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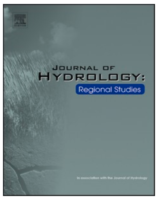

Surface water allocation rules and groundwater pumping during droughts: A hydro-economic approach for the Guadalquivir River Basin

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ABSTRACT

Study region: This research focuses on the Guadalquivir River Basin in southern Spain, a region characterized by high agricultural water demand and increasing vulnerability to drought. The basin serves as a critical case study for semi-arid Mediterranean environments.
Study focus: The study evaluates the impact of three distinct water allocation rules: proportional allocation (uniform allotment reductions), proportional economic losses (equalized relative reduction in gross margins), and optimal allocation (prioritization of water-productive crops). Using a hydro-economic model, the research simulates various scarcity scenarios (10% to 70% reductions) and examines the mitigating role of groundwater reserves during periods of drought.
New hydrological insights for the region: The findings reveal that while proportional allocation is often perceived as equitable, it results in the most severe and uneven economic losses (16.1% at a 50% water deficit). In contrast, an optimal allocation rule minimizes aggregate losses to 12.0%. Access to groundwater significantly cushions the impact, reducing losses to approximately 5.3%–7.0%. The study highlights that traditional water-sharing rules are economically inefficient and socially inequitable, advocating for a transition toward allocation models based on economic efficiency and territorial equity to ensure water sustainability in an uncertain climate. Overall, our results provide a policy-relevant quantification of the efficiency–equity trade-offs of drought rationing and show that strategic conjunctive use can substantially increase irrigation resilience in semi-arid, agriculture-dominated basins.

1. Introduction and objectives

In the event of a drought, it is necessary to establish water rationing rules to allocate the available water among users with water rights. A water rights system determines how water will be allocated when the total volume of water available is less than the sum of the volumes granted through concessions or individual water rights (Gómez-Limón et al., 2020). The problem of how to fairly allocate this available volume is known in the economic literature as the "bankruptcy problem" and it has been applied to water rationing

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(Ansink and Weikard, 2012; Mianabadi et al., 2014; Sechi and Zucca, 2015; Wickramage et al., 2020; Zarezadeh et al., 2017). Of special interest is the study by Alarcón et al. (2014) which analyzed five different allocation rules, three of which are applied in our study. Proportional Allocation (PA) is the most common and applies proportional reductions to agricultural water use in order to prioritize urban supply and environmental flows. The Proportional Economic Losses (PEL) method seeks to ensure that all users experience the same relative reduction in their gross margins. Finally, Optimal Allocation (OA) mimics a free water market, directing water resources toward crops with the highest marginal productivity of water, which maximizes economic efficiency. The application of these and analogous bankruptcy-based rules has been explored across diverse international settings. In Australia, (Iftekhar and Fogarty, 2017) analyzed the effect of proportional allocation rule in large farms. In the Saskatchewan River Basin (Canada), an economically efficient allocation strategy reduced the cost of water restrictions by 28–79% compared to priority-based systems (Eamen et al., 2021). Bankruptcy-based allocation rules have similarly been applied to the Missouri River (US) to resolve conflicts between upstream and downstream users during drought years (Wickramage et al., 2020), and to urban water allocation under scarcity in Chinese river basins (Zheng et al., 2022). In semi-arid Iran, optimal crop water allocation combined with proportional cutback constraints has been applied to the Zayandeh-rud River Basin (Madani and Zarezadeh, 2012). Comparative analyses across countries, including Spain, Australia, and the Western United States, have confirmed that security-differentiated or economically informed rights regimes outperform uniform proportional rationing in terms of allocative efficiency (Calatrava and Garrido, 2006; Gómez-Limón et al., 2020). Despite this growing body of international evidence, studies that simultaneously evaluate the efficiency of allocation rules and the value of conjunctive surface–groundwater use under drought conditions in Mediterranean semi-arid basins remain scarce.

Groundwater is very important from both environmental and socioeconomic perspectives, representing a crucial source of supply for human consumption, agriculture, and industry. In arid and semi-arid regions, it constitutes the main source of available water. During drought periods, aquifers act as natural reserves that can be used to offset a significant amount of surface water loss (Harris, 2024). However, groundwater is treated as a renewable resource that occasionally becomes a non-renewable one because of drought (Amundsen and Jensen, 2019). Overexploitation and the contamination of aquifers are critical problems (Dorado-Guerra et al., 2021; Esteban et al., 2024; Wada et al., 2010). The current pattern of groundwater usage in Spain is alarming: it has surged from 2000 hm^3/year to 6500 hm^3/year over the past forty years, with 75% of this volume being applied to irrigate one million hectares, accounting for more than 30% of the nation's irrigated land (Berbel et al., 2018). Therefore, the proper management of groundwater resources is essential to prevent the degradation of these systems and ensure their availability during drought episodes and for future generations. These pressures are not unique to Spain: in California's Central Valley (US), groundwater depletion accelerated dramatically during the 2012–2017 megadrought, underscoring the structural vulnerability of irrigated agriculture in water-scarce regions (Liu et al., 2022). In Chile, the agricultural sector buffered prolonged drought impacts through increased groundwater use, albeit at the cost of progressive aquifer depletion (Donoso, 2021). In Australia's Murray-Darling Basin, conjunctive water management has been central to sustaining irrigation under climatic variability (Jiang and Grafton, 2012). Globally, conjunctive surface water and groundwater management has been identified as a key mechanism for resolving temporal disconnects between water supply and demand caused by climate extremes (Scanlon et al., 2023). The economics of the conjunctive use of groundwater and surface water has been widely studied for decades (Burt, 1964; Knapp and Olson, 1995).

For the evaluation and analysis of the potential impacts of different water allocation rules, it is necessary to conduct simulations before their implementation. Economic models have been employed to better understand the effects of different groundwater policies on resource allocation in agricultural production (Calzadilla et al., 2014). In this regard, hydro-economic models are sophisticated tools that integrate the temporal and spatial fluctuations of biophysical factors with socioeconomic dynamics, providing information to guide water management decisions and contributing to an informed and enriched understanding of water resource planning (Ortiz-Partida et al., 2023).

The literature reviewed above reveals two important gaps. First, while the economics of bankruptcy-based water allocation rules and conjunctive groundwater use have each been studied extensively and across multiple international contexts, their joint evaluation within a single modelling framework is largely absent from the literature. Second, most existing studies focus either on surface water allocation or on groundwater management in isolation; none has assessed how the choice of surface water allocation rule interacts with the availability of groundwater in modifying the magnitude of drought-induced agricultural losses. These gaps are particularly relevant for semi-arid Mediterranean basins such as the Guadalquivir River Basin (GRB), where both dimensions are simultaneously at play during drought episodes.

Thus, the main objective of this work is to quantify the mitigation of economic losses in irrigation in the Guadalquivir River Basin (GRB) in cases of drought through: 1) the use of groundwater reserves; and 2) the application of different water allocation rules, by using a hydro-economic model where agricultural activities are modeled using Positive Mathematical Programming (PMP), based on Martínez-Dalmau et al. (2023). In this sense, the necessity of this work is twofold: first, GRB irrigation already operates close to 'basin closure', so drought protocols must be assessed not only by administrative feasibility but also by economic and territorial consequences; second, climate projections point to more frequent and longer droughts (IPCC, 2023), increasing the value of well-managed groundwater reserves. Compared with Martínez-Dalmau et al. (2023), which calibrated the GRB hydro-economic model for drought policy assessment using surface water only, we extend the model by explicitly representing groundwater pumping costs and emergency access to aquifer reserves, and we evaluate three allocation rules both with and without groundwater reserves, instead of the water economic instruments evaluated by Martínez-Dalmau et al. (2023) —water markets and pricing. This allows us to (i) quantify the mitigation potential of water allocation rules and conjunctive use, (ii) identify winners and losers across irrigation demand areas, and (iii) discuss the transferability of the main insights to other semi-arid Mediterranean basins.

The following two sections present the case study and methodology. The fourth section outlines the results, and the fifth section analyses and compares them with previous studies' findings. Lastly, the final section is dedicated to the main conclusions, study limitations, and suggestions for future research.

2. Case study

The GRB is located in southern Spain, encompassing over 57,000 km². This region features a typical Mediterranean climate, characterized by unevenly distributed rainfall and frequent hydrological drought events. The average annual temperature is 16.1°C, while the average annual precipitation is 561 mm (CHG, 2022). The basin's available water resources amount to approximately 3720 hm³ per year, with around 3207 hm³ per year allocated to meet the demands of irrigated agriculture, representing 86% of the total water demand within the basin (CHG, 2022).

The basin possesses several features that make it an ideal model for simulating water resources and analyzing water allocation rules applicable to semi-arid Mediterranean regions (Espinosa-Tasón et al., 2020; Martínez-Dalmau et al., 2023). These features include chronic water scarcity, recurrent severe droughts, limited opportunities for augmenting water supply, and the widespread adoption of deficit irrigation practices (Berbel et al., 2024). Table 1 shows main biophysical and socioeconomic characteristics of the GRB.

Fig. 1 illustrates the boundaries of the GRB, along with its primary irrigation zones. In the upper basin, perennial crops predominate, covering 91% of the total area in this zone, with olive groves being the main crop, occupying 88% of the cultivated land. In contrast, the middle basin has a lower proportion of perennial crops, which account for 69% of the total cultivated area, with olive groves covering 56% and cereals, 12%. Lastly, in the lower basin, less than half of the cultivated area (41%) is dedicated to perennial crops. Notably, in this area, cereals, cotton, rice, and horticultural crops are significant, representing approximately 49% of the total cultivated area. This study considers 85% of the total cultivated area of the basin due to the lack of economic data for certain crops, although it includes all major crops.

3. Methodology: the hydro-economic model

Fig. 2 summarizes the methodological framework. The model extends the hydro-economic framework of Martínez-Dalmau et al. (2023) — calibrated to the baseline year 2018 — by incorporating emergency groundwater pumping with quadratic extraction costs and specific aquifer availability limits by Irrigation Demand Area (IDA). Drought scenarios range from 10 to 70% reductions in basin-wide surface water availability, and each is solved under the three allocation rules both with and without additional groundwater reserves. Outputs are analyzed at basin and IDA level.

The hydro-economic model applied in this study builds on the framework developed by Martínez-Dalmau et al. (2023), which is also described in detail in Appendix A of Valle-García et al. (2025). The original model has been extended in two respects: the incorporation of groundwater reserves as an additional supply source, and the implementation of the three alternative water allocation rules evaluated here. The model integrates hydrological and economic components into a single optimization block, linking physical water flows across the basin to the maximization of agricultural gross margin at the irrigation district level. It is programmed in GAMS (General Algebraic Modelling System) using the CONOPT 4 solver.

3.1. Hydrological component

The hydrological component employs principles of mass conservation and flow continuity. Following Kahil et al. (2015), Kahil et al. (2016), and Martínez-Dalmau et al. (2023), the basin is represented as a network of nodes and links, where nodes represent physical units that affect the river system — headwater points, gauging points, diversion nodes, application nodes, consumption nodes, and return flow nodes. A key application node is the agricultural node, the IDA, which is considered the decision-making unit for agricultural water use. The links represent the connections between these nodes characterizing water flow rates (X_i), such as water contributions to the basin, flows at monitoring points, water abstraction, and return flows, among others. The model is static and represents a single average year for the GRB; reservoirs are not explicitly modelled, as the focus is on the annual water balance. The core hydrological constraints are as follows:

Mass balance and flow continuity. Water inflows at each headwater gauge are set equal to average observed annual inflows. At each river gauge, flow is determined by the sum of contributions from all upstream nodes, weighted by a routing coefficient matrix.

Table 1
Main biophysical and socioeconomic characteristics of the Guadalquivir River Basin.

Characteristic	Value / description (data source)
Basin area	≈ 57,000 km² (CHG, 2022)
Climate	Mediterranean; high interannual rainfall variability
Mean annual precipitation	≈ 561 mm (CHG, 2022)
Mean annual temperature	≈ 16.1 °C (CHG, 2022)
Average annual available water resources	≈ 3720 hm³ ·yr⁻¹ (CHG, 2022)
Irrigated agriculture demand / allocation	≈ 3207 hm³ ·yr⁻¹ (≈86% of total demand) (CHG, 2022)
Agricultural decision units	10 Irrigation Demand Areas (IDAs)
Baseline year for calibration	2018
Main crop patterns (by zone)	Upper basin: olives/perennials; Middle basin: olives and cereals; Lower basin: cereals, cotton, rice and horticulture
Model outputs analyzed	Water use, irrigated area, gross margin; basin-level and Irrigation Demand Area-level distributional impacts

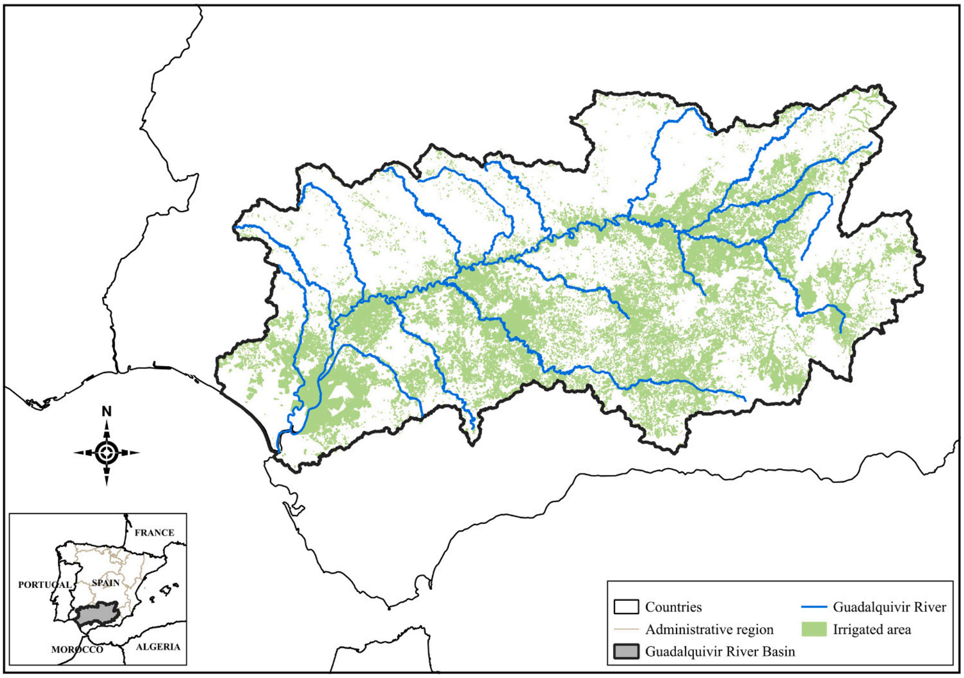

Fig. 1. Case study area. Source: Own elaboration.

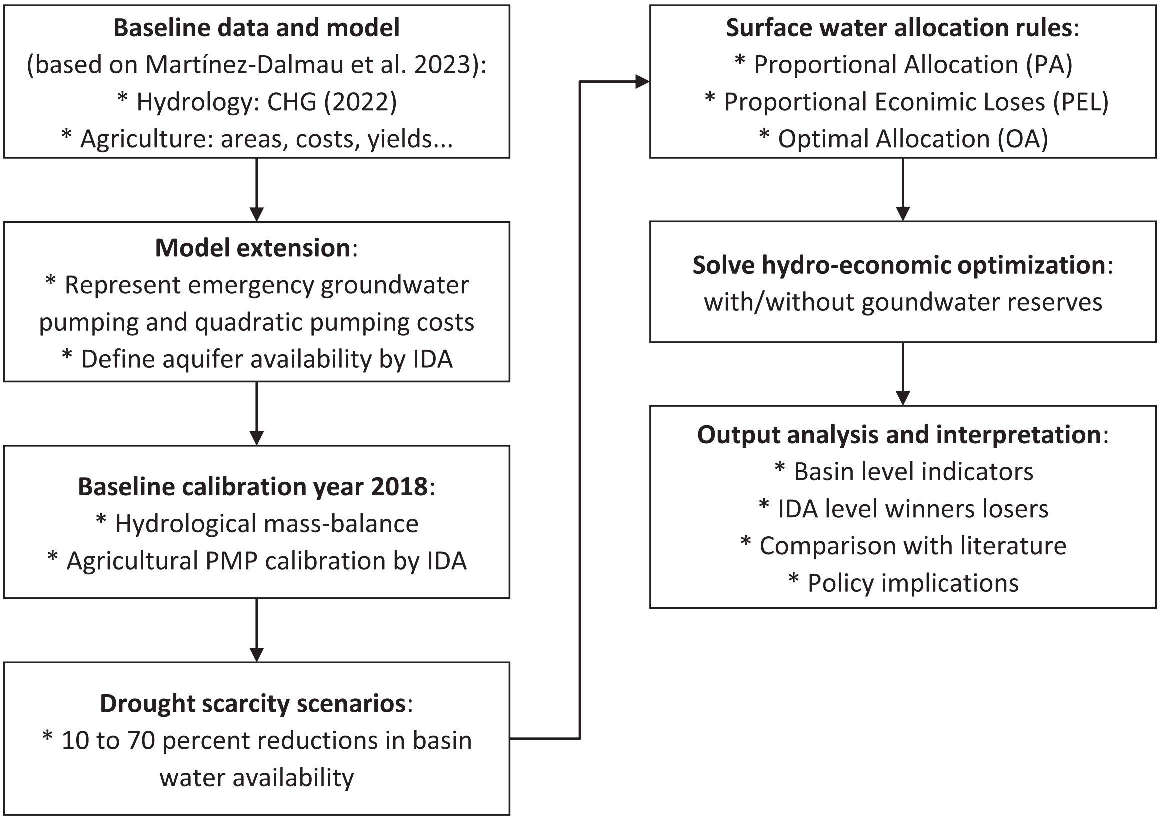

Fig. 2. Methodological framework. Source: Own elaboration.

Diversion constraints. Surface water diversions at each diversion node cannot exceed available streamflow at that node.

Water application. Water applied at each agricultural node (IDA) comes from surface diversions and/or groundwater pumping. A portion of applied water is consumed through crop evapotranspiration; the remainder returns to the river system downstream as return flows, maintaining water balance continuity throughout the basin.

Environmental flow constraints. Minimum ecological flows are enforced at six key gauging points along the main river channel, ensuring that surface water diversions do not compromise environmental requirements. These constraints are binding during drought scenarios and take precedence over agricultural allocations.

Urban water use. Water demand for urban and industrial uses is treated as a fixed parameter sourced from the River Basin Authority (CHG, 2022) and is assigned higher priority than agricultural use. Urban allocations are therefore held constant across all scenarios, and drought-induced restrictions fall exclusively on the agricultural sector.

Groundwater constraints. The model reflects the baseline conjunctive use of surface water and groundwater that is already standard practice in the irrigation districts of the GRB. Under normal (non-drought) conditions, groundwater extraction is broadly in balance with annual aquifer recharge, and this baseline conjunctive use is embedded in the model calibration. In addition, the model allows for the mobilization of additional groundwater reserves — aquifer storage beyond annual recharge — as a supplementary source of supply during drought conditions. Each IDA with access to aquifer resources therefore has an upper bound on total groundwater reserves pumping, determined by the volume of available reserves as reported by the River Basin Authority (CHG, 2022). The cost of groundwater reserves extraction follows a convex quadratic function reflecting increasing pumping depths as reserves are drawn down (Blanco-Gutiérrez, 2006), shown as follows:

$$C_a^{gw} = ax_p^2 + bx_p \tag{1}$$

where C_a^{gw} is the groundwater pumping cost in each IDA, a and b are two parameters dependent on aquifer volume and irrigated area within the IDA, and x_p is the volume of pumped groundwater applied per hectare of irrigated land.

3.2. Economic Component

Most hydro-economic models only provide results on the failure of water supply to meet the needs of the agricultural sector, and some measure economic losses. In contrast, the model developed calibrates the agricultural sector through Positive Mathematical Programming (PMP) and is able to simulate changes in the cropping plan when conditions change with respect to the baseline situation calibrated.

The economic component is an optimization model that maximizes the aggregate gross margin across all IDAs (a), crop types (j), and irrigation technologies (k):

$$Max\ GM_{total} = \sum_a \sum_j \sum_k \left(P_j \cdot Y_{ajk} - C_{ajk} - C_a^{gw} \cdot W_{ajk}\right) \cdot Land_{ajk} \tag{2}$$

where P_j is the output price of crop j, Y_{ajk} is the yield per hectare, C_{ijk} represents variable production costs (including surface water and groundwater in the baseline scenario), C_a^{gw} is the total groundwater reserve cost from Eq. 1, W_{ajk} the volume of groundwater applied per hectare, and $Land_{ijk}$ is the irrigated land area for each crop and technology.

The main economic constraints are the following:

Yield function. For observed crops, yield per hectare follows a linear decreasing function in planted area, consistent with the Ricardian principle of diminishing returns (Dagnino and Ward, 2012):

$$Y_{ajk} = B0_{ajk} + B1_{ajk} \cdot Land_{ajk} \tag{3}$$

where $B0$ and $B1$ are PMP-calibrated parameters (Dagnino and Ward, 2012). As planted area expands, yields decline at the margin. Alternative PMP and multi-attribute approaches have also been implemented in hydro-economic modeling (Blanco-Gutiérrez et al., 2013; Crispin Cunya et al., 2023; Pérez-Blanco et al., 2020).

Land constraints. Total irrigated area across all crops and technologies in each IDA cannot exceed available agricultural land. For perennial crops, area is additionally bounded by the observed baseline to prevent the model from expanding perennial cultivation beyond historical levels.

Perennial crop survival and fallow penalty. The model incorporates two mechanisms specific to perennial crops (olives, almonds, citrus). First, a minimum survival irrigation level ensures that a baseline amount of water can be applied to keep perennial plantations alive even when no economic profit is generated. Second, if perennial land is left fallow due to severe water restrictions, a penalty is subtracted from the objective function to account for expected future yield losses from uprooting. Together, these constraints ensure that minor water reductions do not trigger economically unrealistic abandonment of perennial crops.

4. Drought scenarios and water allocation rules

The hydro-economic model is utilized to assess the adaptive capacity of the basin in responding to severe water scarcity scenarios. Water contributions to the basin are set to reflect the water flow recorded for the reference year at the monitoring points.

Thus, the model is calibrated to a baseline scenario, using economic and hydrological information from the year 2018. Once the model is calibrated, various water allocation rules could be simulated under drought conditions, with the possibility of utilizing groundwater reserves. To this end, it has been assumed that the annual groundwater recharge is normally used alongside surface water as part of the baseline conjunctive management already practiced in the basin. However, under typical conditions, aquifer reserves (i.e., groundwater available beyond the annual recharge) are not utilized. These water reserves are those that could be made available in the event of a drought. This distinction is central to the paper's analytical framework: the scenarios labelled "without groundwater reserves" assume that only baseline conjunctive use is maintained, while those labelled "with groundwater reserves" simulate the emergency mobilization of these additional aquifer reserves as a drought mitigation strategy.

To facilitate the reading and interpretation of the results, we distinguish between "scenarios", or "drought scenarios", referring to the different water availability conditions resulting from droughts; and "rules", or "water allocation rules", referring to the various water allocation rules.

4.1. Baseline scenario

Under normal hydrological conditions, irrigated agriculture throughout the basin generates an estimated gross margin of 1099 M EUR according to the model, using 3127 hm^3 and cultivating a total of 856,429 ha of irrigated land.

4.2. Drought scenarios

Hydrological drought occurs when water storage in reservoirs falls below standard levels. Therefore, simulating prolonged drought periods may be more relevant in this context. This study evaluates the consequences of alternative water allocations and the basin's adaptive capacity during a drought episode. In this framework, some specific water scarcity scenarios are proposed, which involve a 10–70% reduction in available water in the basin compared to the reference conditions.

4.3. Water allocation rules

Various water allocation alternatives are then analyzed: a) proportional allocation, b) equal losses, and c) optimal allocation. A water allocation rule is a method by which scarce water is rationed. This study evaluates the effectiveness of three alternative water allocation rules, applied exclusively to the distribution of surface water. Groundwater reserves are freely available for use and depend solely on their availability and extraction cost. The results will, first, be analyzed under baseline conditions — that is, with surface water and the routine groundwater use already embedded in standard conjunctive management practice, but without access to additional groundwater reserves. Subsequently, the same scenarios and rules will be evaluated incorporating the mobilization of additional groundwater reserves, to quantify their contribution to drought loss mitigation.

Water allocation rules can be classified according to different criteria. Firstly, it is necessary to determine whether the objective is exclusively allocative efficiency, or whether equity in water distribution must also be considered. If the former criterion is applied, water markets, or allocation based on the marginal value of water, constitute the appropriate allocation mechanisms. If the latter criterion is applied, allocation should be governed by centralized rules aimed at maximizing overall welfare associated with water use (Madani and Dinar, 2013). Within centralized allocation rules, a further distinction can be made between symmetrical rules, which observe the axiom of "the equal treatment of equals," and asymmetrical rules, which deviate from this axiom by introducing some form of priority in access to water, such as the prior appropriation doctrine applied in the western United States, or the high-priority rights system employed in Australia (Moulin, 2000).

The selected rationing methods are described below:

a) **Proportional Allocation (PA)**: This is the most common rationing method around the world and the one applied by the water authority in the GRB in cases of water scarcity, which has established a drought protocol for situations of water scarcity called a Drought Management Plan. In this situation, water use is reduced, following proportional allocation, in all agricultural areas. This scenario prioritizes satisfying urban water demand and ensures meeting minimum environmental flow requirements. This method can be classified as "centralized" and "symmetrical." Reductions in water availability do not directly translate into reductions for the agricultural sector, as the initial reductions only affect river flows. For example, in the event of a hypothetical 25% reduction in water availability, agricultural water allocations must decrease by 14%, following proportional allocation, to meet urban water demand and environmental flow requirements. In response to this scenario, farmers would prioritize crops with the highest apparent marginal productivity of water, allocating the minimum amount of water to perennial crops to ensure their survival (if necessary).

The proportional allocation rule is implemented via a constraint that links the net water diversion (X_a^{nd}) at each IDA to a basin-wide scarcity factor f:

$$X_a^{nd} = f \cdot agwap_a, \quad \forall a \tag{4}$$

where $agwap_a$ is the water allocation each IDA would receive under full water availability. This factor f is an endogenous variable common to all IDAs, ensuring that every district faces the same proportional reduction relative to its baseline entitlement. This is consistent with the current Drought Management Plan applied by the River Basin Authority in the GRB (CHG, 2022).

b) **Proportional Economic Losses (PEL)**: This approach consists of applying a method whereby all claimants (IDAs) incur the same percentage loss in gross margin. This represents a theoretical scenario that requires complete information about the consequences of water allocation. Consequently, its practical application is limited, as it assumes a level of informational symmetry between the water authority and the users that is rarely found in reality; users are typically the ones with accurate knowledge of the benefits derived from water use.

As with the PA rule, the goal is to impose the same proportional reduction across all users, but rather than doing so in terms of water volumes, the reduction is implemented in terms of gross margin. The allocation constraint therefore requires that the relative loss in gross margin be equal across all IDAs:

$$f_{PEL} = 1 - \frac{GM_a}{GM_a^{obs}}, \quad \forall a \tag{5}$$

where GM_a is the gross margin of IDA a under the drought scenario and GM_a^{obs} is its observed gross margin under baseline conditions. The factor f_{PEL} is an endogenous variable common to all IDAs, and water is allocated by the model so as to equalize this ratio across the basin. This rule can therefore be regarded as a centralized and symmetrical method. It has been applied in Alarcón et al. (2014), described as "matching relative losses to the reference incomes"

c) **Optimal Allocation (OA)**: This scenario does not utilize proportional allocation but operates similar to a free water market without economic compensation. In this scenario, water is allocated to crops with the highest apparent marginal hydric productivity, regardless of their location within the basin, which could result in greater water use per unit area in some zones compared to others. Again, this is a scenario that requires the water authority to have complete knowledge of the users' economic outcomes.

Mathematically, the OA rule is implemented by removing both the proportional allocation constraint (4) or the equal-losses constraint (5). In their absence, the model allocates water freely across IDAs as part of the gross margin maximization problem (2); since the objective function already directs water towards its highest-value uses, no additional distributional constraint is required. Water is therefore allocated wherever its marginal contribution to basin-wide gross margin is greatest, irrespective of the baseline entitlement of each IDA.

All these scenarios allow farmers to apply survival irrigation to olives and almonds. This measure is important because, although short-term economic losses (loss of the current season's harvest) cannot be avoided, it aims to prevent long-term losses caused by the total loss of perennial crops. Additionally, all these scenarios include a penalty if farmers decide to leave land intended for perennial crops fallow, to quantify the loss of the investment.

5. Results

5.1. *Basin-level impacts across the scarcity gradient*

This subsection examines how the three water allocation rules perform across the full range of drought intensities — from 100% to 30% water availability — in terms of water use, irrigated land area, and gross margin, both with and without groundwater reserves. Understanding these aggregate basin-level outcomes is essential to assess the relative efficiency of each rule before turning to distributional questions.

Figs. 2–4 present the results of the hydro-economic model assessing the impact of different water allocation rules under scenarios of reduced water availability (ranging from 100% to 30%). The analysis focuses on three key indicators: water use (measured in cubic hectometers, Fig. 2), irrigated land area (in thousands of hectares, Fig. 3) and gross margin (in millions of euros, Fig. 4). Together, these indicators provide a comprehensive picture of how different allocation rules affect both resource utilization and economic performance under drought conditions.

Despite the reduction in available water being the same, water usage varies between different allocation rules. For example, in the 50% availability scenario, agricultural water use is reduced by 49% under the PA rule, and 45% under the PEL one, while it decreased by 42% under the OA rule. This is because, under the PA rule, water is reduced by the same proportion for all the IDAs, regardless of whether more water could be used in some areas. However, with the PEL and OA rules, it is possible to reduce water use by different percentages for each IDA and, in the case of OA, meet urban and environmental demands exactly to maximize water use for agriculture.

Comparing the results with and without groundwater, the utilization of groundwater reserves helps mitigate a significant portion of the effects of drought. As a result, the total water use does not decline as sharply, with groundwater consumption surpassing surface water use in the most extreme drought scenarios. The ability to increase water use, albeit at a higher cost, due to pumping, significantly reduces economic and production losses. On average, under a 50% water availability scenario, water use decreases by 22.9% under the PA rule, 15.9% under PEL, and 14.6% under OA, compared to reductions of 49.0%, 45.0%, and 42.0%, respectively, in the absence of groundwater reserves.

The irrigated area (Fig. 3) decreases in all water allocation rules as water availability decreases. Without groundwater, the PA rule exhibits the steepest decline from the 50% scenario downward. However, up to this point, the reduction in irrigated area is more or less similar across all the water allocation rules. Finally, in a scenario of 30% water availability, the PA rule reaches only 222,000 ha (74.1% reduction). In contrast, the PEL and OA rules can sustain a larger irrigated area throughout the water scarcity gradient, ending at 343,000 ha (59.9% reduction) and 308,000 ha (64.0% reduction), respectively. This suggests a greater capacity to preserve productive land when economic considerations guide water allocation. In fact, the PEL scenario maintains a larger irrigated area than the

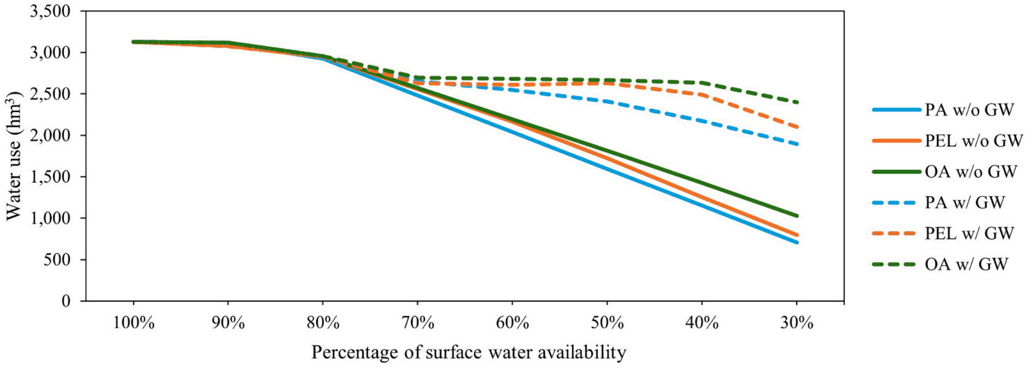

Fig. 3. Water use under different percentages of baseline water availability and allocation rules with and without groundwater reserves. Note: PA-Proportional Allocation; PEL-Proportional Equal Losses; OA-Optimal Allocation; w/o GW - without groundwater; w/ GW - with groundwater.

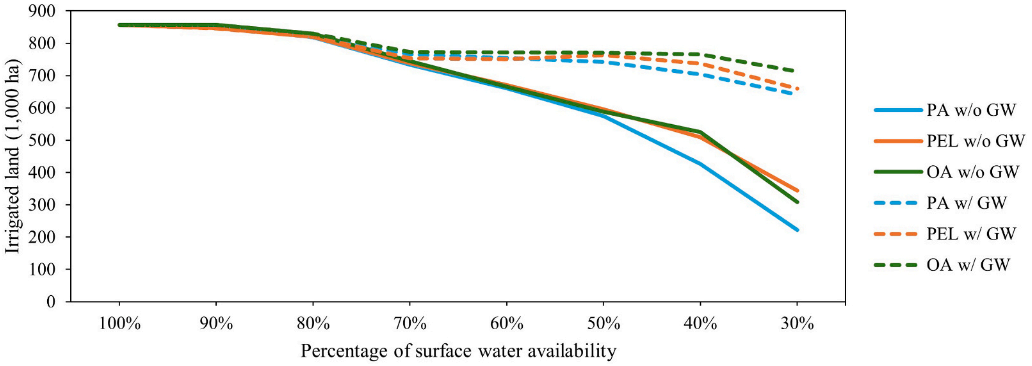

Fig. 4. Irrigated land under different percentages of baseline water availability and allocation rules with and without groundwater reserves. Note: PA-Proportional Allocation; PEL-Proportional Equal Losses; OA-Optimal Allocation; w/o GW - without groundwater; w/ GW - with groundwater.

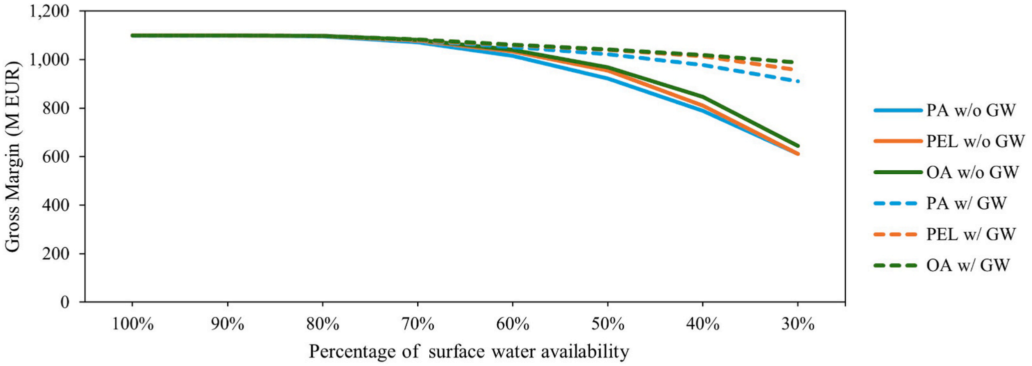

Fig. 5. Gross Margin under different percentages of baseline water availability and allocation rules with and without groundwater reserves. Note: PA-Proportional Allocation; PEL-Proportional Equal Losses; OA-Optimal Allocation; w/o GW - without groundwater; w/ GW - with groundwater.

OA one. However, the possibility of using groundwater reserves reduces irrigated area losses. Taking the 50% water availability scenario as an example, there are reductions in irrigated area of 13.4%, 10.9%, and 10.0% under each rule, compared to 33%, 30.5%, and 31.3% without groundwater reserves, respectively.

Finally, gross margin (Fig. 4) also declines across all the rules, although, in general, PA shows greater economic losses than PEL and OA. At 30% availability without groundwater reserves, OA maintains a gross margin of 645 M EUR, compared to 610 M EUR in the PEL scenario and 611 M EUR in the PA scenario. The OA scenario, despite not allowing for the largest irrigated area, exhibits the highest gross margin under water-constrained conditions. However, using, again, the scenario of 50% water availability as an example, gross margin losses are proportionally much lower than the reduction in water or land use. Under the PA rule a reduction of 16.1% of gross margin is simulated, with a 13.2% reduction for PEL and only a 12.0% for OA. The OA scenario consistently offers the highest gross margins under scarcity conditions, reflecting its greater ability to allocate water based on economic productivity. With the groundwater pumping option, the increase in crop production leads to economic losses of only 7.0%, 5.4%, and 5.3% under the PA, PEL, and OA water allocation rules, respectively.

5.2. *Distributional impacts at 50% baseline water availability*

To identify which IDAs gain or lose under each rule, this subsection disaggregates the analysis to the IDA level at a 50% baseline water availability scenario. Results are presented first without groundwater reserves, to isolate the effect of allocation rules alone, and then with groundwater, to assess how access to aquifers modifies the distributional picture.

Although the OA policy yields the best results, one might question whether allocating water to maximize the total gross margin of the basin ensures equity across regions, as it does not account for winners and losers within the basin. Using, again, the 50% water availability scenario as an example, Table 2 shows the losses with respect to the baseline scenario for the water use, irrigated area and gross margin indicators for each of the irrigation demand areas in the basin (without groundwater). The results reveal significant differences depending on the water allocation rule applied. Contrary to what might be expected, the PA rule generates the greatest economic inequities between regions (in relative terms), despite being the most equitable in terms of water distribution. Thus, a loss in gross margin ranging from 9% to 55% is observed under the PA rule. In contrast, PEL, by design, imposes an equal 13% reduction across all IDAs, being the most equitable rule in economic terms. However, the OA rule achieves the most efficient result, with a general reduction of only 12% and variations between 5% and 15%. OA is shown to be the most robust rule in the context of reduced water availability scenarios, striking the right balance between water use efficiency and maximizing economic benefits.

Table 3 shows that the use of groundwater helps mitigate the effects of drought in IDAs where groundwater reserves are available. Under the PA rule, it can be observed that in IDA 8 (rice-growing area), the reduction in water use remains unchanged compared to the scenario without groundwater reserves, as no such reserves are available. Consequently, economic losses remain at −24%. However, the PEL and OA rules allow for the transfer of additional surface water from other areas, reducing economic losses to −5%. In the case of PEL, economic losses are 5% in all IDAs when groundwater is taken into account, compared to 13% losses when groundwater is not used.

Compared to scenarios without groundwater reserves, the reductions observed in water use, irrigated area, and gross margin are significant and quite evenly distributed under all the allocation rules. However, some exceptions stand out. Under the OA policy, a notable 20% economic loss is observed in IDA 1 (headwaters of the basin) and IDA 6 (river section between Fuente Palmera and Peñaflor), which is higher than under the PA and PEL rules. This is because water use in these areas totally relies on groundwater, while all the available surface water is redirected to other zones to achieve better basin-wide impacts. Nevertheless, these zones have the lowest total gross margins, making the 20% loss relatively insignificant in overall economic terms.

6. Discussion

6.1. *Efficiency and equity trade-offs among allocation rules*

This subsection discusses the comparative performance of the three allocation rules — PA, PEL, and OA — in terms of economic efficiency and distributional equity across IDAs. Table 3 provides a structured summary of the key differences. Understanding these trade-offs is central to any policy recommendation aimed at balancing fairness and efficiency under water scarcity.

The results of this study highlight the significant implications that water allocation rules have on economic efficiency, agricultural productivity, and regional equity in contexts of increasing water scarcity. A comparative summary of the differences between the water allocation rules analyzed in this study can be found in Table 3. Although Proportional Allocation currently remains the dominant approach, due to its administrative simplicity and apparent fairness in terms of resource distribution, its limitations become evident in terms of its economic performance, as other studies have already demonstrated for the GRB (Valle-García et al., 2024, 2025). Under this rule, there are marked disparities in gross margin losses between the different Irrigation Demand Areas. This result is supported by other studies, such as that by Iftekhar and Fogarty (2017), who demonstrated that a proportional reduction in (groundwater) allocations leads to inequities between farms. Larger farms suffer greater revenue losses than smaller farms per unit of water reduced. Based on the results presented in Alarcón et al. (2014), it can also be concluded that proportional allocation generates relative differences in economic outcomes, even though the aggregate results of the PA and PEL rules are very similar. Wegerich (2007) also argues that to achieve equal outputs it might be that very unequal inputs have to be applied, as equal inputs might not lead to equal outputs. Equity is an ambiguous concept that encompasses aspects of equality, fairness and justice, which are beyond the scope of this study. Here, we simply analyze differences in economic losses across different agricultural areas. In this study, equity should be interpreted as “similarity in allocation” or “similarity in losses.”

In contrast, rules based on economic criteria, such as the Proportional Economic Losses rule, and especially the Optimal Allocation rule, achieve greater efficiency in water use. These approaches reduce the irrigated area to a lesser extent and better preserve gross margins under scenarios of severe scarcity. Though counterintuitive, these efficiency gains are not accompanied by distributive implications. The OA rule, while maximizing total economic benefits, does so by concentrating resources in the most productive areas, potentially generating “losers” in less profitable regions. Actually, under the OA rule, every single IDA shows less economic losses than in the case of the PA rule, and only two agricultural areas (IDA 1 and 6) show greater losses than when following the PEL rule, which renders the economic losses between all the IDAs equal. This reveals OA as the best possible rule when rationing water, and PA as the worst, with the PEL rule offering an intermediate alternative that improves system profitability while maintaining a more balanced

Table 2
Main results by Irrigation Demand Area at 50% water availability without groundwater.

		IDA 1	IDA 2	IDA 3	IDA 4	IDA 5	IDA 6	IDA 7	IDA 8	IDA 9	IDA 10
Water use (hm^3)	PA	-49%	-49%	-49%	-49%	-49%	-49%	-49%	-49%	-49%	-49%
	PEL	-24%	-27%	-34%	-43%	-46%	-39%	-56%	-36%	-40%	-49%
	OA	-16%	-19%	-30%	-43%	-44%	-42%	-59%	-22%	-29%	-49%
Irrigated land (1000 ha)	PA	-20%	-15%	-16%	-36%	-36%	-38%	-45%	-49%	-29%	-33%
	PEL	-3%	-6%	-15%	-33%	-35%	-31%	-50%	-36%	-22%	-33%
	OA	-1%	-4%	-12%	-33%	-33%	-32%	-58%	-22%	-19%	-34%
Gross Margin (M EUR)	PA	-55%	-47%	-28%	-18%	-15%	-21%	-9%	-24%	-17%	-13%
	PEL	-13%	-13%	-13%	-13%	-13%	-13%	-13%	-13%	-13%	-13%
	OA	-5%	-6%	-9%	-13%	-12%	-15%	-14%	-5%	-5%	-13%

Table 3
Main results by Irrigation Demand Area at 50% water availability including groundwater reserves.

		IDA 1	IDA 2	IDA 3	IDA 4	IDA 5	IDA 6	IDA 7	IDA 8	IDA 9	IDA 10
Water use (hm^3)	PA	-5%	-12%	-33%	-15%	-16%	-12%	-17%	-49%	-38%	-14%
	PEL	-5%	-6%	-16%	-12%	-13%	-10%	-17%	-23%	-27%	-11%
	OA	-5%	-6%	-9%	-12%	-13%	-10%	-16%	-22%	-11%	-11%
Irrigated land (1000 ha)	PA	-1%	-3%	-13%	-13%	-13%	-11%	-17%	-49%	-22%	-10%
	PEL	0%	-2%	-7%	-11%	-11%	-9%	-17%	-23%	-18%	-8%
	OA	0%	-2%	-4%	-11%	-11%	-9%	-17%	-22%	-9%	-8%
Gross Margin (M EUR)	PA	-10%	-10%	-14%	-8%	-8%	-9%	-5%	-24%	-11%	-5%
	PEL	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%	-5%
	OA	-20%	-5%	-4%	-8%	-8%	-20%	-3%	-5%	-2%	-9%

Table 4
Comparison of criteria between the three water allocation rules.

Criterion / Rule	**Proportional Allocation (PA)**	**Proportional Economic Losses (PEL)**	**Optimal Allocation (OA)**
Allocation principle	Proportional reduction based on rights	Homogeneous reduction of gross margin	Maximization of added economic value
Normative approach	Formal equity / administrative simplicity	Equity in economic impacts	Economic efficiency
Information requirements	Low (only water rights)	High (margins by zone and crop)	Very high (margins, elasticities, etc.)
Flexibility	Low	Medium	High
Impact on gross margins	Highest loss	Intermediate	Lowest loss
Economic equity	Low	Medium	High (except IDA 1 and 6 with groundwater)
Irrigated area preserved	Lowest	High	Medium
Political feasibility	High (currently implemented)	Medium (requires transparency and consensus)	Low (conflictive without compensation)
Adaptability to severe drought	Limited	Medium / High	High
Practical implementation	Frequent	Theoretical / experimental	Rarely applied without a market

distribution of economic losses. Nevertheless, OA consistently achieves superior overall outcomes, making it preferable to the other alternatives. Goetz et al. (2005), Goetz et al. (2017); Martinez and Esteban (2014), and Alarcón et al. (2014) also examine alternative allocation rules in Spain, such as equal gains, equal losses,[1] and market-based mechanisms, and consistently show that proportional allocation — despite its apparent fairness — often results in economically inefficient outcomes, with market allocation outperforming all of them, especially in settings with heterogeneous farm structures (Gómez-Limón et al., 2020).

Although the PA represents the current operational framework, favoring administrative simplicity and equitable allocation, the scenarios incorporating economic efficiency (PEL and OA) demonstrate better performance in terms of cost-effectiveness and resource use efficiency during periods of scarcity.

Our quantitative estimates are consistent with previous applications of bankruptcy-inspired rationing rules to irrigation shortages (Alarcón et al., 2014; Sechi and Zucca, 2015), which generally find that proportional allocation can be dominated by rules that incorporate economic information. The contribution here is that we demonstrate—using a single calibrated basin model—that the ranking of allocation rules (OA $>$ PEL $>$ PA in terms of aggregate gross margin) remains robust when farmers can substitute surface

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[1] Under the equal gains method (also referred to as “uniform gains” or “constrained equal awards”), each claimant is allocated an identical amount, provided that this amount does not exceed their individual claim. In a similar way, the equal losses method (also known as constrained equal losses) reduces all claims by an equal amount. Not to be confused with the equal economic losses rule proposed.

water with groundwater reserves, but the magnitude of the differences shrinks because conjunctive use tends to equalize marginal water values across crops and locations. In addition, we show that ‘apparent’ equity in volumetric rationing does not prevent large territorial disparities in economic impacts, a point often overlooked when drought protocols are discussed only in terms of uniform percentage cuts.

6.2. The mitigating role of groundwater reserves conjunctive use

This subsection examines how access to groundwater reserves modifies the magnitude and distribution of drought-induced losses under each allocation rule. The analysis shows that conjunctive use is a powerful buffer, but that its effect is not uniform across rules or areas — a distinction with important implications for policy design.

The results also demonstrate that groundwater plays a critical buffering role in maintaining agricultural production and economic returns under conditions of surface water scarcity. Across all three allocation rules, the magnitudes of the reductions in water use, irrigated area, and gross margin are consistently lower than in the cases without groundwater. OA, once again, delivers the best performance, minimizing losses across all the indicators. The PEL offers a middle ground, combining a degree of equity with improved efficiency. Meanwhile, the PA, although simple and administratively feasible, remains the least efficient approach, particularly from an economic standpoint.

Groundwater plays a vital role in irrigated agriculture, particularly in regions where limited rainfall restricts the availability of surface water. For this reason, many hydro-economic models combining surface and groundwater resources can be found in the literature (e.g., Hermine Mitter, 2021; Kahil et al., 2016; Medellin-Azuara et al., 2015). The results of this study are consistent with previous research on the use of groundwater as a buffer during drought periods. Mussá et al. (2015) found that during the 1992–1995 drought in South Africa, approximately 60% of the water deficit was offset by groundwater reserves. In our case, for the most severe drought scenario (30% water availability), groundwater compensates for nearly 44% of the deficit, highlighting the need for integrated surface and groundwater management to mitigate the impacts of drought.

This use of groundwater depends on proper prior management that allows for the establishment of reserves, providing a form of insurance against droughts (Pérez-Blanco and Gómez, 2014). An illustrative example can be found in the Goleta Basin (California), where groundwater reserves enabled the use of wells during the 2012–2015 drought, while nearby basins experienced a significant decline in groundwater levels (Langridge and Daniels, 2017). This implies that the value of groundwater, when surface water availability is stochastic, is higher than in a deterministic setting, as it can be used to offset deficits from more variable sources. This phenomenon is known as the “buffer value of groundwater” (Tsur and Graham-Tomasi, 1991), and this buffer value is positive. These authors estimated that the buffer value of groundwater could account for up to 84% of the total resource value, depending on extraction costs, the variability of surface water flows, and aquifer storage capacity. Koundouri et al. (2017) argue that ignoring this buffer value creates a risk externality: each additional unit of groundwater reserve available for future use reduces the income risk faced by all farms by increasing the buffer against water scarcity risk.

In fact, in the Guadalquivir River Basin, water authorities rely on “drought wells”, which are operated only during drought events to supplement surface water supplies (Llamas et al., 2015) but not under normal conditions. Their year-round accessibility and protection from evaporation make them strategic resources for ensuring crop production, stabilizing yields, and coping with drought conditions. Moreover, they support the development of more efficient and resilient irrigation systems in areas where other water sources are insufficient or already overexploited. However, the intensive and often unregulated extraction of aquifers entails significant risks (Berbel et al., 2018). Overexploitation leads to a drop in the water table, which can result in soil salinization, the degradation of water quality (Dorado-Guerra et al., 2021), the drying up of springs and wetlands, and, in some cases, land subsidence (Esteban et al., 2024). These impacts threaten not only environmental sustainability but also the long-term economic viability of agriculture. Recent research demonstrated how drought and over abstractions can significantly impact groundwater level recovery and groundwater quality long after droughts occur (Petersen-Perlman et al., 2022). Therefore, the balanced and responsible management of groundwater is essential. This should involve efficient use, conservation strategies, continuous monitoring, and artificial recharge programs, ensuring the resource remains available.

The inclusion of groundwater reserves in our hydro-economic model significantly increases the flexibility of water allocation rules, allowing systems to maintain a larger irrigated area and higher gross margins even under severe water reduction scenarios. The PA and PEL rules show significant improvements in terms of basin-level and individual outcomes (by IDA). Access to groundwater reserves complements the surface water supply, equalizing the marginal values of water. Although the PR rule does not allocate water seeking an equitable economic distribution, the access to groundwater allows for the use of additional resources when the marginal value of crops exceeds the cost of pumping. The OA rule still exhibits the best overall performance, although the differences with the other two rules are now much slighter, particularly with the PEL rule, which yields very similar overall results. However, at the IDA level, the OA rule results in a less equitable distribution of economic losses (IDA 1 and 6 resulting in 20% of economic losses) compared to the PEL rule, which could be preferable given that its overall performance is very similar to that of OA.

6.3. Policy implications and results transferability

The findings of this study carry direct implications for water governance in the Guadalquivir River Basin and analogous semi-arid basins. This subsection addresses the institutional and operational conditions required to move from current practice — predominantly Proportional Allocation — towards more economically efficient and equitable frameworks, including the governance of groundwater reserves.

The main limitation of the Optimal Allocation rule lies in the lack of information regarding the marginal value of water in each area without prior analysis. However, an intermediate outcome could be achieved through the establishment of a centralized water bank acting as an intermediary between buyers and sellers of temporary water rights (Montilla-López et al., 2018; Soula et al., 2023). Such a water bank would make possible the optimal allocation of resources, although the resulting economic outcome would fall short of that achieved through direct allocation based on economic criteria, due to the influence of trading prices and transaction costs.

Transferability of the findings to other basins rests on the structural features represented in the model rather than on GRB-specific parameter values. The key conditions are: (i) irrigation is the dominant consumptive user, (ii) drought management relies on administrative rationing of water rights, (iii) crop portfolios are heterogeneous in marginal water productivity, and (iv) groundwater (or other backstop supplies) can be mobilized at increasing marginal cost. Under these conditions—which characterize many semi-arid Mediterranean basins and comparable settings in Australia, the western United States and North Africa—economically-informed allocation rules tend to reduce aggregate losses relative to purely proportional cuts, while conjunctive use dampens losses but raises sustainability concerns. Where any of these conditions fail (e.g., severe groundwater depletion, tight pumping constraints, or non-agricultural demands dominating), the size of the gains and the distribution of impacts may differ, so local calibration and stakeholder constraints remain essential.

7. Conclusions

This study quantifies how alternative rationing rules and emergency groundwater pumping jointly shape drought impacts in the Guadalquivir River Basin. Across scarcity scenarios, economically-informed rules reduce aggregate losses relative to proportional cuts; at a 50% baseline water deficit, gross-margin losses fall from 16.1% under proportional allocation to 12.0% under optimal allocation, and to about 5.3%–7.0% when groundwater reserves are available as a buffer.

Contribution relative to similar research is threefold: (i) we extend an existing calibrated GRB hydro-economic model by explicitly representing emergency access to groundwater reserves with increasing pumping costs; (ii) we compare allocation rules both with and without conjunctive use, showing that groundwater dampens drought damages and narrows rule-performance differences; and (iii) we report territorial distributional effects (winners/losers by IDA), highlighting that volumetric proportionality can still produce highly uneven economic outcomes.

From a governance perspective, the Proportional Economic Losses (PEL) rule emerges as a pragmatic compromise that improves efficiency while equalizing relative income losses, whereas Optimal Allocation (OA) maximizes basin-wide benefits but may require complementary instruments (e.g., transparent information systems, water banks, or compensation) to manage distributional concerns.

Key limitations and simplifying assumptions include: fixed crop prices and input costs; a single-year (2018) baseline calibration; perfect-information implementation of PEL and OA; and a simplified representation of groundwater dynamics (no multi-year storage/recovery, quality, or regulatory pumping constraints). Future work could couple the model with dynamic aquifer modules, alternative climate sequences, and institutional constraints to reduce uncertainty and improve policy realism.

CRediT authorship contribution statement

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

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.

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Data Availability

Data will be made available on request.

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