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# Priority water rights. Are they useful for improving water-use efficiency at the irrigation district level?

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ABSTRACT

This paper examines the effectiveness of reforming water rights regimes in the agricultural sector by replacing allocation procedures based on the proportional rule with the implementation of a priority rule that establishes security-differentiated water rights. The main objective is to assess whether this change improves the economic efficiency of water allocation at the irrigation district level, particularly during cyclical scarcity events. To this end, a Positive Mathematical Programming model is built to simulate the performance of the proposed reform in an irrigation district in southern Spain. The results show that the efficiency gains brought about by this change are very small, which casts doubt on its ability to improve water-use efficiency in the agricultural sector at the local level (i.e., irrigation district) under current local climate and water availability conditions. In any case, further research is needed to assess the suitability of this change in allocations rules at basin scale with greater farm heterogeneity, especially given the likelihood of more frequent, more intense droughts due to climate change.

## 1. Introduction and objectives

Water resources provide important ecosystem and socio-cultural services (e.g., biodiversity, pollution sinks, or recreational facilities), and share many characteristics with public goods. In addition, water resources are a commodity used as an input in many economic activities (e.g., agriculture, industry, or energy production). Furthermore, access to supply facilities (drinking water and sanitation) is a basic human right that contributes to the maintenance of public health. All this makes water a complex economic good (Hanemann, 2006). For this reason, water generally enjoys a special legal status, managed according to the 'public trust' doctrine, which aims to ensure efficiency, equity, and environmental sustainability (Rogers et al., 2002). According to this doctrine, water management is usually based on centralized allocation regimes involving water rights (also called entitlements, licenses, concessions, or permits) granted by a public authority that determines how much water can be diverted from water bodies and who is allowed to use these resources (rights holders only).

The current allocation regimes are determined by historical water availability and traditional usage patterns, which generally do not correspond to current social preferences. In fact, most of them are not designed to adapt to changing conditions affecting both the demand (e.g., growing demand for water for economic activities and the environment) and the supply (e.g., climate change) of water resources. These outdated designs lead to inefficiencies in the allocation of water, such as the use of this resource as an input for crops with low water productivity, or the over-abstraction of water bodies, which jeopardizes water supply reliability and the provision of ecosystem services (OECD, 2015). In order to solve these inefficiencies in water allocation, many countries have developed water trading instruments (water markets and water banks) to make allocation regimes more flexible and allow them to be adapted to new circumstances (Bjornlund, 2003a; Debaere et al., 2014; Howitt, 2015). Along the same lines, there have been calls for a reform of these allocation regimes, aimed at achieving a more efficient and sustainable allocation of increasingly scarce water resources (e.g., Bruns et al., 2005; Hodgson, 2006).

It is worth pointing out that the availability of water varies over time and space, which makes the temporal and spatial matching of supply and demand a major challenge for water managers (Hanemann, 2006). This variability means water scarcity is dynamic, ranging from wet periods, when all volumes granted by water rights can be fully provided, to dry periods (droughts), when scarce water resources have to be rationed.

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Although storage (e.g., reservoirs) and conveyance (e.g., channels and pipelines) infrastructure is used to minimize this mismatch, significant fluctuations in resource availability inherent in any water system as a consequence of the natural water cycle (seasonal and interannual variability of rainfall and water flows) mean that water supply cannot be fully guaranteed, especially in more arid regions. Moreover, the frequency and intensity of these episodes of cyclical scarcity (droughts) are exacerbated in many regions by climate change, resulting in water supply becoming less and less reliable (Bisselink et al., 2018). When a drought episode occurs, allocation regimes also determine how the available scarce resources are to be shared among the water rights holders by determining the proportion of the volumes granted by these rights that each holder can actually use.

This paper focuses on the allocation regimes implemented within the agricultural sector, the world's largest water user, and more specifically on the rationing systems to be applied to irrigation water rights holders during cyclical scarcity events (droughts). In this sense, there are two main alternative approaches to rationing irrigation water allocations: those based on the proportional rule and those based on priority rules (OECD, 2016). The proportional rule is the most widely-used rationing method for irrigation water allocation during hydrological droughts. According to this rule, all water rights holders receive a quantity of water proportional to their water rights, so that total demand equals total supply. For the implementation of the priority rule, the irrigation rights holders are divided into priority classes, with their water rights being allocated lexicographically according to the established priority levels. This means that the demands of the rights holders with the highest priority are met first, and only when they are fully met is the remaining resource allocated to the following rights holders according to a criterion of decreasing priority order (Gómez-Limón et al., 2020).

Both allocation rules have their pros and cons. The proportional rule is easy to understand by rights holders and easy to implement in a real-world setting. Moreover, it is generally judged to be a 'fair' procedure for rationing water since it promotes equal shares allocated to equal demands (it fulfills the 'equal treatment of equals' axiom characterizing symmetric rationing methods). While these advantages explain the popularity of this allocation procedure, it fails to achieve an economically efficient distribution of the available water. This is because irrigators are heterogeneous in terms of production potential (pedoclimatic conditions, production technology, or farm size −economies of scale) and the psychological characteristics (e.g., risk aversion) shaping their production decision-making (i.e., crop mixes), with both of these features also determining heterogeneous agricultural and water productivity. Thus, proportional water rationing has quite different impacts on individual irrigators (e.g., intensive vs. extensive farmers), failing to minimize the aggregate losses stemming from water scarcity. There is a wide range of empirical evidence on this source of inefficiency in the irrigation sector (Alarcón et al., 2014; Martínez and Esteban, 2014; Goetz et al., 2017).

Water rights regimes with different levels of priority are an interesting alternative for the allocation of water within the agricultural sector during cyclical scarcity periods since they enable more efficient water use and risk-sharing (Freebairn and Quiggin, 2006; Lefebvre et al., 2012). The key idea behind this allocation procedure is that the irrigators who are more vulnerable to water supply gaps (e.g., farmers with perennial or horticultural crops) are able to reduce the risk related to water reliability by obtaining high-priority rights, transferring this risk to lower priority rights holders, who are better positioned to assume this risk (e.g., farmers with extensive annual crops). Also known as security-differentiated water rights, it is considered an adaptation measure to climate change (Xu et al., 2014; Mallawaarachchi et al., 2020). Furthermore, this allocation rule enables higher priority rights holders to further specialize in higher value-added farming systems, thereby improving economic efficiency in the long-term (Xu et al., 2014). Nevertheless, this rule is seldom implemented because the configuration of efficient portfolios of water rights involves significant transaction costs (Bjornlund, 2003b) and the fact that it is an asymmetric rationing method (rights holders are treated differently) makes it politically and socially controversial. In any case, the literature provides consistent evidence that irrigators are willing to pay to increase water supply reliability (e.g., Rigby et al., 2010; Mesa-Jurado et al., 2012; Alcón et al., 2014; Guerrero-Baena et al., 2019), justifying their interest in obtaining higher priority rights. However, these irrigators' capacity to cover the transactions costs and the compensation claimed by those keeping lower priority rights (i.e., 'reliability losers') is still an open question needing empirical research.

Despite the abovementioned cons, priority allocation rules are in effect in the Western United States, following the 'prior appropriation' doctrine (i.e., priority determined by seniority), and in the Australian states of New South Wales, Queensland, Southern Australia, and Victoria, based on two priority classes (e.g., 'high security' and 'general security' access entitlements in New South Wales, or 'high reliability' and 'low reliability' entitlements in Victoria) (Taylor, 2019). Both cases provide an interesting international experience to learn from in order to improve agricultural water management (Gómez-Limón et al., 2020).

Within this framework, the objective of this paper is to assess the improvement in economic efficiency generated when an allocation regime based on the proportional rule is replaced with a regime based on a priority allocation rule. To that end, we focused on a Spanish irrigation district as a case study, using positive mathematical programming to simulate farmers' willingness to pay (WTP) for higher priority water rights and willingness to accept (WTA) for lower priority rights, considering that their decisions regarding their individual portfolios of water rights determine their water supply reliability and farm profitability in the long-run. This approach will allow us to assess economic efficiency gains (net social gains measured as the overall WTP minus overall WTA) linked to the implementation of the priority allocation rule. If this instrument were found to improve water-use efficiency, it would enable the design of win-win arrangements for all water rights holders, helping to overcome any political or social objection to this institutional change.

The approach followed for this economic assessment contributes to the existing literature by modeling irrigators' heterogeneity through a farm typology based on primary data collection and incorporating an updated distribution of the annual water allotments obtained from a stochastic hydrological simulation. These two features make the results obtained reliable enough to support policy decision-making aimed at improving irrigation water management at the irrigation district (ID) level.

## 2. Agricultural water allocation in Spain: institutional framework

### 2.1. Water allocation at the basin level

The Spanish Water Act states that all water resources are in the public domain. The use of water for economic activities is permitted through administrative concessions or water rights that allow rights holders to extract water from a specific water body (river, aquifer, or reservoir) up to a maximum annual volume (full water allotment), with both of these elements established in the concession record. These rights are granted to private agents by the corresponding river basin authority (RBA). However, they do not guarantee the availability of the maximum water volume approved every year. The volume of water actually available for each rights holder (annual water allotment) is set every year depending on the hydrological situation (i.e., water stored in the reservoirs) and in accordance with the river basin management plan (RBMP).

The Spanish mainland territory (i.e., excluding islands) is divided into 15 river basins, covering an area of 493,800 km$^2$ and home to 46 million people. The total water rights granted amount to 30,797 Mm$^3$/year (full water allotment), of which 5584 Mm$^3$ goes to urban uses, 24,266 $Mm^3$ to agriculture, and 948 $Mm^3$ to other uses (industry, energy, etc.) (DGA and CEH, 2018).

Most of the Spanish river basins have a Mediterranean climate, with an average annual precipitation of 667 mm, over 80% of which falls during the autumn and winter. This rainfall generates average water flows (water availability) of 99,684 $Mm^3$/year. However, it is worth pointing out that most of the demand is concentrated during spring and summer for irrigation purposes. To match supply and demand in a timely manner, RBAs operate well-developed reservoir networks with a total storage capacity of 55,622 $Mm^3$, which in 'normal' hydrological years (i.e., those when enough water is stored in reservoirs) allows all demands (both from water rights holders and 2984 $Mm^3$/year to maintain the minimum ecological flows) to be fully met (DGA and CEH, 2018). This is not the case in drought years when water rationing is needed to balance water availability and demands.

In the case of cyclical scarcity, the RBAs limit water allocations according to the RBMPs, applying a combination of two rationing rules. On the one hand, a priority rule is applied whereby rights holders are ranked by priority based on the use of water: urban uses are at the top of the list, having absolute priority over agricultural use (ranked as the second priority level) and all other economic activities (lowest priority level). The second rationing rule applies when the available water is not enough to meet all rights within the same priority level. In this case, a proportional distribution is applied to all these rights holders. In any case, since urban uses account only for 18.1% of the Spanish water rights, this demand is practically guaranteed, and is met even during the most extreme drought events. In fact, during prolonged droughts in Spain, water rationing using the proportional rule is only applied to agricultural water rights holders (78.8% of the water rights).

Similarly to other countries such as Australia or the United States, Spain has used spot water markets since 1999 as a way to partially solve the problem of inefficient water allocation in the agricultural sector during cyclical scarcity periods due to proportional rationing. However, the performance of water markets in Spain has been rather disappointing, since high transaction costs and multiple trade barriers limit trading activity (Palomo-Hierro et al., 2015). Moreover, it is expected that water trade instruments will be banned by the new left-wing Spanish government, on the grounds that "access to water is a human right and thus should not be considered a commercial asset", as established in the coalition government agreement signed by the two political parties supporting it.

Given that we can reasonably anticipate an institutional context without water markets, the implementation of the priority rule is worth analyzing as an alternative allocation criterion for irrigation water, seeking to prevent the efficiency losses caused by the proportional rule during drought events (Gómez-Limón et al., 2020). However, allocation regimes at the national level are difficult and costly to adjust since they are path-dependent (institutional arrangements and long-lived water infrastructure). Nevertheless, as explained below, this is not the case at the ID level, where it is easier to change the institutional arrangements and the infrastructure. This justifies the scope of this paper, which is focused on changing allocation rules at the ID level.

### 2.2. Water allocation at the irrigation district level: a proposal for reform

Most irrigation water rights are collectively granted to all farmers operating within the same ID, organized into water users associations (WUAs). These WUAs are non-profit organizations that locally manage the water allotments annually set by the RBA, distributing the water available each year among their irrigators following their own allocation rules. Water management services provided by WUAs are financed by the recipient irrigators through annual payments set to ensure cost recovery.

In almost all cases, WUAs have chosen the proportional rule as the internal allocation criterion to cope with water shortages. This paper proposes a shift away from proportional allocation towards a priority rule allowing the implementation of security-differentiated water rights at the ID level. It is worth clarifying that this change would only be implemented locally, simply by modifying water allocations among local farmers, while water allocations at the ID level would remain unchanged (i.e., it is assumed that the RBA would continue to implement the proportional rule when allocating water among IDs).

To effect this change in local allocation rules, following the Australian example, two priority classes are proposed, distinguishing between high-security or 'priority' rights and low-security or 'general' water rights. Irrigators 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).

Under Spanish law, water rights can only be granted by the RBA. These water rights are granted for free to private agents based on general interest criteria, and these rights allow private agents to use water only for the specific purposes established by the RBA in the water entitlement (e.g., irrigation in a specific plot of land). This linkage between water rights and certain uses (i.e., water rights are bundled with land) is one of the principles of Spanish water law. There are two main reasons for this approach: first, to allow public authorities (RBAs) to allocate water resources following general interest objectives that go beyond economic efficiency (e.g., territorial equity or environmental conservation); and second, to enable the public management of the already complex hydrological systems (mainly water storage and delivery) without drastic changes in the water uses (place and time for delivery). This explains why Spanish water law prohibits the exchange of water rights (permanent or entitlements water markets).

The proposed change in the allocation regime to introduce security-differentiated water rights at the ID level does not affect the above-mentioned principle in any way. Taking the current situation as a starting point, we propose that at the beginning of the new allocation regime, water rights collectively granted to farmers within the same ID be shared out among all local irrigators on an area basis (i.e., 1 irrigated hectare = 1 water right), with all these rights initially considered as general rights. This change does not in itself entail any change in water allocations compared to the current implementation of the proportional rule. The real change is allowing a certain share of general water rights to be upgraded into priority rights. To carry out this upgrade process, an auction procedure is proposed. In these auctions, the bids offered by rights holders interested in upgrading would be measured as a surcharge on the annual payment to their WUA. Once this upgrade has been completed, the allocation regime will actually be changed to implement the priority rule.

It is worth pointing out that in following the procedure described above, the principle of bundling water rights with the land is observed. In fact, when implementing the security-differentiated water rights as suggested, the irrigated area would remain unchanged (i.e., the total number of former water rights is equal to the sum of the new general and priority rights, and there is no exchange of rights, which is prohibited by Spanish law). Moreover, the water annually allocated to each ID would be exactly the same as before (i.e., available water at the basin level for irrigation is shared among IDs according to the current proportional rule set by law); thus, public management of water resources at the basin level (water storage and delivery) could be carried out as it is currently done. This proposal is therefore different to the Australian case, where the conversion of rights has been set at defined rates; specifically, existing general rights can be upgraded to priority security via a conversion factor (e.g., 3 general rights = 1 priority security) and a transformation price, drastically altering the management of the hydrological systems.

The change proposed would involve gains for those rights holders upgrading a share of their rights (more reliable water supply). However, this change also involves a loss for those rights holders that do not upgrade their rights, since their water supply based only on general water rights becomes less reliable. This loss is the reason why they should be compensated for this change in the allocation regime. For this purpose, the total amount of money collected through these surcharges would be used to reduce the annual payments of all general rights holders to the WUA (increased income from surcharges on priority rights would allow the payments for general rights to be reduced while the services provided by the WUA remain self-financed).

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 the dynamic allocation of these priority rights.

This proposal for implementing a priority rule would have to be accepted by a majority of irrigators (i.e., approved as an allocation rule within the WUA) if this change is to create a win-win solution, where both 'reliability winners' (those upgrading their rights into priority ones) and 'reliability losers' (those keeping their general rights) increase their profitability. In other words, 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 reduction in the annual payments to the WUA charged to '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 ID level increases.

The main objective of this paper is to empirically test whether the proposed change in the allocation rules can enhance economic efficiency in the case study considered. For this purpose, a simulation exercise is performed, with the programming model also providing information about the optimum percentage of rights to be upgraded into priority rights (i.e., the share that maximizes economic efficiency at the ID level).

## 3. Case study

### *3.1. The Sector BXII irrigation district*

The Sector BXII (SBXII) is an ID covering 14,643 ha close to the mouth of the Guadalquivir River. This district is operated by 569 farmers (average farm size of 25.7 ha) organized into a WUA holding a collective water right of 6000 cubic meters per hectare and year (full water allotment). The WUA is in charge of water allocation among all irrigators, currently doing so according to the proportional rule. The costs of the water management services provided are financed through a binomial tariff, with each irrigator annually paying 294 euros per hectare to recover fixed operational and management costs, plus a volumetric charge of 0.003 euros per cubic meter of water applied to recover energy (pumping) costs.

Although this area was converted to irrigation during the 1980s, the irrigation infrastructure and techniques have since been updated. Sprinkler irrigation predominates (72%), although drip (22%) and surface irrigation (6%) are also used depending on the crop. This modern technology and the good agronomic conditions of the district make it a valuable example of highly profitable irrigation production, where water-use efficiency is relatively high. However, the main problem faced by irrigators in the SBXII is their sensitivity to water supply gaps (i.e., water shortages during drought periods). When the availability of irrigation water is not enough to meet full water allocations, they experience fairly large losses, much higher than those registered by other, less modernized and less efficient irrigators elsewhere in the basin.

The main crops in the area are cotton (44.5%), corn (12.9%), tomato (11.5%), sugar beet (9.4%), wheat (8.7%), sunflower (6.7%), and other vegetables such as carrots and onions (6.3%). However, it is worth mentioning that there are several productive profiles at the farm level. In order to characterize them, a random sample of 59 farms located in the SBXII was selected, gathering data regarding their main productive features (size, crop mixes, productive technologies, and income and costs by crops) and the socio-demographic characteristics of their farmers (age, educational level, etc.). A typology of the farms sampled was identified through cluster analysis, using the percentage of the area devoted to each crop as differentiating variables (for further details, see Montilla-López et al., 2018). The characteristics of each identified farm type are summarized as follows:

- Farm type 1 (FT1): *Large professional farmers*. This type represents 39% of farms in the sample, and accounts for 52% of the total irrigable area. This is the largest farm type in the SBXII (35.8 ha), mainly oriented towards horticultural crops (tomato, 30.3%; carrot, 5.3%; and onion, 1.6%), which are the most profitable crops. Other important crops are cotton (29.6%) and sugar beet (24.0%).
- Farm type 2 (FT2): *Risk diversifiers*. This farm type represents 41% of the farmers in the sample and accounts for 36% of the area of the SBXII. It is a medium-sized farm (23.9 ha), characterized by having a highly diversified crop plan, and dedicating areas to most of the existing crop options in the study area.
- Farm type 3 (FT3): *Extensive conservative farmers*. This type of farm represents the smallest proportion of farmers in the sample (20%), covering just 11% of the total area of the SBXII. It is therefore the smallest farm type, with an average of 15.0 ha. Its agricultural area is cultivated with the most extensive crops such as cotton (57.0%), and sugar beet (39.1%), which are both highly dependent on coupled subsidies.

As shown in Table 1, these farm types are heterogeneous in terms of the profitability and productivity of water. This means that they differ notably in the losses caused by proportional rationing implemented during drought events, with much greater losses occurring in the case of the most intensive farming (FT1, specialized in vegetables, with higher productivity of water) and more moderate losses for extensive farming (FT2 and FT3, focused on industrial crops and cereals, with lower productivity of water). This heterogeneity justifies the choice of this case study to explore the implementation of priority water rights as an instrument to improve water management during scarcity periods.

### *3.2. Annual water allotments in the SBXII irrigation district*

The SBXII is located in a Mediterranean region where irrigated agriculture is particularly vulnerable to the risk of hydrological drought, meaning annual water allotments are frequently lower than those fixed in the water rights (full water allotments). Thus, annual water allotment must be considered as a stochastic variable that needs to be characterized before modeling the potential impact of any change in the

**Table 1**
Characteristic variables of farm types in the SBXII.

| | FT1. *Large professional farmers* | FT2. *Risk diversifying farmers* | FT3. *Extensive conservative farmers* |
|---|---|---|---|
| Farm size (ha) | 35.8 | 23.9 | 15.0 |
| Cotton (ha) | 11.6 | 14.8 | 8.6 |
| Corn (ha) | 0.0 | 2.4 | 0.0 |
| Tomato (ha) | 11.9 | 3.3 | 0.0 |
| Sugar beet (ha) | 9.4 | 1.6 | 5.9 |
| Wheat (ha) | 0.0 | 1.7 | 0.6 |
| Other vegetables (ha) | 2.7 | 0.0 | 0.0 |
| Total income (€/ha) | 5433 | 3877 | 3175 |
| Total variable costs (€/ha) | 2412 | 1840 | 1396 |
| Total gross margin (€/ha) | 3021 | 2037 | 1779 |
| Average water productivity (€/m$^3$) | 0.541 | 0.432 | 0.335 |

Note: Crop mix under full water allotments.
*Source:* Gómez-Limón (2020) based on data gathered by Montilla-López et al. (2018).

allocation rules.

The distribution of the annual water allotments to the SBXII ($\widetilde{wa}_{id}$) could be fitted to different probability distribution functions according to historical records (e.g., Rey et al., 2016). However, this approach is not suitable when the water system analyzed has substantially changed over recent years, as is the case in the Guadalquivir River Basin, where the SBXII is located. Given recent changes in water demands (new water rights granted), reservoir infrastructure (increased storage capacity), and water management rules (larger minimum ecological flows) (Expósito and Berbel, 2019), distributions fitted according to past records are not appropriate for assessing feasible hydrological situations and current water supply reliability. Therefore, an approach based on a stochastic hydrological simulation model considering the new demand and supply constraints and the institutional framework fixed in the Guadalquivir RBMP (CHG, 2015) is needed to estimate the probability distributions of annual water allotments. This approach has been implemented by Gómez-Limón (2020) for the hydrological system where the case study area is located (*Sistema de Regulación General*), yielding the empirical histogram shown in Fig. 1.

The shape of this histogram does not fit to any commonly-used distribution function. For this reason, we directly rely on the simulated observations obtained by Gómez-Limón (2020) as irrigation water allotment scenarios to feed the mathematical programming model built (see next section).

## 4. Modeling approach

A positive mathematical programming model is built to simulate farmers' behavior under the new water rights regime proposed, in order to compare its potential performance with the current proportional allocation rule, in terms of economic efficiency. In the simulation of both allocation regimes, water trading is not allowed (i.e., anticipating an institutional context in Spain without water markets), meaning the analysis is focused on allocation rules as instruments for enhancing water efficiency.

### *4.1. Proportional and priority allocation rules*

The ID (subscript *id*) taken as a case study comprises the three farm types (subscript *f*) which are considered as the decision-making units. Each farm type represents $n_f$ farms with an average size of $s_f$ irrigated hectares, with their weights being $w_f = \frac{n_f \cdot s_f}{s_{id}}$, and where $s_{id}$ is the area of the ID ($s_{id} = \sum_f n_f \cdot s_f$).

Under current internal management rules, annual water allotments granted to the ID ($WA_{id}$ measured in cubic meters) are shared proportionally among all farm types, i.e. water allocations in cubic meters per hectare ($wa_f$) are the same for all farm types within the ID, such that $wa_f = wa_{id} = WA_{id}/s_{id}$ for every $f$. Consequently, the water allocation for farm type *f* measured in cubic meters is $WA_f = wa_f \cdot s_f$.

Under the proposed new distribution rules, the ID would hold water rights defined as a portfolio of two different water rights, priority and general rights, which would be distributed among farms in any proportion. Therefore, each farm type would hold a different portfolio of water rights. The share of priority rights per farm type is denoted as $PR_f$, while the share of general rights is denoted as $GR_f$, with the two shares adding up to one ($PR_f + GR_f = 1$). Initially, the optimal share of priority rights at the ID level ($PR_{id} = \sum_f PR_f \cdot w_f$) is unknown, so it will be parametrized to determine the $PR_{id}$ that yields the best outcome.

Under this new water rights regime, the annual water allotments to be allocated to each farm type are defined as the sum of the allotments granted for priority rights (*wapr*) and for general rights (*wagr*):

$$wa_f = wapr \cdot PR_f + wagr \cdot GR_f \tag{1}$$

These two terms are both determined annually depending on the water allocated to the ID () following the abovementioned priority procedure. Thus, priority rights are served first with the full water allotment granted to the ID ($fwa_{id}$) as long as the water availability $wa_{id}$ is enough to cover all water demands from priority rights holders. After that, the remaining water is allocated proportionally among general rights holders (see Eq. (2)). In the event that there is not enough water to meet full allocations for priority rights, the available water is to be rationed among priority rights holders following the proportional rule. In this case, general rights holders would not receive any water allocation (see Eq. (3)).

Mathematically, this priority allocation rule can be expressed as follows:

$$wa_{id} \geq PR_{id} \cdot fwa_{id} \begin{cases} wapr = fwa_{id} \\ wagr = \dfrac{wa_{id} - PR_{id} \cdot fwa_{id}}{1 - PR_{id}} \end{cases} \tag{2}$$

$$wa_{id} < PR_{id} \cdot fwa_{id} \begin{cases} wapr = \dfrac{wa_{id}}{PR_{id}} \\ wagr = 0 \end{cases} \tag{3}$$

We assume that farmers try to maximize farming profits as a function of their water allotments ($\pi_f = f(wa_f)$). As explained above, irrigators'

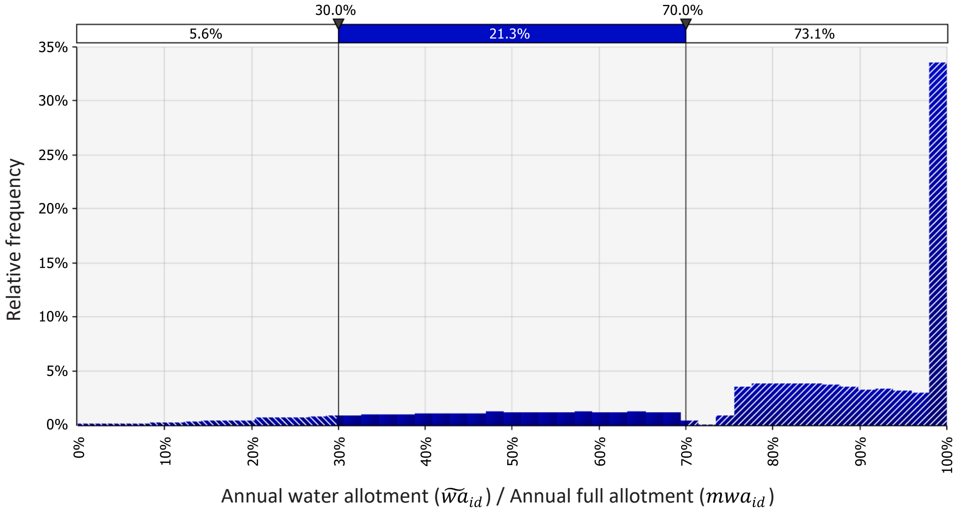

**Fig. 1.** Distribution of the annual water allotments ($\widetilde{wa}_{id}$) for the SBXII.
Source: Gómez-Limón (2020).

annual water allotments are variable depending on the water availability at the ID level. Thus, since water allotments are stochastic variables (both $\widetilde{wa}_{id}$ and $\widetilde{wa}_f$), farming profits are also stochastic variables ($\widetilde{\pi}_f$). To simulate the risk from water supply variability at the ID and farm levels, $N = 5000$ probabilistic values for $\widetilde{wa}_{id}$ drawn from the hydrological simulation model built by Gómez-Limón (2020) have been considered, thus defining 5000 equally probable scenarios ($n = 1, \ldots, 5000$).

### 4.2. Farmers' decision making for a given water allotment scenario

For operative purposes, we take the expected total gross margin (i.e., total income minus variable costs, $GM_f$) as a proxy for farming profits in the short-run, defined as a mathematical function of farmers' decision variables, that is, the area covered by the different crops. In our case study, these variables are denoted by $X_{c,f}$, where $c$ denotes the crop and $f$ indicates the farm type. In addition, farmers can make decisions regarding the share of their water right to be upgraded into priority rights ($PR_f$), with the remaining water rights being considered as general water rights ($GR_f$). Thus, farmers' decision-making is simulated by maximizing the expected total gross margin considering both kinds of decision variables, $GM_f = f\left(X_{c,f}, PR_f\right)$.

Following mainstream mathematical programming techniques used for *ex-ante* policy analysis, our modeling approach is based on Positive Mathematical Programming (PMP) (Heckelei et al., 2012). We implemented the standard approach formally introduced by Howitt (1995) for two reasons. First, it is a simple method to apply in that it does not require exogenous information, facilitating its application to other case studies elsewhere. Second, this method allows us to overcome one of the problems of the PMP: namely, the impossibility of calibrating activities not observed in the reference year, which is a necessity in our case in order to add rainfed crops as alternatives in the event of irrigation water supply gaps. Using Howitt's standard method prevents us from calibrating the activities not observed in the reference year, with these crops being added using their average cost (instead of the usual PMP quadratic cost functions). This approach is suitable because rainfed crops are much less profitable than irrigated crops, so these alternatives only appear in cases when the annual water allotments are much lower than full water allotments and farmers are compelled to reduce the farming area actually irrigated.

This standard PMP procedure calibrates a non-linear objective function for profit based on the observed behavior of farmers (i.e., observed crop mix under a full water allotment scenario) to exactly reproduce activity levels. Among the alternative options for eliciting the calibrating parameters, we use the average cost approach (Heckelei and Britz, 2000), assuming a quadratic variable cost function for every crop $c$ ($cv_c = \alpha_c \cdot X_c + ½ \cdot \beta_c \cdot X_c^2$), where $\alpha_c$ and $\beta_c$ are parameters to be elicited in order to reproduce the exact activity levels for each farm type in the reference year (Mérel and Howitt, 2014). Thus, for farm $f$, the variable costs are:

$$cv_f\left(X_{c,f}\right) = \sum_c \alpha_{c,f} \cdot X_{c,f} + ½ \cdot \beta_{c,f} \cdot X_{c,f}^2 \tag{4}$$

Although there are multiple sets of cost function parameters $\alpha_{c,f}$ and $\beta_{c,f}$ that can exactly reproduce observed behavior, under the average cost approach the quadratic cost function equals the accounting cost of the crop, resulting in the following calibrating parameter definitions:

$$\alpha_{c,f} = avc_{c,f} - \mu_{c,f} \tag{5}$$

$$\beta_{c,f} = \frac{2\,\mu_{c,f}}{X_{c,f}^{obs}} \tag{6}$$

where $avc_{c,f}$ is the average or observed accounting variable cost of crop $c$ in farm type $f$, $X_{c,f}^{obs}$ is the observed area of crop $c$ in a year with full water allotment ($wa_{id} = fwa_{id}$) in farm type $f$, and $\mu_{c,f}$ are the dual values of the calibration constraints reproducing a 'normal' hydrological scenario (i.e., where no water rationing is needed). A review of the standard PMP and the average cost approach can be found in Heckelei and Britz (2005).

The PMP calibrated model can then be used for simulating farmers' decision-making in other scenarios (e.g., water shortage situations and under different water allocation rules) by modifying the objective function, changing the values of the non-calibrating parameters, adding new constraints (e.g., water availability), or adding new decision variables (e.g., new crop alternatives) accordingly. One of the most valuable advantages of the PMP is that it provides more flexible and realistic simulation responses than normative mathematical programming models (Henry de Frahan et al., 2007).

It is assumed that when faced with water shortages (i.e., $wa_{id} < fwa_{id}$), farmers react by changing their crop mixes, replacing crops that have higher water requirements with others that have lower water needs or even rainfed crops (i.e., null irrigation water requirement). Thus, in addition to the observed irrigated crops, two rainfed alternatives (wheat and sunflower) have also been considered as decision variables for simulating decision-making under drought scenarios. Other potential management strategies to cope with cyclical scarcity (e.g., improving irrigation efficiency at farm level or implementing deficit irrigation) have been ruled out since they are not suitable for IDs with modern irrigation technologies (i.e., they have already achieved efficient water use) specialized in herbaceous crops (i.e., deficit irrigation doses do not lead to more profitability).

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

$$\underset{X_{c,f},PR_f}{\mathrm{Max}}\ Z = \sum_f GM_f / s_f \cdot w_f \tag{7.1}$$

$$\text{s.t.}\ GM_f = \sum_c \left\{ \left( p_c \cdot y_c + s_c - \alpha_{c,f} - ½ \cdot \beta_{c,f} \cdot X_{c,f} \right) \cdot X_{c,f} \right\} \quad \forall f \tag{7.2}$$

$$\sum_c X_{c,f} = s_f \quad \forall f \tag{7.3}$$

$$\sum_c wr_c \cdot X_{c,f} \le wa_f \cdot s_f \quad \forall f \tag{7.4}$$

$$wa_f = wapr \cdot PR_f + wagr \cdot GR_f \quad \forall f \tag{7.5}$$

$$wapr = \begin{cases} fwa_{id}, & wa_{id} \ge PR_{id} \cdot fwa_{id} \\ \dfrac{wa_{id}}{PR_{id}}, & wa_{id} < PR_{id} \cdot fwa_{id} \end{cases} \tag{7.6}$$

$$wagr = \begin{cases} \dfrac{wa_{id} - PR_{id} \cdot fwa_{id}}{PR_{id}}, & wa_{id} \ge PR_{id} \cdot fwa_{id} \\ 0, & wa_{id} < PR_{id} \cdot fwa_{id} \end{cases} \tag{7.7}$$

$$PR_f + GR_f = 1 \quad \forall f \tag{7.8}$$

$$\sum_f PR_f \cdot w_f = PR_{id} \tag{7.9}$$

$$\boldsymbol{A}_f \boldsymbol{X}_f \le \boldsymbol{B}_f \quad \forall f \tag{7.10}$$

$$X_{c,f} \ge 0;\ PR_f \ge 0;\ GR_f \ge 0 \quad \forall c,f \tag{7.11}$$

where $GM_f$ represents the farm gross margin, calculated as the sum of total income, including both product sales (crop price, $p_c$, multiplied by crop yield, $y_c$) and coupled subsidies ($s_c$), minus the variable cost function ($\alpha_{c,f} + ½ \cdot \beta_{c,f} \cdot X_{c,f}$) for every crop $c$. Constraints (7.3) is related to land availability and limits the total area covered by the different crop alternatives to the farm size ($s_f$). Eqs. (7.4)–(7.9) are related to water availability. The water constraints Eq. (7.4) establishes that irrigation water use cannot exceed water availability, with the former being the sum of water requirements per crop ($wr_c$) and the latter the water allocation per farm type ($wa_f \cdot s_f$). $wa_f$ is defined in (7.5) as a portfolio of water allocated to priority rights (*wapr*) and general rights (*wagr*) as defined by Eqs. (7.6) and (7.7), derived from Eqs. (2) and (3) explained above. Eq. (7.8) simply states that water rights granted to each farm type are composed of a portfolio of priority and general rights. Constraint (7.9) just limits the maximum share of rights that can be upgraded to priority rights at the ID level, as fixed by the parameter $PR_{id}$. Eq. (7.10) denotes the rest of the constraints defining the feasible solution set, which constitute agronomic (rotational and frequency requirements), policy (cotton and sugar-beet quotas), and market requirements, with $\boldsymbol{X}_f$ being the matrix containing all variables $X_{c,f}$, $\boldsymbol{A}_f$ the technical coefficient matrix for every variable and constraint of the farm type $f$, and $\boldsymbol{B}_f$ the vector of limit values for each constraint for the farm type $f$. Finally, non-negativity constraints are imposed for $X_{c,f}$, $PR_f$ and $GR_f$ (Eq. (7.11)).

Considering the current proportional allocation rule, farm types' decision-making can also be integrated with a simplified version of model (7), skipping Eqs. (7.6)–(7.9) and replacing Eq. (7.5) by $wa_f = wa_{id}$ for every farm type $f$.

### *4.3. Farmers' decision-making considering the full distribution of water allotments*

It should be recalled that the annual water allotment granted to the ID is a stochastic variable ($\widetilde{wa}_{id}$) ranging from $fwa_{id}$ to 0. Within this stochastic framework, it is assumed that farmers make decisions regarding the upgrade of water rights in an attempt to maximize their expected (or average) total gross margin. Thus, considering $N = 5000$ probabilistic values for $wa_{id}$, model (7) becomes:

$$\underset{X_{c,f,n},PR_f}{\text{Max}}\ Z = \frac{1}{N}\sum_{f,n} GM_{f,n}/s_f \cdot w_f \tag{8.1}$$

$$\text{s.t.}\ GM_{f,n} = \sum_c \left\{ \left(p_c \cdot y_c + s_c - \alpha_{c,f} - ½ \cdot \beta_{c,f} \cdot X_{c,f,n}\right) \cdot X_{c,f,n} \right\} \quad \forall f,n \tag{8.2}$$

$$\sum_c X_{c,f,n} = s_f \quad \forall f,n \tag{8.3}$$

$$\sum_c wr_c \cdot X_{c,f,n} \le wa_{f,n} \cdot s_f \quad \forall f,n \tag{8.4}$$

$$wa_{f,n} = wapr_n \cdot PR_f + wagr_n \cdot GR_f\ \forall f,n \tag{8.5}$$

$$wapr_n = \begin{cases} fwa_{id}, & wa_{id,n} \ge PR_{id} \cdot fwa_{id} \\ \dfrac{wa_{id,n}}{PR_{id}}, & wa_{id,n} < PR_{id} \cdot fwa_{id} \end{cases} \tag{8.6}$$

$$wagr_n = \begin{cases} \dfrac{wa_{id,n} - PR_{id} \cdot fwa_{id}}{PR_{id}}, & wa_{id,n} \ge PR_{id} \cdot fwa_{id} \\ 0, & wa_{id,n} < PR_{id} \cdot fwa_{id} \end{cases} \tag{8.7}$$

$$PR_f + GR_f = 1 \quad \forall f,n \tag{8.8}$$

$$\sum_f PR_f \cdot w_f = PR_{id}\ \forall n \tag{8.9}$$

$$\boldsymbol{A}_f \boldsymbol{X}_{f,n} \le \boldsymbol{B}_f\ \forall f,n \tag{8.10}$$

$$X_{c,f,n} \ge 0;\ PR_{id} \ge 0;\ PR_f \ge 0;\ GR_f \ge 0 \quad \forall c,f,n \tag{8.11}$$

This probabilistic approach involves $N$ values for $wa_{f,n}$, also affecting in each scenario $n$ crop mixes ($X_{c,f,n}$), and thus $GM_{f,n}$. The objective function in this model (8.1) allows the joint maximization of the average gross margin for all farm types, as a result of the optimum decision-making regarding the upgrade into priority rights. It is also worth recalling that $PR_{id}$ is parametrized, so we can find the optimal share of priority rights within the ID that maximizes the total efficiency.

To evaluate the possible improvements under this new water allocation regime in terms of economic efficiency, it is necessary to establish a baseline scenario. To do this, the stochastic model is also solved considering current proportional allocation rules (i.e., without the possibility of acquiring priority rights). Thus, model (8) is also solved by ignoring Eqs. (8.6)–(8.9) and substituting Eq. (8.5) with $wa_{f,n} = wa_{id,n}$ for every farm type $f$. In doing so, we are able to obtain any variations in gross margins and water use at the farm and ID level, as well as other indicators for the analysis, allowing an assessment of the proposed allocation rule.

## 5. Results

The results of the simulation model yield evidence that priority rights could enhance overall economic efficiency. In fact, compared to the baseline values of the current proportional water rights regime, the average gross margin at the ID level is increased for every possible value of the parameter $PR_{id}$ (share of priority rights over total water rights). However, these improvements in economic efficiency are almost negligible, registering a disappointing maximum of 0.2% of the current gross margins for the optimum value for $PR_{id}$ (20.5%).

As can be observed in Fig. 2, the increase in the average gross margin at the ID level (black line) is the overall result of heterogeneous impacts on the different farm types considered (gray lines). FT1 shows a significant WTP for upgrading general water rights into priority ones, since this upgrade allows the highest increase in average profitability, reaching a maximum WTP of 2.1% of its current gross margin (i.e., with proportional water rights). Conversely, FT2 and FT3 register the lowest WTA for reducing their water supply reliability as a consequence of keeping general water rights, requiring compensation (i.e., reduction on the annual payment to the WAU) ranging from 0% to 5.1% of their current gross margins depending on the total share of priority rights granted.

In any case, it should be highlighted that, theoretically, the WTA of FT2 and FT3 could be fully met by the WTP of FT1 through the proposed compensation instrument, while still leaving a gross margin surplus (i.e., economic efficiency increase). Nevertheless, it is also worth mentioning that the modeling approach followed has been simplified by assuming null transaction costs, both static and institutional transaction costs (Garrick et al., 2013; Marshall, 2013). Thus, since the WTP-WTA gap is very small in this case study (a surplus of only 0.2% of current gross margins), it is reasonable to assume that in a real-world setting there would actually be no room for any efficiency increase.

Table 2 shows the simulation results for the maximum efficiency solution, based on a 20.5% share of priority water rights granted at the ID level. Taking this solution as the best possible outcome, it can be observed that FT1 upgrades 30.7% of its water rights into priority ones. However, it is worth noting that FT2 and FT3 also upgrade a share of their water rights, although in lower proportions (11.3% and 3.1%, respectively). This optimum allocation of priority water rights allows FT1 to increase its average annual water allocation compared to the current situation (i.e., implementation of proportional water rights), while its water allocation became more stable over time (an increase of 3.2% in the average allocation and a decrease of 11.3% in its standard deviation). Accordingly, this improved water supply reliability leads to an increase in the average gross margin (2.0%) and a decrease in its volatility (18.0% decrease in its standard deviation), prompting this farm type to make the highest bid for a rights upgrade (i.e., annual surcharges to be paid) through the auction procedure suggested.

On the other hand, the irrigation water supply gets worse for FT2 and FT3, both in terms of the average (decreases of 2.9% and 5.5%,

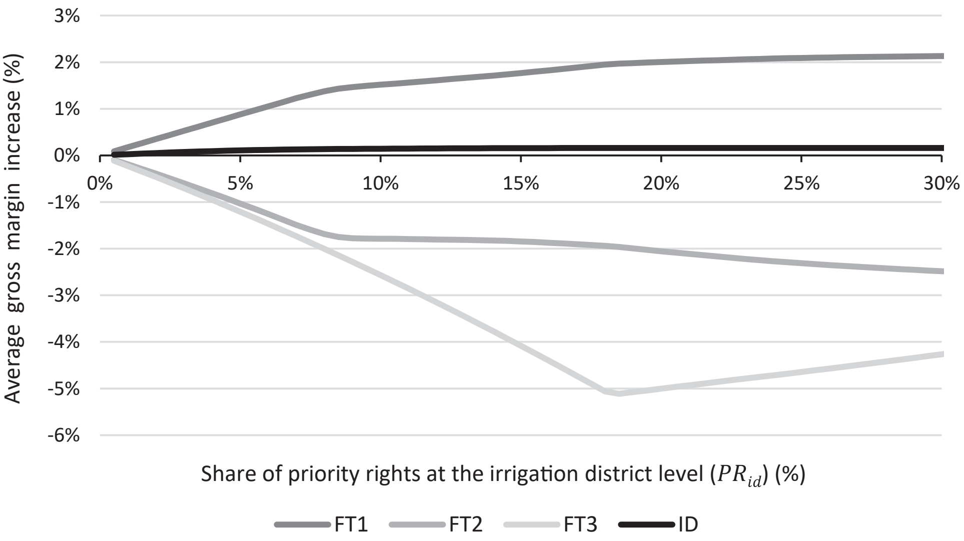

**Fig. 2.** Maximum efficiency solutions parametrizing the share of priority rights at the ID level ($PR_{id}$): average gross margin by farm type.

**Table 2**
Maximum efficiency solution: Share of priority water rights, gross margin, and water use by farm type.

| | | FT1 | FT2 | FT3 | ID |
|---|---|---|---|---|---|
| Priority water rights (%) | | 30.7% | 11.3% | 3.1% | 20.5% |
| Average annual water allocation ($m^3$/ha) | Proportional rule | 4753.2 | 4753.2 | 4753.2 | 4753.2 |
| | Priority rule | 4906.1 | 4615.7 | 4492.8 | 4753.2 |
| | Increase (Priority-Prop.) | 152.9 (3.2%) | -137.5 (−2.9%) | -260.4 (−5.5%) | 0.0 (0.0%) |
| Std. deviation annual water allocation ($m^3$/ha) | Proportional rule | 1454.6 | 1454.6 | 1454.6 | 1454.6 |
| | Priority rule | 1290.0 | 1604.2 | 1738.9 | 1454.6 |
| | Increase (Priority-Prop.) | -164.6 (−11.3%) | 149.6 (10.3%) | 284.3 (19.5%) | 0.0 (0.0%) |
| Average annual gross margin (€/ha) | Proportional rule | 2640.1 | 1990.8 | 1586.5 | 2283.5 |
| | Priority rule | 2693.2 | 1949.3 | 1507.7 | 2287.1 |
| | Increase (Priority-Prop.) | 53.2 (2.0%) | -41.5 (−2.1%) | -78.8 (−5.0%) | 3.6 (0.2%) |
| Std. deviation annual gross margin (€/ha) | Proportional rule | 429.9 | 315.4 | 334.2 | 375.8 |
| | Priority rule | 352.6 | 385.3 | 445.6 | 372.4 |
| | Increase (Priority-Prop.) | -77.3 (−18.0%) | 69.8 (22.1%) | 111.4 (22.1%) | -3.4 (−0.9%) |

*Source: Own elaboration.*

respectively) and the volatility (increases of 10.3% and 19.5%, respectively, in their standard deviations). This deteriorated supply reliability leads to worse profitability indicators: reduced average gross margins (2.1% and 5.0%, respectively) and increased profit volatility (22.1% increase in the standard deviation of the gross margin for both farm types). Nevertheless, these farming losses could theoretically be fully compensated by the surcharges paid by FT1.

In this regard, it is worth noting that the overall volume of water allocated at the ID level is the same as in the proportional water rights baseline. This constraint was implicitly assumed in the proposal, in order to ensure that the proposed change in the water allocation regime has no direct impact on the environment (e.g., water abstractions).

However, the implementation of security-differentiated water rights could involve some spillover effects, both positive and negative, on the environment. First, it could be logically assumed that the priority system may lessen the incentive to steal water for those more efficient farmers who are more sensitive to water supply gaps (Loch et al., 2020b). Second, the reform proposed in the water allocation regime could produce a negative side effect on the environment by decreasing the return flows. Indeed, the farmers who are most willing to acquire priority rights are usually those who are more efficient in water use because they use more modern irrigation techniques. Thus, it could be expected that the more priority rights these farmers acquire, the lower the return flows to watercourses, negatively affecting environmental flows. At any rate, in the case study considered, the effects on returns would not have a significant impact on the environment because this ID is located close to the mouth of the Guadalquivir River, and almost all the returns from the ID go directly to the sea. Nevertheless, because of how difficult they are to assess, none of these potential side effects has been considered in the modeling exercise implemented.

Lastly, the results obtained for specific water allotment scenarios ($wa_{id}$) under the optimum priority rights sharing, as shown in Table 3, are also noteworthy. It can be easily seen that, compared to the proportional rights regime, the implementation of priority rights increases water allotments and annual gross margins in the case of FT1 (the 'reliability winner'), while FT2 and FT3 ('reliability losers') show a decrease in these two variables. However, the most notable result is that the overall variation in gross margins at the ID level is not always positive. For moderate to severe drought scenarios, with an annual ID-level water allocation of between 3723 and 2032 $m^3$/ha, the outcome of the implementation of the proposed priority regime is worse than that of the current proportional water rights. Thus, the implementation of priority rights not only provides a tiny increase in average economic efficiency but also involves annual economic inefficiency for a range of drought scenarios with a probability of occurrence of 14.9%. However, it is also true that priority rights could yield an efficiency increase in the event of an extreme drought (annual water allotment below 1300 $m^3$/ha).

## 6. Discussion and concluding remarks

In light of the results obtained, we reject the initial hypothesis that replacing allocation procedures based on the proportional rule with a

**Table 3**
Maximum efficiency solution: Increase in gross margin by irrigation water allotment scenario and farm type.

| $wa_{id}$ ($m^3$/ha) | **Increase in annual gross margin (Priority-Prop.)** (€/ha and percentage) | | | | **GM increase ID** (1000 €) |
|---|---|---|---|---|---|
| | **FT1** | **FT2** | **FT3** | **ID** | |
| 6000 | 0.0 (0.0%) | 0.0 (0.0%) | 0.0 (0.0%) | 0.0 (0.0%) | 0.0 |
| 5400 | 3.8 (0.1%) | 0.0 (0.0%) | -0.2 (0.0%) | 1.9 (0.1%) | 28.4 |
| 4800 | 34.1 (1.2%) | -1.1 (−0.1%) | -58.2 (−3.4%) | 10.8 (0.4%) | 157.9 |
| 4200 | 56.1 (2.1%) | -28.9 (−1.4%) | -92.8 (−5.9%) | 8.1 (0.4%) | 119.4 |
| 3600 | 89.2 (3.6%) | -92.2 (−4.6%) | -144.5 (−10.1%) | -3.5 (−0.2%) | -51.4 |
| 3000 | 133.9 (5.9%) | -137.0 (−7.7%) | -208.9 (−16.5%) | -3.9 (−0.2%) | -56.4 |
| 2400 | 182.4 (9.0%) | -174.3 (−11.3%) | -288.7 (−26.9%) | -1.2 (−0.1%) | -17.5 |
| 1800 | 238.7 (13.5%) | -218.3 (−17.0%) | -373.2 (−43.5%) | 2.5 (0.2%) | 37.2 |
| 1200 | 340.3 (23.9%) | -276.9 (−27.3%) | -455.0 (−73.4%) | 24.8 (2.1%) | 363.7 |
| 600 | 302.4 (34.7%) | -210.1 (−30.0%) | -240.7 (−66.7%) | 53.8 (7.2%) | 788.5 |

*Source: Own elaboration.*

priority rule establishing security-differentiated water rights can help improve water-use efficiency in the agricultural sector at the local (i.e., irrigation district) level. In fact, although the simulated performance shows that this reform in irrigation water rights could generate a slight efficiency improvement, the economic gains would not be enough to cover the transaction costs associated with the implementation of the proposed allocation regime (an upgrade of water rights through auctions and a compensation procedure to indemnify "reliability losers").

These disappointing results are explained by the fact that priority rights do not reflect the marginal value of water across users in a timely manner (OECD, 2016). If the main political objective is to improve economic efficiency, the most suitable instrument would be the spot water market (allocation trading), as it is the most useful mechanism for equalizing the marginal benefit of water across users (Chong and Sunding, 2006). Water scarcity is a dynamic phenomenon that must be managed through the implementation of sufficiently flexible instruments capable of modifying allocations in the short term, just as the spot water markets do. This is not the case of allocation regimes based on priority rights, which is a rigid instrument that cannot be modulated depending on the level of water scarcity. In fact, as shown by the Australian experience, priority rights should not be considered as an alternative instrument to spot water markets, but rather a complementary instrument to water trading that can help improve water-use efficiency.

As far as the authors know, the assessment performed in this paper is innovative. However, a few previous related studies analyzing other water rationing rules are worth citing. In this sense, Martínez and Esteban (2014), Alarcón et al. (2014), and Goetz et al. (2017) have focused on other allocation rules (uniform, sequential, equal economic loss, or minimization of the total accumulated loss rules) proposed by economic theory, also using mathematical programming simulation techniques. These authors report that while these alternative allocation rules could provide significant efficiency improvements at the ID level compared to the proportional rule currently implemented, all of them are outperformed by spot water markets. Although all this evidence is useful for policy analysis, it is also true that the implementation of these alternative allocation rules could be complex in a real-world setting (e.g., economic analyses of the heterogeneity of farmers' losses due to water shortages would first be needed), involving significant transaction costs. This is one of the reasons why they have not yet been implemented anywhere.

Another related contribution worth noting is the study by Adamson et al. (2006). These authors also assess a water allocation regime with two security-differentiated water rights (high and low priority), which is compared with the proportional allocation rule. For this purpose, they use a state-contingent model of production under uncertainty with three states of nature (normal, drought, and wet), which is applied to the Murray-Darling Basin, including all water rights holders (both urban and agricultural). They conclude that a water allocation solution with two levels of priority rights outperforms that obtained using the proportional rule.

There may be several reasons behind the unexpected and contradictory results reported in this paper. First, the differences found could be largely explained by the different scopes of the changes proposed in water allocation rules. While in this paper the assessment performed considers a change in allocation rules at the ID level only (water allocation among farmers within the same ID), other studies have considered a shift in allocation rules for all water rights holders in a river basin, thus also affecting water allocation among IDs. In this respect, it would seem logical to assume that by including more heterogeneity among water rights holders, priority rights could yield higher water-use efficiency improvements. In any case, further research would be necessary to confirm that greater heterogeneity would lead to priority allocation solutions clearly outperforming those obtained with the proportional rule, as evidenced in the case of the Murray-Darling Basin (Adamson et al., 2006).

Second, the SBXII ID is a particular case study that is notable for its specialization in annual crops (no perennial crop is grown in this district). This characteristic probably also limits the efficiency gains reported here since farms with perennial crops are among those that stand to benefit the most from priority rights (most permanent crops cannot be grown under rainfed conditions in case of irrigation water supply gaps, requiring priority rights to ensure a sufficiently reliable supply). In this regard, it is also worth acknowledging the limitation of the modeling approach proposed to properly account for investment in fixed assets (e.g., perennial crops or production technologies). Thus, the results reported do account for potential further specialization in higher profitability farming systems, also helping to improve water-use efficiency in the long-term, as has been evidenced in the United States or Australia (Xu et al., 2014).

Third, it worth noting that the results reported also reflect the current probability distribution of annual water allotments (see Fig. 1). Although annual water allotments are fairly often lower than the full water allotment, the well-developed network of reservoirs in the Guadalquivir Basin (i.e., interannual storage capacity) means that there is currently a fairly low risk of severe irrigation water supply gaps (e.g., annual water allotments lower than 30% of full water allotment). As a result, the efficiency gains from priority rights are lower than those expected in basins with a higher probability of extreme hydrological droughts. However, this could be the situation in the Guadalquivir Basin in the near future, as climate change projections point to an increase in the frequency and intensity of droughts events.

Fourth, the results obtained could also be influenced by the case-specific agricultural policy framework (i.e., coupled subsidies and production quotas, which may not exist in other regions), which complicates comparisons with other irrigated agricultural systems. In fact, it is worth pointing out that the application of the proposed simulation approach to other irrigated areas would require some fine-tuning to reflect local policy conditions.

In any case, allocation regimes based on priority rights are interesting for two reasons. First, as pointed out by Freebairn and Quiggin (2006) and Lefebvre et al. (2012), these allocation regimes could be successfully combined with spot water markets, as in the Australian experience, where the joint implementation of these two instruments has led to significant improvements in drought management in the irrigation sector. Second, priority rights are an interesting risk management instrument for farmers. As shown in the simulation results, the farmers who are most vulnerable to risk (FT1 in our case study) 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 an important adaptation instrument.

Finally, further research is called for to refine the proposed modeling approach and thereby obtain more accurate results. In this sense, more detailed modeling of decision-making regarding the upgrade of water rights could be achieved by accounting for possible changes in production technologies (investments in irrigation systems or perennial crops), the existence of transaction costs, and heterogeneity in farmers' risk preferences. Moreover, assessing the impact of priority rights at the basin level, incorporating more farm type heterogeneity, could provide relevant new insights into this topic. These new avenues for research pose challenges, since uncertainty about the future state of water systems creates difficulties in simulating farmers' strategic decision-making (i.e., decisions involving investments in fixed capital), and assessing the multiple impacts of investments made chasing higher economic returns (e.g., Loch et al., 2020a suggest potentially irreversible losses of capital tied to water inputs and changing incentives to steal water resources).

## 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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