



Priority Water Rights for Irrigation at the River Basin Level. Do They Improve Economic Efficiency During Drought Periods?

Carlos Gutiérrez-Martín¹ · José A. Gómez-Limón¹ · Nazaret M. Montilla-López¹

Received: 6 April 2022 / Accepted: 15 June 2022 / Published online: 13 July 2022
© The Author(s) 2022

Abstract

This paper assesses the potential efficiency gains of reforming the water rights regime in the Spanish agricultural sector by replacing current allocation procedures based on the proportional rule with a priority allocation procedure based on two tiers of security-differentiated water rights. This assessment is useful for evaluating whether said change in water rights can be considered a suitable policy instrument to improve water management during droughts events. For this purpose, a mathematical programming model is built to simulate the performance of the proposed reform. The empirical analysis is implemented at the basin scale, where water rights holders are highly heterogeneous, considering different climate scenarios accounting for changes in water supply reliability. The Guadalquivir River Basin (GRB) in southern Spain is used as a case study. The results obtained show that this change in the water allocation regime would yield only modest economic efficiency gains under the current climate scenario. However, it is also evidenced that this policy instrument could play a more relevant role as an efficiency enhancer in a climate change scenario, given that more frequent and intense drought episodes are expected. Moreover, priority rights represent an interesting risk management instrument for farmers, allowing the most vulnerable farmers to reduce income volatility. These findings suggest that the combined implementation of the proposed shift in the allocation regime with spot or allocation water markets would lead to successful outcomes, significantly improving drought management in the irrigation sector.

Keywords Water allocation regime · Cyclical scarcity · Security-differentiated water rights · Economic efficiency · Guadalquivir River Basin (Spain)

1 Introduction and Objectives

Existing water rights allocation regimes are the result of local historical trajectories, which often go back centuries (OECD 2015). This is why these allocation regimes do not usually align with society's current priorities, which reflect the growing demand for water for urban and economic

✉ Nazaret M. Montilla-López
g02molon@uco.es

¹ WEARE-Water, Environmental, and Agricultural Resources Economics Research Group, Universidad de Córdoba, Córdoba, Spain

uses, and a focus on ecosystem services (e.g., ecological flows), as opposed to the traditional allocation where agriculture is the largest user. This mismatch of current water allocation and society's priorities is an important source of inefficiency that policy-makers and water managers must seek to minimize. For this reason, various international organizations have raised the need to reform these allocation regimes to achieve a more efficient and sustainable allocation of increasingly scarce water resources (e.g., Bruns et al. 2005; Hodgson 2006; OECD 2015).

Inefficiency in water use becomes especially acute during cyclical scarcity events (i.e., droughts), when matching supply and demand is a major challenge (Hanemann 2006). Under these circumstances, water managers have to ration water allocations until aggregate water supply equals water availability. There are two main alternative approaches to water rationing (Sechi and Zucca 2015; Degefu and He 2016; OECD 2016): proportional and priority rules. The *proportional rule* is the most widely-used procedure for water rationing among water rights holders, especially in countries with more traditional water institutions. According to this rule, all water rights holders receive a quantity of water proportional to their water rights, calculated so that total allocations equals total water availability. This is the rule currently applied in Spain to ration water among agricultural water rights holders (i.e., farmers) during drought periods. On the other hand, the *priority rule* is used to ration water in the Western US and Australia. This rule ensures the demands of the highest priority rights holders are met first, and once they are fully satisfied, the remaining resource is allocated to the other rights holders in decreasing order of priority.

Gómez-Limón et al. (2020) discuss the advantages and disadvantages of both allocation rules. They present a wide range of empirical evidence pointing to the implementation of the proportional rule as a source of inefficiency in the irrigation sector (e.g., Alarcón et al. 2014; Martínez and Esteban 2014; Goetz et al. 2017; Rightnar and Dinar 2020). In fact, the literature suggests that allocation regimes based on priority rights (or security-differentiated water rights) are a suitable alternative to proportional rights since they enable more efficient and sustainable water use (e.g., Freebairn and Quiggin 2006; Lefebvre et al. 2012).

The abovementioned evidence points to the need to reform water allocation regimes currently based on the proportional rule, introducing water rights regimes with different priority levels. Theoretically, this reform would enhance water use efficiency since the aggregate profit gains obtained by water rights holders with higher priority (more reliable supply) would outweigh the aggregate losses suffered by holders with lower priority (less reliable supply). These efficiency gains would be especially critical during drought periods, allowing the scarce resources to be allocated to the highest value-added users. For this reason, security-differentiated water rights are considered an adaptation measure to climate change (Xu et al. 2014; Mallawaarachchi et al. 2020), given that more frequent and intense cyclical water shortages are expected (Bisselink et al. 2018).

However, there is scarce empirical evidence of the efficiency gains that can be achieved by shifting away from proportional allocation towards a priority rule allowing the implementation of security-differentiated water rights. To the best of the authors' knowledge, the only relevant study in this sense is the one by Gómez-Limón et al. (2021), who assessed the efficiency gains achieved through the implementation of the priority rule with two priority rights levels within an irrigation district. However, the improvement in economic efficiency compared to the proportional rule was almost negligible. They conclude that this disappointing result could be due to the lack of heterogeneity in water rights holders (i.e., farmers) within a single irrigation district and the fact that the supply of irrigation water allocations in the irrigation district considered as a case study is fairly reliable (in more than 70% of the years, annual water allocations meet farmers' demands for their crop mixes).

In light of the situation described above, this paper aims to contribute to the existing literature by testing two hypotheses regarding the implementation of priority rights in the irrigation sector. The first is the hypothesis that replacing a water allocation regime based on proportional rights with another regime based on two levels of priority rights would significantly increase economic efficiency when this change is implemented at the basin level, where there is large heterogeneity among agricultural water rights holders. The second hypothesis is that the less reliable the irrigation water supply (i.e., under more frequent and intense droughts due to climate change), the more significant the efficiency gains achieved due to the implementation of priority rights.

Therefore, the main objective of this paper is to test the two abovementioned hypotheses empirically. For this purpose, a mathematical programming simulation exercise is performed to assess the improvement in economic efficiency that could be achieved by replacing the current proportional rule with a priority allocation procedure based on two tiers of security-differentiated water rights. Moreover, the empirical analysis is implemented at the basin scale (i.e., heterogeneous rights holders), considering different climate scenarios (i.e., varying water supply reliability). To that end, we focus on the Guadalquivir River Basin (GRB) in southern Spain as a case study.

2 Water Allocation in Spain: a Proposal for Reform

All water resources in Spain are legally in the public domain. Water use for private activities is allowed through water rights granted by the river basin authorities (RBAs) under the terms of the River Basin Management Plans (RBMPs), according to which rights holders can extract water from a specific water body (river, aquifer, or reservoir) up to a maximum annual volume (full water allotment). However, the RBAs do not guarantee the availability of said maximum water volume every year. The volume of water actually available for each rights holder (annual water allocation) is set every year depending on the hydrological situation (water availability).

Annual water allocations granted to irrigation districts are managed as a common property resource through water user associations, where all farmers obtain the same amount of water per irrigated hectare. However, these farmers can distribute the water as they choose within their own farms.

When a drought occurs in Spain, the RBAs limit water allocations as stipulated by the RBMPs. Since urban uses have absolute priority over agricultural use (ranked as the second priority level), during drought periods, proportional water rationing is only applied to agricultural water rights holders, which account for most of the water rights in the Spanish basins.

This paper proposes a shift away from proportional allocation in agriculture towards a priority rule allowing the implementation of security-differentiated water rights at the basin level, similar to the Australian case. Thus, two priority classes are proposed, with a distinction between high-security or 'priority' rights and low-security or 'general' water rights. Farmers would be able to combine these two priority rights, creating a portfolio of water rights to achieve any desired level of reliability while minimizing the transaction costs involved in dynamically adapting to the optimal mix (Young and McColl 2003).

Initially, all farmers would be considered to hold general water rights, and only a certain share of total rights would be eligible for upgrade into priority rights through an auction procedure. In these auctions, the rights holders would bid to upgrade their rights through a

surcharge on the annual payment to their basin authority. The total amount of money collected through these surcharges would be set aside to compensate all general rights holders in the basin for the decline in their supply reliability. Moreover, under the proposal simulated here, those who win the bid in the auction can hold priority rights forever, enabling long-term investment planning (e.g., fruit orchards or irrigation technology). In any case, our proposal also assumes that there would be a local water rights market allowing a dynamic allocation of these priority rights.

For the proposed change to be successful, the increase in farm profitability achieved by reliability winners must be higher than the surcharges they would have to pay, and the compensation received by reliability losers must outweigh their farm profitability losses. This condition would be met only if the change in allocation rule leads to an increase in economic efficiency, that is, if the aggregate profitability at the basin level increases.

3 Case Study

3.1 The Irrigation Sector in the Guadalquivir River Basin

The Guadalquivir is a 650 km-long river in the south of the Iberian Peninsula. Its basin, which covers an area of 57,527 km², has a typical Mediterranean climate (i.e., mild, wet winters and warm, dry summers) suitable for profitable irrigated agriculture (i.e., olives, other fruits, and vegetables). Annual precipitation usually ranges between 500 and 700 mm, although there are frequent drought episodes (less than 500 mm/year).

After several decades of intensive infrastructure construction to increase the availability of water resources, the basin is now administratively closed to new users (Berbel et al. 2013). As a result, the average water use in the GRB amounts to 3815 hm³ per year, of which approximately 3357 hm³ is used for irrigation (88% of the total water demand) and 379 hm³ is used by households and for other urban demands (10%) (CHG 2015). Spanish water law stipulates that urban demands are served first in the event of a water shortage (priority rule), meaning such demands are always covered. However, during drought episodes, the scarce water resources available for agriculture are rationed among farmers, according to the proportional rule.

Within the GRB, there are more than 850,000 hectares of irrigated land (see Fig. 1). The main crops in the basin are olive groves (52%), winter cereals (8%), cotton (7%), citrus (4%), rice (4%), and fruit trees (3%). The most widely-used irrigation technology is drip irrigation.

According to the most recent data available (MAPA 2020), the irrigated areas in the GRB can be classified into four different categories: a) Traditional irrigated areas with extensive annual crops (5% of the irrigated area in the GRB); b) Modern irrigated areas with intensive annual crops (40%); c) Olive groves (51%); and d) Rice paddies (4%). Considering these categories, we selected seven representative irrigation districts (IDs) in the GRB. Table 1 provides information about the main relevant features (area, number of farmers, main crop, and irrigation technology) of each ID.

The next step after selecting the IDs was to identify the different production profiles at the farm level. In order to characterize the 1624 farms located in these IDs, primary information was obtained from a survey of 355 farmers selected using random route sampling. Data were collected on the farms' main production features (size, crop mix, production

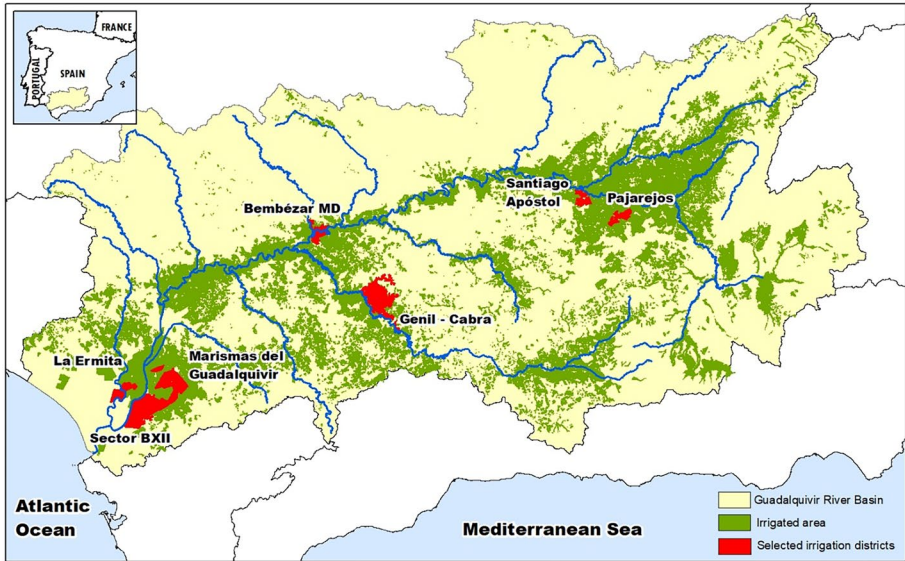


Fig. 1 Irrigated agriculture in the GRB and selected irrigation districts. Source: CHG (2015)

technology, yields, prices, and costs by crops) and the farmers' socio-demographic characteristics. Farms within each ID were divided into farm types (f), accounting for the heterogeneity in terms of profitability and productivity of water. This farm typology was determined by performing cluster analyses in each ID, using the percentage of the area devoted to each crop as differentiating variables. Table 1 shows the most relevant data for each farm type.

Complete primary information on farm types and crop data can be found in the supplementary material, along with other secondary sources also supporting the findings of this study.

3.2 Annual Water Allocations in the GRB

Table 2 presents data related to the irrigated area and full water allotment per ID category (Traditional, Modern, Olive, and Rice). It is worth noting that water rights are granted to each ID, allowing their farmers to receive water allocations that fully cover crop water needs in 'normal' hydrological years.

However, because the GRB is located in a drought-prone region (the Mediterranean basin), water availability varies widely across hydrological years. This means that annual water allocations in each ID (wa_{id}) are frequently lower than the full water allotments (fwa_{id}) established in the water rights. In fact, annual water allocations in the GRB are stochastic variables, which Gómez-Limón (2020) characterized based on a stochastic hydrological model considering current water availability (rainfall, water run-off, and water storage in dams), water demands (existing water rights), and water management rules (e.g., minimum ecological flows) set out in the Guadalquivir RBMP (CHG 2015). This characterization yields the histogram shown in Fig. 2a.

Notwithstanding, the stochastic hydrological model developed by Gómez-Limón (2020) is only suitable for simulating near-future hydrological years, since it does not account for

Table 1 General description of the selected irrigation districts and farm types

Category	Irrigation district (coordinates in DMS format)	Farm type and ID	Irrigated area (ha)	No. of farms	Average farm size (ha)	Main crops (% irrigated area)	Irrigation technology (% irrigated area)
Traditional	Las Marismas del Guadalquivir (37°6'35.2"N 5°56'5.7"W)	f1.1	1670	122	13.64	Cotton (97%)	Furrow (100%)
		f1.2	9698	272	35.65	Cotton (61%), Corn (19%)	Furrow (100%)
		f1.3	612	34	18.00	Alfalfa (57%), Cotton (43%)	Furrow (100%)
Modern	Sector BXII del Bajo Guadalquivir (36°59'21.4"N 6°6'6.9"W)	ID1	11,980	429	27.96	Cotton (63%), Alfalfa (16%), Corn (10%)	Furrow (100%)
		f2.1	7646	214	35.80	Tomato (30%), Cotton (30%), Sugar beet (24%)	Sprinkler (66%), Drip (34%)
		f2.2	5336	223	23.95	Cotton (57%), Tomato (13%)	Sprinkler (76%), Drip (24%)
		f2.3	1671	111	15.00	Cotton (56%), Sugar beet (40%)	Sprinkler (100%)
		ID2	14,654	548	26.75	Cotton (44%), Sugar beet (21%), Tomato (19%)	Sprinkler (75%), Drip (25%)
		f3.1	7187	205	34.99	Olive (31%), Sunflower (27%), Wheat (20%)	Sprinkler (69%), Drip (31%)
		f3.2	3037	117	25.88	Wheat (25%), Orange (23%), Sunflower (20%), Cotton (14%)	Sprinkler (68%), Drip (32%)
Margen Izquierda del Bembézar (37°46'43.0"N 5°9'51.4"W)	f3.3	778	117	6.63	Olive (100%)	Drip (100%)	
	ID3	11,002	440	25.00	Olive (35%), Sunflower (22%), Wheat (20%)	Sprinkler (60%), Drip (40%)	
	f4.1	2714	34	79.65	Corn (32%), Orange (25%), Olive (12%)	Drip (80%), Sprinkler (20%)	
	f4.2	1191	25	47.64	Orange (100%)	Drip (100%)	
ID4	4009	f4.3	104	8	13.10	Corn (100%)	Drip (100%)
		ID4	4009	67	59.82	Orange (48%), Corn (28%)	Drip (88%), Sprinkler (12%)

Table 1 (continued)

Category	Irrigation district (coordinates in DMS format)	Farm type and ID	Irrigated area (ha)	No. of farms	Average farm size (ha)	Main crops (% irrigated area)	Irrigation technology (% irrigated area)
Olive	Pajarejos (37°51'43.1"N 3°31'8.1"W)	f5.1/ID5	627	36	17.40	Olive (100%)	Drip (100%)
	Santiago Apóstol (37°56'15.6"N 3°44'51.1"W)	f6.1/ID6	250	39	6.40	Olive (100%)	Drip (100%)
Rice	La Ermita (37°32'1.9"N 6°12'42.2"W)	f7.1/ID7	2554	65	39.30	Rice (100%)	Furrow (100%)

feasible impacts of climate change at the basin level. In fact, the present study uses the outputs from that hydrological model solely to simulate the performance of the proposed priority rights regime under the ‘current climate’ scenario.

Developing a hydrological model accounting for climate change is a complex task involving the use of simulated climate data reflecting different climate change scenarios for updated hydrological modeling estimating new distributions of rainfall and water inflows (e.g., Raju and Kumar 2018) and revised agronomic modeling estimating new irrigation water needs (e.g., Ewert et al. 2015). However, it is a challenge that goes far beyond the scope of this paper. The present study seeks to explore whether feasible changes in the climate would make priority rights a more suitable policy instrument to improve economic efficiency during drought episodes, assessing the role of this instrument in facilitating adaptation to climate change. For this exploratory assessment, we modified the hydrological model from Gómez-Limón (2020) in order to generate a feasible “climate change” scenario for the Spanish case according to the specialized literature (CEDEX 2017). To that end, we assumed climate change will involve more frequent drought episodes, thus increasing the probability of hydrological years with water shortages ($wa_{id} < fwa_{id}$) by 30%; and more intense drought episodes, increasing the gap $fwa_{id} - wa_{id}$ in every hydrological year with a water shortage by 30%. In any case, it is worth noting that while the climate change scenario built by changing the abovementioned parameters is feasible, it is still hypothetical and its probability of occurrence is unknown. This modified modeling has allowed us to characterize the distribution of annual water allocations under the climate change scenario as shown in the histogram displayed in Fig. 2b.

Table 2 presents data related to water allocations and gross margins per ID category and climate scenarios considering the implementation of the current proportional allocation rule for water rationing. It is worth noting here that recurrent drought episodes involve average water allocations below the full water allotments. This is especially true for the climate change scenario, where water resources become scarcer. The decrease in average water allocations also leads to lower gross margins, although the impact on farms’ profitability is heterogeneous among IDs. Table 2 also shows the coefficients of variation of both

Table 2 Categories of irrigation districts: Irrigated area, full water allotment, and water allocations under current climate and climate change scenarios

	Category of irrigation districts				Basin
	Traditional	Modern	Olive	Rice	
Irrigated area (ha)	39,396	316,022	413,655	35,114	856,428
Full water allotment (m ³ /ha)	6100	4813	1500	11,500	3464
Gross margin with full water allotment (€/ha)	1384	2003	930	1471	1397
Current climate scenario					
Average water allocation (m ³ /ha)	4779	3771	1175	9009	2714
Gross margin for average water allocation (€/ha)	1306	1866	894	1173	1309
Coef. of variation of water allocations	0.31	0.31	0.31	0.31	0.31
Coef. of variation of gross margins	0.13	0.13	0.08	0.28	0.12
Climate change scenario					
Average water allocation (m ³ /ha)	4238	3344	1042	7990	2407
Gross margin for average water allocation (€/ha)	1235	1762	860	1051	1241
Coef. of variation of water allocations	0.43	0.43	0.43	0.43	0.43
Coef. of variation of gross margins	0.18	0.18	0.11	0.39	0.16

stochastic variables (water allocations and gross margins) as statistics describing the dispersion of values around the average.

4 Modeling Approach

A mathematical programming model is built to simulate farmers' behavior under the proposed water rights regime. The simulation exercise enables a comparison of the potential performance of the proposed allocation regime with that of the current proportional allocation rule in terms of economic efficiency.

4.1 Proportional and Priority Allocation Rules

The basin (subscript b) taken as a case study is represented by a sample of seven IDs (subscript id), each of which has a different number of farm types (subscript f) which are considered as the decision-making units. Each farm type represents a number of farms $nf_{id,f}$ with an average size of $s_{id,f}$ irrigated hectares, with s_{id} being the total irrigated area in each ID ($s_{id} = \sum_f nf_{id,f} \cdot s_{id,f}$). Moreover, each ID in the sample represents m_{id} irrigation districts with similar features within the GRB, and s_b is the total irrigated area in the basin ($s_b = \sum_{id,f} m_{id} \cdot nf_{id,f} \cdot s_{id,f}$).

Under current management rules, the annual aggregate volume of water available for irrigation at the basin level (WA_b measured in cubic meters) is shared among IDs proportionally according to the water rights granted to each district. In hydrological years when WA_b is higher than or equal to the sum of water rights granted to every rights holder in the basin (full water allotment, FWA_b), the volume of water allocated to each ID is equal to the water rights granted (FWA_{id}). In years when WA_b is lower than FWA_b , the volume allocated to each ID (WA_{id}) is proportionally reduced as follows:

$$WA_{id} = FWA_{id} \cdot \frac{WA_b}{FWA_b} \tag{1}$$

Similarly, IDs share the water annually allocated proportionally among all their farm types, i.e., water allocations in cubic meters per hectare ($wa_{id,f}$) are the same for all farm types within

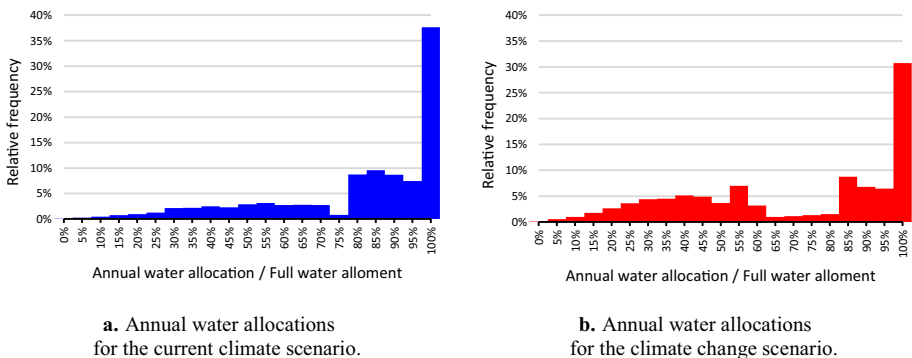


Fig. 2 Distribution of the annual water allocations (wa_{id}/fwa_{id}) in the GRB. Source: Gómez-Limón (2020)

the ID ($wa_{id,f} = wa_{id}, \forall f$), such that $wa_{id} = WA_{id}/s_{id}$. Thus, the annual water allocation for farm type f measured in cubic meters is $WA_{id,f} = wa_{id} \cdot s_{id,f}$.

Under the proposed new distribution rules, each farm type would hold water rights defined as portfolios of two different types of water rights, priority and general rights. Thus, the annual water allocation to each farm type measured in cubic meters would be calculated as the sum of the annual water allocation for holding priority and general water rights, as follows:

$$WA_{id,f} = wapr_{id} \cdot [PR_{id,f} \cdot s_{id,f} \cdot nf_{id,f}] + wagr_{id} \cdot [GR_{id,f} \cdot s_{id,f} \cdot nf_{id,f}] \tag{2}$$

where $wapr_{id}$ is the annual water allocation per hectare for every farm type within an ID for priority rights and $wagr_{id}$ is the same for general rights, while $PR_{id,f}$ and $GR_{id,f}$ are the shares of priority and general rights held by farm type id,f , which add up to one ($PR_{id,f} + GR_{id,f} = 1$) for every farm type. This implies that the same identity applies at the ID level ($PR_{id} + GR_{id} = 1$) and the basin level ($PR_b + GR_b = 1$).

According to the latter expression, the volume of water annually allocated to each farm type measured in cubic meters per hectare is:

$$wa_{id,f} = wapr_{id} \cdot PR_{id,f} + wagr_{id} \cdot GR_{id,f} \tag{3}$$

It is worth explaining that the maximum or full water allotments per hectare and year for priority ($fwapr_{id}$) and general ($fwagr_{id}$) water rights are the same for every farm type within an ID, according to the water rights granted at the ID level. This means that $fw_{id} = fwapr_{id} = fwagr_{id}$.

The aggregate volume of water needed to satisfy all priority rights holders is denoted as $FWAPR_b$, and is calculated as the sum of all priority rights in the basin:

$$FWAPR_b = \sum_{id,f} fwa_{id} \cdot m_{id} \cdot PR_{id,f} \cdot nf_{id,f} \cdot s_{id,f} \tag{4}$$

while the quantity annually available to allocate among priority rights holders ($WAPR_b$) is:

$$WAPR_b = \sum_{id,f} wapr_{id} \cdot m_{id} \cdot PR_{id,f} \cdot nf_{id,f} \cdot s_{id,f} \tag{5}$$

Likewise, $FWAGR_b$ and $WAGR_b$ denote the volume of water needed to fully meet water demands from all general rights holders and the water annually available to be allocated among these rights holders, respectively:

$$FWAGR_b = \sum_{id,f} fwa_{id} \cdot m_{id} \cdot GR_{id,f} \cdot nf_{id,f} \cdot s_{id,f} \tag{6}$$

$$WAGR_b = \sum_{id,f} wagr_{id} \cdot m_{id} \cdot GR_{id,f} \cdot nf_{id,f} \cdot s_{id,f} \tag{7}$$

The share of priority rights at the basin level (PR_b) relates the aggregate volume of water needed to satisfy all priority rights holders ($FWAPR_b$) to the aggregate volume of water needed to satisfy all water rights ($FWA_b = FWAPR_b + FWAGR_b$) as follows:

$$PR_b = FWAPR_b / FWA_b \tag{8}$$

Priority rights are served first with the full water allotment granted to the corresponding ID (fw_{id}) as long as the water availability WA_b is enough to cover all water demands from priority rights holders ($WA_b \geq FWAPR_b$ or, following Eq. (8), $WA_b \geq FWA_b \cdot PR_b$). After that, the remaining water available for sharing is allocated proportionally among general rights holders. In years when there is not enough water to meet full allotments for priority

rights, the available water is rationed among priority rights holders following the proportional rule according to their full water allotments. In these years, general rights holders would not receive any water.

The abovementioned priority allocation rules can be expressed mathematically considering the following formulae:

$$WA_b \geq FWAPR_b \left\{ \begin{array}{l} wapr_{id} = fwa_{id} \\ wagr_{id} = \frac{WA_b - FWAPR_b}{FWAGR_b} \cdot fwa_{id} \end{array} \right. \quad (9)$$

$$WA_b < FWAPR_b \left\{ \begin{array}{l} wapr_{id} = \frac{WA_b}{FWAPR_b} \cdot fwa_{id} \\ wagr_{id} = 0 \end{array} \right. \quad (10)$$

In Eq. (9), when the aggregate volume of water available for irrigation at the basin level (WA_b) is greater than or equal to the water requirements to satisfy all priority rights holders ($FWAPR_b$ or $FWA_b \cdot PR_b$), priority rights holders receive allocations corresponding to the full water allotment for the ID (fwa_{id}). General rights holders receive a proportion of their full water allotments. This proportion depends on how much water remains available for general rights related to the total volume of water needed to cover them ($\frac{WA_b - FWAPR_b}{FWAGR_b}$). Similarly, when there is not enough water available at the basin level to satisfy the demand from priority rights holders (Eq. (10)), they receive a proportion of their full water allotment (fwa_{id}), while general rights holders receive no water at all.

The optimal share of priority rights at the river basin level is initially unknown, so it will be parametrized to determine the PR_b that yields the most efficient outcome.

4.2 Farmers' Decision-making

We assume that farmers try to maximize farming profits as a function of their water allocation ($\pi_{id,f} = f(wa_{id,f})$). As explained above, farmers' annual water allocations vary depending on the availability of irrigation water. Thus, since $\bar{W}A_b$ is a stochastic variable, water allocations $\bar{w}a_{id}$, $\bar{w}apr_{id}$, $\bar{w}agr_{id}$, and $\bar{w}a_{id,f}$ are also stochastic variables ranging from fwa_{id} to 0, which in turn means that farming profits are stochastic variables ($\bar{\pi}_{id,f}$). Within this stochastic framework, it is assumed that farmers make decisions about whether to upgrade their water rights to maximize their expected (or average) profit. To simulate the risk from water supply variability, $N=1000$ probabilistic values for $\bar{W}A_{b,n}$ are considered (the subscript n denotes each irrigation water availability scenario). For the current climate scenario, these values have been taken from the hydrological simulation model built by Gómez-Limón (2020). For the climate change scenario, the values for $\bar{W}A_{b,n}$ have been obtained by modifying the values taken for the current climate scenario to reflect more frequent and intense drought episodes, as explained in Sect. 3.2. In both cases, these scenarios ($n=1, \dots, 1000$) have been considered equally probable.

We use the expected total gross margin ($GM_{id,f,n}$) as a proxy of profit in the short run. Gross margin is a mathematical function of the area covered by the different crops (i.e., farmers' decision variables), denoted by $X_{c,id,f,n}$ where c denotes the crop. In addition, farmers can decide what percentage of their water rights will become priority rights ($PR_{id,f}$), with the remaining rights being kept as general water rights ($GR_{id,f} = 1 - PR_{id,f}$). However, it is worth noting that these last two decision variables do not depend on the water availability scenario n , since both denote long-run decision-making (i.e., this farmer's choice is considered to remain the same for the

$N=1000$ scenarios). Thus, the simulation of farmers' decision-making maximizes the expected total gross margin considering both kinds of decision variables, $GM_{id,f,n} = f(X_{c,id,f,n}, PR_{id,f})$.

The modeling approach is based on the standard Positive Mathematical Programming (PMP) formally introduced by Howitt (1995) and the average cost approach proposed by Heckelei and Britz (2005).

In case of drought, it is assumed that farmers react by changing their cropping pattern, replacing water-intensive crops with others that have lower water needs or even rainfed crops (i.e., no irrigation water is required). Thus, three rainfed alternatives (wheat and sunflower plus olive when this permanent crop is present in a farm type) have also been considered as decision variables for simulations under drought scenarios.

Considering the priority allocation rule proposed, decision-making for the different farm types can be integrated into a single model at the basin level, where optimum values for the variables $X_{c,id,f,n}$ and $PR_{id,f}$ (and $GR_{id,f}$) are to be found for every value considered for the parameter PR_b :

$$\text{Max}_{X_{c,id,f,n}, PR_{id,f}} Z = \frac{1}{N} \sum_{id,f,n} GM_{id,f,n} \cdot m_{id} \cdot nf_{id,f} \tag{11}$$

$$s.t \quad GM_{id,f,n} = \sum_c [(p_{c,id} \cdot y_{c,id,f} + s_{c,id} - \alpha_{c,id,f} - 1/2 \cdot \beta_{c,id,f} \cdot X_{c,id,f,n}) \cdot X_{c,id,f,n}] \quad \forall id,f,n \tag{12}$$

$$\sum_c X_{c,id,f,n} = s_{id,f} \quad \forall id,f,n \tag{13}$$

$$\sum_c wr_{c,id,f} \cdot X_{c,id,f,n} \leq wa_{id,f,n} \cdot s_{id,f} \quad \forall id,f,n \tag{14}$$

$$wa_{id,f,n} = wapr_{id,n} \cdot PR_{id,f} + wagr_{id,n} \cdot GR_{id,f} \quad \forall id,f,n \tag{15}$$

$$PR_{id,f} + GR_{id,f} = 1 \quad \forall id,f \tag{16}$$

$$\begin{cases} wapr_{id,n} = fwa_{id}, & \text{if } WA_{b,n} \geq FWAPR_b \\ wapr_{id,n} = \frac{WA_{b,n}}{FWAPR_b} \cdot fwa_{id}, & \text{if } WA_{b,n} < FWAPR_b \end{cases} \quad \forall id,n \tag{17}$$

$$\begin{cases} wagr_{id,n} = \frac{WA_{b,n} - FWAPR_b}{FWAGR_b} \cdot fwa_{id}, & \text{if } WA_{b,n} \geq FWAPR_b \\ wagr_{id,n} = 0, & \text{if } WA_{b,n} < FWAPR_b \end{cases} \quad \forall id,n \tag{18}$$

$$PR_b = \frac{FWAPR_b}{FWA_b} \tag{19}$$

$$A_{id,f} X_{id,f,n} \leq B_{id,f} \quad \forall id,f,n \tag{20}$$

$$X_{c,id,f,n} \geq 0; PR_{id,f} \geq 0; GR_{id,f} \geq 0 \quad \forall c, id,f,n \tag{21}$$

In the above expressions, $GM_{id,f,n}$ represents the farm's expected gross margin for farm type id,f in scenario n calculated as the sum of total income, including both

product sales (expected crop price, $p_{c,id}$, multiplied by expected crop yield, $y_{c,id,f}$) and coupled subsidies ($s_{c,id}$), minus the variable cost function ($\alpha_{c,id,f} + 1/2 \cdot \beta_{c,id,f} \cdot X_{c,id,f,n}$) for every crop c , where $\alpha_{c,id,f}$ and $\beta_{c,id,f}$ are the PMP calibrating parameters.

The objective function (11 and 12) allows the joint maximization of the average gross margin at the basin level (i.e., maximum economic efficiency solution), as a result of the optimum decision-making regarding the crop mixes in each scenario n and the long-run choices about the upgrade into priority rights. Constraint (13) is related to land availability and limits the total area covered by the different crop alternatives to the farm size ($s_{id,f}$). Equations (14–18) are related to water availability. Equation (14) establishes that irrigation water use cannot exceed water availability, with the former being the sum of water requirements per crop ($wr_{c,id,f}$) and the latter the water allocation per farm type ($wa_{id,f,n} \cdot s_{id,f}$), while Eqs. (15–18), derived from Eqs. (9) and (10) explained above, describe how water availability is shared among farm types according to the priority rules proposed. Constraint (19) just limits the maximum share of rights that can be upgraded to priority rights at the basin level, as fixed by the parameter PR_b . Equation (20) denotes the rest of the constraints defining the feasible solution set, which constitute agronomic (rotational and frequency requirements) and policy (cotton and sugar beet quotas) factors, with $X_{id,f,n}$ being the matrix containing all variables $X_{c,id,f,n}$, $A_{id,f}$ the technical coefficient matrix for every variable and constraint of the irrigation district id and farm type f , and $B_{id,f}$ the vector of limit values for each constraint for the irrigation district id and the farm type f . Finally, non-negativity constraints are imposed for $X_{c,id,f,n}$, $PR_{id,f}$ and $GR_{id,f}$ (Eq. (21)).

Considering the current proportional allocation rule, farm type decision-making can also be simulated for $N=1000$ water availability scenarios using a simplified version of model (11), replacing Eq. (15–19) with a single expression (22) representing how the proportional rule works for every irrigation district id and farm type f .

$$\begin{cases} wa_{id,f,n} = fwa_{id}, & \text{if } WA_{b,n} \geq FWA_b \\ wa_{id,f,n} = \frac{WA_{b,n}}{FWA_b} \cdot fwa_{id}, & \text{if } WA_{b,n} < FWA_b \end{cases} \forall id,f,n \quad (22)$$

Simply by comparing the simulated results obtained for the two allocation rules, we are able to calculate variations in gross margins and water use at the farm, ID, and basin level, as well as other indicators, allowing an assessment of the proposed analysis.

5 Results

5.1 Aggregate Economic Efficiency Gains at the Basin Level

For the current climate scenario, the results from model (11–21) show that the maximum efficiency solution for the proposed priority allocation regimen is achieved with 44.5% of priority rights over total water rights at the basin level (PR_b). As can be seen in Table 3, compared to the baseline values of the current proportional water rights regime (i.e., results from model considering Eq. (22)), for this value of the parameter PR_b , aggregate gross margins at the basin level increase in every water availability scenario (i.e., drought events), with these increases ranging from 0.0% to 6.1%.

Table 3 Maximum efficiency solutions by climate scenario: share of priority water rights and aggregate gross margin increases at the basin level by drought intensity

Water availability at the basin level (WA_b/FWA_b)	Aggregate gross margin increase (Priority-Proportional) (%)	
	Current climate scenario ($PR_b = 44.5\%$)	Climate change scenario ($PR_b = 46.0\%$)
100%	0.0%	0.0%
90%	0.0%	0.0%
80%	0.3%	0.1%
70%	0.5%	0.1%
60%	2.2%	1.8%
50%	4.7%	5.0%
40%	6.1%	6.6%
30%	5.5%	5.9%
20%	5.1%	5.4%
10%	4.5%	4.0%

Similar results are obtained for the climate change scenario considered. In this case, the maximum efficiency solution is reached when 46.0% of total water rights at the basin level are upgraded into priority ones. This share of priority rights would result in an increase in economic efficiency ranging from 0.0% to 6.6%, depending on the water availability scenario.

This is evidence that changing the allocation regimen to replace current proportional rules with the priority rule would enhance economic efficiency in any drought situation and climate scenario.

For light hydrological droughts (i.e., water availability higher than 75% of full water allotments), the improvements in economic efficiency are almost negligible (less than 1% of current aggregate gross margin at the basin level). However, the increase in aggregate gross margins becomes significant for mild droughts (i.e., water availability between 75 and 50% of full water allotments). In fact, for drought scenarios where water availability is lower than 50% of full water allotments (i.e., severe and extreme droughts), priority rights become a valuable policy instrument to enhance overall economic efficiency, raising aggregate gross margins above 4.0%.

5.2 Heterogeneity in Priority Rights Allocation

It is worth noting that the optimum upgrade into priority rights according to the results from model (11–21) is fairly heterogeneous among ID categories and farm types, as shown in Table 4. In this sense, it can be observed that those ID categories and farm types with higher value-added crops and water productivity (modern irrigated areas) upgrade a higher proportion of water rights than those with lower value-added crops and water productivity (traditional irrigated areas). Among the former, Olive and Modern ID categories stand out. In the current climate scenario, farmers in Olive IDs upgrade 56.6% of their water rights into priority ones, while farmers in Modern IDs upgrade almost half (48.2%) of their water rights. Similar upgrade rates are obtained for both ID categories (61.1% and 48.6%, respectively) when the climate change scenario is considered. Conversely, farmers in Traditional IDs upgrade just 28.0% and 28.8% of their water rights in

the current climate and climate change scenarios, respectively, while those operating in Rice IDs do not upgrade any rights in either of the climate scenarios considered.

Moreover, as shown in Table 4, there is also significant heterogeneity among farm types within each ID category in terms of the optimum share of priority water rights. These shares depend on farms' production orientation and water productivity; the higher the value-added of the crops and the higher the water productivity, the greater the share of priority rights.

5.3 Changes in Water Allocation and Gross Margin by ID Categories

Table 5 shows more detailed results for the maximum efficiency solution of model (11–21) considering the current climate scenario (i.e., based on a 44.5% share of priority water rights at the basin level). As indicated in rows using a blue color spectrum, the heterogeneity in the share of priority rights granted to the various farm types for this climate scenario would lead to a relevant change in water allocation regime for the different scenarios of water availability (WA_b/FWA_b). As expected, for those ID categories with a higher share of priority rights (i.e., Olive and Modern IDs), water allocations increase for every drought scenario when a regime based on priority rights is implemented compared to the current situation (i.e., implementation of proportional water rights). In fact, as can be seen in Table 7, these ID categories increase their average water allocations (+4.9% in the case of Olive IDs and +3.8% in the case of Modern IDs), while their water allocations

Table 4 Share of priority rights in the maximum efficiency solutions per climate change scenario and farm type and ID category

ID category	ID	Farm type	Current climate scenario	Climate change scenario
Traditional	ID1	f1.1	26.6%	32.0%
	ID1	f1.2	25.5%	28.1%
	ID1	f1.3	71.0%	30.4%
	Total Traditional			28.0%
Modern	ID2	f2.1	75.4%	72.8%
	ID2	f2.2	55.8%	61.1%
	ID2	f2.3	64.0%	58.4%
	ID3	f3.1	24.7%	24.5%
	ID3	f3.2	30.5%	27.3%
	ID3	f3.3	0.0%	0.0%
	ID4	f4.1	35.0%	41.0%
	ID4	f4.2	60.6%	67.4%
	ID4	f4.3	100.0%	100.0%
Total Modern			48.2%	48.6%
Olive	ID5	f5.1	57.7%	61.4%
	ID6	f6.1	53.8%	60.5%
	Total Olive			56.6%
Rice	ID7	f7.1	0.0%	0.0%
	Total Rice			0.0%

Table 5 Current climate scenario: water allocation and gross margin implementing proportional and priority water rights by drought intensity

ID Categ.	Water availability at the basin level (WA_b/FWA_b)									
	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
Water allocation implementing proportional water rights (m ³ /ha)										
Traditional	6100	5490	4880	4270	3660	3050	2440	1830	1220	610
Modern	4813	4332	3851	3369	2888	2407	1925	1444	963	481
Olive	1500	1350	1200	1050	900	750	600	450	300	150
Rice	11,500	10,350	9200	8050	6900	5750	4600	3450	2300	1150
Basin	3464	3118	2771	2425	2078	1732	1386	1039	693	346
Water allocation implementing priority water rights (m ³ /ha)										
Traditional	6100	5309	4517	3726	2935	2143	1535	1152	768	384
Modern	4813	4414	4015	3616	3217	2818	2336	1752	1168	584
Olive	1500	1383	1265	1148	1031	913	763	572	381	191
Rice	11,500	9428	7356	5284	3212	1140	0	0	0	0
Basin	3464	3118	2771	2425	2078	1732	1386	1039	693	346
Changes in water allocation (Priority-Proportional) (%)										
Traditional	0.0%	-3.3%	-7.4%	-12.7%	-19.8%	-29.7%	-37.1%	-37.1%	-37.1%	-37.1%
Modern	0.0%	1.9%	4.3%	7.3%	11.4%	17.1%	21.3%	21.3%	21.3%	21.3%
Olive	0.0%	2.4%	5.4%	9.3%	14.5%	21.8%	27.2%	27.2%	27.2%	27.2%
Rice	0.0%	-8.9%	-20.0%	-34.4%	-53.5%	-80.2%	-100.0%	-100.0%	-100.0%	-100.0%
Basin	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gross margin implementing proportional water rights (€/ha)										
Traditional	1384	1380	1375	1365	1309	1225	1106	952	762	535
Modern	2003	2000	1960	1906	1821	1684	1520	1341	1125	824
Olive	930	930	930	930	893	836	780	724	667	611
Rice	1471	1333	1196	1058	921	783	646	508	371	233
Basin	1397	1390	1368	1340	1279	1186	1081	968	839	674
Gross margin implementing priority water rights (€/ha)										
Traditional	1384	1382	1380	1324	1210	1033	856	729	590	438
Modern	2003	2000	1993	1965	1906	1829	1700	1490	1246	908
Olive	930	930	930	930	930	898	842	770	698	627
Rice	1471	1223	975	728	480	232	96	96	96	96
Basin	1397	1386	1372	1347	1308	1241	1147	1022	882	705
Changes in gross margin (Priority-Proportional) (%)										
Traditional	0.0%	0.2%	0.4%	-3.0%	-7.6%	-15.7%	-22.7%	-23.5%	-22.5%	-18.1%
Modern	0.0%	0.0%	1.7%	3.1%	4.7%	8.6%	11.8%	11.1%	10.7%	10.3%
Olive	0.0%	0.0%	0.0%	0.0%	4.2%	7.4%	7.9%	6.4%	4.6%	2.5%
Rice	0.0%	-8.3%	-18.4%	-31.3%	-47.9%	-70.4%	-85.2%	-81.2%	-74.2%	-59.0%
Basin	0.0%	0.0%	0.3%	0.5%	2.2%	4.7%	6.1%	5.5%	5.1%	4.5%

became less volatile over time (change of -16.8% in the coefficient of variation for Olive IDs and -13.4% for Modern IDs). On the other hand, allocations to ID categories with a lower share or no share of priority rights (i.e., Traditional and Rice IDs) are reduced in every drought scenario. These ID categories thus get worse both in terms of the average

Table 6 Climate change scenario: water allocation and gross margin implementing proportional and priority water rights by drought intensity

ID Categ.	Water availability at the basin level (WA_b/FWA_b)									
	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
Water allocation implementing proportional water rights (m ³ /ha)										
Traditional	6100	5490	4880	4270	3660	3050	2440	1830	1220	610
Modern	4813	4332	3851	3369	2888	2407	1925	1444	963	481
Olive	1500	1350	1200	1050	900	750	600	450	300	150
Rice	11,500	10,350	9200	8050	6900	5750	4600	3450	2300	1150
Basin	3464	3118	2771	2425	2078	1732	1386	1039	693	346
Water allocation implementing priority water rights (m ³ /ha)										
Traditional	6100	5296	4491	3687	2882	2078	1527	1145	764	382
Modern	4813	4410	4007	3604	3200	2797	2292	1719	1146	573
Olive	1500	1392	1284	1176	1068	960	797	598	399	199
Rice	11,500	9370	7241	5111	2981	852	0	0	0	0
Basin	3464	3118	2771	2425	2078	1732	1386	1039	693	346
Changes in water allocation (Priority-Proportional) (%)										
Traditional	0.0%	-3.5%	-8.0%	-13.7%	-21.2%	-31.9%	-37.4%	-37.4%	-37.4%	-37.4%
Modern	0.0%	1.8%	4.1%	7.0%	10.8%	16.2%	19.0%	19.0%	19.0%	19.0%
Olive	0.0%	3.1%	7.0%	12.0%	18.7%	28.0%	32.9%	32.9%	32.9%	32.9%
Rice	0.0%	-9.5%	-21.3%	-36.5%	-56.8%	-85.2%	-100.0%	-100.0%	-100.0%	-100.0%
Basin	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Gross margin implementing proportional water rights (€/ha)										
Traditional	1384	1380	1375	1365	1309	1225	1106	952	762	535
Modern	2003	2000	1960	1906	1821	1684	1520	1341	1125	824
Olive	930	930	930	930	893	836	780	724	667	611
Rice	1471	1333	1196	1058	921	783	646	508	371	233
Basin	1397	1390	1368	1340	1279	1186	1081	968	839	674
Gross margin implementing priority water rights (€/ha)										
Traditional	1384	1379	1371	1312	1196	1019	862	736	596	441
Modern	2003	2000	1991	1953	1896	1821	1697	1485	1242	895
Olive	930	930	930	930	930	915	854	779	704	630
Rice	1471	1216	962	707	452	198	96	96	96	96
Basin	1397	1385	1370	1341	1302	1245	1153	1025	884	701
Changes in gross margin (Priority-Proportional) (%)										
Traditional	0.0%	-0.1%	-0.3%	-3.9%	-8.6%	-16.8%	-22.1%	-22.7%	-21.8%	-17.6%
Modern	0.0%	0.0%	1.5%	2.5%	4.1%	8.1%	11.6%	10.8%	10.4%	8.6%
Olive	0.0%	0.0%	0.0%	0.0%	4.2%	9.4%	9.5%	7.7%	5.6%	3.0%
Rice	0.0%	-8.8%	-19.6%	-33.2%	-50.9%	-74.8%	-85.2%	-81.2%	-74.2%	-59.0%
Basin	0.0%	0.0%	0.1%	0.1%	1.8%	5.0%	6.6%	5.9%	5.4%	4.0%

allocations (decreases of -6.6% and -17.9%, respectively) and their stability over time (increases of +27.1% and +85.3%, respectively, in their coefficients of variation).

Moreover, it is worth noting that the overall volume of water allocated at the basin level when the priority rights are implemented remains the same as in the proportional water

Table 7 Water allocation and gross margin averages and coefficients of variation for proportional and priority water rights per climate scenario and ID category

Climate scenario	ID category	Water allocation average (m ³ /ha)			Water allocation coef. of variation		
		Proportional	Priority	Change %	Proportional	Priority	Change %
Current climate	Traditional	4779	4461	-6.6%	0.31	0.39	27.1%
	Modern	3771	3915	3.8%	0.31	0.27	-13.4%
	Olive	1175	1232	4.9%	0.31	0.26	-16.8%
	Rice	9009	7395	-17.9%	0.31	0.57	85.3%
	Basin	2714	2714	0.0%	0.31	0.31	0.0%
Climate change	Traditional	4238	3832	-9.6%	0.43	0.55	28.9%
	Modern	3344	3507	4.9%	0.43	0.37	-12.3%
	Olive	1042	1130	8.4%	0.43	0.34	-19.8%
	Rice	7990	5944	-25.6%	0.43	0.79	86.7%
	Basin	2407	2407	0.0%	0.43	0.43	0.0%
		Gross margin average (£/ha)			Gross margin coef. of variation		
		Proportional	Priority	Change %	Proportional	Priority	Change %
Current climate	Traditional	1306	1257	-3.7%	0.13	0.19	47.3%
	Modern	1866	1910	2.3%	0.13	0.11	-18.3%
	Olive	894	907	1.4%	0.08	0.07	-20.2%
	Rice	1173	980	-16.5%	0.28	0.52	82.1%
	Basin	1309	1322	1.0%	0.12	0.11	-1.4%
Climate change	Traditional	1235	1148	-7.1%	0.18	0.26	46.2%
	Modern	1762	1824	3.5%	0.18	0.15	-17.6%
	Olive	860	887	3.2%	0.11	0.09	-20.0%
	Rice	1051	806	-23.3%	0.39	0.74	91.0%
	Basin	1241	1265	1.9%	0.16	0.14	-1.9%

rights baseline. This constraint is implicitly assumed in the proposal for the reform, evidencing that this change in the allocation regime has no impact on water abstractions (i.e., on the environment).

The changes in water allocations discussed above also lead to changes in gross margins, as shown at the bottom of Table 5 (see rows using a yellow color spectrum). The improvement in water supply reliability compared to the current situation means farmers in Olive and Modern IDs achieve higher levels of profitability for every drought scenario when priority rights are implemented. This leads to an increase in their average gross margins (+1.4% and +2.3% for Olive and Modern ID categories, respectively), and a decrease in volatility (-20.2% and -18.3% in their coefficients of variation, respectively), as shown in Table 7. On the contrary, under the new water allocation regime based on priority rights, farmers in Traditional and Rice IDs see a decline in their profitability indicators: reduced average gross margins (-3.7% and -16.5%, respectively) and increased profit volatility (+47.3% and +82.1% in the coefficients of variation, respectively).

The key point worth highlighting is that aggregate average profitability gains by the farmers who upgrade their rights into priority ones are larger than aggregate average losses affecting farmers who maintain their general rights; i.e., the average variation in gross margins at the basin level is positive overall. This fact has two important implications. First, the priority allocation regime is more economically efficient than the proportional

allocation regime. As shown in Table 7, this average improvement in economic efficiency is 1% of the current aggregate gross margin at the basin level. And second, these changes in average profitability allow the farmers to upgrade their rights into priority ones (reliability/profitability winners) to compensate those holding general rights (reliability/profitability losers) through the auction procedure suggested (i.e., annual surcharges to be paid by those upgrading their rights). This suggests that the proposed change in allocation rules is a win–win solution for every farmer in the basin.

Table 6 shows detailed results for the maximum efficiency solution of model (11–21) considering the climate change scenario (i.e., a 46.0% share of priority water rights at the basin level). These results are similar to those described above for the current climate scenario, leading to enhanced water reliability and farm profitability for irrigators operating in the Olive and Modern IDs and a deterioration in reliability and profitability for those farming in Traditional and Rice IDs. In any case, it is worth noting that under this climate scenario, changes in water allocations and gross margins are more pronounced than in the current climate scenario; thus, the proposed allocation regime leads to a bigger improvement in economic efficiency. In fact, under the climate change scenario, the average efficiency increase at the basin level is 1.9% of the current aggregate gross margin, almost doubling the increase achieved in the current climate scenario (see Table 7). This means priority rights will be more useful for increasing economic efficiency when the effects of climate change on the availability of irrigation water become more perceptible.

For the sake of brevity, the analysis of the abovementioned heterogeneous effects of the proposed priority rights regime on water allocations and gross margins has focused solely on the results by ID categories. However, it is worth pointing out that this heterogeneity is even larger when the various farm types are considered. Interested readers can confirm this by checking the results provided in the supplementary material, both for the current climate scenario and the climate change scenario. As noted in the previous section, the different impacts on farm types depend on their production orientation and water productivity; the higher the value-added of the crops and the higher the water productivity, the greater the share of priority rights, and the greater the improvement in water reliability and farm profitability.

6 Discussion and Concluding Remarks

The results show modest average economic efficiency gains from the proposed change in the water allocation regime: just 1% of the average aggregate gross margin for the current climate scenario. The improvements in economic efficiency estimated in this paper are much greater than those reported by Gómez-Limón et al. (2021) for a similar change in the allocation regime at the irrigation district level (0.2% of the average aggregate gross margin). This confirms the first hypothesis presented in the introduction, supporting the idea that the implementation of priority rights in a real-world setting only makes sense if there is enough heterogeneity in water productivity among the rights holders involved.

In any case, the simulated performance of priority rights at the basin level is somewhat disappointing, raising doubts about the suitability of this instrument for reducing the inefficiency of water allocation caused by proportional water allocation in cyclical scarcity events. In fact, it may be reasonable to assume that the potential economic gains would not be enough to cover the transaction costs associated with implementing the proposed allocation regime in a real-world setting (McCann 2013; McCann and Garrick

2014); namely, the costs incurred for the auction to upgrade water rights through auctions and the procedure to compensate reliability losers.

This unsatisfactory performance is mainly explained by the fact that priority rights do not reflect the marginal value of water across users in a timely manner (OECD 2016); like any other allocation regime, the implementation of priority rights is a rigid instrument that cannot be adapted depending on the level of water scarcity (i.e., drought or water availability scenarios). In fact, since water scarcity is a dynamic phenomenon, droughts must be managed by implementing sufficiently flexible instruments capable of modifying allocations in the short term, just as the spot water markets do (Chong and Sunding 2006).

However, there are several reasons for implementing the proposed change in the allocation regime. First, because annual efficiency gains become relevant in severe and extreme droughts, indicating that this policy instrument can play a valuable role in minimizing the negative impact of water shortages. Moreover, as evidenced in this paper, this role could be more important for the climate change scenario, given that more frequent and intense drought episodes are expected in the Mediterranean irrigated areas. This confirms the second hypothesis set out in the introduction, which posits that priority rights could achieve higher efficiency gains considering feasible climate change scenarios. Therefore, the proposed regime can be considered an instrument for adaptation to climate change (Xu et al. 2014; Mallawaarachchi et al. 2020).

Second, it is also worth noting that priority rights represent an interesting risk management instrument for farmers. As shown in the simulation results, the farmers who are most vulnerable to drought risk can use priority rights as a hedging mechanism, reducing gross margin volatility. In the context of climate change, where farmers are eager to stabilize their income, these priority rights constitute a useful adaptation instrument.

The third and probably most relevant reason is that the proposed shift in the allocation regime can be successfully implemented in combination with other economic instruments aimed at improving water management during scarcity periods, such as allocation water markets and temporary water banks. As pointed out by Freebairn and Quiggin (2006) and Lefebvre et al. (2012) and demonstrated by the Australian experience, the combined implementation of priority water rights and spot water markets can lead to significant improvements in drought management in the irrigation sector.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11269-022-03228-8>.

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and modeling were performed by Carlos Gutiérrez-Martín and Nazaret M. Montilla-López. Result analysis and discussion were performed by Carlos Gutiérrez-Martín and José A. Gómez-Limón. The first draft of the manuscript was written by José A. Gómez-Limón, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding provided thanks to the Universidad de Córdoba and the CRUE-CSIC agreement with Springer Nature. This work was financially supported by the Spanish Ministry of Science, Innovation, and Universities, the Andalusian Department of Economy and Knowledge, and the European Regional Development Fund (ERDF) through the research projects IRRIDROUGHT [grant number: RTI2018-095407-B-I00] and FINAGUA [grant number: UCO-1264548].

Data Availability The data that support the findings of this study are openly available in the supplementary material.

Declarations

Ethical Approval The authors undertake that this article has not been published in any other journal and that no plagiarism has occurred.

Consent to Participate Not applicable.

Consent to Publication The authors agree to publish this work in the “Water Resource Management” journal.

Conflict of Interest The authors declare no conflict of interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Alarcón J, Garrido A, Juana L (2014) Managing irrigation water shortage: a comparison between five allocation rules based on crop benefit functions. *Water Resour Manag* 28(8):2315–2329. <https://doi.org/10.1007/s11269-014-0617-z>
- Berbel J, Pedraza V, Giannoccaro G (2013) The trajectory towards basin closure of a European river: Guadalquivir. *Int J River Basin Manage* 11(1):111–119. <https://doi.org/10.1080/15715124.2013.768625>
- Bisselink B, Bernhard J, Gelati E, Adamovic M, Guenther S, Mentaschi L, De Roo A (2018) Impact of a Changing Climate, Land Use, and Water Usage on Europe’s Water Resources: A Model Simulation Study. Publications Office of the European Union, Luxembourg
- Bruns BR, Ringler C, Meinzen-Dick RS (2005) Water Rights Reform: Lessons for Institutional Design. International Food Policy Research Institute (IFPRI), Washington, D.C.
- CEDEX (Centro de Estudios Hidrográficos) (2017) Evaluación del impacto del Cambio Climático en los recursos hídricos y sequías en España. CEDEX, Madrid
- CHG (Confederación Hidrográfica del Guadalquivir) (2015) Plan Hidrológico de la Demarcación Hidrográfica del Guadalquivir (2015–2021). Confederación Hidrográfica del Guadalquivir, Sevilla, Spain
- Chong H, Sunding DL (2006) Water markets and trading. *Annu Rev Env Resour* 31(1):239–264. <https://doi.org/10.1146/annurev.energy.31.020105.100323>
- Degefu DM, He W (2016) Allocating water under bankruptcy scenario. *Water Resour Manag* 30(11):3949–3964. <https://doi.org/10.1007/s11269-016-1403-x>
- Ewert F et al (2015) Crop modelling for integrated assessment of risk to food production from climate change. *Environ Modell Softw* 72:287–303. <https://doi.org/10.1016/j.envsoft.2014.12.003>
- Freebairn J, Quiggin J (2006) Water rights for variable supplies. *Aust J Agr Resour Econ* 50(3):295–312. <https://doi.org/10.1111/j.1467-8489.2006.00341.x>
- Goetz R-U, Martínez Y, Xabadia À (2017) Efficiency and acceptance of new water allocation rules - the case of an agricultural water users association. *Sci Total Environ* 601–602:614–625. <https://doi.org/10.1016/j.scitotenv.2017.05.226>
- Gómez-Limón JA (2020) Hydrological drought insurance for irrigated agriculture in southern Spain. *Agric Water Manag* 240:106271. <https://doi.org/10.1016/j.agwat.2020.106271>
- Gómez-Limón JA, Gutiérrez-Martín C, Montilla-López NM (2020) Agricultural water allocation under cyclical scarcity: the role of priority water rights. *Water* 12(6):1835. <https://doi.org/10.3390/w12061835>
- Gómez-Limón JA, Gutiérrez-Martín C, Montilla-López NM (2021) Priority water rights. Are they useful for improving drought management at the irrigation district level? *Agric Water Manag* 257:107145. <https://doi.org/10.1016/j.agwat.2021.107145>

- Hanemann WM (2006) The economic conception of water. In: Roegers PP, Llamas MR, Martínez-Cortina L (eds) *Water Crisis: Myth or Reality*. Taylor & Francis, London, pp 61–91
- Heckelee T, Britz W (2005) Models based on Positive Mathematical Programming: state of the art and further extensions. In: Arfini F (ed) *Modelling Agricultural Policies: State of the Art and New Challenges*. University of Parma, Parma, Italy, pp 48–73
- Hodgson S (2006) *Modern Water Rights: Theory and Practice*. vol 92. Food and Agriculture Organization (FAO), Rome
- Howitt RE (1995) Positive Mathematical Programming. *Am J Agr Econ* 77(2):329–342. <https://doi.org/10.2307/1243543>
- Lefebvre M, Gangadharan L, Thoyer S (2012) Do security-differentiated water rights improve the performance of water markets? *Am J Agr Econ* 94(5):1113–1135. <https://doi.org/10.1093/ajae/aas060>
- Mallawaarachchi T, Auricht C, Loch A, Adamson D, Quiggin J (2020) Water allocation in Australia's Murray-Darling Basin: managing change under heightened uncertainty. *Econ Anal Policy* 66:345–369. <https://doi.org/10.1016/j.eap.2020.01.001>
- MAPA (Ministerio de Agricultura Pesca y Alimentación) (2020) Encuesta sobre Superficies y Rendimientos de Cultivos. Informe sobre Regadíos en España ESYRCE 2020. Ministerio de Agricultura Pesca y Alimentación, Madrid
- Martínez Y, Esteban E (2014) Social choice and groundwater management: application of the uniform rule. *Cienc Investig Agrar* 41:153–162. <https://doi.org/10.4067/S0718-16202014000200002>
- McCann L (2013) Transaction costs and environmental policy design. *Ecol Econ* 88:253–262. <https://doi.org/10.1016/j.ecolecon.2012.12.030>
- McCann L, Garrick D (2014) Transaction costs and policy design for water markets. In: Easter KW, Huang Q (eds) *Water Markets for the 21st Century: What Have We Learned?* Springer, New York, pp 11–34
- OECD (Organisation for Economic Co-operation and Development) (2015) *Water Resources Allocation. Sharing Risks and Opportunities*. OECD Publishing, Paris
- OECD (Organisation for Economic Co-operation and Development) (2016) *Mitigating Droughts and Floods in Agriculture. Policy Lessons and Approaches*. OECD Publishing, Paris
- Raju KS, Kumar DN (2018) Hydrological modeling. Impact of climate change on water resources. In: Raju KS, Kumar DN (eds) *Impact of Climate Change on Water Resources. With Modeling Techniques and Case Studies*. Springer Singapore, Singapore, pp 137–167
- Rightnar J, Dinar A (2020) The welfare implications of bankruptcy allocation of the Colorado River Water: The case of the Salton Sea Region. *Water Resour Manag* 34(8):2353–2370. <https://doi.org/10.1007/s11269-020-02552-1>
- Sechi GM, Zucca R (2015) Water resource allocation in critical scarcity conditions: a bankruptcy game approach. *Water Resour Manag* 29(2):541–555. <https://doi.org/10.1007/s11269-014-0786-9>
- Xu W, Lowe SE, Adams RM (2014) Climate change, water rights, and water supply: the case of irrigated agriculture in Idaho. *Water Resour Res* 50(12):9675–9695. <https://doi.org/10.1002/2013wr014696>
- Young MD, McColl JC (2003) Robust reform: the case for a new water entitlement system for Australia. *Aust Econ Rev* 36(2):225–234. <https://doi.org/10.1111/1467-8462.00282>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.