_{i,j} - \frac{\lambda_i}{y_{i,j} p_{i,j} \bar{x}_{i,j}^0} \bar{x}_i \right) + \\ + s_{i,j} - c_{i,j} - \left[t_{w1} \cdot (3000 - \alpha) + t_{w2} \cdot (\beta - \delta) + t_{w3} \cdot \delta \right] \end{array} \right] \right\} + SFP \quad [10a]$$

Subject to:

General constraint: $A\vec{X} \leq \vec{B}$ [10b]

First block water constraint: $$\frac{\sum_{i^r} \sum_{j^r} \frac{WR_{i,j}}{Efic_{i,j}}}{\sum_{i^r} \sum_{j^r} x_{i,j}} + \alpha - \beta = 3000 \quad [10c]$$

Second block water constraint: $$\frac{\sum_{i^r} \sum_{j^r} \frac{WR_{i,j}}{Efic_{i,j}}}{\sum_{i^r} \sum_{j^r} x_{i,j}} + \gamma - \delta = 6000 \quad [10d]$$

Non-negativity constraints: $\alpha \geq 0;\ \beta \geq 0;\ \gamma \geq 0;\ \delta \geq 0$ [10e]

where t_{w1} (t_{w1} = €0.01, €0.02, €0.03 and €0.04/m^3) refers to the unitary water tariff for the first block of water consumption applied to the volume 3000-α derived from expression [10c], t_{w2} (t_{w2} = €0.02, €0.04, €0.06 and €0.08/m^3) is the unitary water tariff corresponding to the second block of water consumption, which charges the quantity β–δ, which is deduced from the expressions [10c] and [10d], and t_{w3} (t_{w3} = €0.03, €0.06, €0.09 and €0.12 /m^3) is the third tariff corresponding to the third block of water consumption, which is charged for the volume δ, derived from the expression [10d].

4.7. Calibration of the models

It is worth pointing out that the different PMP models built for this research were calibrated bearing in mind the crop mix followed by the producers in the 2007-2008 farming year (Baseline scenario), where the regulatory framework of the CAP refers to the Mid-Term Review approved in 2003 (partial decoupling of support). However, faced with the subsequent change in the CAP and the implementation of the 2009 Health Check (total decoupling of production support), the change in the CAP was also taken into consideration when the various economic instruments for irrigation water pricing were simulated. This was done in order to give greater meaning to the results obtained, and thus to allow us to differentiate the impact on farm sustainability as a result of the CAP reform (Mid-Term Reform to the Health Check) and the subsequent implementation of water pricing.

5. Results

The resolution of the models described above made it possible first, to obtain results for each farm-type. Subsequently, through weighted aggregation of these partial results, we have obtained the results for the whole irrigated system. However, in order to summarise the presentation of the results, this section focuses on the analysis of the aggregated results for the Campos district, as these are the most important for supporting political decision-making. In any case, Table A-3 in the appendix also presents the impact of the different scenarios by farm-type.

Tables A-1 and A-2 show the values of the base indicators for the study area as a whole in each of the simulated pricing scenarios. In any case, in accordance with the methodology adopted for evaluating sustainability, the overall results are presented on the basis of the values obtained for the CIIA composite indicator and its dimensional components ($CIIA_{eco}$, $CIIA_{soc}$ and $CIIA_{env}$).

Taking into consideration the results obtained for the CIIA index, it is worth pointing out first, that the recent change in the CAP (application of the Health Check) will have in itself only a slight negative effect on the sustainability of irrigation farming in the study area. This negative impact is expressed through the reduction of the composite sustainability indicator, which falls from a value of 0.69 (Baseline scenario) to 0.65 (scenario following application of the Health Check - without application of any water pricing), as can be seen in Table 4. In this regard, it is worth nothing that the fall in the sustainability performance of irrigation is due to two basic issues: a) total decoupling of production support, which encourages greater extensification of production (introduction of rainfed crops in irrigated areas), which in turn reduces the generation of added value and worsens the social performance of farming, and b) the reform of the CMO for sugar, which will mean that the area devoted to sugar-beet (a crop with high added value and one which plays an important social role due to its high demand for labour) will fall significantly in the study area. Both circumstances explain that the above-mentioned fall in the CIIA is due to worsening of the farms' economic and social performance (observe the $CIIA_{eco}$ and $CIIA_{soc}$ indicators in Table 4), without there being significant variations in environmental sustainability ($CIIA_{env}$).

Regarding the results obtained for implementing irrigation water pricing, it is important to point out that, in general terms, the different charges generate impacts in the same direction: a reduction in the sustainability of the irrigated agricultural system analysed. Thus, as Table 4 shows, as the different types of water charges increase, additional falls take place in the CIIA index compared to the Baseline scenario. The explanation for this lies in the fact that the farmers introduce new changes in their productive strategies as a response to water pricing, substituting irrigated crops for rainfed alternatives (production extensification). This leads to a worsening in the economic and social performance of farming, while environmental sustainability remaining practically stable. The results shown below analyse how the productive strategies that farmers will adopt produce a different impact on each of the three sustainability dimensions, and how these impacts in turn differ, based on the different pricing mechanisms considered.

Table 4. Simulation results for the Campos district

Water pricing scenarios	Composite indicators			
	$CIIA_{eco}$	$CIIA_{soc}$	$CIIA_{env}$	**CIIA**
Baseline scenario	0.20	0.32	0.17	0.69
Pricing instrument: irrigated area				
0 €/ha	0.17	0.31	0.17	0.65
100 €/ha	0.15	0.25	0.17	0.56
200 €/ha	0.12	0.17	0.17	0.46
300 €/ha	0.10	0.11	0.17	0.38
400 €/ha	0.07	0.07	0.16	0.31
500 €/ha	0.05	0.04	0.16	0.26
Pricing instrument: volumetric tariff				
0.00 €/m^3	0.17	0.31	0.17	0.65
0.01 €/m^3	0.16	0.26	0.17	0.59
0.02 €/m^3	0.14	0.20	0.18	0.52
0.03 €/m^3	0.12	0.15	0.18	0.46
0.04 €/m^3	0.11	0.12	0.18	0.42
0.05 €/m^3	0.10	0.11	0.18	0.39
0.06 €/m^3	0.10	0.09	0.18	0.37
0.08 €/m^3	0.08	0.07	0.18	0.32
0.10 €/m^3	0.06	0.04	0.18	0.28
Pricing instrument: two-part tariff system				
0 €/ha + 0.00 €/m^3	0.17	0.31	0.17	0.65
50 €/ha + 0.02 €/m^3	0.13	0.17	0.18	0.48
50 €/ha + 0.04 €/m^3	0.11	0.12	0.18	0.41
50 €/ha + 0.06 €/m^3	0.10	0.09	0.18	0.36
100 €/ha + 0.02 €/m^3	0.12	0.14	0.18	0.44
100 €/ha + 0.04 €/m^3	0.10	0.10	0.18	0.38
100 €/ha + 0.06 €/m^3	0.08	0.07	0.17	0.32
150 €/ha + 0.02 €/m^3	0.11	0.11	0.18	0.39
150 €/ha + 0.04 €/m^3	0.09	0.08	0.17	0.34
150 €/ha + 0.06 €/m^3	0.07	0.05	0.17	0.29
Pricing instrument: block-rate system				
0.00 - 0.00 - 0.00 €/m^3	0.17	0.31	0.17	0.65
0.01 - 0.02 - 0.03 €/m^3	0.15	0.21	0.18	0.55
0.02 - 0.04 - 0.06 €/m^3	0.14	0.16	0.18	0.48
0.03 - 0.06 - 0.09 €/m^3	0.13	0.12	0.19	0.44
0.04 - 0.08 - 0.12 €/m^3	0.13	0.10	0.18	0.41

With regards to economic sustainability, we can see that as the different levels of irrigation water pricing are implemented, the performance of the $CIIA_{eco}$ worsens, thus reducing the overall sustainability of the farming system analysed. This erosion of economic viability of irrigated agriculture is due to the fact that these economic instruments produce a significant reduction in farmers' private profitability (TGM indicator), produced both by the payments which they must make to the authorities in the form of fees (transfer of income from the private to the public sector), and because of changes in their crop plans (substitution of irrigated crops by other rainfed land crops with lower added value). It is therefore clear that the losses in private profitability arising from water pricing lead to a loss in economic efficiency, to the extent that the losses are greater than the money collected by this instrument and passed to the public sector. This inefficiency is equivalent to the reduction in the farms' profitability caused by the changes in the crop plans. This explains why the reduction in the TGM indicator is more marked than the increase in the contribution to the GDP (CONGDP indicator) indicator, with the result that the overall result for economic sustainability measured by the $CIIA_{eco}$ index is negatively affected. These results are in agreement with those provided by Berbel and Gómez-Limón (2000) and Gómez-Limón and Riesgo (2004) from other irrigated areas of the Duero river basin.

Along the same lines, it is important to point out how those pricing instruments which take into account the actual consumption of irrigation water (volumetric and block-rate pricing, which transmit the cost signal for water use more directly) lead to less reduction in the $CIIA_{eco}$ index compared to tools that price water irrespective of actual consumption (pricing by irrigated area). In fact, for the case of block-rate pricing (for the four simulated price scenarios), the economic index falls by only 30%. These differences in behaviour caused by the different instruments occur because volumetric pricing and block-rate pricing minimise the appearance of the above-mentioned economic inefficiency (reduction of farm profitability due to the introduction of crops with lower added value), to the extent that these pricing systems basically lead to a transfer of income from the private sector to the public sector. However, it must be stated that this is only true for low volumetric tariffs; as the amount of the charge increases, the losses in farmers' incomes increase to a greater extent than the rise in public sector revenues; that is, the level of inefficiency similarly increases.

Furthermore, the introduction of pricing would similarly damage the social sustainability of irrigated land in the study area. It can be seen how the values of the $CIIA_{soc}$ index fall rapidly and significantly as the charges for irrigation water increase. This is due to three causes: a) the loss of direct employment in irrigation (reduction in the EMPLT indicator), due to the reduction in demand for work as a consequence of substituting irrigated crops for rainfed land crops which are less labour-intensive, b) the increase in the seasonality of labour demand (SEAS indicator), caused by the change in crop plans, and c) the increase in the risk of farm abandonment (ABAND indicator), which is an aspect closely linked to the loss of the farm income for the reasons mentioned above. In any case, unlike the $CIIA_{eco}$ index, the development of the social component of sustainability does not display significant differences as a result of the pricing instrument used; they all generate a significant decrease in the $CIIA_{soc}$ index.

From the point of view of environmental sustainability ($CIIA_{env}$), it is important to point out that the implementation of irrigation water pricing has an almost neutral effect, as can be seen from the results obtained (see Table 4). These results may at first seem counterintuitive. However, it is important to understand that they are a reflection of the offsetting in terms of the $CIIA_{env}$ that occurs between the positive and negative environmental externalities associated with irrigation water pricing. It is therefore worth pointing out that the introduction of water pricing generates an improvement in the WATER base indicators (reduction in the quantitative pressure of irrigation on water resources) and PESTRISK (reduction in the release of plant protection products to the environment). However, at the same time, the values of the SPEC indicator (increase in single-crop farming of winter cereals on non-irrigated land - reduction in biodiversity), SOILCOV (increase in the risk of wind and water soil erosion), BALN and BALP (increase in diffuse contamination by nitrogen and phosphorus derived from farming)[6] and ENBA (reduction in the irrigation system's efficiency as a CO_2 sink) worsen. This mixed environmental effect of pricing means that once the different base indicators have been weighted, the $CIIA_{env}$ index remains relatively stable when this type of water tariff is applied. In any case, a slightly beneficial effect can be seen for volumetric and block-rate pricing instruments (which take actual water consumption into account).

6. Conclusions

Given the results obtained in this paper, the first conclusion that we can reach refers to the practical utility of using composite sustainability indicators as a tool for improving governance of the agricultural sector. Indeed, the use of composite sustainability indicators makes it possible to implement a complicated concept, such as agricultural sustainability, allowing joint consideration of economic, social and environmental indicators. These indexes can then offer potentially useful information for public decision-makers in charge of

[6] The increased pressure caused by the use of nitrogen and phosphorus is also counterintuitive in terms of the literature. The cause of these results for the case study lies in the relative importance of alfalfa in irrigation, a legume crop with virtually zero balances of nitrogen and phosphorus. Indeed, in most cases, water pricing causes the abandonment of this crop in irrigation and its replacement by rainfed winter cereals, which have a greater demand for chemical fertilizers than alfalfa.

designing and implementing the programmes of measures for new water plans required by the WFD. As with this study of the case of irrigation water pricing, such a methodology is suitable for *ex-ante* analysis aimed at comparing the potential impacts of alternative instruments and setting selection criteria for those instruments. The aim would be to select those measures whose implementation in the irrigated areas would lead to a more balanced performance of the different sustainability dimensions (economic viability, social acceptability and eco-compatibility).

Our results also highlight the differential impacts of the different pricing instruments on socioeconomic and environmental indices. However, we can detect a series of effects that are common to all of them: a) a significant reduction in quantitative pressures (extraction from river flows), and b) the generation of damaging economic effects (loss of private irrigation profitability) and social effects (loss of employment generated by the sector). These results agree with the conclusions obtained by previous research. In terms of the composite indicator calculated (CIIA), these dimensional effects would lead to a reduction in the overall sustainability of the agricultural system analysed here.

However, it is important to bear in mind that irrigation water pricing is not merely an option, but a mandatory measure that has been established by the WFD for all member states of the EU. The requirement is based on the premise that establishing cost-recovery pricing is a suitable instrument for achieving the Directive's environmental objectives (the "good status" of water bodies). However, the results obtained demonstrate that although pricing is effective for achieving the planned objective, it may not be truly efficient, insofar as this water pricing policy also generates substantial costs which need to be taken into account, both socioeconomic (profitability and employment) and even environmental (erosion risk, CO_2 capture etc). This leads to certain doubts about the suitability of the lexicographic order of the objectives pursued by the WFD, in which achieving socioeconomic and environmental objectives that are different from improving the water environment are legally subordinate to improving the status of water bodies.

Whatever the merits of water-pricing instruments in general, block-rate pricing would appear to be the most suitable instrument for irrigation water pricing policy, in that it is the alternative that generates the least reduction in the CIIA index (as that which makes it possible to maintain greatest overall sustainability in the irrigated area). However, it is important to mention that if this instrument was too demanding, by applying high prices to each block (full recovery of financial, environmental and resource costs), it could lead to large-scale abandonment of irrigation due to its socioeconomic unsustainability. For this reason, it is reasonable to suppose that in the study area there are objective reasons which justify derogating the application of water pricing, as established in the WFD itself.

Finally, it should be noted that the results of the application performed may not easily be extrapolated to other irrigated areas outside the Castilla y León region. As we have made clear, the operability of the CIIA index has been made on the assumption that agricultural sustainability is a "social construction", which aims to quantify the ability of farming to satisfy a range of social demands (economic, social and environmental). Consequently, the values of the composite indicator used depend on particular weightings of the base indicators established on the basis of such social demands, and in the case of Castilla y León, social aspects assume a greater importance than other aspects. In this regard, any transfer of benefits to other space-time contexts must be made with extreme caution.

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Table A-1. Non-normalized basic indicators for the Campos district

	Economic indicators		Social indicators			Environmental indicators						
Water pricing scenarios	TGM	CONGDP	EMPLT	SEAS	ABAND	SPEC	SOILCOV	BALN	BALP	PESTRISK	WATER	ENBA
	(€/ha)	(€/ha)	(Mday/ha)	(%)	(%)	(%)	(%)	(kg N/ha)	(kg P/ha)	(kg/ha)	(m^3/ha)	(kcal/ha)
Baseline scenario	481.70	270.04	11.51	0.52	0.01	29.77	0.74	33.68	28.59	686.36	6577	$1.16\ 10^{7}$
Pricing instrument: irrigated area												
0 €/ha	468.15	239.20	11.31	0.53	0.03	30.93	0.74	32.30	29.64	593.64	6482	$1.07\ 10^{7}$
100 €/ha	423.29	309.51	10.79	0.55	0.12	33.52	0.74	32.16	30.00	560.54	6429	$1.03\ 10^{7}$
200 €/ha	385.76	346.76	9.85	0.60	0.20	37.19	0.73	32.81	30.52	513.10	6033	$1.00\ 10^{7}$
300 €/ha	355.80	358.25	9.09	0.65	0.26	40.33	0.72	33.01	30.94	471.37	5629	$9.62\ 10^{6}$
400 €/ha	331.76	358.94	8.65	0.67	0.33	42.60	0.72	32.72	31.26	443.28	5427	$9.18\ 10^{6}$
500 €/ha	312.43	348.94	8.33	0.69	0.35	44.54	0.72	31.95	31.38	426.63	5347	$8.88\ 10^{6}$
Pricing instrument: volumetric tariff												
0.00 €/m^3	468.15	239.20	11.31	0.53	0.03	30.93	0.74	32.30	29.64	593.64	6482	$1.07\ 10^{7}$
0.01 €/m^3	438.82	286.12	10.75	0.56	0.09	32.74	0.74	32.98	29.94	565.30	6217	$1.06\ 10^{7}$
0.02 €/m^3	415.17	306.95	9.78	0.61	0.14	35.55	0.73	34.37	30.37	523.26	5594	$1.05\ 10^{7}$
0.03 €/m^3	397.20	311.18	9.03	0.66	0.18	37.75	0.72	35.37	30.72	488.03	4965	$1.03\ 10^{7}$
0.04 €/m^3	382.68	320.00	8.74	0.68	0.21	38.86	0.72	35.53	30.98	467.94	4695	$1.00\ 10^{7}$
0.06 €/m^3	356.82	346.10	8.60	0.69	0.26	40.28	0.72	35.15	31.36	443.02	4650	$9.49\ 10^{6}$
0.08 €/m^3	333.45	367.36	8.49	0.69	0.31	41.50	0.72	34.48	31.49	431.48	4672	$9.27\ 10^{6}$
0.10 €/m^3	312.25	380.26	8.38	0.70	0.35	42.72	0.72	33.83	31.64	420.47	4702	$9.07\ 10^{6}$
Pricing instrument: two-part tariff system												
0 €/ha + 0.00 €/m^3	468.15	239.20	11.31	0.53	0.03	30.93	0.74	32.30	29.64	593.64	6482	$1.07\ 10^{7}$
50 €/ha + 0.02 €/m^3	399.80	328.07	9.55	0.62	0.17	36.49	0.72	34.05	30.45	509.29	5532	$1.03\ 10^{7}$
50 €/ha + 0.04 €/m^3	371.69	347.32	8.86	0.67	0.23	38.94	0.72	34.55	30.96	465.98	4911	$9.74\ 10^{6}$
50 €/ha + 0.06 €/m^3	348.19	376.69	8.74	0.68	0.28	40.21	0.72	34.03	31.20	447.82	4930	$9.37\ 10^{6}$
100 €/ha + 0.02 €/m^3	383.53	338.74	9.19	0.64	0.20	38.05	0.72	34.21	30.68	488.77	5317	$1.01\ 10^{7}$
100 €/ha + 0.04 €/m^3	357.85	357.68	8.74	0.67	0.26	39.96	0.72	34.28	31.15	453.56	4923	$9.50\ 10^{6}$
100 €/ha + 0.06 €/m^3	335.61	383.14	8.64	0.68	0.30	41.13	0.72	33.61	31.27	441.06	4973	$9.25\ 10^{6}$
150 €/ha + 0.02 €/m^3	368.79	346.30	8.91	0.66	0.23	39.42	0.72	34.22	30.90	471.08	5142	$9.83\ 10^{6}$
150 €/ha + 0.04 €/m^3	345.05	364.25	8.62	0.68	0.28	40.99	0.72	33.96	31.26	444.66	4930	$9.36\ 10^{6}$
150 €/ha + 0.06 €/m^3	323.99	383.85	8.52	0.69	0.33	42.14	0.72	33.26	31.36	433.55	4994	$9.14\ 10^{6}$
Pricing instrument: block-rate system												
0.00-0.00-0.00 €/m^3	468.15	239.20	11.31	0.53	0.03	30.93	0.74	32.30	29.64	593.64	6482	$1.07\ 10^{7}$
0.01-0.02-0.03 €/m^3	426.37	312.13	9.97	0.60	0.11	34.76	0.73	34.43	30.27	534.08	5660	$1.06\ 10^{7}$
0.02-0.04-0.06 €/m^3	399.74	364.33	9.21	0.64	0.17	37.33	0.72	35.02	30.62	496.08	5161	$1.03\ 10^{7}$
0.03-0.06-0.09 €/m^3	381.74	398.09	8.72	0.68	0.21	38.84	0.72	35.68	31.01	464.39	4642	$9.96\ 10^{6}$
0.04-0.08-0.12 €/m^3	364.26	449.33	8.64	0.69	0.24	39.68	0.72	35.63	31.36	444.71	4583	$9.57\ 10^{6}$

Table A-2. Normalized basic indicators for the Campos district

Water pricing scenarios	Economic indicators		Social indicators			Environmental indicators						
	TGM	CONGDP	EMPLT	SEAS	ABAND	SPEC	SOILCOV	BALN	BALP	PESTRISK	WATER	ENBA
Baseline scenario	0.88	0.23	0.76	0.92	0.97	0.81	0.68	0.57	0.55	0.13	0.11	0.81
Pricing instrument: irrigated area												
0 €/ha	0.82	0.12	0.72	0.86	0.92	0.77	0.69	0.64	0.48	0.32	0.14	0.61
100 €/ha	0.60	0.36	0.62	0.77	0.68	0.68	0.67	0.65	0.45	0.39	0.16	0.51
200 €/ha	0.41	0.49	0.44	0.57	0.47	0.55	0.62	0.61	0.41	0.49	0.30	0.43
300 €/ha	0.27	0.53	0.29	0.39	0.30	0.43	0.58	0.60	0.38	0.57	0.44	0.34
400 €/ha	0.15	0.53	0.21	0.28	0.17	0.35	0.57	0.62	0.36	0.63	0.51	0.24
500 €/ha	0.05	0.49	0.14	0.19	0.06	0.28	0.56	0.66	0.35	0.67	0.54	0.17
Pricing instrument: volumetric tariff												
0.00 €/m^3	0.82	0.12	0.72	0.86	0.92	0.77	0.69	0.64	0.48	0.32	0.14	0.61
0.01 €/m^3	0.67	0.28	0.61	0.76	0.76	0.71	0.66	0.60	0.45	0.38	0.23	0.56
0.02 €/m^3	0.56	0.35	0.43	0.54	0.63	0.61	0.60	0.53	0.42	0.47	0.45	0.54
0.03 €/m^3	0.47	0.37	0.28	0.34	0.53	0.53	0.56	0.47	0.40	0.54	0.67	0.50
0.04 €/m^3	0.40	0.40	0.22	0.26	0.45	0.49	0.55	0.46	0.38	0.58	0.76	0.43
0.06 €/m^3	0.27	0.48	0.20	0.21	0.31	0.44	0.57	0.48	0.35	0.63	0.78	0.31
0.08 €/m^3	0.16	0.56	0.18	0.18	0.18	0.39	0.57	0.52	0.34	0.66	0.77	0.26
0.10 €/m^3	0.05	0.60	0.15	0.15	0.06	0.35	0.57	0.56	0.33	0.68	0.76	0.21
Pricing instrument: two-part tariff system												
0 €/ha + 0.00 €/m^3	0.82	0.12	0.72	0.86	0.92	0.77	0.69	0.64	0.48	0.32	0.14	0.61
50 €/ha + 0.02 €/m^3	0.48	0.42	0.38	0.49	0.55	0.57	0.59	0.55	0.42	0.50	0.47	0.49
50 €/ha + 0.04 €/m^3	0.34	0.49	0.25	0.30	0.39	0.48	0.56	0.52	0.38	0.59	0.69	0.37
50 €/ha + 0.06 €/m^3	0.23	0.59	0.22	0.26	0.26	0.44	0.58	0.55	0.36	0.62	0.68	0.28
100 €/ha + 0.02 €/m^3	0.40	0.46	0.31	0.40	0.45	0.52	0.57	0.54	0.40	0.54	0.55	0.44
100 €/ha + 0.04 €/m^3	0.28	0.52	0.22	0.27	0.31	0.45	0.57	0.53	0.37	0.61	0.68	0.31
100 €/ha + 0.06 €/m^3	0.17	0.61	0.20	0.24	0.19	0.41	0.57	0.57	0.36	0.64	0.67	0.26
150 €/ha + 0.02 €/m^3	0.33	0.48	0.26	0.33	0.37	0.47	0.56	0.54	0.39	0.58	0.61	0.39
150 €/ha + 0.04 €/m^3	0.21	0.55	0.20	0.24	0.24	0.41	0.57	0.55	0.36	0.63	0.68	0.28
150 €/ha + 0.06 €/m^3	0.11	0.61	0.18	0.21	0.12	0.37	0.57	0.59	0.35	0.65	0.66	0.23
Pricing instrument: block-rate system												
0.00-0.00-0.00 €/m^3	0.82	0.12	0.72	0.86	0.92	0.77	0.69	0.64	0.48	0.32	0.14	0.61
0.01-0.02-0.03 €/m^3	0.61	0.37	0.46	0.58	0.69	0.64	0.61	0.52	0.43	0.44	0.43	0.57
0.02-0.04-0.06 €/m^3	0.48	0.55	0.31	0.40	0.54	0.54	0.57	0.49	0.41	0.52	0.60	0.51
0.03-0.06-0.09 €/m^3	0.39	0.66	0.22	0.25	0.44	0.49	0.55	0.46	0.38	0.59	0.78	0.42
0.04-0.08-0.12 €/m^3	0.31	0.83	0.21	0.22	0.35	0.46	0.57	0.46	0.35	0.63	0.80	0.33

Table A-3. Simulation results by farm-type

Water pricing scenarios	Minimum tillage cereal growers				Conventional farmers with diversified production				Min. tillage and spray irrigation cereal-sugar-beet growers				Direct sowing cereal growers			
	$CIIA_{eco}$	$CIIA_{soc}$	$CIIA_{env}$	**CIIA**	$CIIA_{eco}$	$CIIA_{soc}$	$CIIA_{env}$	**CIIA**	$CIIA_{eco}$	$CIIA_{soc}$	$CIIA_{env}$	**CIIA**	$CIIA_{eco}$	$CIIA_{soc}$	$CIIA_{env}$	**CIIA**
Baseline scenario	0.19	0.32	0.16	0.67	0.22	0.35	0.18	0.76	0.20	0.32	0.18	0.71	0.16	0.28	0.18	0.62
Pricing instrument: irrigated area																
0 €/ha	0.17	0.30	0.15	0.62	0.20	0.34	0.17	0.72	0.18	0.30	0.19	0.67	0.14	0.26	0.18	0.59
100 €/ha	0.14	0.24	0.15	0.53	0.18	0.30	0.17	0.64	0.16	0.24	0.18	0.58	0.12	0.20	0.18	0.50
200 €/ha	0.12	0.17	0.15	0.44	0.15	0.23	0.17	0.55	0.13	0.17	0.18	0.48	0.09	0.12	0.19	0.39
300 €/ha	0.09	0.10	0.15	0.35	0.12	0.18	0.17	0.47	0.10	0.11	0.18	0.39	0.07	0.08	0.18	0.33
400 €/ha	0.07	0.06	0.15	0.28	0.10	0.14	0.16	0.40	0.08	0.06	0.18	0.32	0.04	0.05	0.18	0.27
500 €/ha	0.05	0.03	0.15	0.23	0.08	0.10	0.16	0.34	0.06	0.03	0.18	0.27	0.02	0.03	0.16	0.21
Pricing instrument: volumetric tariff																
0.00 €/m^3	0.17	0.30	0.15	0.62	0.20	0.34	0.17	0.72	0.18	0.30	0.19	0.67	0.14	0.26	0.18	0.59
0.01 €/m^3	0.15	0.25	0.16	0.56	0.19	0.31	0.17	0.67	0.16	0.25	0.19	0.60	0.13	0.22	0.19	0.53
0.02 €/m^3	0.13	0.19	0.16	0.49	0.17	0.25	0.18	0.60	0.15	0.19	0.19	0.53	0.12	0.16	0.20	0.47
0.03 €/m^3	0.12	0.14	0.17	0.43	0.15	0.21	0.18	0.54	0.13	0.13	0.20	0.46	0.11	0.13	0.20	0.43
0.04 €/m^3	0.11	0.11	0.17	0.39	0.14	0.18	0.18	0.50	0.11	0.10	0.21	0.42	0.10	0.12	0.19	0.41
0.06 €/m^3	0.09	0.08	0.16	0.34	0.12	0.15	0.18	0.45	0.10	0.07	0.20	0.36	0.08	0.09	0.19	0.36
0.08 €/m^3	0.07	0.06	0.16	0.29	0.10	0.12	0.18	0.39	0.08	0.05	0.20	0.33	0.06	0.06	0.18	0.31
0.10 €/m^3	0.05	0.03	0.16	0.25	0.08	0.09	0.17	0.34	0.07	0.02	0.20	0.29	0.05	0.05	0.18	0.27
Pricing instrument: two-part tariff system																
0 €/ha + 0.00 €/m^3	0.17	0.30	0.15	0.62	0.20	0.34	0.17	0.72	0.18	0.30	0.19	0.67	0.14	0.26	0.18	0.59
50 €/ha + 0.02 €/m^3	0.12	0.16	0.16	0.44	0.15	0.22	0.18	0.55	0.13	0.15	0.19	0.48	0.13	0.19	0.17	0.50
50 €/ha + 0.04 €/m^3	0.10	0.10	0.17	0.37	0.13	0.17	0.18	0.47	0.10	0.08	0.20	0.39	0.14	0.18	0.17	0.49
50 €/ha + 0.06 €/m^3	0.08	0.07	0.16	0.31	0.11	0.13	0.18	0.42	0.09	0.06	0.20	0.34	0.14	0.17	0.16	0.47
100 €/ha + 0.02 €/m^3	0.11	0.13	0.16	0.40	0.14	0.20	0.18	0.51	0.12	0.12	0.20	0.43	0.10	0.11	0.18	0.40
100 €/ha + 0.04 €/m^3	0.09	0.08	0.16	0.33	0.12	0.15	0.18	0.45	0.10	0.07	0.20	0.36	0.10	0.10	0.18	0.38
100 €/ha + 0.06 €/m^3	0.07	0.06	0.16	0.29	0.10	0.12	0.17	0.39	0.08	0.04	0.20	0.32	0.09	0.09	0.17	0.36
150 €/ha + 0.02 €/m^3	0.10	0.10	0.16	0.36	0.13	0.17	0.18	0.48	0.11	0.09	0.20	0.40	0.08	0.08	0.18	0.33
150 €/ha + 0.04 €/m^3	0.08	0.07	0.16	0.31	0.11	0.14	0.17	0.42	0.09	0.05	0.20	0.34	0.07	0.07	0.17	0.31
150 €/ha + 0.06 €/m^3	0.06	0.04	0.16	0.26	0.09	0.11	0.17	0.36	0.07	0.03	0.20	0.30	0.06	0.06	0.16	0.29
Pricing instrument: block-rate system																
0.00-0.00-0.00 €/m^3	0.17	0.30	0.15	0.62	0.20	0.34	0.17	0.72	0.18	0.30	0.19	0.67	0.14	0.26	0.18	0.59
0.01-0.02-0.03 €/m^3	0.15	0.21	0.16	0.52	0.18	0.27	0.18	0.63	0.16	0.21	0.19	0.56	0.13	0.17	0.20	0.49
0.02-0.04-0.06 €/m^3	0.14	0.15	0.17	0.45	0.17	0.21	0.18	0.56	0.15	0.14	0.20	0.49	0.12	0.14	0.20	0.46
0.03-0.06-0.09 €/m^3	0.13	0.11	0.17	0.41	0.16	0.18	0.18	0.52	0.14	0.09	0.21	0.44	0.12	0.12	0.19	0.43
0.04-0.08-0.12 €/m^3	0.12	0.09	0.17	0.38	0.15	0.15	0.18	0.49	0.14	0.08	0.20	0.40	0.11	0.10	0.19	0.41