



# Impact of alternative water policies for drought adaptation in the Guadalquivir Mediterranean river basin, southern Spain

Javier Martínez-Dalmau<sup>a,\*</sup>, Carlos Gutiérrez-Martín<sup>a</sup>, Taher Kahil<sup>b</sup>, Julio Berbel<sup>a</sup>

<sup>a</sup> Water, Environmental and Agricultural Resources Economics Research Group (WEARE) Universidad de Córdoba, Campus de Rabanales, 14014 Córdoba, Spain

<sup>b</sup> Water Security Research Group, Biodiversity and Natural Resources Program. International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

## ARTICLE INFO

### Keywords:

Hydro-economic model  
Water policy  
Drought management  
Drought  
Mediterranean

## ABSTRACT

*Study region:* The Guadalquivir Basin in Spain as a representative Mediterranean basin.

*Study focus:* The aim of this study is to assess the adaptive capacity of Mediterranean basins to long periods of severe drought. To do so, a hydro-economic model has been developed that includes a spatial representation of the major economic uses of water and enables an analysis of the economic and environmental effects of alternative water management policies under a single event of water scarcity.

*New hydrological insights for the region:* Results highlight the trade-offs among economic uses of water and environmental flow requirements since water resources in the Guadalquivir are fully allocated. Moreover, the increase of irrigated perennial crops area will aggravate vulnerability to drought by limiting the adaptive capacity of the basin. Survival irrigation is the first option for farmers to adapt to the simulated extreme drought. 148,000 ha are shifted from normal irrigation to survival irrigation in the Drought Management Protocol scenario. These findings call for policy interventions to ensure greater management flexibility toward optimising water use while meeting environmental goals. For instance, enabling water trading among farmers would reallocate 22 % more water to the upper basin, reducing drought losses by 22 M EUR. The hydro-economic model developed here can be adapted to basins elsewhere and the results show that it can be a useful tool to guide the design of efficient water management policies to address severe droughts in water-stressed basins.

## 1. Introduction

Structural water scarcity is common to all Mediterranean river basins. Despite the uncertainty surrounding the impact of climate change on the frequency and intensity of droughts, many researchers predict an increase in drought frequency, intensity, and duration due to rising global temperatures (Liu et al., 2018). According to the European Environment Agency (2019), the consequences of climate change (a temperature rise of 1.5–2 °C) is likely to increase drought risks in Mediterranean Europe. This expected decrease in available water resources, coupled with growing water use for economic and social activities, could lead to more problems regarding water management. These problems may result in social conflict if water resources need to be reallocated from historical uses (e.g.,

\* Corresponding author.

E-mail address: [javier.martinez@uco.es](mailto:javier.martinez@uco.es) (J. Martínez-Dalmau).

<https://doi.org/10.1016/j.ejrh.2023.101444>

Received 6 February 2023; Received in revised form 6 June 2023; Accepted 8 June 2023

Available online 10 June 2023

2214-5818/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

irrigation) to new societal preferences (e.g., environmental, or industrial uses).

The overexploitation of water resources has been identified as an outcome of the so-called "basin closure" path (Molle et al., 2010), a process that has been described for Guadalquivir (Expósito and Berbel, 2019). In such cases, demand continues to grow beyond the capacity to increase supply and generates a situation of overexploitation and overallocation of resources. Sustainable management of water resources requires scientific knowledge and sufficient relevant information to establish policies that balance the different uses of water. Various international institutions have called for the introduction of mechanisms that enable a more efficient allocation of water resources (European Commission, 2019; Gruère and Boëdec, 2019; OECD, 2015). MITECO. Ministerio para la Transición Ecológica y el Reto Demográfico (2020) underlines the need in Spain for a more flexible allocation of rights that is better adapted both to the long-term demands of society and to episodes of cyclical shortages (e.g., frequent episodes of drought).

Hydro-economic models provide useful analytical tools for assessing the effectiveness of water resources management at basin level. The advantage of hydro-economic modelling is that it integrates the agronomic, hydrological, environmental, and economic components of a water resource system, which enables a more comprehensive evaluation of water policy options (Expósito et al., 2020) and means it is well-suited for the assessment of management and policy strategies for the adaptation to climate change (Arias Montevechio et al., 2023; Harou et al., 2009; Ortiz et al., 2023; Sapino et al., 2022; Ward, 2021). This integrated view allows a more realistic approach to resource allocation (Bekchanov et al., 2017; Eamen et al., 2022; Medellín-Azuara et al., 2010; Vichete et al., 2023). Pérez-Blanco et al. (2022) show how the integration of hydro-micro-macro-economic models can provide essential information in the efficient design of agricultural water policies.

Many studies have addressed the issue of adaptation of irrigated agriculture to the impacts of drought. Farm-level measures can contribute to this adaptation (Leclère et al., 2013; Reidsma et al., 2010; Ricart et al., 2019; Ward, 2022). One of the key measures promoted by water authorities in recent years is the modernisation of agriculture (improving water-use efficiency), both at the plot level and the overall irrigation system infrastructure. This measure is a critical factor for rural development, since it enhances high-value cropping patterns and crop yields, leading to an increase in the profitability of the irrigation water used (Pérez-Blanco et al., 2020). However, several studies call for a reconsideration of current water policies and the implementation of new institutional measures (Bhaduri et al., 2021; Hervás-Gámez and Delgado-Ramos, 2019). In the European Union (EU), the Water Framework Directive (WFD) calls for the use of economic instruments to manage water resources and achieve the good environmental status of water bodies in the EU member states (European Commission, 2000). The WFD highlights the relevance of estimating the economic value of water uses, the cost of associated water services, and the level of cost recovery. The WFD also encourages the use of water pricing as a tool to achieve efficient water use, although some authors question the effectiveness of water pricing in water scarce basins (Berbel and Expósito, 2020). Nevertheless, there are other economic tools that could help mitigate the economic impact of droughts, such as water markets, the pros and cons of which have been extensively analysed in the literature (Bajaj et al., 2022; Montilla-López et al., 2016; Palomo-Hierro et al., 2015).

However, the studies conducted to date have tended to focus on small spatial areas and/or specific uses, without considering the relationship between uses and water flows at the basin level. To our knowledge, there is a lack of models that integrate both river water

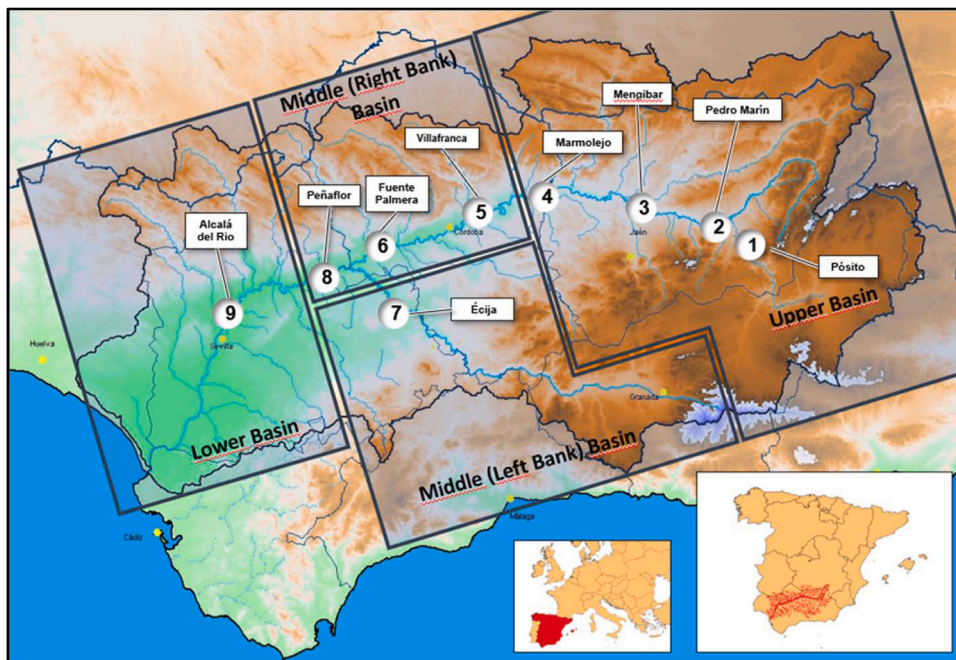


Fig. 1. Map of the Guadalquivir basin showing the main gauges.  
Source: CHG. Confederación Hidrográfica del Guadalquivir (2021, 2022).

flows and agents' behaviour, while specifically analysing the effects on water use of farms and agricultural infrastructure modernisation, water pricing policies and water markets at river basin scale where available water resources are already fully allocated. This study aims to help fill this gap by analysing the economic and environmental impacts of droughts and water scarcity in the Guadalquivir basin, through an examination of alternative water allocation policies. To this end, a basin-scale hydro-economic model incorporating the main water uses has been developed, reflecting the mutual relationships between social agents and the natural system. The model can capture the response of the system to various management policies when faced with a severe, long-lasting drought with ongoing massive investment in perennial crops upstream. Another new development explored in this study is the widespread use of deficit irrigation, which impacts resilience and vulnerability to droughts.

This study contributes to the literature by providing a detailed assessment of water allocation at the river basin level through hydro-economic modelling. The study not only analyses how to achieve a more sustainable management of the Guadalquivir River basin, but also adds to the scientific debate on policies and measures for sustainable water management worldwide. A common response to closure and scarcity is modernisation (investment in water saving measures), which has opened an academic debate on the "rebound effect" of such measures; some authors claim the rebound effect is inevitable (Perry and Steduto, 2017), while others defend the possibility of preventive actions (Berbel and Mateos, 2014). Previous hydrological models of the Guadalquivir basin only include subbasins (Hervás-Gómez and Delgado-Ramos, 2020) or specific irrigation districts (Reca et al., 2001a, 2001b), or assume a fixed agricultural water demand as in AQUATOOL model (CHG. Confederación Hidrográfica del Guadalquivir, 2021). Our contribution in the case study is the use of positive mathematical programming (PMP) to simulate water demand at basin level. This allows simulating the response of the agricultural sector to different situations of water availability or to different water policies.

This paper is organised as follows. Section 2 describes the Guadalquivir basin. Section 3 explains the development of the hydro-economic model of the Guadalquivir basin. Section 4 introduces the simulated scenarios. The results obtained are presented in Section 5. Finally, Section 6 outlines the main conclusions.

## 2. Case study area: the Guadalquivir basin

The Guadalquivir basin in southwestern Europe has a surface area of 57,527 km<sup>2</sup> and supports the economic activities of a population of more than 4.2 million people living in 476 municipalities (Fig. 1). The Guadalquivir basin has several particular features that make it an interesting basin for modelling water resources and analysing water management policies, which can be applied to other semi-arid areas with a Mediterranean climate: structural water scarcity (Espinosa-Tasón et al., 2020); recurrent and severe droughts; limited opportunities for increasing water supply; widespread use of deficit irrigation; use of water trading instruments (Palomo-Hierro et al., 2015); and the relevance of Guadalquivir basin as one of the main irrigated areas (25 % of Spain) and orchards of Europe.

The renewable resources available exceed 7000 hm<sup>3</sup>/year. Water abstractions total 3830 hm<sup>3</sup>/year, of which 2903 hm<sup>3</sup> comes from surface water and 927 hm<sup>3</sup> from groundwater (CHG. Confederación Hidrográfica del Guadalquivir, 2021). These abstractions exceed 50 % of renewable resources and agriculture is the largest user of water, accounting for 87 % of the water rights in the basin.

The River Basin Authority (RBA), *Confederación Hidrográfica del Guadalquivir*, is responsible for water management in the basin. Rainfall variability in the basin is high, and hence the allocation of water to users is not fully guaranteed. Each farmer receives an amount of water allocated by the RBA as "an administrative concession" or as "water rights". The water rights depend on the crop and location, ranging from 1500 m<sup>3</sup>/ha/year for olive groves to 10,450 m<sup>3</sup>/ha/year for rice; however, farmers in the Guadalquivir basin only receive their full allocation of water rights around 80–85 % of the years. The average water allocation during the drought in the period 2005–2008 was approximately 50 % of the granted administrative water rights. After this period, there was a return to

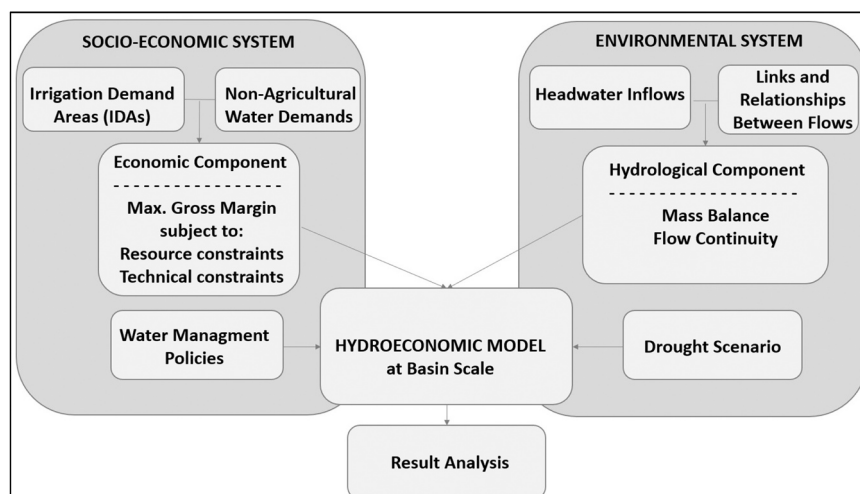


Fig. 2. Modelling framework.

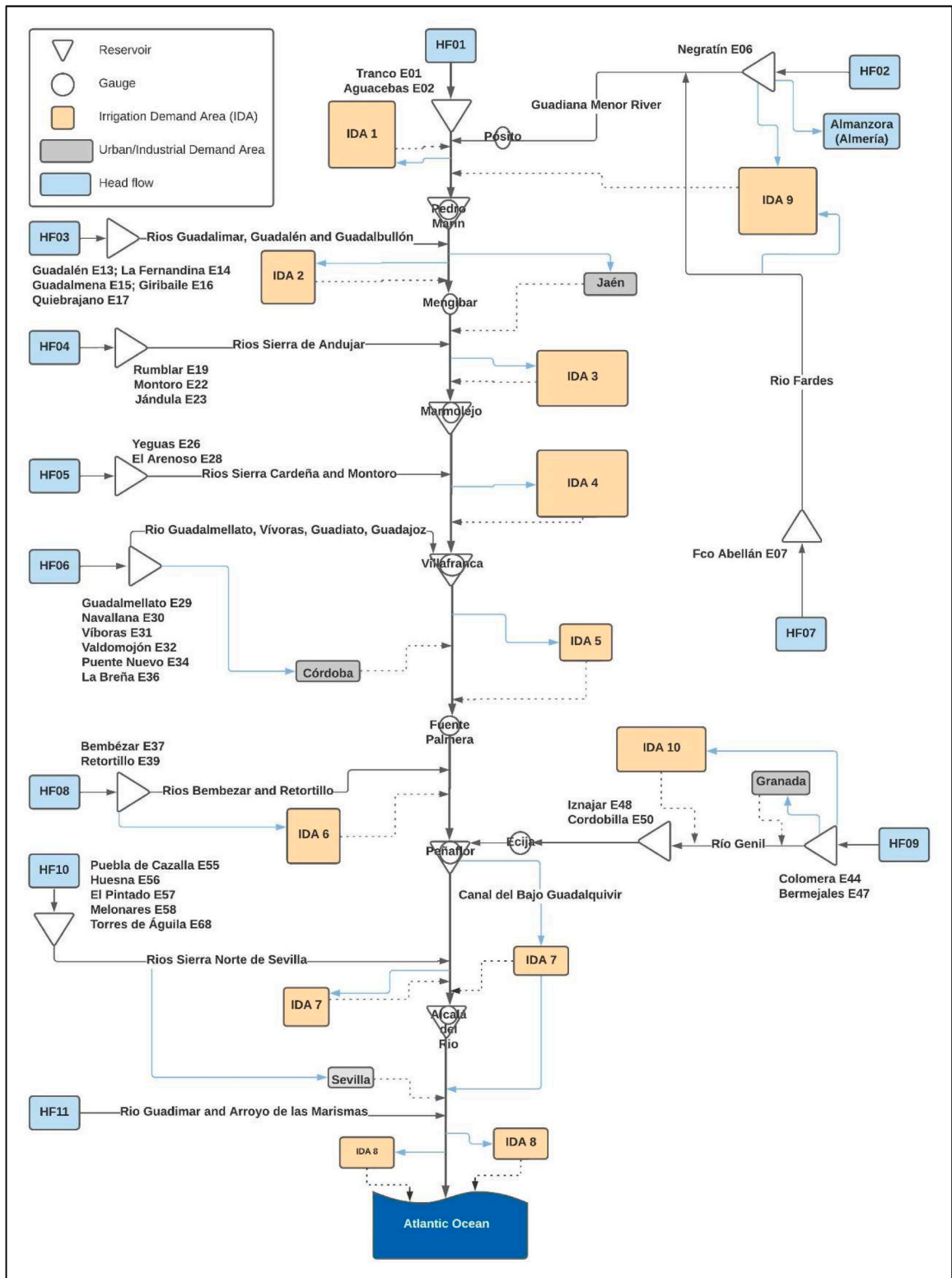


Fig. 3. Guadalquivir basin flowchart.

normality from 2008 to 2020, until the 2020–21 season, when another drought protocol came into effect with a 50 % reduction, and further reduction to 20 % for 2021–22.

The location of crops follows a certain geographical distribution. i) in the upper basin, irrigated olive trees occupy 98 % of the irrigated area and are virtually a monocrop, accounting for more than 85 % of the total cultivated area in these zones; ii) herbaceous crops are more prevalent in the areas close to the Guadalquivir estuary, where olive groves become less predominant (due to climatic reasons), giving way to other crops such as rice (12 % of the total cultivated area) or extensive winter crops such as wheat, sunflower, and cotton (43 %), with perennial crops accounting for only 38 % of the total cultivated area; iii) between both extremes there is a transition of crops in the Middle Basin (left and right bank) (see Fig. 1).

In terms of water-use efficiency, over the last 20 years the basin has undergone a technological transformation with traditional production systems being replaced by more intense systems based on efficient irrigation techniques encouraging an increase in perennial crops cultivation. Drip irrigation is the irrigation system in 78 % of the cultivated area in the basin, with this figure reaching 92 % in the upper basin area (see Fig. 1). Moving further down the basin, drip technology is gradually replaced by sprinkler technology, to the point where it covers 61 % of the cultivated area in the lower basin, with the greatest use of flood irrigation found on rice farms.

### 3. The hydro-economic model

The hydro-economic model is used to evaluate drought scenarios and adaptation measures. It combines two components: hydrological and economic. Fig. 2 shows the outline of the hydro-economic modelling process.

#### 3.1. Hydrological component

The hydrological component is a reduced-form hydrological model of the Guadalquivir basin. It has been calibrated with the observed flows, applying the hydrological principles of mass balance and continuity of river flow. Based on the model developed by Kahil et al. (2016, 2018), the model used in this study depicts a network of nodes and links, with nodes representing the water supply and demand units in the basin, and links indicating the flow relationships between them. Balances are defined for each flow,  $i$ , with the main flow variables in the model,  $X_i$ , being headwater inflows, abstractions, return flows, losses, and flows measured at selected gauge points in the basin. The information fed into the model is provided by the RBA (CHG. Confederación Hidrográfica del Guadalquivir, 2021, 2022), and is used to replicate the flow rates at each node and the spatial distribution of the available water between the different units (Fig. 3).

The headwater inflows are calculated as the total annual flows measured at the different headwater gauges, with the inflows,  $X_h$ , at each headwater gauge  $h$  (a subset of  $i$ ) being equal to the total source supply.

The streamflow,  $X_v$ , at each river gauge  $v$  (a subset of  $i$ ) is equal to the sum of the flows at any upstream node  $i$  affecting said streamflow. These nodes include headwater inflow, river gauges, diversion, and surface return flow. The flow at each river gauge must be a non-negative value, and is calculated as follows:

$$X_v = \sum_i b_{i,v} * X_i, \forall v \tag{1}$$

where  $b_{i,v}$  is a vector of coefficients linking flow nodes  $i$  to river gauge nodes  $v$ . For non-contributing nodes, the coefficients have a value of 0, while those that increase the flow take a value of + 1, and those that reduce flow – 1.

Water diversions. During drought events, a restriction must be applied to surface water diversion to guarantee that the available flow at each diversion node  $d$  (a subset of  $i$ ) is greater than the diverted flow  $X_d$ :

$$X_d \leq \sum_i b_{i,d} * X_i, \forall d \tag{2}$$

where  $b_{i,d}$  is a vector of coefficients linking flow nodes,  $i$ , to diversion nodes,  $d$ . The right-hand-side term represents the sum of all contributions to flow at diversion nodes from upstream sources (headwater inflow, river gauge, diversion, and return flow). For non-contributing nodes, the  $b$  coefficients have a value of 0, nodes that increase the flow have a value of + 1, while those that reduce the flow have a value of – 1.

Water application. Water applied at each application node  $a$  (a subset of  $i$ ) is defined as follows:

$$X_a \leq \sum_d b_{d,a} * X_d, \forall a \tag{3}$$

where  $b_{d,a}$  is a vector of coefficients linking application nodes to diversions. For application nodes that withdraw water from available sources, the coefficients have a value of + 1, while for those that do not, the coefficients have a value of 0.

Total water applied for irrigation in each agricultural node is defined as follows:

$$X_a^{ag} = \sum_{j,k} b_{a,j,k} \left( \sum_d b_{d,a} * L_{d,j,k} \right), \forall a \tag{4}$$



According to Eq. (4), the irrigation water applied to crops,  $X_a^{ag}$ , is equal to the sum over crops ( $j$ ) and irrigation technologies ( $k$ ) of water application per ha,  $b_{a,j,k}$ , multiplied by the irrigated area,  $L_{d,j,k}$ , for each crop and irrigation technology.  $L_{d,j,k}$  is multiplied by a binary matrix,  $b_{d,a}$ , to set nodes.

Water consumption,  $X_c$ , at each consumption node,  $c$  (a subset of  $i$ ), is an empirically determined proportion of applied water,  $X_a$ . For irrigation, water consumption is the volume of water that goes to crop evapotranspiration (ET), whereas for urban uses it is the share of the urban water supply that is not returned through the sewer system. This use, which cannot have a negative value, is defined as follows:

$$X_c = \sum_a b_{a,c} * X_a, \forall c \tag{5}$$

where  $b_{a,c}$ , are coefficients denoting the share of the applied water that is consumed in each consumption node. For agricultural use nodes, water consumed is measured as

$$X_c^{ag} = \sum_{j,k} b_{c,j,k} * L_{c,j,k}, \forall c \tag{6}$$

According to Eq. (6), the irrigation water consumed,  $X_c^{ag}$ , is equal to the sum over crops ( $j$ ) and irrigation technologies ( $k$ ) of empirically estimated ET per ha,  $b_{c,j,k}$ , multiplied by the irrigated area,  $L_{c,j,k}$ , for each crop and irrigation technology.

Return flows,  $X_r$ , at each return flow node,  $r$  (a subset of  $i$ ), is the proportion of the water applied,  $X_a$ , that returns to the river system. Return flows are defined as follows:

$$X_r = \sum_a b_{a,r} * X_a, \forall r \tag{7}$$

where  $b_{a,r}$  are coefficients indicating the proportion of total water applied that is returned to the river system. For agricultural nodes, returns flows are defined as follows:

$$X_r^{ag} = \sum_{j,k} b_{r,j,k} \left( \sum_u b_{d,r} * L_{d,j,k} \right), \forall r \tag{8}$$

According to Eq. (8), the irrigation return flows,  $X_r^{ag}$ , are equal to the sum over crops ( $j$ ) and irrigation technologies ( $k$ ) of the empirically estimated return flows per ha,  $b_{r,j,k}$  multiplied by the irrigated area,  $L_{d,j,k}$ , for each crop and irrigation technology.  $L_{d,j,k}$  is multiplied by a binary matrix,  $b_{d,r}$ , to determine the nodes. Water applied must equal water consumed plus water returned.

The hydro-economic model has been calibrated by establishing a set of slack variables for each river reach, such that the model replicates the real observed flows. The slack variables represent unobserved inflows and outflows (e.g., groundwater flows, evaporation, and returns) and are calculated as the difference between the initially estimated flows and the flows measured at the gauge points. By including these variables in the model, the mass balance can be balanced.

### 3.2. Economic component

The economic component consists of an optimisation model for agricultural value. The agricultural activity of the basin has been divided into ten Irrigation Demand Areas (IDAs) based on the Irrigation Zones defined by the hydrological network according to current supply infrastructure as reported by the RBA (CHG. Confederación Hidrográfica del Guadalquivir, 2021). Farmers' private gross margin on crop production subject to technical and resource constraints has been specifically determined for each IDA, that is our decision unit. In the model, it is assumed that factor and product prices are constant, while yield functions decrease linearly with crop area expansion (see Eq. (15) below). A perennial land-fallowing penalty has been included in the objective function, to quantify the possible future yield losses if farmers decide to fallow perennial land. The optimisation problem is formulated as follows:

$$Max \quad TGM^{ag} = \sum_{d,j,k} GM_{d,j,k}^{ag} * L_{d,j,k} - Pty \tag{9}$$

where the variable to maximise,  $TGM^{ag}$ , is the total gross margin generated by the agricultural sector on all irrigated areas in the basin.  $GM_{d,j,k}^{ag}$  is the gross margin achieved per hectare of crop  $j$  using irrigation technology  $k$  in the diversion node  $d$ .  $L_{d,j,k}$  is the irrigation area of crop  $j$  using irrigation technology  $k$  in the diversion node  $d$ , and  $Pty$  represents a perennial land fallowing penalty, indicating possible future yield losses if farmers decide to fallow perennial crop lands.

$$Pty = \sum_{d,per,k} [PT * AF_{d,per,k}] \tag{10}$$

Where  $per$  is the subset of  $j$  of perennial crops,  $PT$  is the penalty coefficient, and  $AF_{d,per,k}$  is the area of perennial crops fallowed in the diversion node  $d$ ,

subject to:

$$\sum_{j,k} L_{d,j,k}^{ag} \leq Tland_d, \forall d \tag{11}$$

$$X_d \leq Twater_d \tag{12}$$

$$[L_{d,per,k} + L_{d,per,k}^{IS}] \leq l_{d,per,k}, \forall d, per, k \tag{13}$$

Eq. (11) includes a land constraint, where the irrigated area variable at each node  $d$  cannot be greater than the observed area at that node,  $Tland_d$ . Eq. (12) links the farm activity optimisation model to the hydrological component by setting an available water constraint,  $Twater_d$ . Finally, Eq. (13) prevents the area allocated to normal and survival irrigation from exceeding the observed area of each perennial crop in the baseline scenario ( $l_{d,per,k}$ ).

Agricultural production is represented by 55 crops, while economic indicators are based on the Study of Costs and Incomes of Agricultural Farms (Ministry of Agriculture, Fisheries and Food, MAPA). Information on crop area is taken from the Statistical Yearbook (MAPA). To convert the administrative information (provincial scale) to hydrological IDAs, we have relied on the official Common Agricultural Policy crop declarations (municipality scale). Likewise, crop yield sourced from the Statistical Yearbook has been adapted using the Common Agricultural Policy Regionalisation Plan (county scale). Table 1 shows the sources of the main model parameters.

The gross margin per hectare  $GM_{d,j,k}^{ag}$  is given by Eq. (14):

$$GM_{d,j,k}^{ag} = P_j * Y_{d,j,k} - C_{d,j,k} \tag{14}$$

where  $P_j$  is the price of the crop  $j$ ,  $Y_{d,j,k}$  is the yield of crop  $j$  under irrigation technology  $k$ , in node  $d$ , and  $C_{d,j,k}$  are the variable costs of crop  $j$  under technology  $k$ , in node  $d$ .

Positive mathematical programming is used in the calibration of the crop model to obtain the observed water and land use solution in the baseline scenario (Howitt, 1995). The main advantage offered by PMP is its ability to produce smooth changes as a result of the implementation new drought management policies, while ensuring optimised results that match observed outcomes (Gohar and Cashman, 2016). The variant of PMP proposed by Dagnino and Ward (2012) is employed to calibrate the model, with the parameters being estimated for a linear yield function from first-order gross margin maximisation conditions. The yield function used (15) is a linear function with diminishing returns; it follows the Ricardian rent principle in which the rents that are used first are those with the highest yields and, therefore, the yield of a crop decreases as the scale of production increases.

$$Y_{ijk} = B_{0,ijk} + B_{1,ijk} * L_{d,j,k} \tag{15}$$

Urban and industrial water use has been calculated using the RBA database (CHG. Confederación Hidrográfica del Guadalquivir, 2021), and defined as a constant parameter in the model both for supply and return flows.

#### 4. Drought adaptation and water policy scenarios

##### 4.1. Baseline scenario

The hydro-economic model is employed to analyse the adaptive capacity of the Guadalquivir basin to situations of severe water scarcity. The baseline scenario represents the water flows recorded in the 2015/16 hydrological year, with an average rainfall of 532 mm (CHG. Confederación Hidrográfica del Guadalquivir, 2021). The mean annual rainfall in the basin from 1980 to 2010 is 573 mm, and ranges between 260 mm and 983 mm (standard deviation of 161 mm). The available water has been estimated to meet a "business as usual" situation, in which all system water demands can be met.

Table 2 shows the baseline cultivated area (total and per irrigation method), water use, and gross margins per basin sector in the baseline scenario. Under normal climatic conditions, the gross margin of the whole basin amounts to 1099 M EUR, the total agricultural water used is 3127 hm<sup>3</sup>, and irrigated crop land covers 856,429 ha, with 68 % of those crops being perennial, mainly olive

**Table 1**  
Main model parameters and their sources of information.

Indicator/variable	Description	Source
Water resource supply	Annual resources	Water Resources Management Plan (CHG. Confederación Hidrográfica del Guadalquivir, 2021)
Observed river flow	Water flow at selected locations (current, historical)	(CHG. Confederación Hidrográfica del Guadalquivir, 2022)
Water supply network	Network with abstraction points and allocated resources	Water Resources Management Plan (CHG. Confederación Hidrográfica del Guadalquivir, 2021)
Crop cost (NUTS2)	Study of Costs and Incomes of Agricultural Farms	MAPA (mean 2011–2018)
Crop area (NUTS3)	Statistical Yearbook & 1T Sheet	MAPA (2018)
Crop Yield (NUTS3)	Statistical Yearbook & CAP regionalisation plan	MAPA (mean 2011–2018)
Crop prices	Statistical Yearbook	MAPA (mean 2011–2018)

MAPA = Ministry of Agriculture, Fisheries and Food.

**Table 2**  
Irrigated land, water allocation, and gross margin under the baseline scenario.

Basin region	Crop land per irrig. technology (ha)				Water allocation (hm <sup>3</sup> ; %)		Gross margin (M EUR; %)	
	Flood	Sprinkler	Drip	Total				
Upper	21,623	1511	269,326	292,461	617	20%	206	19 %
Middle (RB)	2755	14,932	95,470	113,157	361	12 %	112	10 %
Middle (LB)	21,164	14,741	124,045	159,950	483	15 %	229	21 %
Lower	84,207	30,259	176,395	290,862	1666	53 %	551	50 %
Basin	129,750	61,444	665,236	856,429	3127	100 %	1099	100 %

RB = Right bank; LB = Left Bank.

Source: Own elaboration.

trees.

The financial outcomes of agricultural activity (gross margin) closely align with those of water use. The upper basin accounts for 20 % of the irrigation water used and 19 % of the gross margin of the whole basin. The middle and lower basin consume 28 % and 53 %, respectively, of the irrigation water used in the basin and account for 31 % and 50 % of the gross margin of the basin.

#### 4.2. Drought management scenarios

Hydrological drought occurs when stream flows and reservoir storage fall below normal levels. Basins with a high level of storage, such as the Guadalquivir basin, can cope with seasonal or annual droughts. Thus, simulation of multi-year droughts could be more relevant in this type of context. Guadalquivir basin is currently suffering a severe drought with 5 years below average precipitation that had impacted water reserves producing drastic reduction in water supply. Last severe drought occurred in the period 2005–2008, when precipitation decreased by 47.5 % (vs. average precipitation 1940–2004), resulting a reduction to irrigation quotas to 50 % of their water rights (Espinosa-Tasón et al., 2022). In addition, climate change scenarios projected by CEDEX (Centro de Estudios y Experimentación de Obras Públicas) (2012) estimate impacts in the form of an average reduction in water resources of 36 % for the Guadalquivir basin, with an increase in the frequency of droughts as the 21st century progresses. This study aims to analyse the effect of alternative management policies and the adaptative capacity of the basin to a prolonged period of severe drought. Therefore, based on the most pessimistic forecasts of CEDEX (Centro de Estudios y Experimentación de Obras Públicas) (2012), a single event of water scarcity scenario is proposed with a 40 % reduction in water available in the basin compared to the baseline scenario. Several alternative or complementary water policy measures will be studied: a) quotas (proportional allocation), b) efficiency improvement, c) water reallocation, and d) pricing (water rates). A management scenario is defined as a collection of measures intended to contribute to drought adaptation. The four alternative management scenarios are:

- **Drought Management Protocol (DMP).** The application of the DMP requires that the allocation of water to urban areas (higher priority use) and minimum environmental flows are maintained (see current DMP at [www.chguadalquivir.es/plan-de-sequia-vigente](http://www.chguadalquivir.es/plan-de-sequia-vigente)). Therefore, faced with a hypothetical 40 % reduction in water availability, agricultural water allocations should be reduced by 35 % to meet urban demand and comply with environmental flow constraints. In such a scenario, farmers' response would be to allocate water to crops that maximise their gross margins, while ensuring that perennial crops receive the minimum amount of water needed to guarantee their survival. Survival irrigation implies a minimum annual allocation of 600 m<sup>3</sup>/ha for olive trees and a 50 % reduction of the baseline application for almond orchards with a water productivity of 0.25 kg/m<sup>3</sup> (Moldero et al., 2021). While olive trees may be managed with lower doses, the income would not cover the fixed cost of irrigated orchards.
- **Increased Efficiency.** This scenario combines the proportional allocation of the DMP with institutional and farm-level adaptation measures that lead to an increase in water-use efficiency estimated at 5 % over current levels. This improvement would result in higher water use at the farm level and a decrease in return flows of 5 %.
- **Optimal Allocation.** This scenario does not follow the DMP and instead assumes that the system freely allocates water resources to maximise the total gross economic value of the basin. As such, this scenario does not involve the proportional rationing rule of the previous two, but it does maintain the efficiency improvement. It thus behaves similarly to a water market without transaction costs, trading water resources from low-value to high-value uses.
- **Water pricing.** Water pricing involves a increase in water rates, although this scenario also incorporates the drought conditions and irrigation efficiency improvement. In this scenario, the model is free to allocate the water resources released by the price increase so as to optimise the total gross margin. The rates will be set at a level that leads to a reduction in water use, similar to the DMP scenario. However, unlike the scenario with the proportional rationing rule, the decrease in water use in this case is caused by the pricing.

## 5. Results

Firstly, we present the distribution of land among the main crop groups per scenario and the water flows at each node per scenario, along with the results for irrigated land, water use and gross margin, followed by a detailed analysis per scenario. Results for the water pricing scenario refer to a water rate of 0.039 EUR/m<sup>3</sup> as this is the price level that achieves the amount of water savings closest to the



35 % reduction proposed in the DMP scenario.

Table 3 shows the main results for cultivated area, water consumed, and gross margin obtained in the simulated scenarios. The absolute figures and the percent of variation with respect to the baseline situation (average year-no drought) are shown for each one, providing a breakdown of the four sub-zones into which the basin has been divided. Fig. 4 shows the distribution of the different crops for the four simulated scenarios and the four basin zones.

Fig. 5 shows the water flows through each of the main gauges checked in the basin, listing the cubic hectometres per year in each simulated scenario and the percentage variation with respect to the baseline. The number in brackets for each gauge corresponds to the label in Fig. 1. Note that the water flowing through gauge no.9 (Alcalá de Río) equals the legally established minimum environmental flow in the Optimal Allocation and Water Pricing scenarios.

### 5.1. DMP scenario

Adaptation to water scarcity requires a 33 % decrease in irrigated cropland area. Farmers can apply survival irrigation to perennial crops to protect the plantation. This measure does not prevent economic losses in the current season, but it does prevent future losses that may be incurred due to the loss of the initial investment in the farm. Survival irrigation is particularly effective in the upper part of the basin, which is cultivated almost exclusively with perennial crops; survival irrigation provides farmers with a solution that prevents them from losing the investment in their farms. This farmer response results in 148,000 ha (Fig. 4) of perennial crops switched to survival irrigation (76 % in the upper basin). Perennial crop survival irrigation means that the loss of irrigated area in the upper zone is only 8 %, compared to around 25 % in the middle areas and 35 % in the lower area. Regarding the economic results, the upper basin again suffers the greatest losses compared to the baseline situation, due to the difficulty of changing crops in farms relying on perennial crops. Survival irrigation allows farmers to prevent future losses, but not in the current year (Table 3 and Fig. 4).

### 5.2. Increased efficiency scenario

In the Increased Efficiency scenario, the quantity of water used is the same as in the DMP scenario, but all the available water that is “saved” by the improvement of on-farm water-use efficiency is used by farmers to increase their gross margin. In the upper basin, the increase in available water allows 13,464 ha of olive and almond trees to go from survival irrigation to full irrigation, resulting in a 3 % increase in the gross margin obtained in the area with the same amount of water as in the DMP scenario. In the middle basin, this shift to full irrigation (mainly extensive winter crops) allows an increase of 1.4 % in the gross margin with respect to the DMP scenario. In the lower basin, there is an increase of 9147 ha of cultivated area (mainly wheat and rice) with respect to the previous scenario, using the same volume of water, which allows an improvement of 1 % in the gross margin of the area (Table 3 and Fig. 4).

A consequence of the improved water-use efficiency is the reduction of the water flows due to reduced return flows to the system. There is a 3 % reduction in the average water flow in the representative gauges in the basin compared to the DMP scenario. Nevertheless, Fig. 5 shows how in both scenarios, average water flows at control points (gauges) remain above the minimum legal level (295 % above the environmental flow, on average).

### 5.3. Optimal allocation scenario

The Optimal Allocation scenario removes the proportional allocation followed in the previous scenarios and allows the model to allocate the available resources to maximise the total basin gross margin. This simulation allocates 22 % more water to the upper basin, thereby increasing the gross margin by 22 M EUR with respect to the Increased Efficiency scenario in this area. As a consequence, there is a decrease of 9200 ha of irrigated area in the lower basin (mainly cereals and winter crops – wheat, oat, corn and sunflower), 5 % lower than the Increased Efficiency scenario. This shows that when the model optimises water use, it allocates more water to the upper

**Table 3**

Main outcomes by scenario and basin zone (absolute values and percentage with respect baseline).

		Upper basin	Middle (right bank)	Middle (left bank)	Lower basin	Total
<b>Irrigated land</b> (1000 ha; %)	<b>Baseline</b>	292	113	160	291	856
	<b>DMP</b>	267 (– 9 %)	81 (– 28 %)	122 (– 24 %)	190 (– 35 %)	660 (– 23 %)
	<b>Increased Efficiency</b>	268 (– 8 %)	84 (– 26 %)	124 (– 22 %)	199 (– 32 %)	676 (– 21 %)
	<b>Optimal Allocation</b>	275 (– 6 %)	85 (– 25 %)	124 (– 22 %)	190 (– 35 %)	673 (– 21 %)
	<b>Water Pricing</b>	274 (– 6 %)	84 (– 26 %)	124 (– 22 %)	183 (– 37 %)	666 (– 22 %)
<b>Water use</b> (hm <sup>3</sup> ; %)	<b>Baseline</b>	617	361	483	1666	3127
	<b>DMP</b>	401 (– 35 %)	235 (– 35 %)	314 (– 35 %)	1083 (– 35 %)	2032 (– 35 %)
	<b>Increased Efficiency</b>	401 (– 35 %)	235 (– 35 %)	314 (– 35 %)	1083 (– 35 %)	2032 (– 35 %)
	<b>Optimal Allocation</b>	490 (– 20 %)	237 (– 34 %)	315 (– 35 %)	1098 (– 34 %)	2140 (– 32 %)
	<b>Water Pricing</b>	489 (– 21 %)	234 (– 35 %)	315 (– 35 %)	993 (– 40 %)	2030 (– 35 %)
<b>Gross margin</b> (M EUR; %)	<b>Baseline</b>	206	112	229	551	1099
	<b>DMP</b>	173 (– 16 %)	104 (– 8 %)	216 (– 6 %)	523 (– 5 %)	1015 (– 8 %)
	<b>Increased Efficiency</b>	180 (– 13 %)	105 (– 6 %)	218 (– 5 %)	528 (– 4 %)	1032 (– 6 %)
	<b>Optimal Allocation</b>	201 (– 3 %)	106 (– 6 %)	219 (– 5 %)	521 (– 5 %)	1047 (– 5 %)
	<b>Water Pricing</b>	182 (– 12 %)	96 (– 14 %)	206 (– 10 %)	480 (– 13 %)	965 (– 12 %)

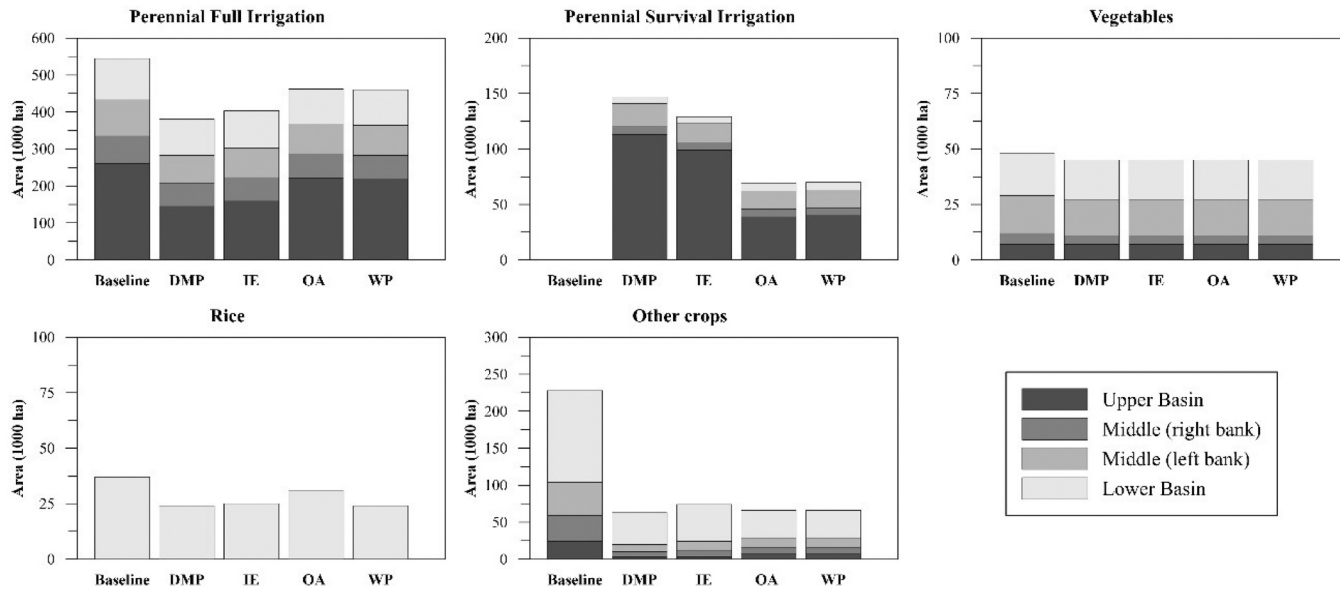


Fig. 4. Main crop groups' pattern according to the scenarios. Note: IE – Increased Efficiency; OA – Optimal Allocation; WP – Water Pricing.

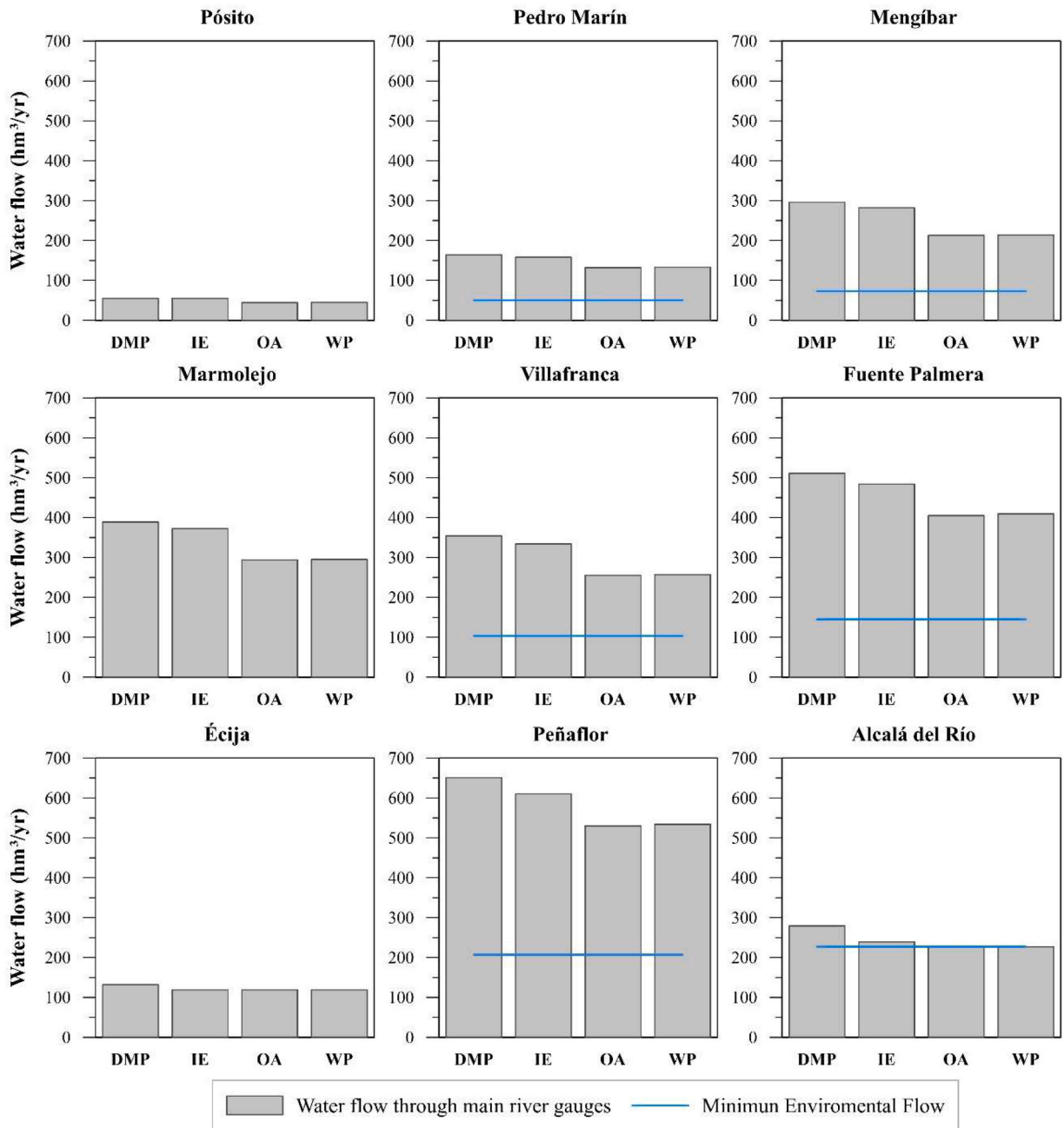


Fig. 5. Water flow through main river gauges and Minimum environmental flows. Note: IE – Increased Efficiency; OA – Optimal Allocation; WP – Water Pricing=.

part of the basin to maximise the number of crops returned to full irrigation after using survival irrigation. A total of 59,618 ha of olive and almond trees return to full irrigation in this scenario. The improvement in gross margin achieved in the upper basin is partly offset by the loss of 7 M EUR of gross margin in the lower basin (Table 3 and Fig. 4).

This management option allocates more water to the IDAs whose irrigation methods are more efficient, thereby reducing irrigation return flows and resulting in an 8 % average reduction in river flow with respect to the Increased Efficiency scenario (Fig. 5).

Fig. 6 shows a gross margin sensitivity analysis under the Optimal Allocation scenario to stepwise environmental flow reductions in the Alcalá del Río gauge. Reductions in the environmental flow result in increments in the gross margin of the basin. The gross margin can be increased by up to 16.8 M EUR if the environmental flow is reduced to zero. This implies a shift in water use from the rice cultivating zone in Lower Basin, with a marginal water productivity of 0.06 €/m<sup>3</sup>, to Middle and Upper Basin, which have higher productivities. However, this short-term adjustment would be different in the long term if an increase in the most efficient crops were

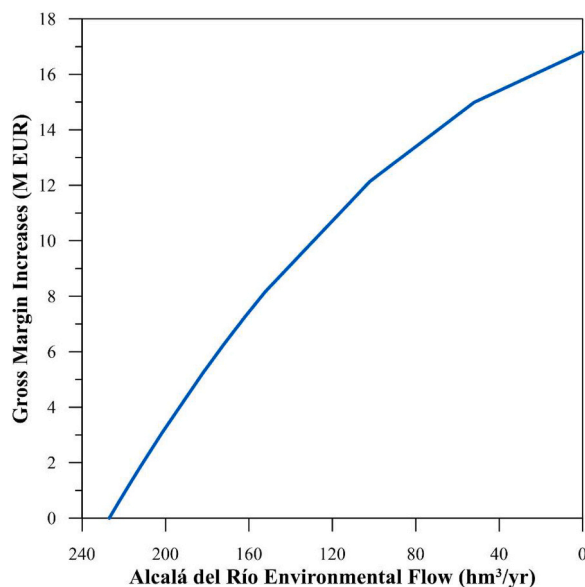


Fig. 6. Total gross margin increase vs. environmental flow decrease in Alcalá del Río.

allowed in upstream areas.

#### 5.4. Water pricing scenario

If the RBA decided to use water pricing as an instrument to encourage water savings (a solution favoured by some academics and environmental groups), a rate of 0.039 EUR/m<sup>3</sup> would be necessary to achieve an amount of water savings like the 35 % proposed in the DMP scenario. The use of water pricing affects farmers' income, who suffer a gross margin loss of 12 % (vs. baseline).

Higher water pricing impacts low value crops (e.g., rice, cotton, maize), while perennials and horticultural crops can accommodate a rise in water rates due to their high gross margin per hectare.

The total revenue obtained by the authorities for water supply (volume of water used multiplied by price) is lower than the gross margin loss resulting from the abandonment of cultivated land in the sector. A water tariff of 0.039€/m<sup>3</sup> generates revenues of 79 M EUR, while farmers gross margin decreases 134 M EUR, thereby resulting in an overall welfare loss. In this scenario, there is a 11 % average reduction in water flows with respect to the DMP scenario (Fig. 5).

In terms of gauge measures, this scenario is like that of Optimal Allocation: water resources are allocated to the farms with the highest water-use productivity and water-use efficiency (perennials, drip-irrigated crops), reducing return flows to the basin.

All policies simulated in the scenarios satisfy the minimum environmental flow constraints established by the RBA for the gauges of the main regulation facilities (CHG. Confederación Hidrográfica del Guadalquivir, 2021). The gauge at the Alcalá del Río dam (last gauge before the estuary) is binding all the system with 227 hm<sup>3</sup>/y under the Optimal Allocation and Water Pricing scenarios. The environmental constraint of the last river gauge prevents the allocation of more water resources to higher-value crops upstream and ensures that part of the rice (low-value crop) is kept under cultivation since this is compatible with the minimum flow in transitional waters (from Alcalá del Río gauge to the ocean).

## 6. Discussion

The hydro-economic model presented here provides insight into water-scarce, overallocated "closed" basins, which have little room for manoeuvre in terms of policy measures to cope with a drought event. Results of this analysis show that increasing water-use efficiency implies a reduction in return flows that should be accounted for when designing water-saving policies. The impact of market-based water reallocation (optimal allocation) would have territorial effects as water moves from commodity production regions to more competitive areas, meaning higher-value crops capture more resources than commodities and low-value crops. Another conclusion that emerges from our model is the impact of recent crop transformations, characterised by an increase in perennials and high-value crops (e.g., olive, almonds, citrus) at the expense of herbaceous commodity crops (e.g., cotton, maize), which results in an agricultural system that is highly vulnerable to drought and offers little flexibility when it comes to policy options. These are general conclusions that go beyond our specific case study; indeed, a similar result is reported by Mall and Herman (2019).

Our model is used to test some policy alternatives (scenarios) for reducing economic losses during droughts. A feature they all have in common is that the minimum environmental flow constraint is binding, meaning that environmental flow constraints are impacting farmers' income. This can be observed in Fig. 5, where the alternatives involving the free reallocation of water rights (Optimal Allocation and Water Pricing scenarios) are bounded by the minimum flow constraint at the Alcalá del Río gauge, which puts limits on

the reallocation of water to economic uses upstream. The Alcalá del Río gauge is the last one before the estuary, and the 80 km from this gauge to the sea requires a minimum flow to maintain low salinity and good environmental conditions. As stated above, in the last two scenarios, the environmental flow constraint in Alcalá del Río limits the transfer from low-value crops (rice) to higher-value crops in middle and upper regions. Relaxing this environmental flow constraint in the short term would lead to increases in the gross margin of up to 16.8 M EUR.

Rightnar and Dinar (2020) apply financial bankruptcy rules to water allocation in the case of scarcity and find that proportional allocation is less conducive to regional welfare, although it presents a more politically feasible and robust option. These bankruptcy rules are also described in the study of Gómez-Limón et al. (2020), which shows that other "symmetric" allocation methods, other than proportional allocation, such as the equal gains method (also called uniform gains method) or the equal losses method, can improve water allocation without the need for asymmetric methods that rely on some form of priority allocation.

The Water Pricing scenario has a greater impact on the gross margin (82 % compared to the baseline scenario) than other scenarios based on quotas (DMP and Increased Efficiency with 93 % and 94 % compared to the baseline scenario, respectively). This feeds into the long-standing debate on quotas vs. pricing instruments (Molle, 2009; Parrado et al., 2020). In Spain, drought management protocol measures are linked to different stages of drought indicators (pre-alert, alert, and emergency). The results of the model show that policies based on water pricing would be more advisable during the pre-alert and alert periods, applied as a proactive approach to drought management. Applying price increases at the stage of a drought when users are already affected by water scarcity has no effect due to the low demand elasticity of deficit irrigated crops in the context explained in Expósito and Berbel (2016). It should also be mentioned that most of the basin is irrigated using pressurised networks, meaning energy is an important cost component. This context is consistent with the evolution observed at Spanish national level (Espinosa-Tasón et al., 2020) describing an increase of energy consumption for irrigation from 0.03 kWh/m<sup>3</sup> (1960) to 0.17 kWh/m<sup>3</sup> (2017), explained by the energy consumption linked to modernization, where energy cost accounts for 30–50 % of total operating costs in Water User Associations (Berbel et al., 2019). The behavioural impact of this component is relevant as the energy cost is linked directly to volumetric water consumption, and can therefore lead to water-saving behaviour compared with pre-modernisation where water rates were applied per-hectare with no volumetric component (Pronti and Berbel, 2023). Our model assumes that volumetric pricing is applied in most of the basin. This affects water demand, as the flat rate per area basis has no direct impact on savings (Pronti and Berbel, 2023). Optimal Allocation and Water Pricing policies entail a shift in water rights away from historical holders (commodities) to the most dynamic perennial farming entrepreneurs. This is illustrated by the fact that the upper region maintains 83–82 % of water use while lower regions only use 57–55 % compared to the baseline scenario (Fig. 4). The water saving in the lower basin is mainly due to the partial halt in rice cultivation while other crops in the lower basin (perennials, vegetables) are maintained.

According to our model simulations, responses to future water scarcity may require flexibility and reallocation. The transfer of water rights between regions can either be carried out by buying back water rights to compensate farmers who stop irrigating, or it can be facilitated by trading water rights, as in the Australian market system. The Spanish legislative framework may present a barrier to the implementation of an extensive market (Berbel and Esteban, 2019; Palomo-Hierro et al., 2022). Water trading has been shown to provide an effective tool for positive water allocation outcomes at both the level of the individual user and at the social and environmental levels (Grafton and Wheeler, 2018; Nauges et al., 2016). Implementing water trading without the full implementation of the necessary laws, institutional capacity, and administrative systems in this basin will only increase transaction costs. Moreover, it will fuel scepticism regarding the benefits of the market system. One way to lower transaction costs and boost water transactions involves the establishment of a water bank acting as an intermediary between buyers and sellers, regardless of whether those transfers are temporary (annual water allocation) or permanent (water rights) (Montilla-López et al., 2018). In cases where environmental flows are not met, water banks can also act by buying back temporary or permanent rights from agriculture (Gutiérrez-Martín et al., 2020).

There is no work on previous hydro-economic modelling in the Guadalquivir basin at the basin scale. Reça et al. (2001a) and Reça et al. (2001b) develop a hydro economic model for the Bembezar irrigation district and Hervás-Gámez and Delgado-Ramos (2020) for the Genil subbasin focusing mainly on the optimal irrigation quantities for crops and the supply capacity of the network in different climatic and economic scenarios. Our results are consistent with the findings of several previous hydro-economic analyses applied to Mediterranean river basins (Baccour et al., 2021; Escrivá-Bou et al., 2017; Frija et al., 2021; Gohar et al., 2021; Kahil et al., 2015), indicating that a combination of water trading and irrigation efficiency improvements could help improve the sustainability of water use in those river basins. However, the level of efficiency of those policy interventions varies across the different studies and depends on the characteristics of the basin, including socio-economic conditions, crop mix, spatial distribution of uses, sources of water, and infrastructure. For the Guadalquivir basin, our results show that water trading could potentially constitute a valuable instrument for adaptation to water scarcity given the importance of perennial crops in the upstream area of the basin and the possibility of reallocating water from annual to perennial crops.

Regarding the methodology applied, it should be noted that other PMP techniques can also be used for the calibration and simulation of the economic component. The advantage of the Dagnino and Ward (2012) approach is that it skips the first stage of calibration, meaning there are no marginal crops that lack a shadow price. However, this methodology does not allow the addition of crops that were not observed in the reference year, even if they have no quadratic component in the yield function. If new crop alternatives are to be added, the standard approximation of Howitt (1995) can be used. Our methodology includes a penalty for future yield losses due to the fallowing of land dedicated to irrigated perennial crops. Connor et al. (2009) performed a similar analysis by modelling the response of crop yields to water in the lower Murray-Darling basin in Australia.



## 7. Concluding remarks

This work has added to the body of knowledge on the water resource management of the Guadalquivir basin, which is representative of Mediterranean systems and constitutes one of the most important water basins in southern Europe. The study has involved analysing the availability of water and the capacity of the various agricultural activities in the Guadalquivir basin to adapt to a severe drought situation. To that end, a hydro-economic model has been developed to conduct an integrated analysis of different water allocation policies in the basin.

The results indicate that the economic uses (agriculture) are highly vulnerable to a reduction in the basin's water resources. The fact that agricultural activity in the basin is largely based on perennial crops, such as olive, almond, and citrus, limits the capacity to deal with water scarcity and droughts. This reliance on perennial crops makes it harder to adapt the system to drought, which requires flexible management mechanisms to optimise the use of the water consumed. Perennials (trees) account for more than 80 % of the cultivated area in the upper basin, which makes agriculture highly inflexible and does not respond well to proportional allocation management scenarios based on historical water rights (as proposed by the current DMP).

The Optimal Allocation scenario assigns more water resources to the upper basin, where activity is overwhelmingly based on perennial crops, thereby preventing future losses caused by the abandonment of this type of crop and consequent loss of the initial investment. The transfer of rights between farmers and between locations can be carried out either with the support of market instruments that compensate herbaceous crop farmers for their losses, or by using economic compensatory measures. Nevertheless, it is not only the question of economic efficiency that should be considered, but also that of social equity to attain a fair distribution of water rights.

The model has been used for the analysis of different water policies in an arid and semiarid basin in southern Spain. The Guadalquivir basin is a good case to study policies related to water scarcity and drought impacts. This is a common situation in many arid and semi-arid basins around the world. The hydro-economic model proposed here can be used in any basin in the world to help decision-makers address problems related to water scarcity.

We have tried to build a simplified digital twin of the complex Guadalquivir River basin by developing a hydro-economic model for a single drought event. It enables the assessment of water management policies in simulated scenarios, is user-friendly, includes economic instruments to analyse water demand, and the option of deficit irrigation in perennial crops. On the other hand, reservoir stocks have not been included, the time scale is annual and multiannual simulations are not available yet. Future research should incorporate a more complex hydrological model that includes an interannual and seasonal analysis, studying the effect of drought across different months of the year and the buffering effect of reservoir storage, use of non-conventional water sources, and other uses of water, and jointly consider quantity and quality aspects.

## CrediT authorship contribution statement

**Javier Martínez-Dalmau:** Investigation, Methodology, Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Carlos Gutiérrez-Martín:** Investigation, Conceptualization, Writing – review & editing. **Taher Kahil:** Methodology, Conceptualization, Visualization, Supervision, Writing – review & editing. **Julio Berbel:** Conceptualization, Supervision, Writing – review & editing.

## 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.

## Acknowledgement

This research has been financed by projects PRIMA-BONEX (Grant no. 2141), PRIMA-GOTHAM (Grant. no. 301011), BHYEM (PID2019-107127RB-I0), SEKECO (1263831-R) and is part of the project e-MOHICAN (TED2021-131066B-I00), funded by MCIN/AEI/10.13039/501100011033 and European Commission "NextGenerationEU"/PRTR.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ejrh.2023.101444](https://doi.org/10.1016/j.ejrh.2023.101444).

## References

- Arias Montevechio, E., Crispin Cunya, M., Fernández Jorquera, F., Rendon, E., Vásquez-Lavin, F., Stehr, A., Ponce Oliva, R.D., 2023. Traditional crops and climate change adaptation: insights from the Andean agricultural sector. *Clim. Dev.* 1–15. <https://doi.org/10.1080/17565529.2022.2151307>.
- Baccour, S., Albiac, J., Kahil, T., Esteban, E., Crespo, D., Dinar, A., 2021. Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain. *J. Clean. Prod.* 327, 129459. <https://doi.org/10.1016/j.jclepro.2021.129459>.
- Bajaj, A., Singh, S.P., Nayak, D., 2022. Impact of water markets on equity and efficiency in irrigation water use: a systematic review and meta-analysis. *Agric. Water Manag.* 259, 107182. <https://doi.org/10.1016/j.agwat.2021.107182>.
- Bekchanov, M., Sood, A., Pinto, A., Jeuland, M., 2017. Systematic review of water-economy modeling applications. *J. Water Resour. Plan. Manag.* 143 (8), 04017037. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000793](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000793).
- Berbel, J., Esteban, E., 2019. Droughts as a catalyst for water policy change. Analysis of Spain, Australia (MDB), and California. *Glob. Environ. Change* 58, 101969. <https://doi.org/10.1016/j.gloenvcha.2019.101969>.
- 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.
- Berbel, J., Mateos, L., 2014. Does investment in irrigation technology necessarily generate rebound effects? A simulation analysis based on an agro-economic model. *Agric. Syst.* 128, 25–34. <https://doi.org/10.1016/j.agsy.2014.04.002>.
- Berbel, J., Expósito, A., Gutiérrez-Martín, C., Mateos, L., 2019. Effects of the irrigation modernization in Spain 2002–2015. *Water Resour. Manag.* 33 (5), 1835–1849. <https://doi.org/10.1007/s11269-019-02215-w>.
- Bhaduri, A., Dionisio Pérez-Blanco, C., Rey, D., Iftekhar, S., Kaushik, A., Escrivá-Bou, A., Calatrava, J., Adamson, D., Palomo-Hierro, S., Jones, K., Asbjornsen, H., Altamirano, M.A., Lopez-Gunn, E., Polyakov, M., Bekchanov, M., 2021. Economics of water security. In: Bogardi, J.J., Gupta, J., Nandalal, K.D.W., Salamé, L., van Nooijen, R.R.P., Kumar, N., Tingsanchali, T., Bhaduri, A., Kolechikina, A.G. (Eds.), *Handbook of Water Resources Management: Discourses, Concepts and Examples*. Springer International Publishing, Cham, pp. 273–327. [https://doi.org/10.1007/978-3-030-60147-8\\_10](https://doi.org/10.1007/978-3-030-60147-8_10).
- CEDEX (Centro de Estudios y Experimentación de Obras Públicas), 2012. Estudio de los impactos del cambio climático en los recursos hídricos y las masas de agua, Ficha 1: Evaluación del impacto del cambio climático en los recursos hídricos en régimen natural, Centro de Estudios Hidrográficos, Madrid.
- CHG. Confederación Hidrográfica del Guadalquivir, 2021. Plan hidrológico de la demarcación hidrográfica del Guadalquivir (2015–2021), Sevilla.
- CHG. Confederación Hidrográfica del Guadalquivir, 2022. Sistema automático de información hidrográfica del Guadalquivir.
- Connor, J., Schwabe, K., King, D., Kaczan, D., Kirby, M., 2009. Impacts of climate change on lower Murray irrigation\*. *Aust. J. Agric. Resour. Econ.* 53 (3), 437–456. <https://doi.org/10.1111/j.1467-8489.2009.00460.x>.
- Dagnino, M., Ward, F.A., 2012. Economics of agricultural water conservation: empirical analysis and policy implications. *Int. J. Water Resour. Dev.* 28 (4), 577–600. <https://doi.org/10.1080/07900627.2012.665801>.
- Eamen, L., Brouwer, R., Razavi, S., 2022. Comparing the applicability of hydro-economic modelling approaches for large-scale decision-making in multi-sectoral and multi-regional river basins. *Environ. Model. Softw.*, 105385. <https://doi.org/10.1016/j.envsoft.2022.105385>.
- Escriva-Bou, A., Pulido-Velazquez, M., Pulido-Velazquez, D., 2017. Economic value of climate change adaptation strategies for water management in Spain's Júcar basin. *J. Water Resour. Plan. Manag.* 143 (5), 04017005. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000735](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000735).
- Espinosa-Tasón, J., Berbel, J., Gutiérrez-Martín, C., 2020. Energized water: evolution of water-energy nexus in the Spanish irrigated agriculture, 1950–2017. *Agric. Water Manag.* 233, 106073. <https://doi.org/10.1016/j.agwat.2020.106073>.
- Espinosa-Tasón, J., Berbel, J., Gutiérrez-Martín, C., Musolino, D.A., 2022. Socioeconomic impact of 2005–2008 drought in Andalusian agriculture. *Sci. Total Environ.* 826, 154148. <https://doi.org/10.1016/j.scitotenv.2022.154148>.
- European Commission, 2000. Water Framework Directive. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Off. J. Law* 327 (22/12/2000), 0001–0073.
- European Commission, 2019. European Overview – River Basin Management Plans. SWD(2019) 30 final, European Commission.
- European Environment Agency, 2019. Climate change adaptation in the agriculture sector in Europe.
- Expósito, A., Berbel, J., 2016. Why is water pricing ineffective for deficit irrigation schemes? A case study in southern Spain. *Water Resour. Manag.* 31 (3), 1047–1059. <https://doi.org/10.1007/s11269-016-1563-8>.
- Expósito, A., Berbel, J., 2019. Drivers of irrigation water productivity and basin closure process: analysis of the Guadalquivir river basin (Spain). *Water Resour. Manag.* 33 (4), 1439–1450. <https://doi.org/10.1007/s11269-018-2170-7>.
- Expósito, A., Beier, F., Berbel, J., 2020. Hydro-economic modelling for water-policy assessment under climate change at a river basin scale: a review. *Water* 12 (6), 1559. <https://doi.org/10.3390/w12061559>.
- Frija, A., Oulmane, A., Chebil, A., Makhlof, M., 2021. Socio-economic implications and potential structural adaptations of the tunisian agricultural sector to climate change. *Agron* 11 (11), 2112. <https://doi.org/10.3390/agronomy11112112>.
- Gohar, A.A., Cashman, A., 2016. A methodology to assess the impact of climate variability and change on water resources, food security and economic welfare. *Agric. Syst.* 147, 51–64. <https://doi.org/10.1016/j.agsy.2016.05.008>.
- Gohar, A.A., Cashman, A., El-bardisy, H.A.E.H., 2021. Modeling the impacts of water-land allocation alternatives on food security and agricultural livelihoods in Egypt: welfare analysis approach. *Environ. Dev.* 39, 100650. <https://doi.org/10.1016/j.envdev.2021.100650>.
- Gómez-Limón, J.A., Gutiérrez-Martín, C., Montilla-López, N.M., 2020. Agricultural water allocation under cyclical scarcity: the role of priority water rights. *Water* 12 (6), 1835. <https://doi.org/10.3390/w12061835>.
- Grafton, R.Q., Wheeler, S.A., 2018. Economics of water recovery in the Murray-Darling Basin, Australia. *Annu. Rev. Resour. Econ.* 10 (1), 487–510. <https://doi.org/10.1146/annurev-resource-100517-023039>.
- Grüner, G., Boëdec, H.L., 2019. Navigating pathways to reform water policies in agriculture. *Annu. Rev. Resour. Econ.* 10 (1), 487–510. <https://doi.org/10.1787/906cea2b-en>.
- Gutiérrez-Martín, C., Gómez-Limón, J.A., Montilla-López, N.M., 2020. Self-financed water bank for resource reallocation to the environment and within the agricultural sector. *Ecol. Econ.* 169, 106493. <https://doi.org/10.1016/j.ecolecon.2019.106493>.
- Harou, J.J., Pulido-Velazquez, M., Rosenberg, D.E., Medellín-Azuara, J., Lund, J.R., Howitt, R.E., 2009. Hydro-economic models: concepts, design, applications, and future prospects. *J. Hydrol.* 375 (3), 627–643. <https://doi.org/10.1016/j.jhydrol.2009.06.037>.
- Hervás-Gómez, C., Delgado-Ramos, F., 2019. Drought management planning policy: from Europe to Spain. *Sustainability* 11 (7), 1862. <https://doi.org/10.3390/su11071862>.
- Hervás-Gómez, C., Delgado-Ramos, F., 2020. Cross-subsidies between water users in Spain: the Guadalquivir River Basin case. *Water Resour. Manag.* 34 (15), 4577–4591. <https://doi.org/10.1007/s11269-020-02675-5>.
- Howitt, R.E., 1995. Positive mathematical programming. *Am. J. Agric. Econ.* 77 (2), 329–342. <https://doi.org/10.2307/1243543>.
- Kahil, T., Dinar, A., Albiac, J., 2015. Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. *J. Hydrol.* 522, 95–109. <https://doi.org/10.1016/j.jhydrol.2014.12.042>.
- Kahil, T., Ward, F.A., Albiac, J., Eggleston, J., Sanz, D., 2016. Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management. *J. Hydrol.* 539, 510–524. <https://doi.org/10.1016/j.jhydrol.2016.05.057>.
- Kahil, T., Parkinson, S., Satoh, Y., Greve, P., Burek, P., Veldkamp, T.I.E., Burtcher, R., Byers, E., Djilali, N., Fischer, G., Krey, V., Langan, S., Riahi, K., Tramberend, S., Wada, Y., 2018. A continental-scale hydroeconomic model for integrating water-energy-land nexus solutions. *Water Resour. Res.* 54 (10), 7511–7533. <https://doi.org/10.1029/2017WR022478>.
- Leclère, D., Jayet, P.-A., de Noblet-Ducoudré, N., 2013. Farm-level autonomous adaptation of european agricultural supply to climate change. *Ecol. Econ.* 87, 1–14. <https://doi.org/10.1016/j.ecolecon.2012.11.010>.
- Liu, W., Sun, F., Lim, W.H., Zhang, J., Wang, H., Shioyama, H., Zhang, Y., 2018. Global drought and severe drought-affected populations in 1.5 and 2 °C warmer worlds. *Earth Syst. Dyn.* 9 (1), 267–283. <https://doi.org/10.5194/esd-9-267-2018>.

- Mall, N.K., Herman, J.D., 2019. Water shortage risks from perennial crop expansion in California's Central Valley. *Environ. Res. Lett.* 14 (10), 104014 <https://doi.org/10.1088/1748-9326/ab4035>.
- Medellín-Azuara, J., Harou, J.J., Howitt, R.E., 2010. Estimating economic value of agricultural water under changing conditions and the effects of spatial aggregation. *Sci. Total Environ.* 408 (23), 5639–5648. <https://doi.org/10.1016/j.scitotenv.2009.08.013>.
- MITECO. Ministerio para la Transición Ecológica y el Reto Demográfico, 2020. Libro Verde de la Gobernanza del Agua. Ministerio para la Transición Ecológica y el Reto Demográfico, Madrid.
- Moldero, D., López-Bernal, Á., Testi, L., Lorite, I.J., Fereres, E., Orgaz, F., 2021. Long-term almond yield response to deficit irrigation. *Irrig. Sci.* 39 (4), 409–420. <https://doi.org/10.1007/s00271-021-00720-8>.
- Molle, F., 2009. Water scarcity, prices and quotas: a review of evidence on irrigation volumetric pricing. *Irrig. Drain. Syst.* 23 (1), 43–58. <https://doi.org/10.1007/s10795-009-9065-y>.
- Molle, F., Wester, P., Hirsch, P., 2010. River basin closure: processes, implications and responses. *Agric. Water Manag.* 97 (4), 569–577. <https://doi.org/10.1016/j.agwat.2009.01.004>.
- Montilla-López, N.M., Gutiérrez-Martín, C., Gómez-Limón, J.A., 2016. Water banks: what have we learnt from the international experience. *Water* 8 (10), 466. <https://doi.org/10.3390/w8100466>.
- Montilla-López, N.M., Gómez-Limón, J.A., Gutiérrez-Martín, C., 2018. Sharing a river: potential performance of a water bank for reallocating irrigation water. *Agric. Water Manag.* 200, 47–59. <https://doi.org/10.1016/j.agwat.2017.12.025>.
- Nauges, C., Wheeler, S.A., Zuo, A., 2016. Elicitation of irrigators' risk preferences from observed behaviour. *Aust. J. Agric. Resour. Econ.* 60 (3), 442–458. <https://doi.org/10.1111/1467-8489.12134>.
- OECD, 2015. Water Resources Allocation: Sharing Risks and Opportunities. OECD Studies on Water, Paris.
- Ortiz, J.P., Fernandez-Bou, A.S., Maskey, M., Rodríguez-Flores, J.M., Medellín-Azuara, J., Sandoval-Solis, S., Ermolieva, T., Kanavas, Z., Sahu, R.K., Wada, Y., Kahil, T., 2023. Hydro-economic modeling of water resources management challenges: current applications and future directions. *Water Econ. Policy*. <https://doi.org/10.1142/s2382624X23400039> (0ja): null).
- Palomo-Hierro, S., Gómez-Limón, J.A., Riesgo, L., 2015. Water markets in Spain: performance and challenges. *Water* 7 (2), 652–678. <https://doi.org/10.3390/w7020652>.
- Palomo-Hierro, S., Loch, A., Pérez-Blanco, C.D., 2022. Improving water markets in Spain: lesson-drawing from the Murray-Darling Basin in Australia. *Agric. Water Manag.* 259, 107224 <https://doi.org/10.1016/j.agwat.2021.107224>.
- 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 modeling 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., Hrast-Essenfelder, A., Perry, C., 2020. Irrigation technology and water conservation: a review of the theory and evidence. *Rev. Environ. Econ. Policy* 14 (2), 216–239. <https://doi.org/10.1093/reep/reaa004>.
- Pérez-Blanco, C.D., Parrado, R., Essenfelder, A.H., Bodoque, J., Gil-García, L., Gutiérrez-Martín, C., Ladera, J., Standardi, G., 2022. Assessing farmers' adaptation responses to water conservation policies through modular recursive hydro-micro-macro-economic modeling. *J. Clean. Prod.* 360, 132208 <https://doi.org/10.1016/j.jclepro.2022.132208>.
- Perry, C., Steduto, P., 2017. Does Improved Irrigation Technology Save Water? A Review of the Evidence. Food and Agriculture Organization of the United Nations, Cairo, 42, Cairo.
- Pronti, A., Berbel, J., 2023. The impact of volumetric water tariffs in irrigated agriculture in Northern Italy. *Environ. Impact Assess. Rev.* 98, 106922 <https://doi.org/10.1016/j.eiar.2022.106922>.
- Reca, J., Roldán, J., Alcaide, M., López, R., Camacho, E., 2001a. Optimisation model for water allocation in deficit irrigation systems: I. Description of the model. *Agric. Water Manag.* 48 (2), 103–116. [https://doi.org/10.1016/S0378-3774\(00\)00126-8](https://doi.org/10.1016/S0378-3774(00)00126-8).
- Reca, J., Roldán, J., Alcaide, M., López, R., Camacho, E., 2001b. Optimisation model for water allocation in deficit irrigation systems: II. Application to the Bémbezar irrigation system. *Agric. Water Manag.* 48 (2), 117–132. [https://doi.org/10.1016/S0378-3774\(00\)00127-X](https://doi.org/10.1016/S0378-3774(00)00127-X).
- Reidsma, P., Ewert, F., Lansink, A.O., Leemans, R., 2010. Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. *Eur. J. Agron.* 32 (1), 91–102. <https://doi.org/10.1016/j.eja.2009.06.003>.
- Ricart, S., Olcina, J., Rico, A.M., 2019. Evaluating public attitudes and farmers' beliefs towards climate change adaptation: awareness, perception, and populism at European level. *Land* 8 (1), 4. <https://doi.org/10.3390/land8010004>.
- Rightnar, J., Dinar, A., 2020. The welfare implications of bankruptcy allocation of the Colorado river water: the case of the Salton sea region. *Water Resour. Manag.* 34 (8), 2353–2370. <https://doi.org/10.1007/s11269-020-02552-1>.
- Sapino, F., Pérez-Blanco, C.D., Saiz-Santiago, P., 2022. A hydro-economic model to calculate the resource costs of agricultural water use and the economic and environmental impacts of their recovery. *Water Econ. Policy* 08 (04), 2240012. <https://doi.org/10.1142/s2382624X22400124>.
- Vichete, W.D., Mélo Júnior, A.V., Soares, G.A., 2023. A water allocation model for multiple uses based on a proposed hydro-economic method. *Water* 15 (6). <https://doi.org/10.3390/w15061170>.
- Ward, F.A., 2021. Hydroeconomic analysis to guide climate adaptation plans. *Front. Water* 3 (80). <https://doi.org/10.3389/frwa.2021.681475>.
- Ward, F.A., 2022. Enhancing climate resilience of irrigated agriculture: a review. *J. Environ. Manag.* 302, 114032 <https://doi.org/10.1016/j.jenvman.2021.114032>.