Agricultural Water Management 281 (2023) 108245

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

The impact of the territorial gradient and the irrigation water price on agricultural production along the first phase of the Navarra Canal in Spain

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ARTICLE INFO

Handling Editor - Dr. R. Thompson

Keywords:
Water value
Water use
Socioeconomic aspects
Irrigation project
Positive mathematical programming
Navarra Canal
Spain

ABSTRACT

Water is an issue in Spain, where it is generally scarce, and its availability is highly variable in different areas and times, particularly in agriculture, the main water consumer. Water pricing is one of the policy instruments used to control irrigation water use. However, specific contextual studies to provide greater details, understand farmers' behaviour, and clarify the consequences and effectiveness of water pricing are generally unavailable. Here, we developed and applied a simulation model based on two Positive Mathematical Programming (PMP) methods, which makes the model more robust, to better understand and quantify the impact of the north–south territorial gradient on farmers' decisions concerning agricultural water pricing in the first phase of the Navarra Canal irrigation area in northern Spain. This model couples water use with rainfed and irrigated areas, farmer revenue, and labour. The results show spatial north–south variability in the 50 km of the first phase of the Navarra Canal. In northern and middle regions, when water prices are increased, rainfed crops are chosen to substitute irrigated crops due to abundant rainfall and a lack of the appropriate climate and soil to grow other crops. Meanwhile, southern regions depend mainly on irrigation and are more sensitive to water price increases. These very productive southern regions also show larger gross margins and paid labour values. In every canal region, with an increase of 0.1 EUR/m^3 in the water price, economic losses can reach up to 400 EUR/ha. Meanwhile, an increase in water prices over 0 EUR/m^3 leads to decreased water use per hectare.

1. Introduction

Spanish water problems and conflicts are generally due to bad governance (De Stefano and Llamas, 2013). Incentives to better manage this resource and reconcile the economic, social and environmental demands are key, particularly in the agricultural sector, which is the largest water user and comprises about 70 per cent of freshwater use in Spain (Rey et al., 2011). Irrigation in Spain is currently based on volumetric management either at the bulk level (6188 *comunidades de regantes* are granted volumetric water-use licences) or at the individual level (farmers within state-managed schemes) (Molle, 2009). A total of 41% of Spain's irrigated area is sprinkler or micro-irrigation, which enables easier volumetric control (Molle, 2009).

There are different mechanisms for improving agricultural water management, including policies, property rights, prices, and governance. In many cases, a combination is needed to address water pollution and ecosystem conservation while allowing agriculture to adjust to market demand. For instance, in Australia, priority-differentiated water rights in combination with water markets have greatly contributed to the flexibility of water allocations and therefore improving risk exposure and economic efficiency (Freebairn and Quiggin, 2006). Another example is the conjunctive management of surface water and groundwater resources, which alleviates the effects of droughts on the profitability and sustainability of irrigated agriculture in the Yaqui Valley,

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https://doi.org/10.1016/j.agwat.2023.108245
Received 28 July 2022; Received in revised form 21 February 2023; Accepted 24 February 2023
Available online 6 March 2023

Mexico (Schoups et al., 2006). In the Nile River basin, establishing a legal and institutional framework is a prerequisite for effective cooperation between the riparian countries along the river (Wehling, 2020). The modernisation of irrigation generally leads to favourable outcomes, such as higher crop yields, the diversification of crops, and a general increase in family incomes (Haro-Monteagudo et al., 2022). However, in some cases, such as some Spanish areas, it can also result in the intensification of irrigation and a reduction in return flows (Playán and Mateos, 2006; Lecina et al., 2010; López-Moreno et al., 2020). Regarding water pricing, there are different experiences in different parts of the globe. The countries employing water pricing include Australia, England, France, Israel, Jordan, Mexico, Morocco, India, Spain, and the USA.

The European Water Framework Directive (2000/60/EC) (WFD), in Article 9, encourages member states to use water pricing as one of the instruments to achieve efficient water use and contribute to the full cost recovery of water services and environmental objectives of the Directive (Molle, 2009). Water prices can be powerful signals to trigger behavioural change (Berbel and Expósito, 2020). However, in some cases, due to the low elasticity of agricultural water demand and other factors, pricing policies may not deliver the expected outcomes (Molle and Berkoff, 2007; Rey et al., 2011). For instance, Berbel and Gomez-Limón (2000) report negative impacts of water pricing on farm income and labour, as farmers, in response to price increases, may reduce water consumption through shifts in crop plans, substituting high-value crops with high water demand with less-profitable crops.

Different methods and simulation models based on different mathematical programming methods have been applied to simulate and quantify the expected water pricing impact on agricultural water use, farm income, government revenue, labour generation, and social welfare at the microeconomic (Berbel and Gomez-Limón, 2000; Gómez-Limón et al., 2016; Gutiérrez-Martín and Gómez-Gómez, 2011; Gutiérrez-Martín et al., 2014; Momeni et al., 2019; Montilla-López et al., 2017; Speelman et al., 2009) and macroeconomic level (Parrado et al., 2019, 2020). This research has traditionally focused on water demand in irrigated schemes. However, only a few of them (e.g., Sapino et al., 2020; Pérez-Blanco et al., 2021; Sapino et al., 2022) are based on more robust decision making using multi-model ensemble frameworks encompassing several mathematical programming models.

Moreover, to successfully implement water-pricing mechanisms, it is important to consider the social, environmental, and institutional context (Dinar et al., 2015), particularly in the case of large irrigation projects. However, none of the studies on water pricing has assessed the influence of the territorial and climate gradient on the water-pricing simulation results. The present study focuses on these three dimensions using two calibration approaches to obtain more robust results.

This paper aims to analyse the impact of the north–south territorial gradient on water demand, rainfed and irrigated areas, and socio-economic variables through the current system of irrigation water pricing in the ten sectors (I-X) of the 1st phase of the Navarra Canal irrigation area in northern Spain. Hitherto, there has been no contextual study of the water-pricing effects in this irrigation project, which is one of the largest irrigation schemes in northern Spain. The analysis was aggregated for the first phase of the Navarra Canal and per region (grouping northern, middle, and southern sectors according to the different climate conditions). This study innovatively assesses and confirms how the territorial distribution—closely related to climate and soil variations—and the resulting crop gradient affect crop choices for a given water price and thus also has implications for water use, revenues, and social aspects (labour), in an area that combines rainfed and irrigated systems. Furthermore, this study shows how a water price increase affects farmers' decisions and the subsequent effects on gross margin, labour, and water use in different regions. The territorial context is key for understanding the impacts of water-pricing policies and should be considered in water policies and planning processes.

2. Material and methods

2.1. A case study in the Navarra Canal

The first phase of the Navarra Canal is an irrigation and water supply channel network located in the Navarra Autonomous Community, in the north of Spain, which captures a wide range of climatic diversity. It is part of a larger infrastructure, the Navarra Canal, which transports water from the Irati river in northern Navarra to the central and southern areas of Navarra and has a length of about 180 km.

The first phase of the Navarra Canal is located within the Ebro river basin between the Itoiz reservoir and the municipality of Pitillas. It irrigates 22.473 ha (in 2017), variable between years, all irrigated with drip and localised systems (INTIA, 2018a). It is divided into 16 sectors (or irrigable areas) benefiting 29 municipalities located in agricultural regions III (2.326 ha), V (15.895 ha), and VI (7739 ha) in the year 2017 (see Fig. 1 and Table A.1 in the Appendix). Some of the leaders of the food industry in Spain (especially in vegetable transformation) are located in the first phase of the Navarra Canal, with national and foreign capital (SABI, 2022).

The climate is Mediterranean, drier in the southern part, with less oceanic influence, less rainfall (between 400 and 600 mm as an annual average), and higher temperatures (14 °C as an annual average) (Fig. 2). The climatic conditions, together with the soil properties, influence the spatial distribution of crop types and agricultural systems since different crops require different amounts of rainfall, humidity, warmth, and

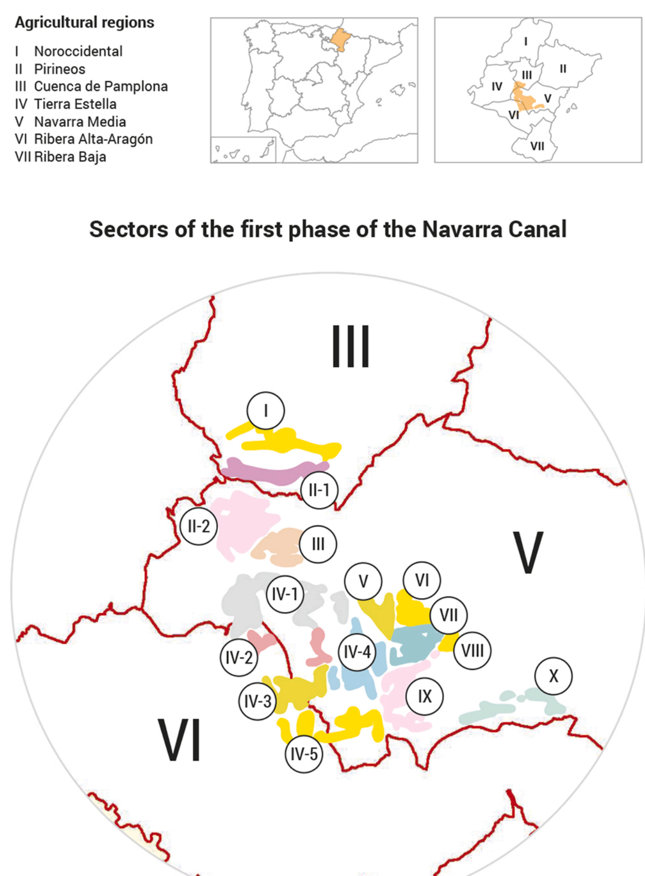

Fig. 1. Location and main features of the first phase of the Navarra Canal, Spain. Agricultural regions: I: Noroccidental, II: Pirineos, III: Cuenca de Pamplona, IV: Tierra Estella, V: Navarra Media, VI: Ribera Alta-Aragón, VII: Ribera Baja (top right). Sectors of the first phase of the Navarra Canal, Spain: Sectors I, II.1, II.2, III, IV.1, IV.2, IV.3, IV.4, IV.5, V, VI, VII, VIII, IX, and X (below). Source: based on INTIA (2021).

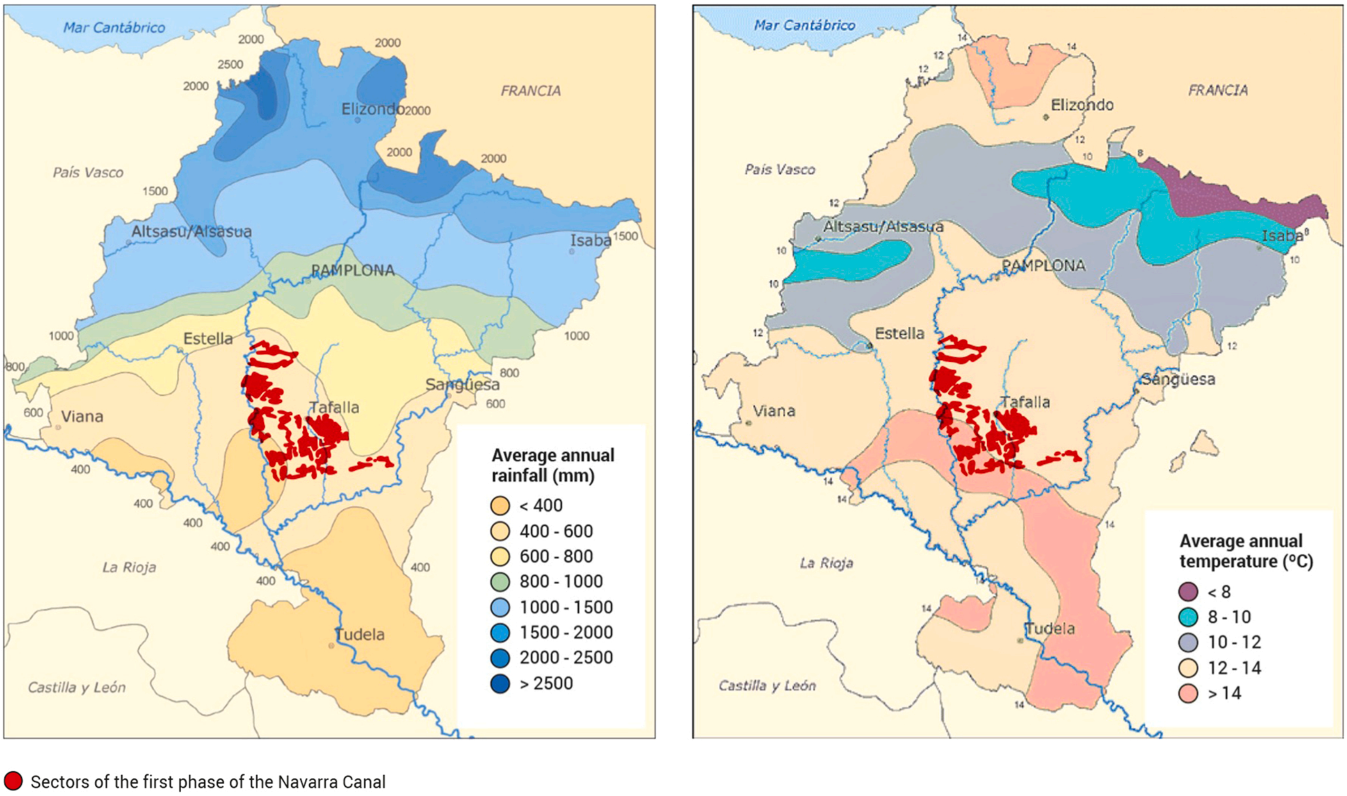

Fig. 2. Map of average annual rainfall in Navarra and first phase of the Navarra Canal (left). Map of average annual temperature in Navarra and first phase of the Navarra Canal (right).
Sources: Government of Navarra (2021a,b,c), based on INTIA (2021).

sunshine, as well as different types of soil.

Cereals are the most extended crop, representing 46% of the area, with grain corn as the main crop, followed by winter wheat. Rainfed barley tends to be the option chosen for unequipped plots. This is followed by vegetables, comprising 22% of the area (mainly peas, beans, broccoli, tomato, sweet corn, spinach, and fava beans); vineyards, comprising 10%; industrial crops, comprising 9%; fodder, comprising 8%; olive trees, comprising 2%; fruit trees, comprising 1%; grain legumes, comprising 1%; and nursery crops, comprising 1% (INTIA, 2018a).

In terms of crop diversity, 55 different crops are planted in the first phase. Sectors II.2, IV.1, IV.3, IV.4, V, and IX have the greatest crop diversity, comprising between 30 and 29 different crops (INTIA, 2018a).

The area of double crops represents 16% of the utilised area. Sectors IV.5 and IX stand out, comprising between 48% and 25% of double crops, respectively. The main double crops are 17% grass–corn, 17% peas–beans, 7% cereal–broccoli, 6% peas–corn, 6% cereal–beans, 6% peas–sweet corn, and 5% bean–grain corn (INTIA, 2018a).

The crop mix for each sector and region are included in the Supplementary Materials.

The operating costs for irrigators are composed of a fixed charge per hectare per year and a variable charge depending on water consumption (Table 1). The average crop data can be found in the Supplementary Materials.

Table 1
Fixed and variable charges in the first phase of the Navarra Canal in the year 2017.

Concept	Details	Tariff 2017
Itoiz reservoir regulation fee[a]	Fixed fee	17.34 EUR/ha
	Consumption fee	0.0045 EUR/m^3
Canasa usage fee[b]	Fixed fee	86.50 EUR/ha
	Consumption fee	0.03 EUR/m^3
Aguacanal operating fee[c]	Operating royalty	22.47 EUR/ha
General Community of Irrigators expenses[d]	EUR/ha	10.00 EUR/ha
Total fixed term[e]		136.31 EUR/ha
Total variable term		0.03 EUR/m^3

[a] Itoiz reservoir regulation fee: charged by the Ebro Hydrographic Confederation per sector. In this case, it is charged to irrigators through the General Community of Irrigators of the Navarra Canal. The consumption fee is 0.0045 EUR/m^3.
[b] Canasa usage fee: fee paid to Canasa for the construction and operation of the canal.
[c] Aguacanal operating fee: payment to Aguacanal as the concessionary company for the operation, conservation, maintenance, and replacement of the irrigation area.
[d] General Community of Irrigators of the Navarra Canal administration and management expenses.
[e] Administration and management expenses of the base community.
Source: INTIA (2018a).

2.2. Price simulation model

A farmer behaviour simulation model through Positive Mathematical Programming (PMP) was developed and applied to the first phase of the Navarra Canal in 2012–2017. The PMP was formally proposed by Howitt (1995) and consisted of eliciting a non-linear objective function that typically includes a quadratic cost (or yield) function such that observed activity levels are reproduced by the optimal solution. The non-linear function relies on information contained in dual values of calibration constraints of a linear programming model, where variables are constrained to observed activity levels by Stage 1.

There are several advantages of the PMP over other mathematical programming models: i) it perfectly reproduces the level of activities of the reference year without using artificial constraints; ii) it provides flexible, smooth simulation behaviour, avoiding questionable over-specialisation and abrupt discontinuities in the simulation solutions; iii) it can be developed with relatively scarce data; and iv) it allows calibrating complex economic, technical, and environmental relationships, capturing adjustments in the intensive and extensive margins.

Instead of using a single method, we will use two PMP calibration methods to obtain more robust results. To keep it simple, we will use two methods that do not require exogenous information, such as land rent or exogenous elasticities.

The first method is based on the standard approach of Howitt (1995) using quadratic cost functions. We will use the average cost approach of Heckelei and Britz (2000), which ensures that, in the reference year, the quadratic cost function reproduces the observed average cost of each activity. Moreover, to avoid the marginal crop behaving differently from the rest by having a linear cost, the non-preferred crop area will not be subject to change. This is possible because it will be a rainfed crop of little relevance in the study area.

The second PMP method is developed by Dagnino and Ward (2012), which relies on a quadratic yield function whose calibrating parameters are elicited from the first-order conditions using only crop information, skipping the first calibration stage. This method, like the approach of Heckelei and Britz (2000), also ensures that the profit of the activities in the reference year coincides with the average profit since it reproduces the average observed yield. By skipping the first calibration step, full information on the quadratic yield function parameters is available for every crop.

The variables of the models are the area devoted to each crop in every sector of the Navarra Canal ($X_{c,s}$). The whole irrigated and rainfed area was simulated. This area includes all representative irrigated crops, double cropping, and rainfed crops. As already mentioned, the main irrigated crops are corn, wheat, and vineyards, while the main rainfed alternative crops in terms of crop area were identified as wheat, barley, and vineyards (INTIA, 2018a).

New activities were created for each double crop (wheat–broccoli, wheat–beans, wheat–corn, etc.). Then, the area of the first crop (e.g., wheat) was divided into different activities when a second crop succeeded it in the same agronomic year. Finally, the areas devoted to each activity with double crops were estimated by their relative presence in 2017, as area data by sector were available for this year.

The most common double croppings during 2012–2017 were winter cereal–corn, bean–corn, fodder–corn, pea–green bean, winter cereal/green bean and ray-grass–corn (Aguacanal, 2012–2017). The most common triple cropping during the same period was spinach/pea/sweet corn (cereal–corn, bean–corn, fodder–corn, pea–green bean, winter cereal/green bean and ray-grass–corn (Aguacanal, 2012–2017). However, triple croppings were not included, as they represent a very small part of the land and complete information is unavailable.

2.2.1. Calibration

Each sector of the Navarra Canal was calibrated and simulated independently, with the main crops present, including double crops. In each irrigation sector, a typical farmer was considered as one whose crop distribution was the average of his sector. For this typical farmer, we obtained two utility functions maximising profit, one from each PMP method. The profit was considered in the short term and measured through the expected gross margin (*GM*), which is the result of subtracting all the variable costs associated with the crop from the income. By maximising the objective functions, the (positive) models exactly reproduce the crop distribution in the observed year. In the case of the standard approach, the objective function takes the following form:

$$GM_s = \sum_c \left(Price_c \cdot Yield_c - \left(\alpha_{c,s} + \tfrac{1}{2} \cdot \beta_{c,s} \cdot X_{c,s} \right) \right) \cdot X_{c,s} \forall s \tag{1}$$

where GM_s is the gross margin in sector s; $X_{c,s}$ is the area of crop c in sector s; $Price_c$ and $Yield_c$ are the price and yield of each crop, respectively; and $\alpha_{c,s}$ and $\beta_{c,s}$ are the linear and quadratic calibrating parameters calculated in the first stage for every crop and sector. Among all the variants available for determining the calibration parameters, the average cost approach of Heckelei and Britz (2000) was followed, with the following calibrating parameters:

$$\alpha_{c,s} = Avgcost_c - \mu_{c,s} \tag{2}$$

$$\beta_{c,s} = \frac{2\mu_{c,s}}{X_{c,s}^{obs}} \tag{3}$$

where $Avgcost_c$ is the average cost of every crop and $\mu_{c,s}$ is the dual value or shadow price of the calibrating constraint of each crop in the first stage. The calibrating constraints of the linear model (Stage 1) consist of equating the area variables ($X_{c,s}$), plus a negligible term epsilon, to the observed level of each activity.

The objective function of the second method of Dagnino and Ward (2012) is as follows:

$$GM_s = \sum_c \left(Price_c \cdot \left(B_{0,c,s} + B_{1,c,s} \cdot X_{c,s} \right) - Avgcost_c \right) \cdot X_{c,s} \forall s \tag{4}$$

where $B_{0,c,s}$ and $B_{1,c,s}$ are the linear and quadratic terms of the yield function, respectively:

$$B_{0,c,s} = Yield_c - B_{1,c,s} \cdot X_{c,s}^{obs} \tag{5}$$

$$B_{1,c,s} = \frac{GM_c^{obs}}{Price_c \cdot X_{c,s}^{obs}} \tag{6}$$

where GM_c^{obs} is the average income per unit of land.

After the calibration of the models, a simulation of water price increases by 0.01 EUR/m^3 steps was performed on the current tariffs. During the simulation, farmers could change the crop pattern, but no other actions were allowed, such as new investments or the possibility of deficit irrigation. New investments in irrigation technology, which increase the perennial crop area, were not allowed since farmers' responses are only considered in the short term. For the same reason, disinvestment in the form of a reduction in the area of perennial crops was not allowed. Only in the case of perennial crops with rainfed alternatives were these perennial crops allowed to be shifted to their rainfed options. On the other hand, including deficit irrigation requires dose–response functions for each crop. This requires a dose–response function for each climatic zone, and this information is unavailable. These simulations were completed per sector, and the results were aggregated for each price increase. Additionally, in the Howitt calibration method, a constraint was introduced on the marginal crop (the one with the lowest gross margin and no dual value in the calibration constraints). The constraint prevented the marginal crop from growing excessively in the simulation. Therefore, the area of marginal crops was limited to the observed area. This point will be further analysed in the discussion.

2.3. Clustering of sectors

To analyse the north–south climatic gradient, the ten sectors (sectors I-X) of the first phase of the Navarra Canal were grouped according to their geographical location as follows:

- Northern region: I, II.1, II.2, and III;
- Middle region: IV.1, IV.2, IV.4, V, VI, VII, and VIII;
- Southern region: IV.3, IV.5, IX, and X.

2.4. Data sources

A summary of the data and their sources is offered in Table 2.

The annual water cost data based on the water origin (surface water)

Table 2
Summary of the data and data sources used for the study.

Data	Source
Fixed and variable water costs	INTIA[a]
Irrigation field application efficiency	Aguacanal (2012–2017), INTIA (2019, 2018b)[b]
Irrigation water applied	Aguacanal (2012–2017)[b]
Crop water requirements	INTIA (2018b)[a]
Irrigated crop area	Aguacanal (2012–2017)[b]
Common Agricultural Policy payments	MAPAMA (2018)[c]
Prices paid to producers	Government of Navarra (2012–2017a)
Crop yield	Government of Navarra (2012–2017b)
Direct costs	Government of Navarra (2012–2017c)
Labour per crop	Government of Navarra (2012–2017c)

[a] INTIA: public data from the INTIA (Navarre Institute of Transfer and Innovation in Agri-Food sector).
[b] Aguacanal: data from Aguacanal, the concessionary company for the operation, conservation, maintenance, and replacement of the irrigation area.
[c] MAPAMA: public data from the MAPAMA (Spanish Ministry of Agriculture, Fisheries and Food).

for the first phase of the Navarra Canal area during 2012–2017—in terms of fixed costs (EUR/ha) and variable costs (EUR/m^3)—were obtained from public data from the administration (Navarre Institute of Transfer and Innovation in Agri-Food sector—INTIA).

The irrigation field application efficiencies per crop and sector were obtained by crosschecking two different sources:

1) The crop area per irrigation system per sector (INTIA, 2019) was combined with the field application efficiency's widely used values, assuming a sprinkler irrigation efficiency of 85% and a drip irrigation efficiency of 95% (INTIA, 2018b).

2) Water use efficiency was the ratio between the estimated crop water requirements (INTIA, 2018b) and the actual irrigation applied (Aguacanal, 2012–2017).

The crop water requirements, based on the reference evapotranspiration values (ETo), crop coefficients, effective rainfall, and irrigation efficiency (Allen et al., 1998) per crop and sector were obtained from INTIA (2018b). The actual irrigation water applied (m^3/ha) per crop and sector was obtained from Aguacanal, a company that manages the infrastructure of the Navarra Canal irrigation area (2012–2017).

Average crop water requirements were estimated for crops with different planting dates, cycles, and growing systems: broccoli (February 1, August 1, August 15, September 1, September 15), barley (short cycle: January–February, short cycle: November–December, long cycle: November–December, long cycle: October–November), sunflower (May 20, April 20), bean (early, late), green bean (July 1, June 10), pea (early, late), and olive grove (standard and grown on trellises).

The area of irrigated crops per sector was obtained from Aguacanal (2012–2017), and the crop area of rainfed and irrigated crops in each sector and agricultural region was obtained from INTIA (2019). The payments associated with the production of the Common Agricultural Policy 2015–2020 were obtained from MAPAMA (2018), and the prices paid to producers were obtained from the Government of Navarra (2012–2017a).

The crop yield per agricultural region and year was obtained from the Government of Navarra (2012–2017b). The yield is attributed according to the agricultural region where the crop is located (Table A.1 in the Appendix). When the sectors were in more than one agricultural region, the yield data were weighted by the crop area in each sector and region. If the crop distribution was not available (as in the case of rapeseed, rye, green beans, potatoes, grain green fava beans, broccoli, cauliflower, and vetch in some cases), an average of both regions was used.

The yield data of the category "tree" were weighted according to the different types of tree areas in each sector, mainly almond and walnut trees. The category "pea" refers to the green pea grain when irrigated and dry peas when rainfed. The category "beans" refers to green beans. The olive grove is used to produce olive oil. Tomato and pepper were grown for industry. The yield data of the category "corn" were weighted according to the different types of corn areas in each sector, including sweet corn, corn for grain, forage corn, and seed corn.

The yield of the "winter cereal" category refers to the weighted average yield of common wheat, barley, and oat. If no vineyard type was specified, the yield was assumed to be the average of "winemaking vineyards", "D.O. Navarra vineyards", and "other wines". If the potato type was not specified, the yield was assumed to be the average of mid- and late-season potatoes.

Direct costs and labour per crop were obtained from the Government of Navarra (2012–2017c).

3. Results and discussion

3.1. Simulation of water prices: aggregated results

Figs. 3 and 4 present the aggregated water price simulation results for the first phase of the Navarra Canal related to the irrigated/rainfed crop area, amount of water used, gross margin, and labour using both the Dagnino and Ward and Howitt calibration methods. As can be seen, the results differ from one calibration method to another. Using two calibration/simulation methodologies has allowed us to obtain more robust results, considering the zone of uncertainty between the two resulting curves. We cannot claim that one model is methodologically superior to the other as both have pros and cons, which are described below in Section 3.3. The intermediate zone between the two calibration method results is assumed to be the level of uncertainty derived from the calibration method. This intermediate zone is where the actual results are likely to be. Fig. 3 shows the evolution of the area occupied by the main crops in relation to water-price increases. In general, the substitution of irrigated crops can be observed, mainly corn for rainfed winter cereals (wheat and barley), but also for irrigated winter cereals (wheat and barley), given their low water requirements.

Fig. 3 helps to understand the different behaviours of the two calibration methods in terms of the change from irrigated to rainfed crops, water use, gross margin, and labour. In Dagnino and Ward's method, the substitution of corn for winter cereals occurs linearly up to a water price of 0.45 EUR/m^3. In the case of Howitt, this change occurred before, up to a price of only 0.30 EUR/m^3. The total substitution of corn for winter crops at 0.45 and 0.30 EUR/m^3 marks the changes in the slope of water use in Fig. 4b. On the other hand, the substituted crop also varies depending on the method used. In the first case, the substitution is towards irrigated wheat and rainfed barley. Following Howitt's method, the substitution is more prominent towards rainfed wheat and rainfed barley. It can also be seen that the areas of irrigated wheat and barley, while initially increasing up to the turning point of 0.30 EUR/m^3, decrease in favour of their rainfed variants.

Fig. 4 shows the aggregated irrigated/rainfed crop area, amount of water used, gross margin, and labour in relation to water price variations.

Fig. 4a shows the change from irrigated to rainfed areas occupied by the main crops due to the effect of water prices. As can be seen, irrigated crops begin to be replaced by rainfed crops starting at 0 EUR/m^3. The intermediate striped zone between the irrigated and the rainfed area represents the area of uncertainty that one calibration model considers to be irrigated and the other model does not consider to be irrigated.

Fig. 4b illustrates the water use simulation when the water price increases. That is, the water demand curve at each price level. This figure shows an elastic phase from .00 to 0.30–0.40 EUR depending on the calibrating method. In this phase, a small water price increase means a strong decrease in water use. Then, there is an inelastic stretch, where an increase in the price of water does not translate into a significant decrease in water use.

This reveals that water pricing encourages water conservation from

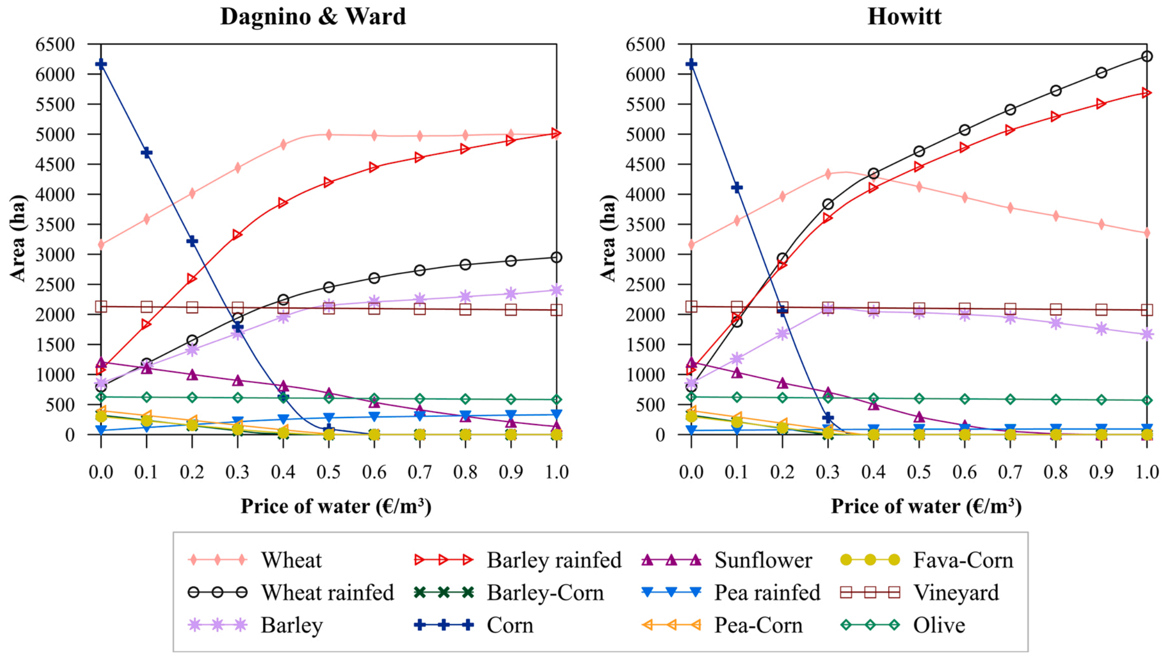

Fig. 3. Area occupied by the main crops (hectares) as a function of water prices (EUR/m^3) in the first phase of the Navarra Canal based on data for 2012–2017 in line with two calibration methods: Dagnino and Ward and Howitt.

the first cent increase in the first phase of the Navarra Canal, as water use decreases above a water price of 0 EUR/m^3. Water pricing is, therefore, an effective policy instrument to encourage water-saving measures in the region.

Conversely, the water demand curves estimated in previous studies based on different mathematical programming methods and regions present a totally inelastic first section (Berbel and Gomez-Limón, 2000; Gómez-Limón et al., 2016; Gutiérrez-Martín and Gómez-Gómez, 2011; Gutiérrez-Martín et al., 2014; Momeni et al., 2019; Montilla-López et al., 2017; Speelman et al., 2009). This means that, in the very first stretch of the curve, water price changes do not affect water use.

These differences in the first stretch of the water demand curve seem to be due to the methodology used and the context of the study. A first elastic stretch is common when applying mathematical programming techniques, such as in the case study shown in this paper. When using PMP approaches, changes in water use normally occur from the first increase in water prices. Nevertheless, sometimes, when using PMP methodologies, an initial inelastic stretch can still appear, as shown by Montilla-López et al. (2017). This may be due to the high profitability of all crops and agronomic constraints representing crop rotations, market, or agricultural policy constraints.

Sapino et al. (2020) developed a multi-model ensemble framework encompassing two PMP models without inelastic stretch and three multi-attribute models: a Weighted Goal Programming adapted to a Cobb-Douglas function with inelastic stretch and two slightly less inelastic PMAUP (Positive Multi-Attribute Utility Programming) functions.

Sapino et al. (2022) present a very interesting PMAUP-based case with an inelastic section at the beginning of the water demand curve that becomes elastic when there is the possibility to shift to deficit irrigation. This means that when there is only the possibility to shift the crop, the farmers do not reduce water use as they do not change the crop plan. However, when introducing water-response functions, farmers can reduce the irrigation dose without changing the crop grown. Then, the curve loses its inelastic section, contradicting some of the previous papers that state that water pricing makes no sense due to the existence of the inelastic section (Expósito and Berbel, 2017; Berbel and Expósito, 2020). However, in the cases where deficit irrigation is already being applied, as in many cases in the Guadalquivir river basin in the south of Spain, this inelastic section could continue to exist (Montilla-López et al., 2017).

Furthermore, depending on the area's profitability, the inelastic stretch can be shorter or longer. For instance, the stretch is longer in rich horticultural areas where irrigated crops provide a higher return than rainfed alternatives. In these areas, farmers are willing to pay the water price increase. Montilla-López et al. (2017) report an inelastic section up to 0.30 EUR/m^3 in the Lower Guadalquivir. At the same time, Berbel and Gomez-Limón (2000) show an inelastic section up to 0.07 EUR/m^3 in the mid-Guadalquivir valley and Bajo Carrión in southern Spain.

Obviously, a water price increase has economic effects. As shown in Fig. 4c, losses of up to 400 EUR/ha can be observed for water price increases of 0.10 EUR/m^3.

Wages and agricultural labour are also affected by farmers' cropping decisions (Fig. 4d). In this case, an increase in the price of water does not translate into a significant decrease in labour. Although labour is not an attribute that is part of the objective function, this indicator is also measured in the model.

3.2. *Simulation of water prices: results per region*

Fig. 5 shows the variation in crop acreage as the price of water increases, mainly the replacement of corn with rainfed winter cereals in the three regions of the first phase of the Navarra Canal. This is due to several factors, including the water price and other variables, such as the climate and market prices. For instance, corn production has changed in recent years depending on international market prices, which fluctuate widely. Wheat and other cereals have a similar profitability to corn, with payment of the fixed charge, but the variable part is saved. When corn prices fall, the northern sectors opt for rainfed crops, while the southern sectors opt for vegetables. The lower the price of corn, the greater the diversification in the south.

Fig. 6 presents stacked areas of crops as a function of water prices per region, where blue represents irrigated areas, and green represents rainfed areas. In this figure, the northern and middle regions clearly change from irrigated to rainfed crops when water prices increase. Southern regions show a very wide area of uncertainty. In southern

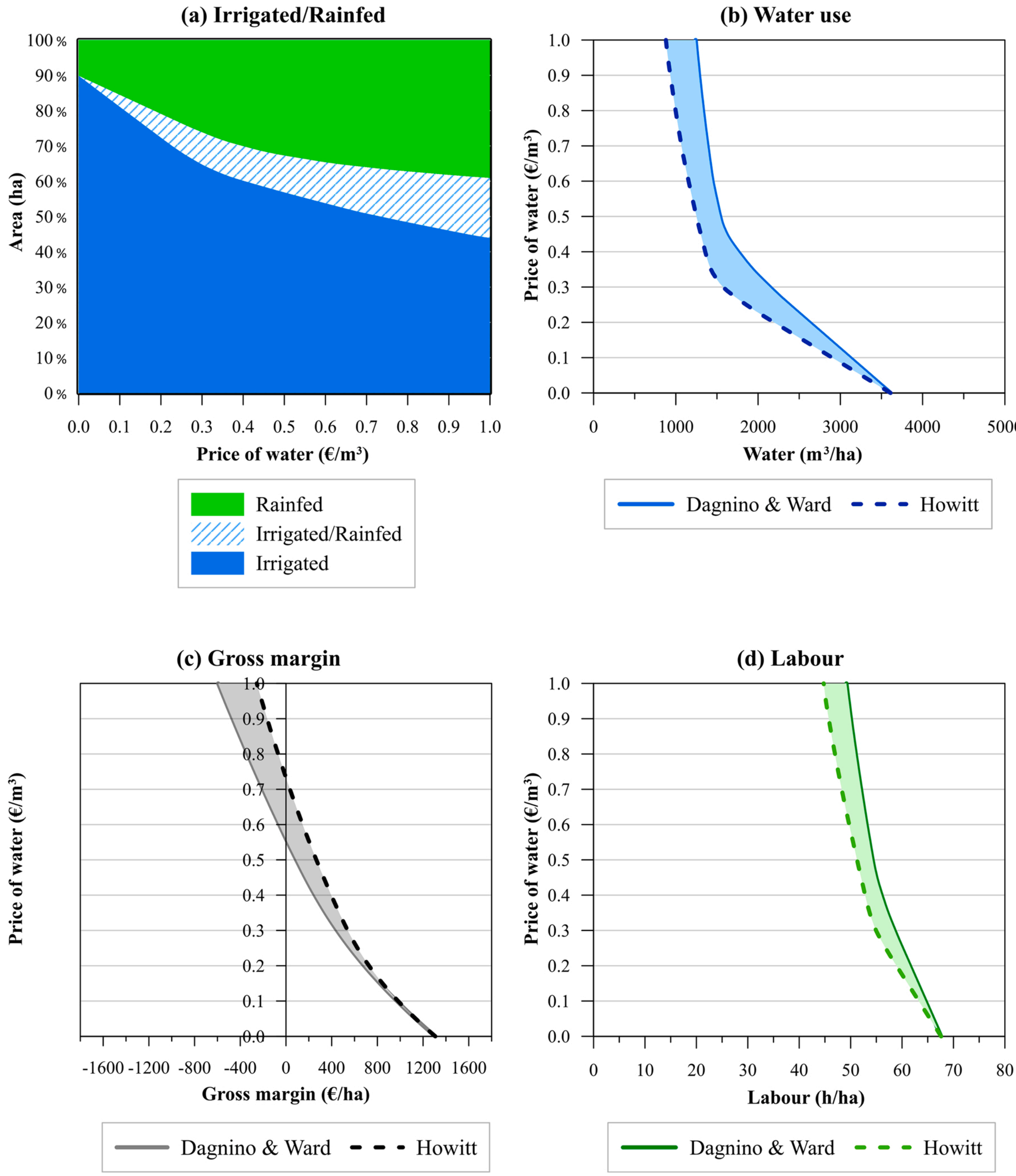

Fig. 4. Simulation of a) water use (m^3/ha), b) gross margin (EUR/ha), c) labour (h/ha), and d) irrigated/rainfed area occupied by the main crops (ha) as a function of water prices (EUR/m^3) in the first phase of the Navarra Canal based on data for 2012–2017 in line with two calibration methods: Dagnino and Ward and Howitt. The intermediate zone is assumed to be the level of uncertainty derived from the calibration method.

regions, rainwater is scarcer and more irregular, and vegetables and fruit trees, especially irrigated crops with the highest economic productivity, have a larger presence.

There are two different agricultural models in the first phase of the Navarra Canal. 1) "Simplification" (no irrigation) of irrigated agriculture in northern and middle areas to reduce irrigation costs. These are very productive cereal areas, where the main limiting factors when choosing the crop are climate and soil. There are a few alternatives for crop diversification and a limited possibility of double cropping, with very good cereal predictions. 2) Intensification of irrigation in productive southern areas, with more options of double and even triple cropping in areas where the climate and soil quality allow it. According to Monjardino et al. (2022), the agronomy, including plant genetics and physiology, meteorology, and soil science, had greater influence on financial performance than irrigation infrastructure in the irrigation region of the Riverina, in the Murray-Darling Basin of eastern Australia. In their case, when analysing the trade-offs of irrigation simplification/intensification/diversification to manage economic risk in this region, intensified scenarios had the highest net value overall, while crop diversification with moderate inputs was superior in mitigating economic risk due to higher returns per litre of irrigated water and more diverse sources of income.

Fig. 7 shows whether and how much a water pricing measure can generate water savings, with a consequent decrease in the gross margin (see Fig. 8). Southern regions begin at a higher level of irrigation water use (4400 m^3/ha) compared to the middle and northern areas

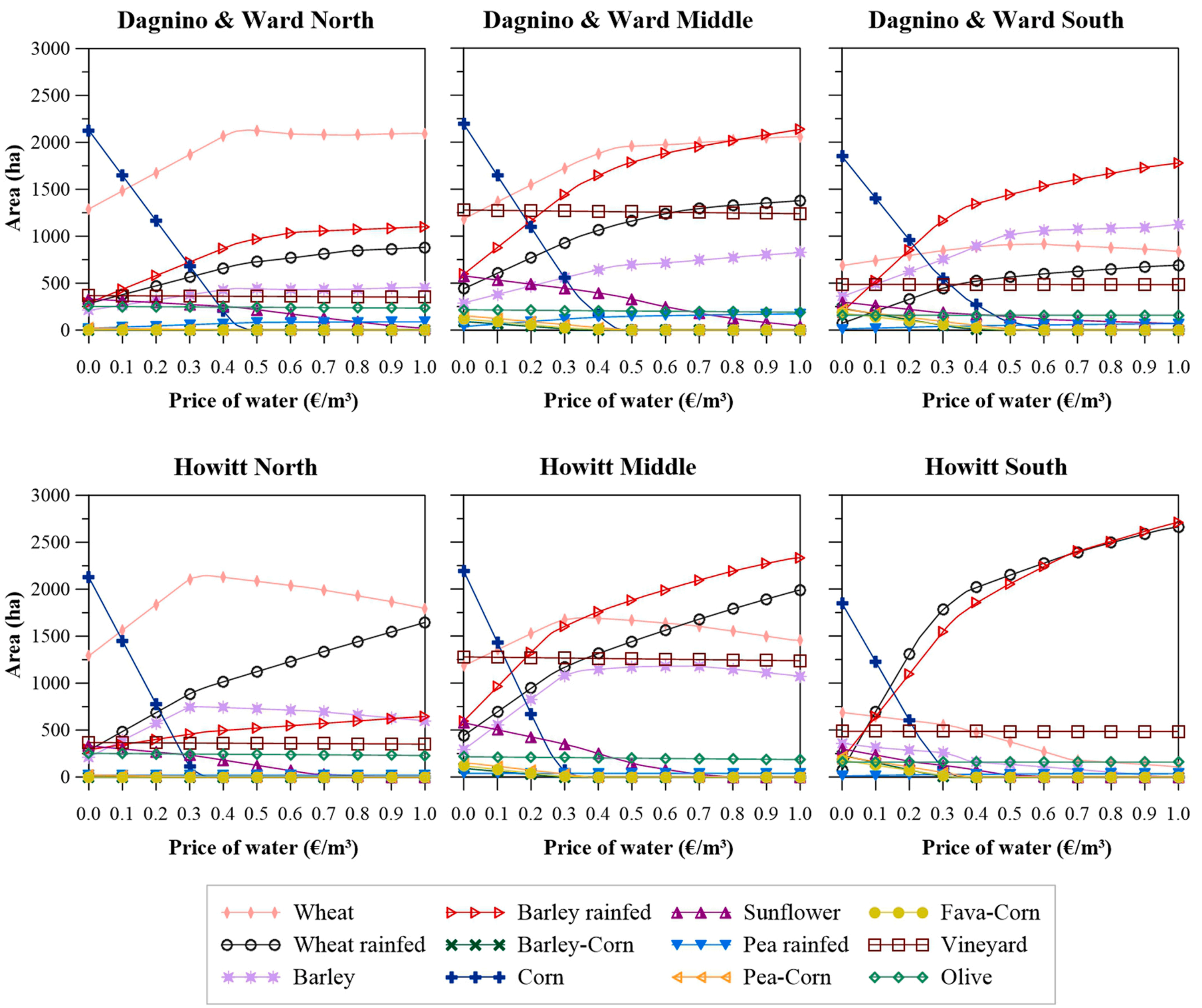

Fig. 5. Area occupied by the main crops (hectares) per region as a function of water prices (EUR/m^3) in the first phase of the Navarra Canal based on data for 2012–2017 in line with two calibration methods: Dagnino and Ward and Howitt.

(3200 m^3/ha) due to the lack of rainfall in those areas.

Southern regions seem to be the most elastic, particularly in their first section (Fig. 7). They also show greater "uncertainty" because the models give a wider range of results. Northern and middle regions are almost equal in terms of water use. They are a bit less elastic and less affected by water price changes. This might be because they can use rainwater as well as irrigation water (e.g., rainfed vs. irrigated wheat). Southern sectors are more sensitive to price changes because they depend on and use irrigation water more.

In northern and middle regions, a price of water above 0.3 EUR/m^3 has economic effects (Fig. 8) and a slight social effect on paid labour (Fig. 9) but no environmental consequences (similar amount of water used) (Fig. 7).

In the case of water prices versus gross margin (Fig. 8), the southernmost regions seem to show higher elasticity. By maximising utility, we are maximising the gross margin overall. This causes the curve to have smooth changes. This graph is useful for understanding the extent of the economic impact if the price of water is increased.

Fig. 8 also shows differences between the northern and middle regions. Northern areas become negative at about 0.5 EUR/m^3, while middle areas become negative at 0.7 EUR/m^3. Southern areas also become negative at 0.5 EUR/m^3. This number, even if uncertain, seems similar to the northern region.

The wage of agricultural labour responds differently to the water pricing in different regions (Fig. 9). In northern and middle regions, increases in the price of water do not translate into significant decreases in labour. In these regions, the maximum difference in terms of labour is about 10/15 h per hectare between water prices of 0 and 1 EUR/m^3. The crops of the northern and middle regions do not require much labour in irrigated or rainfed conditions, with similar labour in irrigated and rainfed areas.

On the other hand, the south is slightly less inelastic and shows a maximum difference of about 35/40 h per hectare between 0 and 1 EUR/m^3. This is because, in southern regions, there are more horticultural crops, which generate the most labour.

3.3. Results and limitations related to the methodology

The PMP has some shortcomings, mainly the underdetermination of calibration parameters and the bias of the first calibration stage. The underdetermination is the fact that many sets of calibrating parameters can exactly reproduce the observed level of every activity. To overcome

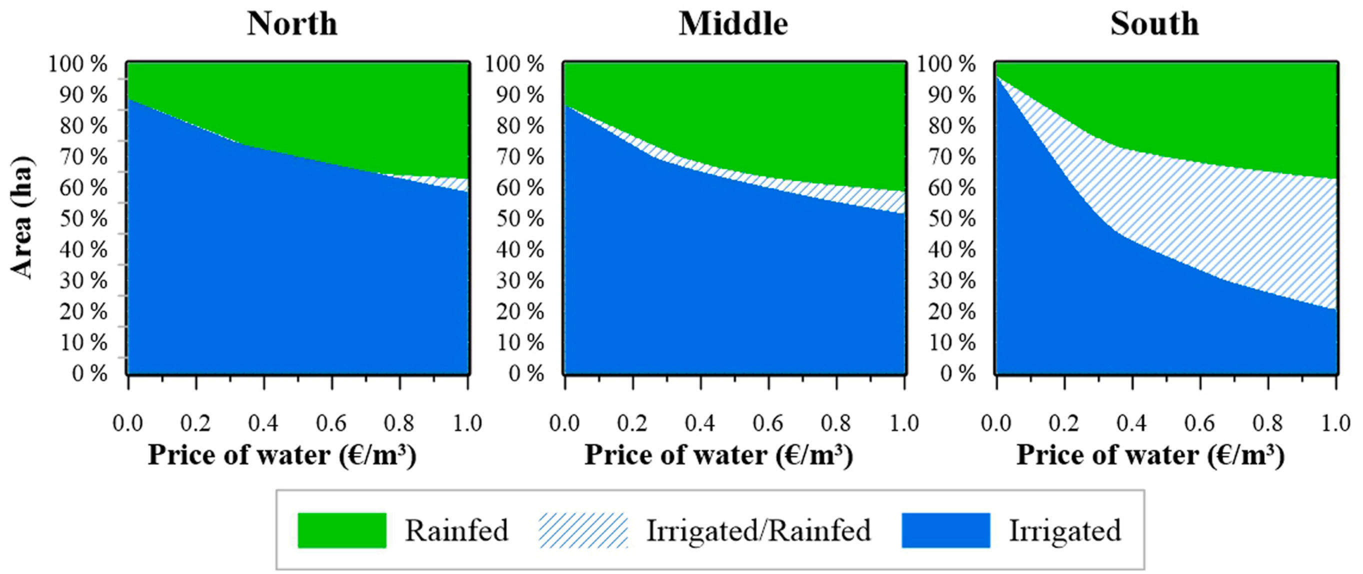

Fig. 6. Crop area (ha) as a function of water prices (EUR/m^3) per region in the first phase of the Navarra Canal. Blue: irrigated area, green: rainfed area based on data for 2012–2017 in line with two calibration methods: Dagnino and Ward and Howitt. The intermediate zone is assumed to be the level of uncertainty derived from the calibration method.

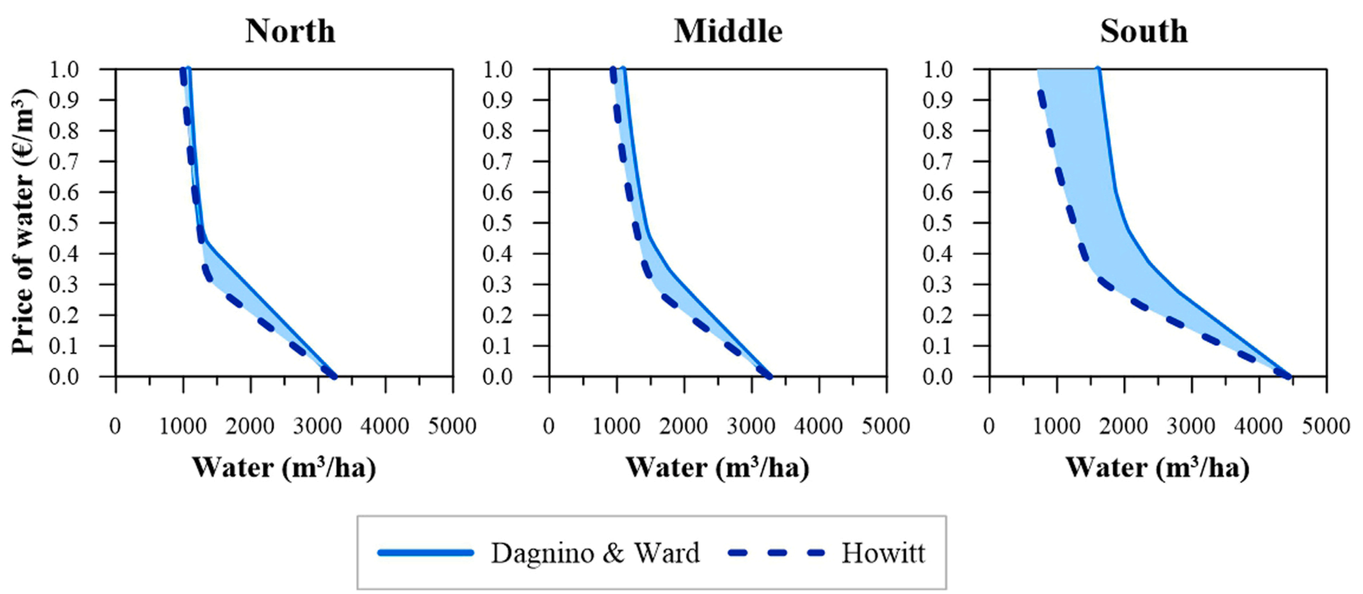

Fig. 7. Water use (m^3/ha) as a function of water prices (EUR/m^3) in the first phase of the Navarra Canal based on data for 2012–2017 in line with two calibration methods: Dagnino and Ward and Howitt. The intermediate zone is assumed to be the level of uncertainty derived from the calibration method.

this problem, many alternatives have been proposed, including the average cost approach proposed by Heckelei and Britz (2000), the use of exogenous supply elasticities (Helming et al., 2001), and the generalised maximum entropy criterion (Paris and Howitt, 1998). Apart from these alternatives, some other problems arise from the first stage as it is not possible to calibrate non-observed activities since information on land use for this crop is necessary to calibrate it. Due to the problems stemming from the first phase of the standard approach, skipping it is proposed using exogenous data that provide the shadow prices of land and other resources (Júdez et al., 2001; Graveline and Mérel, 2014).

With regard to the methodology, there are two main findings related to the rainfed crop simulations, which are explained in detail below. First, the existence of marginal crops in the calibration equations of Howitt's standard approach could make the shift to rainfed crops occur faster, at lower water prices, if no preventive measures are taken. Second, the low presence of rainfed crops hinders their expansion when the cost of water is increased under the Dagnino and Ward method.

A known problem with Howitt's standard approach is that the marginal (least profitable) activity has no dual value in the calibration constraints. This causes the beta of the cost function for this crop to have no value. The entire cost is, therefore, linear. This marginal crop coincides with some rainfed alternatives, mainly peas and barley. This means there can be a faster substitution of these marginal crops because an increase in their area does not increase their cost. For instance, if we take Sector IV.1 with 2200 ha irrigated, all the barley (113 ha) is replaced by the marginal crop at the first 0.04 EUR/m^3; corn (817 ha) at the first 0.19 EUR/m^3; rapeseed (118 ha) at 0.25 EUR/m^3; and wheat, sunflower, and pea–corn (636 ha) at approximately 0.30 EUR/m^3. All these crops are replaced by the marginal crop, which in this case is rainfed barley.

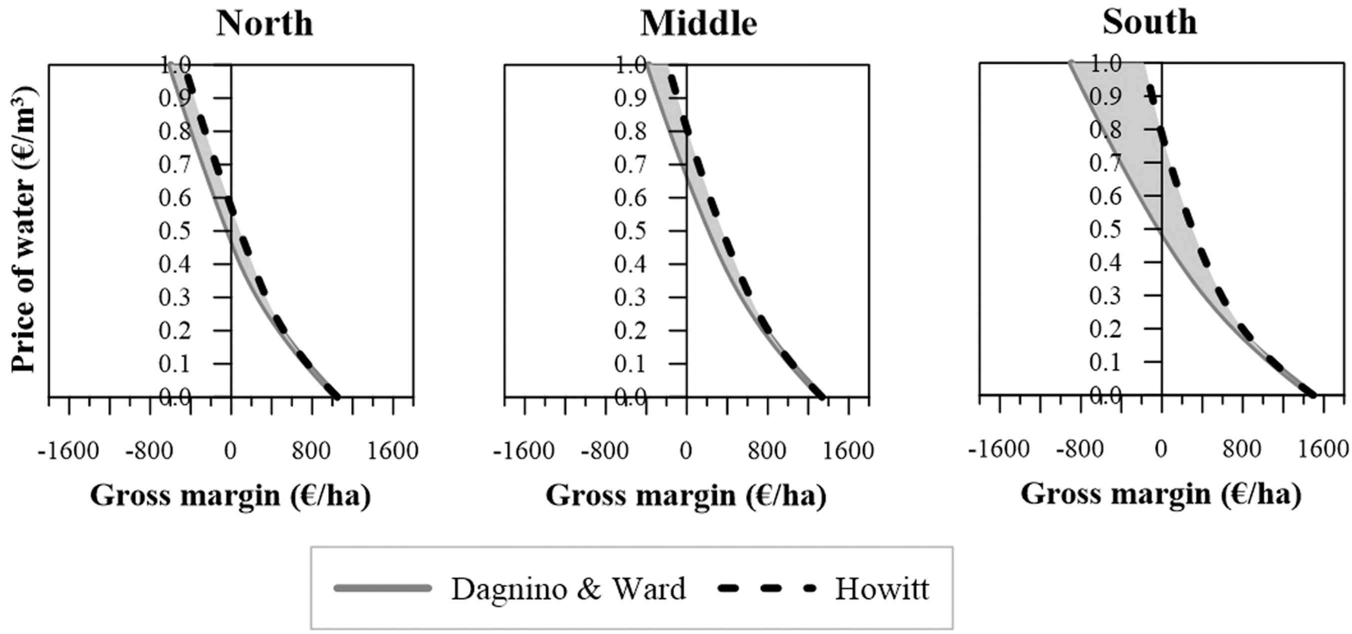

Fig. 8. Farmers' gross margin (EUR/ha) as a function of water prices (EUR/m^3) in the first phase of the Navarra Canal based on data for 2012–2017 in line with two calibration methods: Dagnino and Ward and Howitt. The intermediate zone is assumed to be the level of uncertainty derived from the calibration method.

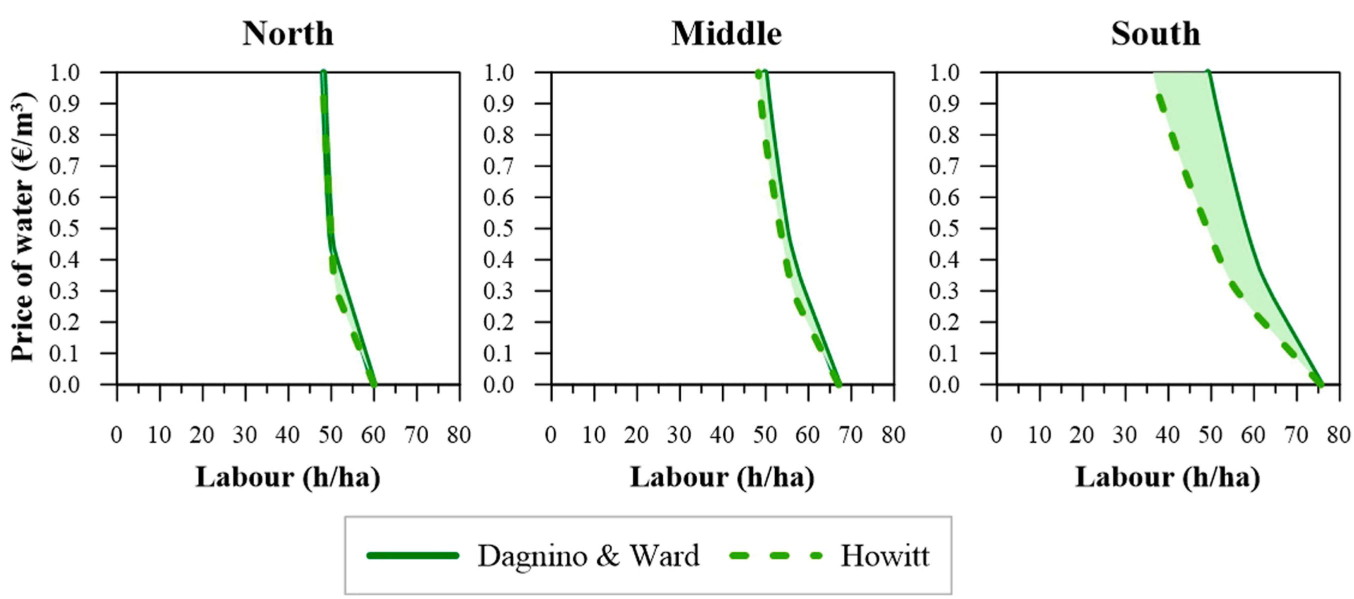

Fig. 9. Farmers' labour (h/ha) as a function of water prices (EUR/m^3) in the first phase of the Navarra Canal based on data for 2012–2017 in line with two calibration methods: Dagnino and Ward and Howitt. The intermediate zone is assumed to be the level of uncertainty derived from the calibration method.

To prevent this issue, which causes only the area of marginal crops to increase during the simulations, the area of marginal crops was limited to the observed area. The idea is that in the case of substitution by rainfed crops, more profitable crops are preferable. The result has been greater diversity in crop substitution and a delay in substitution timing in terms of water prices. That is, substitution with other crops occurs at higher prices, although not as high as in Dagnino and Ward's method, as shown in Fig. 4.

On the other hand, in areas where rainfed barley was the marginal crop, the area could not expand, causing the other predominant winter cereal, i.e., rainfed wheat, to grow much faster. Nevertheless, in aggregate, rainfed barley increases more with the Howitt method than with the Dagnino and Ward method, where substitution is also made with irrigated winter cereals. This is undoubtedly the main difference between the two methods, in addition to the greater presence of rainfed wheat.

The substitution of winter cereals in Dagnino and Ward's method deserves another methodological reflection. As can be seen in Fig. 6, the uncertainty zone in the southern region is much larger than in the other regions. This is mainly due to sectors IV.5 and IX of this region. In these sectors, the initial non-irrigated cereal area (i.e., rainfed wheat and barley) is small (10 ha in total (0.5%) in sector IV.5 and 79 ha (3.4%) in sector IX). This causes the B1 calibration coefficient to be relatively high for these winter cereals in relation to other irrigated crops. This means that if the area of these rainfed cereals is extended, their yield decreases rapidly (the B1 coefficient reduces the yield and is multiplied by the square of the area). Consequently, there is hardly any substitution for rainfed crops even when prices rise sharply because rainfed crops are not profitable. This situation does not make much sense agronomically because we assume that rainfed crops would grow well on the land previously occupied by irrigated crops. This problem in Dagnino and Ward's methodology is reflected in the uncertainty of rainfed and irrigated areas, water use (Fig. 7), and gross margin (Fig. 8) in the southern region.

4. Conclusions

The first phase of the Navarra Canal is a unique case in which, along its 50 km expanse, there are several territorial features and climatic zones, which are key to explaining the different farmers' responses to increases in water prices. The northernmost regions abandon irrigation because the rainfed/irrigation differential does not compensate well enough. Meanwhile, southern regions, which are warmer and drier, introduce fruit trees and vegetables.

The findings from this study reveal that, when formulating water-pricing policies, it is key to consider the local and regional circumstances such as the climate, soil type, crops grown, and possible alternative crops and market conditions. Climate-change projections could also be a variable factor to consider. In this way, incorporating the green water footprint component (water from precipitation that is stored in the root zone of the soil and evaporated, transpired, or incorporated by plants) in water-pricing modelling might be helpful to identify appropriate policies to set water pricing in the agricultural sector. Moreover, it is important to anticipate water pricing impacts not only on the environment but also on socio-economic facets. It is important and necessary to incorporate the triple dimension of sustainability.

Funding

The project leading to these results received funding from "la Caixa" and Caja Navarra Foundation, under agreement LCF/PR/PR13/51080004, from Programa Operativo FEDER Andalucía 2014–2020 (Ref 1263831-R) and the Spanish Ministry of Science and Innovation (TED2021-131066B-I00).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank the Navarre Institute of Agrifood Technology and Infrastructure (Instituto Navarro de Tecnologías e Infraestructuras Agroalimentarias, INTIA) for providing the data for conducting this research. Particularly, we would like to thank Juan Manuel Intxaurrandieta, Beatriz Preciado, Amaya Yabén, and Joaquín Garnica from INTIA. We are grateful to Ignacio Gil Jordán, Director-General for Agriculture, Livestock and Rural Development of the Government of Navarre (2015–2019 term), for his good advice. We would also like to thank Jesús García from Aguacanal for his advice and for providing the maps of the Navarra Canal with the agricultural holdings. We are grateful to Inaki Ezkurra, from the Statistics Bureau of the Rural Development, Environment and Local Administration Department of the Government of Navarre, for his clarifications regarding the nomenclature and data of pastures. Finally, we would like to thank Julio Berbel, Professor at the Universidad de Córdoba, for his useful advice and reflections.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108245.

References

Aguacanal (Concessionary Society of the irrigable area of theNavarra Irrigation Canal), 2012–2017. Concession Contract of the Infrastructuresof General Interest of the Irrigable Area of the 1st Phase of the Navarra Irrigation Canal. Annual Technical Report 2012–2017. Aguacanal (Concessionary Society of the Irrigable Area Of the Navarra Irrigation Canal).

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome.

Berbel, J., Gomez-Limón, J.A., 2000. Impact of water pricing policy in Spain: an analysis of three irrigated areas. Agric. Water Manag. 43, 219–238. https://doi.org/10.1016/S0378-3774(99)00056-6.

Berbel, J., Expósito, A., 2020. The theory and practice of water pricing and cost recovery in the Water Framework Directive. Water Altern. 13 (3), 659–673.

Dagnino, M., Ward, F.A., 2012. Economics of agricultural water conservation: empirical analysis and policy implications. International Journal of Water Resources Development 28, 577–600.

De Stefano, L., Llamas, M.R. (Eds.), 2013. Water, Agriculture and the Environment in Spain: Can We Square the Circle? Taylor & Francis Group, London.

Dinar, A., Pochat, V., Albiac, J. (Eds.), 2015. Water Pricing Experiences and Innovations. Global Issues in Water Policy 9. Springer, Switzerland.

Expósito, A., Berbel, J., 2017. Why is water pricing ineffective for deficit irrigation schemes? A case study in southern Spain. Water Resour. Manag. 31, 1047–1059. https://doi.org/10.1007/s11269-016-1563-8.

Freebairn, J., Quiggin, J., 2006. Water rights for variable supplies. Aust. J. Agric. Resour. Econ. 50, 295–312. https://doi.org/10.1016/j.agwat.2021.107248.

Gómez-Limón, J.A., Gutiérrez-Martín, C., Riesgo, L., 2016. Modeling at farm level: positive multi-attribute utility programming. Omega 65, 17–27. https://doi.org/10.1016/j.omega.2015.12.004.

Government of Navarra, 2012–2017a. Prices paid to producers. Agricultural Observatory, Government of Navarra. Available from: ⟨http://www.navarra.es/home_es/Temas/Ambito+rural/Vida+rural/Observatorio+agrario/Agricola/Informacion+estadistica/Temas+economicos.htm⟩.

Government of Navarra, 2012–2017b. Yields. Agricultural Observatory, Government of Navarra. Available from: ⟨http://www.navarra.es/home_es/Temas/Ambito+rural/Vida+rural/Observatorio+agrario/Otras+estadisticas/Superficies+y+producciones/⟩.

Government of Navarra, 2012–2017c. Agricultural Production Economics. Available from: ⟨http://www.navarra.es/home_es/Temas/Ambito+rural/Vida+rural/Observatorio+Precios+Agrarios/precio+costes+Productor/EconomiaProduccion.htm⟩.

Government of Navarra, 2021a. Map of Average Annual Temperature in Navarra. Available from: ⟨http://meteo.navarra.es/climatologia/TempMediaAnual.pdf⟩.

Government of Navarra, 2021b. Map of Average Annual Rainfall in Navarra. Available from: ⟨http://meteo.navarra.es/climatologia/PrecipMediaAnual.pdf⟩.

Government of Navarra, 2021c. Navarra Canal. Government of Navarra, General Directorate of Public Works and Infrastructure, Department of Territorial Cohesion. Available from: ⟨http://www.cfnavarra.es/obraspublicas/departamento/canalnavarra.htm⟩.

Graveline, N., Mérel, P., 2014. Intensive and extensive margin adjustments to water scarcity in France's Cereal Belt. Eur. Rev. Agr. Econ.

Gutiérrez-Martín, C., Gómez-Gómez, C.M., 2011. Assessing irrigation efficiency improvements by using a preference revelation model. Span. J. Agric. Res. 9, 1009–1020. https://doi.org/10.5424/sjar/20110904-514-10.

Gutiérrez-Martín, C., Pérez Blanco, C.D., Gómez Gómez, C.M., Berbel, J., 2014. Price volatility and water demand in agriculture. A case study of the Guadalquivir River Basin (Spain). In: Bournaris, T., Berbel, J., Manosand, B., Viaggi, D. (Eds.) Economics of Water Management in Agriculture. Boca Ratón, EEUU, CRC Press. Taylor & Francis Group, pp. 319–348.

Haro-Monteagudo, D., Palazón, L., Zoumides, C., Beguería, S., 2022. Optimal implementation of climate change adaptation measures to ensure long-term sustainability on large irrigation systems. Water Resour. Manag. https://doi.org/10.1007/s11269-022-03225-x.

Heckelei, T., Britz, W., 2000. Positive Mathematical Programming with multiple data points: A cross-sectional estimation procedure. Cah. Econ. Sociologie Rurales 57, 28–50.

Helming, J.F.M., Peeters, L., Veendendaal, P.J.J., 2001. Assessing the consequences of environmental policy scenarios in Flemish agriculture, in: Heckelei, T., Witzke, H.P., Henrichsmeyer, W. (Eds.), Agricultural sector modelling and policy information systems. Proceedings of the 65th Seminar of the European Association of Agricultural Economics. Vauk Verlag, Kiel, Germany, pp. 237-245.

Howitt, R.E., 1995. Positive Mathematical Programming. Am. J. Agr. Econ. 77, 329–342.

INTIA (Navarre Institute of Transfer and Innovation in Agri-Food sector), 2018a. Current Situation and Evolution of Irrigation in the 1st Phase of the Irrigable Area of the Navarra Canal from an Economic and Social Point of View. INTIA, Government of Navarra, Villaba, p. 155.

INTIA (Navarre Institute of Transfer and Innovation in Agri-Food sector), 2018b. Irrigation Advisory Service. Irrigation Recommendations. Navarre Institute of Transfer and Innovation in Agri-Food sectors, Government of Navarra, Villaba.

Available from: ⟨https://www.intiasa.es/es/comunidad-de-regantes/areas-de-interes/servicio-asesoramiento-al-regante/recomendaciones-de-riego.html⟩.
INTIA (Navarre Institute of Transfer and Innovation in Agri-Food sector), 2019. Information on Irrigated Areas and Crops. Agro-industrial Supply Service. Navarre Institute of Transfer and Innovation in Agri-Food sectors, Government of Navarra, Villaba. Available from: ⟨https://www.intiasa.es/0AppAgroindustrial/?request=zonas⟩.
INTIA (Navarre Institute of Transfer and Innovation in Agri-Food sector), 2021. Map of the first phase of the Navarra Canal. Navarre Institute of Transfer and Innovation in Agri-Food sectors 2021 Government of Navarra Villaba.
Júdez, L., Chaya, C., Martínez, S., González, A.A., 2001. Effects of the measures envisaged in "Agenda 2000" on arable crop producers and beef and veal producers: an application of Positive Mathematical Programming to representative farms of a Spanish region. Agr. Syst. 67, 121–138.
Lecina, S., Isidoro, D., Playán, E., Aragüés, R., 2010. Irrigation modernisation and water conservation in Spain: the case of Riegos del Alto Aragón. Agric. Water Manag. 97 (10), 1663–1675. https://doi.org/10.1016/j.agwat.2010.05.023.
López-Moreno, J.I., García-Ruiz, J.M., Vicente-Serrano, S.M., Alonso-González, E., Revuelto-Benedí, J., Rico, I., Beguería-Portugués, S., 2020. Critical discussion of: "A farewell to glaciers: ecosystem services loss in the Spanish Pyrenees". J. Environ. Manag 275, 111247. https://doi.org/10.1016/j.jenvman.2020.111247.
MAPAMA, 2018. Payments Associated with the Production. Common Agricultural Policy 2015–2020. Spanish Ministry of Agriculture and Fisheries, Food and Environment (MAPAMA). Technical Note 4.
Molle, F., 2009. Water scarcity, prices and quotas: a review of evidence on irrigation volumetric pricing. Irrig. Drain. Syst. 23, 43–58. https://doi.org/10.1007/s10795-009-9065-y.
Molle, F., Berkoff, J. (Eds.), 2007. Irrigation Water Pricing: The Gap Between Theory And Practice. Comprehensive Assessment of Water Management in Agriculture, 4. CABI, Wallingford, UK. https://doi.org/10.1079/9781845932923.0000.
Momeni, M., Zakeri, Z., Esfandiari, M., Behzadian, K., Zahedi, S., Razavi, V., 2019. Comparative analysis of agricultural water pricing between Azarbaijan Provinces in Iran and the state of California in the US: a hydro-economic approach. Agric. Water Manag. 223, 105724 https://doi.org/10.1016/j.agwat.2019.105724.
Monjardino, M., Harrison, M.T., DeVoil, P., Rodriguez, D., Sadras, V.O., 2022. Agronomic and on-farm infrastructure adaptations to manage economic risk in Australian irrigated broadacre systems: a case study. Agric. Water Manag. 269, 107740 https://doi.org/10.1016/j.agwat.2022.107740.
Montilla-López, N.M., Gutiérrez-Martín, C., Gómez-Limón, J.A., 2017. Impact of irrigation water pricing in the Bajo Guadalquivir. ITEA 113 (1), 90–111. https://doi.org/10.12706/itea.2017.006.
Paris, Q., Howitt, R.E., 1998. An analysis of ill-posed production problems using maximum entropy. Am. J. Agr. Econ. 80, 124–138.
Parrado, R., Pérez-Blanco, C.D., Gutiérrez-Martín, C., Standardi, G., 2019. Micro-macro feedback links of agricultural water management: insights from a coupled iterative positive multi-attribute utility programming and computable general equilibrium model in a Mediterranean basin. J. Hydrol. 569, 291–309. https://doi.org/10.1016/j.jhydrol.2018.12.009.
Parrado, R., Pérez-Blanco, C.D., Gutiérrez-Martín, C., Gil-García, L., 2020. To charge or to cap in agricultural water management. Insights from modular iterative modelling for the assessment of bilateral micro-macro-economic feedback links. Sci. Total Environ. 742, 140526 https://doi.org/10.1016/j.scitotenv.2020.140526.
Pérez-Blanco, C.D., Gutiérrez-Martín, C., Gil-García, L., Montilla-López, N.M., 2021. Microeconomic ensemble modeling to inform robust adaptation to water scarcity in irrigated agriculture. J. Water Resour. Plan. Manag 147, 04021038. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001385.
Playán, E., Mateos, L., 2006. Modernisation and optimisation of irrigation systems to increase water productivity. Agric. Water Manag. 80 (1–3), 100–116. https://doi.org/10.1016/j.agwat.2005.07.007.
Rey, D., Garrido, A., Mínguez, M.I., Ruiz Ramos, M., 2011. Impact of climate change on maize's water needs, yields and profitability under various water prices in Spain. Span. J. Agric. Res. 4, 1047–1058. https://doi.org/10.5424/sjar/20110904-026-11.
SABI, 2022. SABI Database on Financial and Economic Results of Spanish and Portuguese Companies. 2022 Bureau van Dijk Electronic Publishing. Available from: ⟨https://sabi.bvdinfo.com/version-20221115/Search.QuickSearch.serv?_CID=1&context=3CZV9FQ7DLMM3CN⟩.
Sapino, F., Pérez-Blanco, C.D., Gutiérrez-Martín, C., Frontuto, V., 2020. An ensemble experiment of mathematical programming models to assess socio-economic effects of agricultural water pricing reform in the Piedmont Region, Italy. J. Environ. Manag. 267, 110645 https://doi.org/10.1016/j.jenvman.2020.110645.
Sapino, F., Pérez-Blanco, C.D., Gutiérrez-Martín, C., García-Prats, A., Pulido-Velazquez, M., 2022. Influence of crop-water production functions on the expected performance of water pricing policies in irrigated agriculture. Agric. Water Manag. 259, 107248 https://doi.org/10.1016/j.agwat.2021.107248.
Schoups, G., Addams, C.L., Minjares, J.L., Gorelick, S.M., 2006. Sustainable conjunctive water management in irrigated agriculture: model formulation and application to the Yaqui Valley, Mexico. Water Resour. Res. 42, W10417. https://doi.org/10.1029/2006WR004922.
Speelman, S., Buysse, J., Farolfi, S., Frija, A., D'Haese, M., D'Haese, L., 2009. Estimating the impacts of water pricing on smallholder irrigators in North West Province, South Africa. Agric. Water Manag. 96 (11), 1560–1566. https://doi.org/10.1016/j.agwat.2009.06.014.
Wehling, P., 2020. Toward a legal and institutional framework for cooperation along the Nile. Nile Water Rights. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-60796-1_10.