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Integrated assessment of resilience to drought by coupling hydro-economic and macroeconomic models

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ABSTRACT

Hydro-economic models combine biophysical and socioeconomic variables and are tools that inform decision-making related to water resources planning. This study analyses the coupling of a hydro-economic model of the Guadalquivir River Basin (GRB) in southern Spain with a Computable General Equilibrium (CGE) macroeconomic model, applied to a drought situation and different water management policy scenarios. The two models are interconnected through changes in land use and crop prices. Results show that when the macroeconomic price effects are included in the analysis, there is an improvement in producers' gross margin across all scenarios, with some scenarios (Drought Management Plan, Increased Efficiency, and Optimal Allocation) even registering a higher gross margin for irrigated land than the baseline scenario without drought (+4.5 %; +3.2 % and +2.6 %, respectively). However, this increase is not uniform across all crops; rather, the rise in gross margin for certain crops contributes to an overall average producers' gain throughout the entire basin. Thus, by considering the price effect, the market equilibrium generated in the coupled model attenuates the microeconomic impact of a drought for producers. This improvement in producer surplus translates into a worsening of consumer surplus between 33 and 67 M EUR depending on the scenario. Finally, the Optimal Allocation scenario is the one in which welfare decreases the least (5 M EUR).

1. Introduction and objectives

Freshwater is becoming an increasingly scarce natural asset in numerous regions around the world. Paralleling the growth of the world population and the rising wealth of nations, the ever-increasing global demand for water is leading to higher consumption rates (Wada et al., 2016). As a consequence, there has been a noticeable surge in worldwide water withdrawal and utilization in recent decades (Gómez-Limón et al., 2020a). The situation is particularly acute in Mediterranean and semi-arid zones, which are characterized by persistent water scarcity and periods of drought that aggravate water shortages. During these cycles of water scarcity, the demand significantly surpasses the available water resources, intensifying the competition for resource utilization (Gómez-Limón et al., 2020b). Additionally, in alignment with climate change projections (IPCC, 2018), these regions anticipate more frequent and intense drought episodes. When water availability falls short of meeting demand, water resources must be efficiently allocated among users according to their needs. This challenge becomes particularly daunting during drought periods, when the disparity between supply and demand reaches its peak (OECD, 2015).

Within this context, traditional supply-side approaches, such as constructing new infrastructure like reservoirs and waterways to meet the growing human demand for water, have become impractical in regions with well-established water economies. In these areas, it is not economically feasible to increase supply and there is particular pressure to preserve water-associated ecosystems, resulting in the basin closure (Molle et al., 2010). New demands can only be accommodated by reducing existing ones via demand-side policies such as water quotas, pricing, or water markets, or incentives for water-saving technologies (Gómez et al., 2017; Lago et al., 2015). Implementing demand-side policies effectively will limit users' options and prompt adaptive reactions that have significant consequences for the economy, especially

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in the agricultural sector. This sector is one of the largest consumers of water in the Mediterranean region. Nevertheless, despite yielding comparatively lower returns to water than other economic sectors, irrigated agriculture remains a crucial source of income and employment in rural areas worldwide (Pérez-Blanco et al., 2021).

Water allocation rights serve as a crucial mechanism for the management of water resources in closed basins, where the availability of water is limited, necessitating meticulous control and regulation of its use. These rights are assigned to users based on the available water supply and diverse user needs (Molle, 2009; Molle et al., 2010). They determine the allowable extraction of water, granted through concessions, or permits, which can be temporary or permanent. In some cases, these rights are transferable, allowing users to buy and sell them in the market. In situations where the available water is insufficient to meet all stakeholders' rights, there are two principal approaches to rationing irrigation water allocations: the proportional rule and the priority rule (OECD, 2016). Under the proportional rule, which has been widely adopted for irrigation water allocation, each water rights holder receives a share proportional to their granted rights, ensuring a balance between total demand and total supply (Gómez-Limón et al., 2021; OECD, 2015). On the other hand, under the priority rule, irrigation rights holders are categorized into priority classes, and water rights are distributed based on these classes. This means that the highest-priority rights holders have their demands met first, and any remaining resources are then allocated to other rights holders in order of diminishing priority (Gómez-Limón et al., 2020a).

Another widely discussed policy instrument is water pricing, an economic tool designed to encourage efficient water utilization and conservation. Article 9 of the European Water Framework Directive (2000/60/EC) (WFD) promotes the use of water pricing by Member States as a key instrument to ensure effective water use and support the complete cost recovery of water services. This approach aligns with the environmental objectives outlined in the WFD, as emphasized by Molle (2009).

Moreover, there are additional economic instruments that could help to alleviate the economic repercussions of droughts. One example is water markets, a tool that has been studied by many authors in different places around the world (Megdal et al., 2014; Milanés Murcia, 2020; Montilla-López et al., 2016). Other example is the subsidization of irrigation efficiency improvement as a policy to improve water management which can produce a rebound effect that can be avoided only through well-designed policy intervention (Berbel et al., 2019; Berbel et al., 2018; Martínez-Dalmau et al., 2023b). Economic instruments can be quantified using hydro-economic models at basin scale.

It is important to conduct a preliminary analysis of the outcomes of these policies, assessing both the economic ramifications and the impacts on water dynamics in the hydrological system. Water resources modeling enables an assessment of these aspects, taking into account human needs for water, as well as available resources and infrastructure, while also integrating biophysical, technological and economic elements.

Hydro-economic modeling is a sophisticated tool that integrates the temporal and spatial fluctuations of biophysical factors with socioeconomic dynamics, offering insights to guide water management decisions, thereby helping to ensure well-informed water resource planning (Harou et al., 2009). It has thus become a valuable instrument for examining water-human systems, predicting water management scenarios, formulating water policies, and enhancing the efficiency of water-related infrastructure operations (Ortiz-Partida et al., 2023). Many authors have evaluated water policies using hydro-economic models, which offer the advantage of integrating agronomic, hydrological, environmental, and economic components at river basin scale (Esteve et al., 2015; Expósito et al., 2020; Kahil et al., 2016a; Kahil et al., 2015; Martínez-Dalmau et al., 2023a; Martínez-Dalmau et al., 2023b). Furthermore, other authors have used these models to assess strategies for adapting to climate change (Baccour et al., 2022; Crispin Cunya et al., 2023; Sapino et al., 2022; Ward, 2021). However, there are only a few authors who have studied the complex relationships between economic sectors of a region (macroeconomic model) and their connection with irrigators' responses to external shocks (microeconomic model) taking into account the hydrological system (hydrological model); examples include the study by Almazán-Gómez et al. (2023) and the one by Pérez-Blanco et al. (2022), which combines three types of model—hydrological, micro-agroeconomic and macroeconomic. Some other studies such as those by Roe et al. (2005) and Parrado et al. (2019) establish links between a microeconomic model and a macroeconomic model, although these studies only incorporate water policies without a hydro-economic model.

Therefore, the main objective of this article is to improve the existing framework by using hydrological and economic models (at micro and macro levels), establishing an internally consistent framework that links all these models in a more robust and coherent manner. The novelty of this approach is that it combines the hydrological model and the microeconomic model of each agent in a single hydro-economic model that is much more robust. In this model, both the hydrological component and the economic component form a single block (hard link) rather than distinct modules that feed back into each other, as in previous (Pérez-Blanco et al., 2022; Sapino et al., 2022). Subsequently, this (hydro-) microeconomic model is coupled to a macroeconomic model (soft link) to identify the connections between economic sectors of a region, as demonstrated by Pérez-Blanco et al. (2022) and Parrado et al. (2019), although the latter study lacks the hydrological component.

Our analysis includes two sub-models: i) the microeconomic model is a hydro-economic model consisting of a network of nodes and links in which the nodes represent the physical units that affect the river system and the links represent the connection between those units (Kahil et al., 2015; Kahil et al., 2018), with the agricultural sector calibrated using Positive Mathematical Programming (PMP) (Dagnino and Ward, 2012); and ii) the macroeconomic model is a Computable General Equilibrium (CGE) model calibrated at a regional level (Bosello and Standardi, 2015). The hydro-economic model is then coupled to the macroeconomic model by the exchange of information between these models; namely, the information on land use from the hydro-economic model, and on commodity prices from the macroeconomic model. To illustrate the methods, several water policy scenarios will be analysed with and without the inclusion of the macroeconomic model, using the Guadalquivir River Basin (GRB) in southern Spain as a case study. This case has been selected due to several key factors: a) First, the GRB has been the most drought-affected basin in Spain since the 1980s, serving as a representative example of a Mediterranean basin, highly prone to frequent and severe drought episodes. Projections indicate that this drought risk is expected to increase as a result of climate change (Bisselink et al., 2018); b) Second, irrigation plays a crucial role in Spain, covering approximately 3.8 million hectares (22.8 % of the nation's total agricultural area) and accounting for more than 60 % of the Final Agricultural Product (MAPA, 2023); c) Finally, the GRB covers 25 % of Spain's total irrigated area.

The rest of this paper is structured as follows: the next section provides an overview of the GRB. The third section explains the hydro-micro-macroeconomic model coupling applied to the specific case of the GRB. In the fourth section, various simulated scenarios are compared. Section five describes the results, and the two final sections present the discussion and the main conclusions.

2. Case study

The GRB, located in southwestern Europe, spans an area of 57,679 km^2 and supports the livelihoods of over 4.4 million people (CHG, 2022). This basin has some specific characteristics that make it a compelling subject for modeling water resources and analysing water management strategies, which can then be extrapolated to other semi-arid regions with Mediterranean climates (Martínez-Dalmau et al., 2023b). These features include structural water scarcity, recurrent and severe droughts, limited options for augmenting water supply, widespread adoption of deficit irrigation (Berbel et al., 2024), and the utilization of water trading mechanisms; moreover, the GRB is crucial for one of Europe's primary areas of irrigated agriculture, accounting for 25 % of Spain's irrigated area (Espinosa-Tasón et al., 2020; Palomo-Hierro et al., 2022), of which 63 % is cultivated with perennials crops (Tocados-Franco et al. (2023).

As illustrated in Fig. 1, the river basin has been segmented into four zones: Upper Basin, Middle Basin (right and left bank), and Lower Basin, based on the distinctive features of each agricultural region and its crops. The Upper Basin is distinguished by the prevalence of perennial crops, which cover 91 % of the total area in this zone. Olive groves are the primary crop, covering 88 % of the total cultivated area. In contrast, the Middle Basin has a smaller percentage of perennial crops, as they account for 69 % of the total crops area in this zone. Again, olive groves are the primary crop, comprising 56 % of the total area, while cereals account for 12 %. Lastly, in the Lower Basin, less than half of the cultivated area (41 %) is dedicated to perennial crops; olive groves are the principal perennial crop, followed by orange trees with 10 % of the total cultivated area. Notably, in this zone, crops such as cereals, cotton, rice, and vegetable crops play an important role, representing approximately 49 % of the total crops area. This study considers 85 % of the total crops area in the basin, with the analysis encompassing all major crops, due to a lack of economic information for some other crops.

In addition to the GRB, the case study will focus on the region of Andalusia because the macroeconomic model uses economic data from this region.

3. Methodology: The model coupling

The hydro-economic model, as described by Martínez-Dalmau et al. (2023b), serves as a tool for assessing drought conditions and evaluating adaptation measures. This tool is complemented at the macroeconomic level by coupling it with a regional CGE model (Bosello and Standardi, 2015) to account for agricultural commodity price feedback derived from the land use decisions indicated by the hydro-economic model. The macroeconomic model is calibrated to encompass broader economic aspects providing an economy-wide description of the Andalusia region and the rest of the Spanish regions.

3.1. The hydro-economic model

Hydro-economic modeling is a robust tool for analysing issues related to water scarcity, drought and climate change. The hydro-economic river basin model captures the dynamic interactions between hydrological and economic systems and integrates institutional and environmental variables, ensuring that optimal economic outcomes take into account the spatial allocation of water resources (Kahil et al., 2015). A detailed description of the hydro-economic model can be found in Appendix 1.

The hydrological component for the GRB utilizes mass balance and river flow continuity principles. Based on Kahil et al. (2015), Kahil et al. (2016b) and described by Martínez-Dalmau et al. (2023b), the model employs nodes and links to represent water supply and demand units, with key variables including a range of water flows (X_i), headwater inflows, abstractions, return flows, losses, and flows at gauge points. Certain assumptions have been made, such as the water consumption in urban and industrial areas is defined as a constant parameter in the model, ensuring that their water needs are always met. The model is static and represents a single average year for the GRB. The model does not incorporate reservoirs, assuming an average year where only the balance of water inflows and outflows within the system is considered. During droughts, restrictions are imposed on surface water diversions to ensure diverted flows at each node do not exceed available flows. In accordance with the regulations of the River Basin Authority (RBA), the water application for each node depends on the percentage reduction applied relative to the water that each node would receive under conditions of complete water availability. This is referred to as the proportional rule. The amount of urban and industrial water usage has been sourced from the RBA (CHG, 2022) database and is considered a fixed parameter in the model for both supply and return flows.

The calibration process of the hydro-economic model involves the introduction of slack variables for each river reach. These variables are crucial for aligning the model with actual observed flows. The slack variables represent unobserved factors, including inflows and outflows

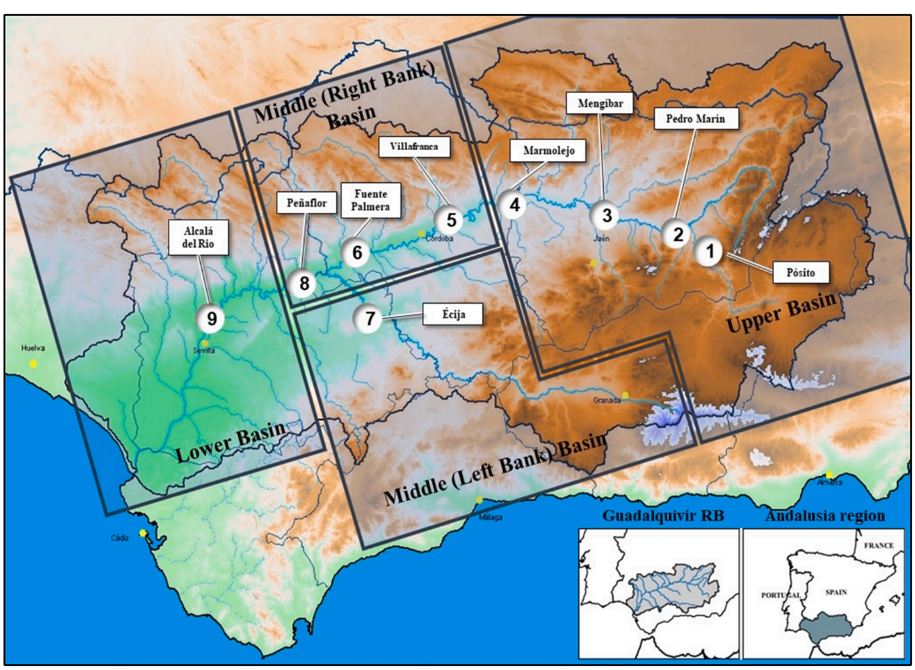

Fig. 1. Case study area.
Source: Adapted from Martínez-Dalmau et al. (2023b).

such as groundwater movements, evaporation, and returns. They are computed as the disparity between the initially estimated flows and the flows recorded at the gauge points. Integrating these slack variables into the model facilitates the achievement of a balanced mass balance, ensuring that the simulated flows align closely with the observed flows.

The economic component involves an optimization model focusing on the agricultural value within the basin. The agricultural zones are divided into 10 Irrigation Demand Areas (IDAs) based on the hydrological sub-basins of the GRB. The private gross margin for crop production by farmers, considering technical and resource constraints, is individually determined for each specific IDA, which serves as our decision unit. The model assumes constant factors and product prices, with yield functions decreasing linearly as the crop area expands. To assess potential future yield losses if farmers opt to leave perennial land fallow, a penalty for perennial land fallowing has been incorporated into the objective function.

The variant of PMP introduced by Dagnino and Ward (2012) is used for the calibration of the agricultural component of the model. In this approach, parameters are estimated for a linear yield function based on the first-order gross margin maximization conditions. The specified yield function is a linear function incorporating diminishing returns. This function aligns with the Ricardian rent principle, wherein the yield of a crop decreases as the scale of production increases. The principle follows the logic that the highest yielding lands are utilized first, resulting in diminishing returns as production scales up. The hydro-economic model has been programmed with the latest version of GAMS (Bussieck and Meeraus, 2004) using the CONOPT solver.

The hydrological and economic components interact endogenously so that, in the event of an external shock, the model allocates water in a manner that maximizes overall welfare, subject to all hydrological constraints. These include the physical feasibility of water allocation, taking into account municipal demands and environmental flow requirements along the different segments of the river. Thus, water management under drought conditions determines both the allocation strategy and the volume of water distributed, while simultaneously maximizing returns in the agricultural sector. This, in turn, influences land use decisions.

3.2. *The macroeconomic model*

The macroeconomic model used in this study is the same as the one in Parrado et al. (2019). Specifically, it is a regionalized CGE model based on the Global Trade Analysis Project (GTAP) model developed by Hertel (1997), and further developed at the subnational level for the European Union (EU) (Bosello and Standardi, 2015). The fundamental aspects of this model adhere to a neoclassical formulation, assuming perfect competition, full employment of production factors, and investments driven by savings. The economic structure is depicted through representative agents for households and firms, where market equilibrium is achieved by adjusting prices to ensure that demand equals supply in each simulation. Spain has been divided into 17 NUTS2 regions, accompanied by two additional macro regions as shown in Table 1. One of these macro regions stands for the remaining EU28 countries, and the other represents the rest of the world. Within each region, the economy is further divided into 15 sectors encompassing eight representative crop categories which have been linked to the hydro-economic model by mapping the eight crop categories onto the more detailed crop information available in the hydro-economic model.

First, it is important to note that the Guadalquivir River basin accounts for 60 % of Spain's olive oil production, 80 % of table olives, and 50 % of citrus; thus, any shifts in these crops will influence national prices. However, our focus is not on estimating national prices but rather regional prices, as a substantial portion of agribusiness inputs, such as cotton, maize, wheat, and vegetables, are produced locally. Andalusia itself represents approximately 30 % of Spain's agricultural output and has a geographic area, population, and GDP comparable to that of

Table 1
Regions and sectors of the regionalized CGE model.

Regions		Sectors	
Spain (NUTS 2)	1) Galicia	Crops	1) Rice
	2) Asturias		2) Wheat
	3) Cantabria		3) Other cereals
	4) Basque Country		4) Vegetables and fruits
	5) Navarra		5) Oil seeds
	6) La Rioja		6) Sugar cane & beet
	7) Aragon		7) Plant based fibers
	8) Madrid		8) Crops not elsewhere classified
	9) Castile and Leon	Industry	9) Livestock
	10) Castile-La Mancha		10) Extraction, fishing and forestry
	11) Extremadura		11) Food industry
	12) Catalonia		12) Rest of industry
	13) Valencian Community	Services	13) Utilities
	14) Balearic Islands		14) Construction
	15) Andalusia		15) Services
	16) Murcia		
	17) Canary Islands		
Rest of the World	18) Rest of EU		
	19) Rest of the world		

Portugal, hence our interest in capturing these variations at the regional level.

Accordingly, our macroeconomic model is not an EU wide macroeconomic model, but a regionalized CGE model able to provide economy-wide indicators for the Andalusia region as well as for the other 18 remaining regions (16 in Spain + Rest of EU + Rest of the World). This means that the changes in prices within the regionalized model refer only to the Andalusia region and not to the rest of Spain nor the Rest of EU.

The software used for running the simulations on the regionalized CGE model and post-process the results is GEMPACK economic modelling (Horridge and Rokicki, 2018).

3.3. *Coupling protocol*

The models are coupled through the exchange of information on changes in land use among agricultural crops from the hydro-economic model, which is fed into the eight crop categories of the macroeconomic model; in turn, the macroeconomic model feeds the corresponding changes in commodity prices back into the hydro-economic model, as depicted in Fig. 2. The sequence of steps in each simulation begins with a simulation of the hydro-economic model in Step 1. The changes in land use simulated by the microeconomic model constitute the input into the agricultural sector of the macroeconomic model within the study area (Andalusia). The macroeconomic model is then simulated using the input information on land use to find a new economic equilibrium and provide a set of commodity prices for the eight categories of the macroeconomic model.

Therefore, in Step 2, changes in agricultural commodity prices from the macroeconomic model are fed back into the hydro-economic model, and the decision on crop portfolios is simulated again producing new information on land use based on the changes in commodity prices. Steps 1 and 2 occur iteratively until convergence is achieved, i.e. when no further changes in crop distribution and prices take place (Hasegawa et al., 2016; Ronneberger et al., 2009). In order to establish a proper exchange of information between the two models, specific modifications have been made in each model to enable the receipt of information from the other model while respecting the main elements of each model. These modifications allow the coupling protocol between the hydro-economic and macroeconomic models, involving the exchange of information about changes in land use and crop prices, to produce a stable system, as demonstrated in Parrado et al. (2019). The routines for

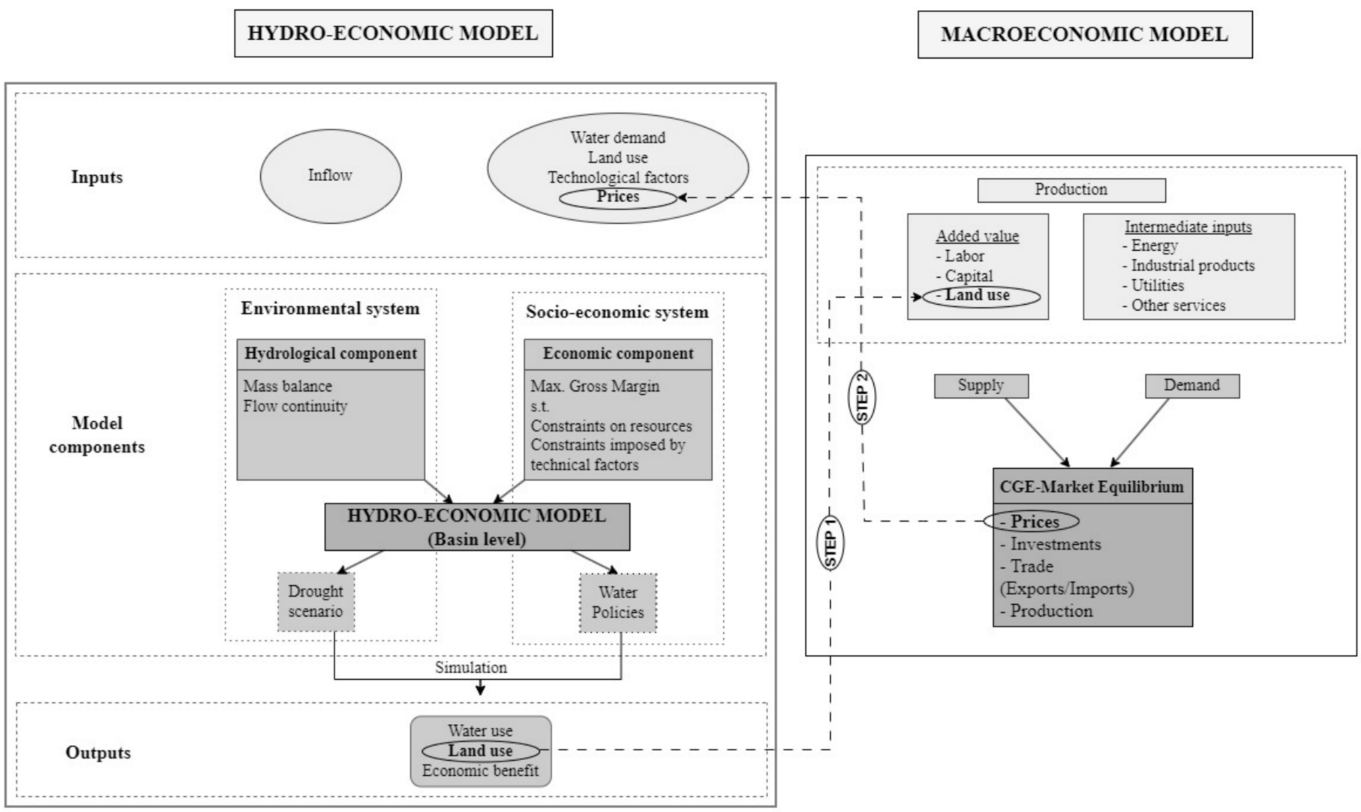

Fig. 2. Modeling framework.
Source: Adapted from Martínez-Dalmau et al. (2023b) and Pérez-Blanco et al. (2022).

coupling the micro and macro models have been implemented using visual basic in Excel.

4. Drought and water policies scenarios

4.1. Baseline scenario

The hydro-economic model is used to assess the adaptive capacity of the GRB in coping with severe water scarcity scenarios. The baseline scenario shows the water flows documented in the 2015–16 hydrological year, characterized by an average rainfall of 480 mm (MITECO, 2019). The mean annual rainfall in the basin in the period 1980–2010 is 570 mm (CHG, 2022). Water inflows into the basin are set to reflect the circulating water registered for that year at the gauging points.

Under normal hydrological conditions, the irrigated agriculture in the entire basin produces an estimated gross margin of 1,099 million euros, uses 3,127 hm^3 of irrigation water, and covers 856,429 ha (Table 2). It should be noted that 63 % of the crops are perennial, predominantly olive (83 % of total perennial crops).

Table 2
Summary of the main model parameters in the baseline scenario.

Sector	Irrigated land (1,000 ha)	Water use (hm^3)	Gross margin (M EUR)
Upper basin	292	617	206
Middle basin (right bank)	113	361	112
Middle basin (left bank)	160	483	229
Lower basin	291	1,666	551
Total basin	856	3,127	1,099

4.2. Drought and water policies scenarios

Hydrological drought occurs when reservoir storage drops below standard levels. GRB reservoir capacity is close to 8 km^3, with 6.9 km^3 of water inflows over the last 25 years, demonstrating the multiyear storage capacity to cope with periodical droughts. Consequently, the simulation of extended drought periods may be more relevant in such contexts. This study evaluates the consequences of alternative management policies and the basin's ability to adapt during an extended period of severe drought. Within this framework, we suggest a specific water scarcity scenario entailing a 25 % decrease in the available water within the basin compared to the baseline conditions. We then investigate various alternative or complementary water policy measures including a) quotas (proportional allocation), b) efficiency improvement, c) water reallocation, and d) pricing (water rates). A management scenario is characterized as a combination of measures formulated to enable better drought adaptation. The study evaluates the efficacy of four alternative management scenarios. It is important to note that successive scenarios are in order of cumulative improvements. Afterwards, these same scenarios are evaluated to determine the effect of introducing the coupling with the macroeconomic model.

a) **Drought Management Protocol (DMP).** This scenario establishes the priority for urban use and ensures minimum environmental flows are maintained. In the event of a hypothetical 25 % reduction of water inflows, agricultural water allocations to every farmer should be decreased by 14 %, following the proportional rule. This adjustment is necessary to fully meet urban water demand and adhere to environmental flow requirements and the rules are included in the Hydrological Plan under DMP specifications and follows the national normative. In response to this DMP scenario, farmers would likely prioritize crops with higher gross margins, allocating to perennial crops the minimum amount of water needed to ensure their survival.

b) **Increased Efficiency (IE)**. In this scenario, the proportional allocation of the DMP is combined with institutional and farm-level adaptation measures, resulting in a projected 5 % increase in water-use efficiency compared to current levels, meaning that crops need less water applied to produce the same yield. This enhancement is expected to lead to the same water use at the farm level, and greater evapotranspiration accompanied by a corresponding 5 % reduction in return flows.
c) **Optimal Allocation (OA)**. This scenario does not follow the proportional rule of the DMP but operates as a free water market, although it does incorporate the 5 % increase in efficiency.
d) **Water Pricing (WP)**. As in the OA scenario, water is freely allocated and improved irrigation efficiency is incorporated. However, the water tariff applied ensures that the water use is the same as in the DMP scenario. In this case, because of the increase in the water price, there is a reduction in water use until it equals that in the DMP scenario.

All scenarios allow farmers to apply survival irrigation to perennial crops. This measure is important because, although economic losses cannot be avoided in the short term (loss of the current season's harvest), it aims to prevent long-term losses caused by total perennial crop failure. Additionally, all scenarios include a penalty in the event that farmers decide to fallow perennial crops, to quantify potential future yield losses.

5. Results

Results of the model are described in the following order: firstly, we will examine the convergence process and the final equilibrium between the hydro-economic and macroeconomic models. Next, changes in irrigated agricultural area, water usage, and farmers' gross margins will be analysed, both from the hydro-economic model in isolation and in conjunction with the macroeconomic model. Following this, we will assess welfare changes to consider the outcomes for both producers and consumers. Finally, the impact of the new equilibrium on each crop group will be evaluated.

5.1. Convergence process of the coupling

The DMP scenario has been chosen to illustrate the coupling process since it is the one in which the greatest impact is observed. Wheat and other cereals are chosen for the same reason.

Fig. 3 shows the relationship between land use and crop price for the selected crops. In the first iteration, wheat area decreases by 50 % and wheat price increases by 9.3 %. In the second iteration, farmers respond to the price increase by increasing the area cultivated with wheat, which in turn leads to a decrease in price in the macroeconomic model. Similar behaviour is observed for other cereals: when the area decreases by 56 % in the first iteration, the price increases by 30 %. Then, in the next iteration, the increased price results in an increase in cultivated area, causing the price to drop, and so on. The process continues until changes in area and price are negligible, at which point, for the macroeconomic equilibrium price, there is no reaction from the agricultural sector.

After showing that the coupling process reaches full convergence, we now analyse the differences in the results without the coupling and with the coupled model. For this purpose, the results of irrigated land, water use, and gross margin are shown before and after the coupling of the hydro-economic model with the macroeconomic model for each

Table 3
Main results of the hydro-economic model before and after the coupling with the macroeconomic model, by scenario.

		Before coupling		After coupling	
Indicator	Scenario	Total basin		Total basin	
Irrigated land (1,000 ha, %)	Baseline	856		856	
	Drought Management Plan	718	−16.2 %	725	−15.3 %
	Increased Efficiency	762	−11.0 %	767	−10.4 %
	Optimal Allocation	781	−8.8 %	785	−8.3 %
	Water Pricing	780	−9.0 %	780	−8.9 %
Water use (hm^3; %)	Baseline	3,127		3,127	
	Drought Management Plan	2,689	−14.0 %	2,689	−14.0 %
	Increased Efficiency	2,689	−14.0 %	2,689	−14.0 %
	Optimal Allocation	2,701	−13.6 %	2,701	−13.6 %
	Water Pricing	2,688	−14.0 %	2,693	−13.9 %
Gross margin (M EUR; %)	Baseline	1,099		1,099	
	Drought Management Plan	1,087	−1.1 %	1,148	+4.5 %
	Increased Efficiency	1,094	−0.5 %	1,134	+3.2 %
	Optimal Allocation	1,095	−0.3 %	1,127	+2.6 %
	Water Pricing	1,049	−4.5 %	1,086	−1.2 %

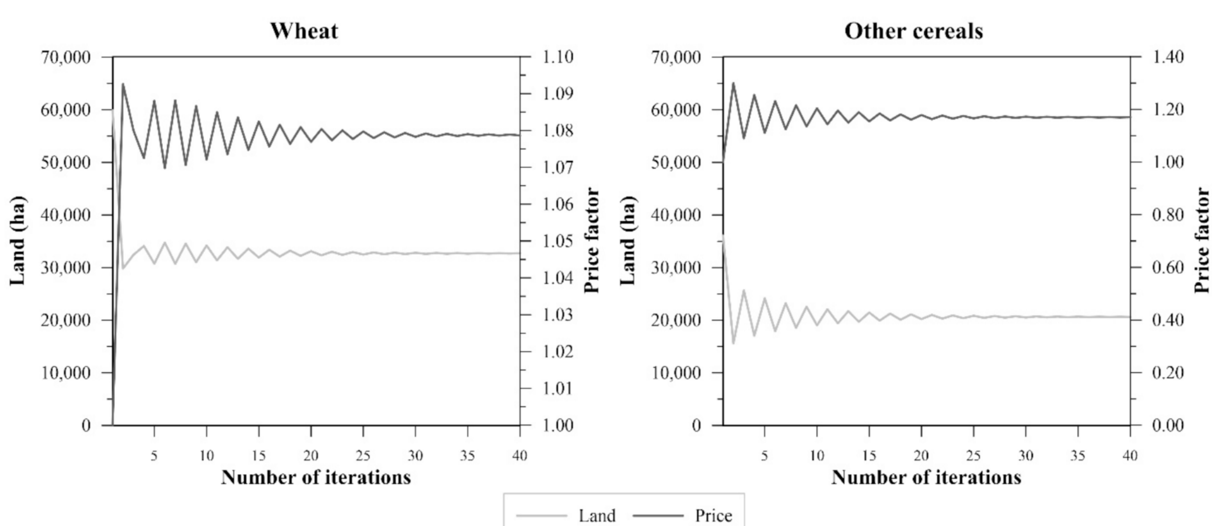

Fig. 3. Results of land and price effect due to the recursive iterations between hydro-economic and macroeconomic models in the DMP scenario for wheat and other cereals.

scenario once convergence is reached within the coupled model (Table 3). The analysis of the main results from the pre-coupling hydro-economic model for each scenario can be found in Martínez-Dalmau et al. (2023b), although those authors use a different level of drought impact (described as irrigation water availability vs normal year) from the one in this study. As in that previous study, there is a predictable decrease in the irrigated land, water use, and gross margin compared to the baseline scenario without drought (Table 3). Therefore, the focus of the analysis will be on the changes that occur when macroeconomic effects are considered.

5.2. Main results considering the coupling

In general, the irrigated land area decreases slightly less than before the coupling for all scenarios. In the case of water use, there are no differences before and after the coupling because water availability is a constraint imposed by the policy scenario. However, the gross margin of irrigated agriculture shows an improvement in all scenarios; indeed, the gross margin is higher than the baseline scenario without drought in almost all policy scenarios except for the WP scenario. This increase is not observed in all crops, but the gross margin increase in some crops leads to an average overall increase for the entire basin. This is called the price effect: a contraction in supply that forces the price up, such that the gain from the price increase exceeds the quantity loss.

It should be noted that the DMP scenario represents the business-as-usual scenario that would be applied in the case of a drought. Therefore, the remaining scenarios will be analysed relative to the DMP scenario.

After the coupling with the macroeconomic model in the DMP scenario, the irrigated land area is slightly higher than before (Table 3). In other words, irrigated land does not decrease as much when considering the economy-wide general equilibrium effects from the macroeconomic model. Despite the decrease in crop area and consequent loss of production, the coupling results show an overall average gain of +4.5 % in the gross margin compared to the baseline scenario without drought, demonstrating the so-called price effect. Thus, by incorporating into the analysis the interactions with the rest of the economy provided by the macroeconomic model, it can be seen that the economic impact of the reduction in cultivated area is mitigated by increasing prices.

Martínez-Dalmau et al. (2023b) reported a larger irrigated land area in the IE scenario than in the DMP scenario. In other words, the irrigated land area in the IE scenario does not decrease as drastically as in the DMP scenario (Table 3). The difference between these scenarios lies in the fact that more efficient irrigation application means less water is applied even though the evapotranspiration remains the same; consequently, more land can be irrigated while lowering economic losses. Specifically, a result of the increase in available water is that 16,700 fewer hectares of olive and almond trees must be converted to survival irrigation than in the DMP scenario, resulting in a lower gross margin loss. After coupling the models, 14,200 ha (instead of 16,700 ha) are switched from survival to normal irrigation and the gross margin changes from −0.5 % before the coupling to +3.2 % after considering the price information fed in from the macroeconomic model. Counter-intuitively, in this scenario where economic losses are lower in the hydro-economic model, the gross margin improvement after coupling is lower than in the DMP scenario. Since better use of water means a smaller reduction in agricultural output, the price effect is also reduced, ultimately resulting in a lower total gross margin than in the DMP scenario. Increased efficiency does not necessarily lead to higher profits with the price effect compared to the DMP scenario.

The OA scenario operates by distributing the available resources in a way that maximizes the total gross margin of the basin. It thus eliminates the proportional allocation rule imposed in the previous scenarios, although this would not comply with current legislation in Spain. However, the improvement in water use efficiency is maintained in this scenario. By optimizing water allocation, it is possible to make slightly better use of resources and the reduction in water is somewhat smaller. This scenario displays similar results to the previous one; that is, the hydro-economic model simulates a lower gross margin loss, but after coupling, the increase in the gross margin due to the price effect is lower than in the previous IE and DMP scenarios.

The last scenario is WP. In this scenario, the proportionality rule is eliminated, and water is allocated as in a free market with a water additional price of 0.017 EUR/m^3. This is the price, considering the drought situation, that is needed to achieve the 14 % water reduction proposed in the DMP scenario. In other words, this scenario is like the OA scenario, in which there is a water reduction due to drought restrictions, but a price is applied that ensures the final water reduction is equal to that of the DMP scenario.

The use of water tariffs has an impact on producer incomes. It affects lower-value crops such as cereals, rice, or cotton, among others, while crops with a higher gross margin, such as perennials or vegetables, can better absorb the impact of these tariffs. Although the gross margin loss improves when considering the macroeconomic model, this scenario shows the worst economic performance. Regarding total revenues collected by the water authority (water use multiplied by the established price), it is noteworthy that they are lower than the gross margin losses resulting from the abandonment of agricultural land.

5.3. Analysis of the changes on welfare

Fig. 4 and Table 4 present the economic impact of drought across different social groups in terms of welfare. In the short term, production supply can be assumed to be perfectly inelastic (Pindyck and Rubinfeld, 2014) due to the limitations in expanding land, water, and capital within a single season. Welfare can be measured as the sum of consumer surplus and producer surplus. Consumer surplus represents the difference between the maximum amount a consumer is willing to pay for a good or service and the actual amount they pay. It reflects the extra utility or satisfaction gained from purchasing a product at a price lower than what they are prepared to pay. In a supply–demand graph, consumer surplus is the area between the demand curve and the market price line, up to the quantity purchased. Consumer surplus is the difference between the actual revenue a producer receives from selling a good or service and the minimum amount they are willing to accept for it. This surplus reflects the added benefit producers gain from selling at a market price higher than their minimum acceptable price, often associated with production costs. In a supply–demand graph, producer surplus is the area between the market price line and the supply curve, up to the quantity sold.

After the drought, the consumer surplus (initially A + B + C) undergoes two main changes. First, consumer surplus declines by the amount that producer surplus increases due to the price effect (B). Additionally, there is an unrecoverable welfare loss impacting consumer surplus, depicted as deadweight loss C in Fig. 4.

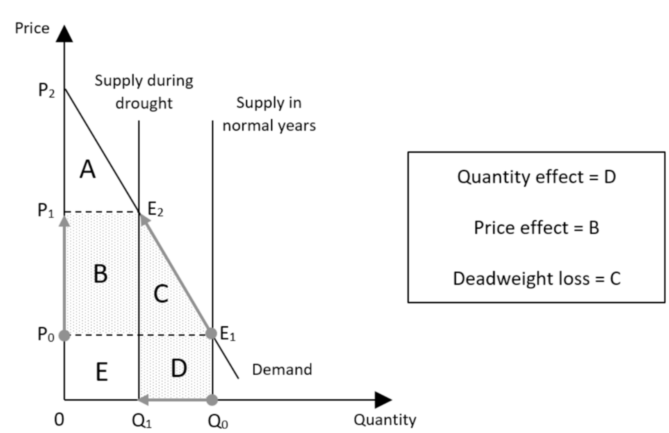

Fig. 4. Short-term effects of drought on the agricultural sector. Source: Espinosa-Tasón et al. (2022).

Table 4
Changes in total welfare (M EUR).

	Changes in welfare	Quantity effect	Priceeffect	Deadweight loss	Tax collection	Total
Drought Management Plan	Producer surplus	−11	61			50
	Consumer surplus		−61	−6		−67
	Global welfare	−11		−6		−17
Increased Efficiency	Producer surplus	−5	40			35
	Consumer surplus		−40	−2		−42
	Global welfare	−5		−2		−7
Optimal Allocation	Producer surplus	−4	32			28
	Consumer surplus		−32	−1		−33
	Global welfare	−4		−1		−5
Water Pricing	Producer surplus	−4	37		−46	−13
	Consumer surplus		−37	−2		−39
	Global welfare	−4		−2		−6

Drought results in an overall welfare loss for society (represented as areas D + C). However, examining the components of this effect reveals an increase in producer surplus (+ B – D in Fig. 4), driven by the price increase (area B), which compensates for lower yields and reduced production (area D). This price effect benefits farmers but simultaneously imposes a cost on consumers, who not only bear the price increase (– B) but also face a loss in consumer surplus by the deadweight loss (represented as C in the figure).

Overall, consumer losses (– B – C) exceed producer gains (+ B – D), resulting in a net societal welfare loss. The magnitude of these effects depends on demand elasticity, assumed to be inelastic in the short term based on empirical evidence (see macroeconomic model description).

In summary, during water shortage conditions, producer surplus transitions from E + D to E + B, while consumer surplus shifts from A + B + C to only A. Table 4 illustrates these changes, detailing the impacts on consumer surplus, producer surplus, and overall welfare, and categorizing them by quantity effect, price effect, and deadweight loss. The values shown in Table 4 have been calculated based on the geometry of the areas described in Fig. 4. Demand between market equilibrium points E_1 and E_2 has been assumed to be linear.

In all scenarios, the loss in consumer surplus consistently exceeds the gain in producer surplus, leading to an overall welfare loss. The case of water pricing is unique, as producer surplus is reduced not only by the quantity effect but also by the imposition of water fees. To reflect this transfer of funds from producers to administrative authorities, a tax collection column has been added, distinguishing it from the producer surplus loss attributed to the quantity effect.

Within this comprehensive analytical framework, as anticipated, the optimal allocation scenario exhibits the smallest total welfare loss. This scenario minimizes the impact of water shortages on agricultural production and results in the lowest price effect, as drought effects are less pronounced in consumer prices.

5.4. Main result by crop group

Analysing the results considering the eight crop categories of the macroeconomic model, the effect of the coupling is uneven across those crop groups. Each group follows a similar pattern in land and water use in the different scenarios (Fig. 5). That is, when irrigated land increases (decreases) after the coupling, the response in water use is similar. However, in all scenarios and crop groups, the private gross margin increases after the coupling (Fig. 6).

Results by crop group show that, after the coupling, the irrigated land area of wheat, other cereals and oil (mainly olive oil) is higher than before. However, the area of cotton is reduced after the coupling while rice, vegetables and fruits maintain the same area before and after the coupling. An increase in gross margin is observed for all crop groups because of the price effect, even if the irrigated area does not change before and after the coupling (land use was already reduced with respect to the baseline scenario). The gross margin increase is most pronounced in wheat, other cereals, and oil.

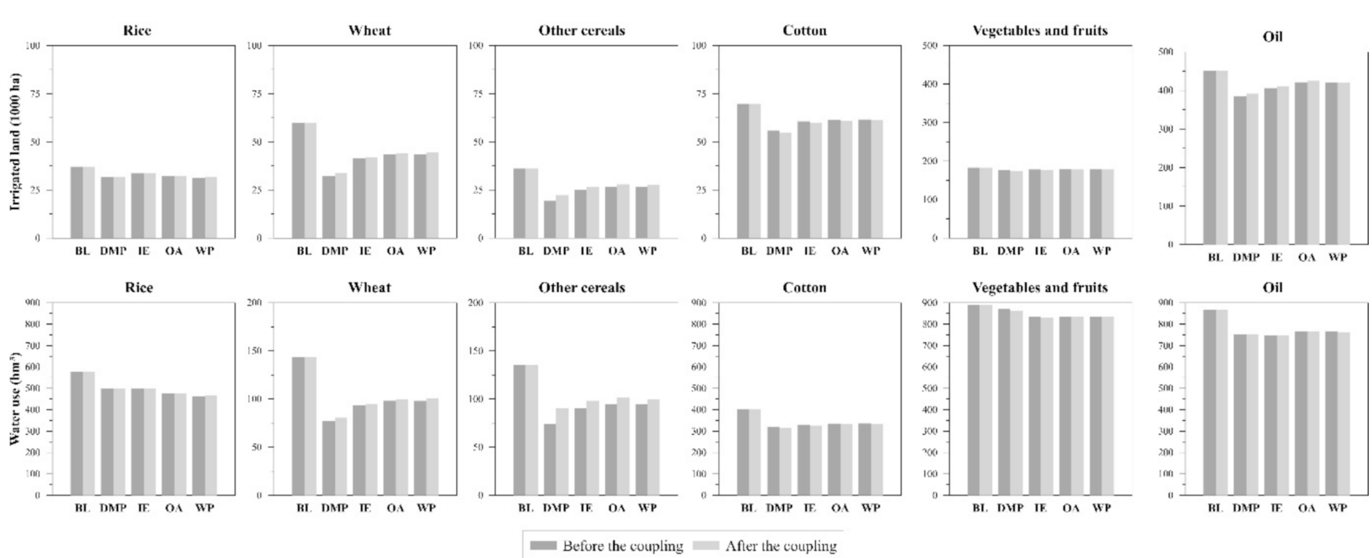

Fig. 5. Irrigated land and water use by scenario and crop group before and after the coupling of the models. Note: BL-Baseline; DMP-Drought Management Protocol; IE-Increased Efficiency; OA-Optimal Allocation; WP-Water Pricing.

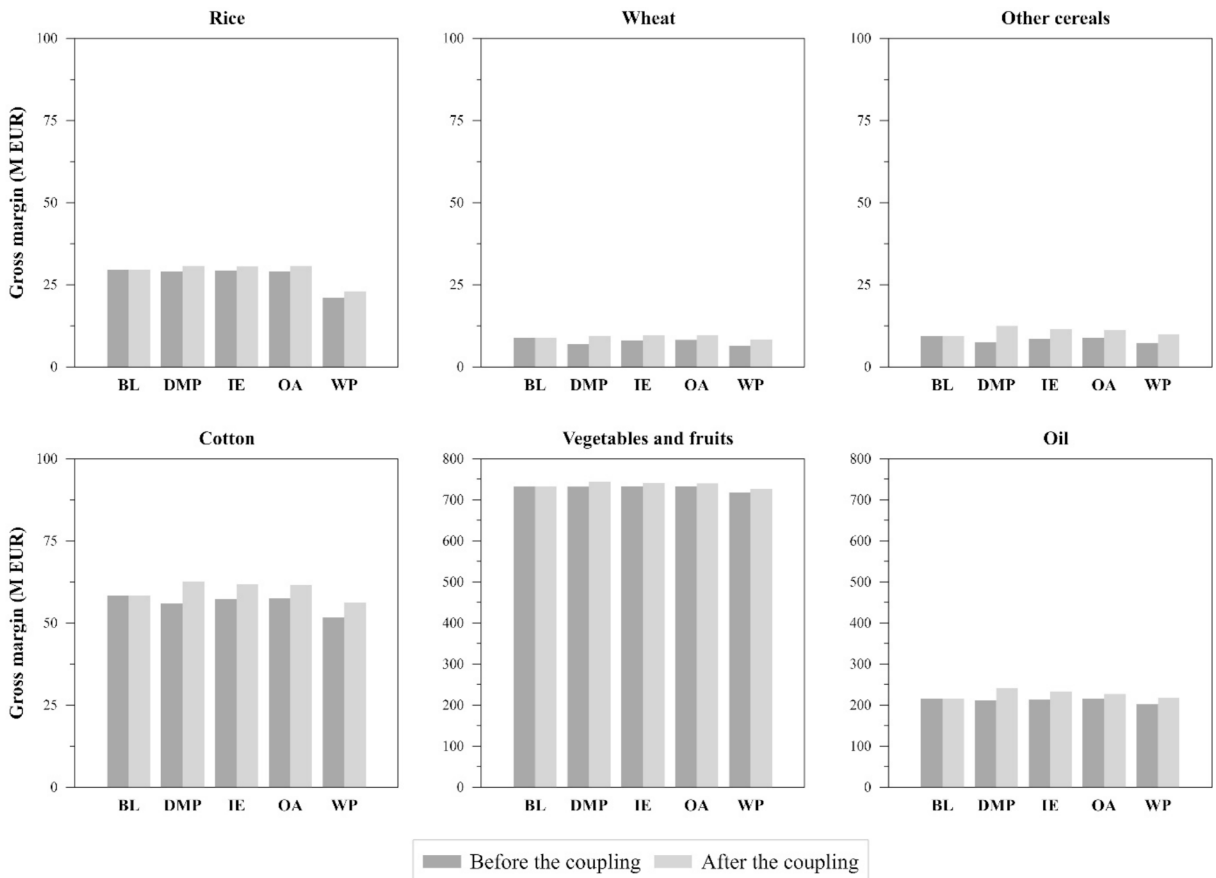

Fig. 6. Gross margin by scenario and crop group before and after the coupling of the models. Note: BL-Baseline; DMP-Drought Management Protocol; IE-Increased Efficiency; OA-Optimal Allocation; WP-Water Pricing.

6. Discussion

Our model yields interesting results for drought management, specifically by simulating water policy options for irrigated agriculture affected by hydrological drought conditions. It should be noted that hydrological droughts in Spain usually lasts a few years (usually two or three consecutive years) after a meteorological drought (low precipitation), when water storage reserves cannot recover from annual deficits. Historical data from the past 80 years in Spain indicate that hydrological droughts often affect one or multiple adjacent river basins, leading initially to regional impacts. Depending on the basin's importance for particular crops, these droughts can have broader repercussions, potentially extending to national or, in rare instances, even global scales.

Therefore, we focus on a specific basin (the GRB) to examine how prices vary in Andalusia, and our CGE model shows significant variations only for this region. The price variation observed is due to the local shortage of products that are in demand by consumers and the agri-food industry.

It is also important to highlight and compare the results obtained after reaching convergence between the two models versus the results provided by the first iteration. One possible interpretation is that the first iteration of the convergence process occurs in the second year, with farmers reacting once prices have changed. In this way, the iterations would be understood as successive years in which the farmer adapts the area to changes in crop prices. However, the convergence process should not be seen as an adaptive process over time; rather, it should be considered an almost instantaneous process where all available information has been shared between the models that are being coupled.

Firstly, due to their experience, farmers do not overreact to such situations; that is, just because the price of a product is high in a specific year, the farmers do not react by seeding much more of that crop the following year. Farmers know from experience that the crop area will likely increase the following year, meaning the price may drop again due to the market equilibrium between supply and demand. Secondly, convergence would be reached instantly if instead of having two independent models feeding back into each other, one model was embedded in the other (i.e. if the hydro-economic model was embedded in the macroeconomic model). Another path for future research would be calculating the price endogenously in the hydro-economic model through price-dependent crop demand functions. The iterative convergence process should only be seen as the procedure to reach the solution to the proposed optimization problem, not to an actual price and area swing. Therefore, the information to be used in the analysis is the final convergence result.

While many authors have comprehensively addressed hydrological and economic aspects independently (Pérez-Blanco et al., 2022; Sapino et al., 2022), the uniqueness of our approach lies in the full integration of these two components into a single hydro-economic model. This not only represents a methodological innovation but also enhances the robustness of the analysis, thereby establishing a clear distinction from previous studies. By consolidating both hydrological and economic variables within a unified framework, our model provides a more comprehensive and interconnected view of the relationship between these two aspects, thus making a valuable contribution to the field of hydro-economic model research. In addition to this, we coupled the new hydro-economic model with a macroeconomic model to account for price effects from an extended economy-wide analysis.

The results of the model coupling presented in this article demonstrate that the feedback between micro- and macro-economic models has a significant impact. By coupling the two models, the economy-wide market equilibrium effects can mitigate economic losses caused by droughts or irrigation restrictions (losses attributed to quantity effects) through an increase in crop prices. It has been shown that a mild drought such as the one simulated does not lead to large losses within the agricultural sector. On the contrary, the gross margin of the agricultural sector increases due to the local tensions in agricultural prices. However, it has also been shown that the gains of the agricultural sector occur at the expense of the consumers, who would bear higher prices. At the global level, there is a decrease in general welfare since there is a loss in both producer surplus (due to the quantity effect) and consumer surplus (deadweight loss).

Other papers, such as Parrado et al. (2019), Parrado et al. (2020) or Pérez-Blanco et al. (2022) have carried out feedback links between microeconomic and macroeconomic models. In all of them, it has been possible to verify an increase in the prices of agricultural products that has improved the final results of the sector, although in none of them has the final result been higher than that of the starting scenario. This indicates that the price effect was not greater than the quantity effect.

According to Parrado et al. (2019), a simplified linear dynamic system composed of two differential equations can be used to evaluate the convergence potential of the coupling process between the models. While each model starts in equilibrium, the coupling process will result in an exchange of information that moves the models away from their initial state until they reach a new equilibrium where both converge. This linear dynamic model is designed to analyze the primary dynamics of the coupling process through a simplified framework that emphasizes key variables and employs a representative commodity. The objective is to enhance understanding of the coupling process dynamics and to provide insights into the essential coupling variables and their behavior, which can later be generalized to scenarios involving multiple markets.

Price effect offsets the negative effects on income from yield losses, as demonstrated by other studies such as Parrado et al. (2019). Our results align with findings from other related studies, such as Espinosa-Tasón et al. (2022), which reports an increase in irrigated farms' margins and a decrease in rainfed crops in the Andalusia region during the drought of 2005–2008; Musolino et al. (2017), focusing on droughts in Italy in 2003 and 2005–2007; and Musolino et al. (2018), which focuses on Italy, Portugal, and the Jucar basin in Spain during droughts in 2003 and 2005–2007. These authors assert that not all farmers suffer losses due to quantity effects. In fact, farmers may even see an increase in profits due to the price effect caused by the scarcity of agricultural products. It is important to highlight that our study reflects an overall average profit. The reality is that within the farm sector, there will be winners and losers. The price effect will only benefit those who have managed to harvest some crops, but there will be cases where the price effect will not compensate for the losses because there may be no production. This study represents a "typical farm" and is not representative of every farmer.

Therefore, an evaluation of water management policies using only the hydro-economic model would provide only partial results because it only considers the quantity effect. However, the coupling of the hydro-economic model with a macroeconomic model provides a complementary analysis factoring in price changes derived from economy-wide interactions among all economic sectors. In fact, after coupling the two models, all scenarios show an improvement in farmers' gross margin; however, this is an overall average gain as not all farmers gain.

The comparison of water management policies suggest that the OA policy provides the best results when considering the gross margin, followed by the IE and the DMP policies, while the WP policy is the scenario with the worst output, as reported in other similar studies (Molle, 2009; Valle-García et al., 2024). This is even more evident in the results from the coupled model, as shown in Table 3, but another finding emerges. The price effect of the drought is dampened by the increase in allocation efficiency, given that the gross margin is lower in the OA policy, followed by IE and DMP. This suggests that the price increases in agricultural products are lower when the water management is more efficient, such as in the OA policy. In the OA scenario, consumer surplus decreases the least due to a smaller increase in prices, making this the scenario with the lowest overall welfare loss. An indirect implication of this for the economy in general is that lower agricultural prices mean lower inflation signals and also lower negative effects for households with tighter budget constraints. This is a result that could not be observed without the model coupling procedure, thus allowing us to draw some policy implications for income distribution effects.

7. Conclusions

A hydro-economic model has been coupled with a macroeconomic model to examine indirect effects of water policies within the agricultural sector, although the impact on the overall economy of the region has not been explored in this study.

Several water policy scenarios have been analysed with the hydro-economic model and with the coupled model. The results show an improvement in gross margin in all scenarios; indeed, most scenarios even register a higher gross margin than in the baseline scenario without drought. This increase is not observed for all crops, but the increase in the gross margin for some crops leads to an overall average gain for the entire basin. These results do not mean that all farmers make higher profits, but that, on average, the total agricultural gross margin of the basin is higher.

Thus, it is evident that an analysis of water policies using only the hydro-economic model without including the coupling with a macroeconomic model provides an insufficient understanding of the final outcomes, as it only considers the quantity effect (i.e., crop area and production changes) and not the price effect (i.e., crop price changes). The coupling of the models allows a complementary analysis that shows what happens when consistent price variations are included in the analysis. According to the coupled model, all scenarios result in smaller basin-wide agricultural economic losses, although not every farmer benefits.

Any solution that does not account for changes in product prices will fail to accurately forecast the economic impacts of drought and management policies. Nonetheless, it is also true that coupling the hydro-economic and macro-economic models has an almost negligible effect on water use and allocation. Only under the water pricing scenario is a 1 % increase in water use observed when the models are coupled. Therefore, if the objective is limited to understanding water allocation and use, the hydro-economic model alone is sufficient. However, if the goal is to assess the full economic impact, coupling with the macroeconomic model becomes essential.

The novelty of this work lies in the fact that hydrological and microeconomic components form an inseparable block in both computational and analytical terms, which avoids the common inconsistencies found in flexible couplings. This simultaneous integration allows for a more accurate capture of the direct and indirect relationships between water management decisions and their economic consequences.

However, one of the limitations of this study is that the agricultural areas have been divided into only 10 IDAs. The lack of spatial differentiation is a problem because it produces an aggregation bias, meaning that some areas which are not in fact homogeneous are assumed to be so. It also poses a problem in achieving convergence, since for other levels of water scarcity, changes in prices have led to an increase in the crop areas more than the initial area. As a result, subsequent iterations have diverged, making it impossible to achieve convergence between the two models. Further research is needed to explore whether greater spatial differentiation would significantly change the results. Similarly, it would be worth exploring whether the inclusion of specific demand elasticities for each crop in the microeconomic model could produce similar results without having to link it to a macroeconomic model. Analysis of the dynamic nature of water demand and supply under changing climatic conditions is also proposed as future research.

CRediT authorship contribution statement

Ángela Valle-García: Writing – review & editing, Writing – original draft, Visualization, Investigation. **Nazaret M. Montilla-López:** Writing – review & editing, Supervision, Conceptualization. **Ramiro Parrado:** Writing – review & editing, Software, Methodology. **Julio Berbel:** Writing – review & editing, Supervision. **Javier Martínez-Dalmau:** Software. **Taher Kahil:** Writing – review & editing, Methodology. **Carlos Gutiérrez-Martín:** Writing – review & editing, Supervision, Software, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Carlos Gutierrez-Martin reports financial support was provided by Ministry of Science and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The hydro-economic river basin model integrates hydrologic, economic, institutional, and environmental variables, encompassing the primary water users within the basin, such as irrigation districts, main cities, and the environment through ecological flows. This model simulates a range of policy scenarios in a mild drought event to evaluate the potential for enhancing economic outcomes in the basin under such conditions.

Hydro-economic modeling serves as a robust tool for analyzing issues related to water scarcity, drought, and climate change. These models incorporate all critical spatially distributed hydrologic and engineering components within the river basin under study. Furthermore, hydro-economic models capture the dynamic interactions between hydrologic and economic systems, ensuring that optimal economic outcomes consider the spatial allocation of water resources (Kahil et al., 2015).

Fig. A1 represents the Guadalquivir River Basin's simplified flowchart showing main elements of the basin, reservoir, main gauges, irrigation district areas, urban demand areas, headflows, return flows, etc.

This is a static, annual-scale model representing a typical year for the GRB. The model does not incorporate reservoirs, assuming an average year where only the balance of water inflows and outflows within the system is considered. Water consumption in urban and industrial sectors is defined as a constant parameter, ensuring that their water needs are always satisfied.

The reduced-form hydrological model estimates the volume of water available for economic activities after accounting for environmental constraints. The mathematical formulation of this reduced-form model includes:

$$W_p^{out} = W_p^{in} - W_p^{DivIRR} - W_p^{DivURB} \tag{A1}$$

$$W_{p+1}^{in} = W_p^{out} + r_p^{IRR} \cdot W_p^{DivIRR} + r_p^{URB} \cdot W_p^{DivURB} + W_{p+1}^{runoff} \tag{A2}$$

$$W_p^{out} \geq minEF_p \tag{A3}$$

The mass balance equation (1) stipulates that the water outflow at a given river point p equals the water inflow minus diversions for irrigation and urban uses. The continuity equation (2) ensures river flow continuity, where water inflow at a point is the sum of outflows from upstream reaches, return flows from prior irrigation districts, urban return flows, and runoff from tributaries into that reach. Equation (3) is a constraint requiring water outflow to be at least equal to the minimum environmental flow in that river reach.

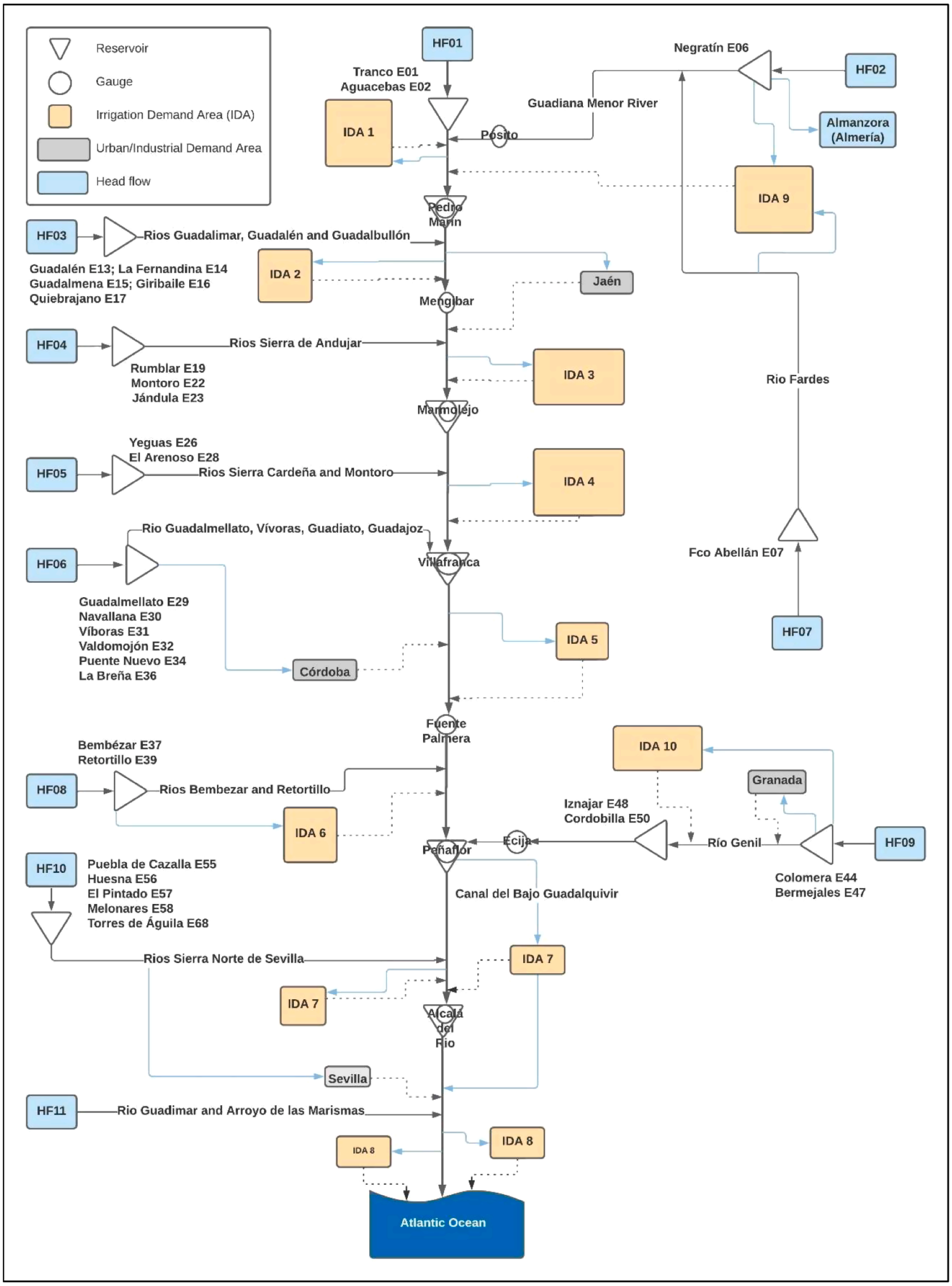

Fig. A1. Guadalquivir River Basin's simplified flowchart. **Source:** Martínez-Dalmau et al. (2023)

A1. Headflows

Headwater inflows are calculated based on the total annual flows recorded at various headwater gauges, with the inflows, X_h, at each headwater gauge h (a subset of i) equaling the total source supply.

A2. Streamflows

Streamflow, X_v, at each river gauge v (a subset of i) represents the sum of flows from upstream nodes i contributing to that streamflow. These nodes include headwater inflows, river gauges, diversions, and surface return flows. Streamflow at each river gauge must be non-negative and is defined as:

$$X_v = \sum_i b_{i,v} * X_i, \forall v \tag{4}$$

where $b_{i,v}$ is a matrix of coefficients linking flow nodes i to river gauge nodes v. No related nodes have coefficients of 0, nodes increasing flow are assigned $+1$, and nodes reducing flow are assigned -1.

A3. Water diversions

Water supply to users within the basin may be met partially or fully through stream diversions. During drought periods, a surface water diversion constraint is necessary to ensure that diversions, X_d, do not exceed the available streamflow at each diversion node d (a subset of i). Diversions, which must be non-negative, are defined as follows:

$$X_d \leq \sum_i b_{i,d} * X_i, \forall d \tag{A5}$$

where $b_{i,d}$ links flow nodes i to diversion nodes d. The right-hand side represents cumulative contributions from upstream sources (headwater inflow, river gauges, diversions, and return flows). Non-contributing nodes have coefficients of 0, nodes increasing flow have coefficients of $+1$, and nodes reducing flow are -1.

A4. Water application

Water applied is the water that reaches the application node (irrigation district or municipality) a (a subset of i). It is defined as follows:

$$X_a \leq \sum_d b_{d,a} * X_d, \forall a \tag{A6}$$

where $b_{d,a}$ links application nodes to diversions. Application nodes withdrawing water from available sources are assigned $+1$; non-withdrawing nodes have coefficients of 0. Total water applied for irrigation at each agricultural node is defined as:

$$X_a^{ag} = \sum_{j,k} b_{a,j,k} \left(\sum_c b_{c,a} * L_{c,j,k} \right), \forall a \tag{A7}$$

where the irrigation water applied to crops X_a^{ag} is the sum over crops j and irrigation technologies k of water application per hectare, $b_{a,j,k}$, multiplied by the irrigated area $L_{c,j,k}$ for each crop and irrigation technology. $L_{c,j,k}$ is multiplied by a binary matrix $b_{c,a}$ to conform nodes.

A5. Water consumption

Water consumption X_c at each consumption node c (a subset of i) is a proportion of applied water, X_a. In irrigation, consumption is the volume consumed via crop evapotranspiration (ET); in urban areas, it is the portion of supply not returned to the sewer system. Consumption, which must be non-negative, is expressed as:

$$X_c = \sum_a b_{a,c} * X_a, \forall c \tag{A8}$$

where $b_{a,c}$ indicates the share of water applied that is consumed at each node. For agricultural use, consumption is given by:

$$X_c^{ag} = \sum_{j,k} b_{c,j,k} * L_{c,j,k}, \forall c \tag{A9}$$

where irrigation water consumed X_c^{ag} is the sum over crops j and irrigation technologies k of ET per hectare, $b_{c,j,k}$, multiplied by irrigated area $L_{c,j,k}$ per crop and technology.

A6. Return flows

Return flows X_r at each return flow node r (a subset of i) represent the proportion of applied water X_a returning to the river system, defined as:

$$X_r = \sum_a b_{a,r} * X_a, \quad \forall r \qquad 10)$$

where $b_{a,r}$ indicates the proportion of applied water that returns to the hydrology system. For agricultural nodes, return flows are:

$$X_r^{ag} = \sum_{j,k} b_{r,j,k} \left(\sum_c b_{c,r} * L_{c,j,k} \right), \forall r \qquad 11)$$

where irrigation return flows X_r^{ag} are equal to the sum over crops j and technologies k of return flows per hectare $b_{r,j,k}$ times the irrigated area $L_{c,j,k}$. $L_{c,j,k}$ is multiplied by a binary matrix $b_{c,r}$ to conform nodes. Applied water must equal consumed water plus return flows.

The hydro-economic model is calibrated by introducing slack variables for each river reach, allowing the model to replicate observed flows. Slack variables account for unobserved inflows and outflows (e.g., groundwater flow, evaporation, returns) and are computed as the difference between initial estimates and flows measured at gauges, enabling mass balance in the model.

Data availability

Data will be made available on request.

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