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Water Pricing and Quotas: A Quantitative Analysis from a Private and Social Perspective

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Abstract
The current situation of structural water scarcity due to the rise in demand, the reduction in supply as a consequence of climate change, increasingly frequent drought periods, and overall quantitative pressure on water resources creates a need for economic instruments to reduce the amount of water used, especially in the agricultural sector. Thus, water pricing and allocation quotas (proportional reduction of allocations) may be suitable tools to reduce demand or allocate scarce water resources. For a comparative analysis of the performance of these two measures, a Positive Mathematical Programming model has been developed, using the Guadalquivir River Basin as a case study. Additionally, the analysis takes into account the revenue generated from water pricing and the marginal cost of public funds. The results indicate that, from the farmer's perspective, quotas result in smaller losses than water pricing. However, when considering water pricing along with the revenue generated from this measure, this mechanism would be more beneficial for society as a whole, since the taxes collected could be used for other purposes, albeit with efficiency losses measured by the marginal cost of public funds and the excess burden of taxation.

Keywords Water pricing · Water quotas · Spain · Positive Mathematical Programming · Marginal cost of public funds

1 Introduction and Objectives

Water resources are one of the most crucial factors of production and have a direct and indirect impact on all sectors of the global economy in all regions of the world. One of the greatest challenges currently facing society is the availability of an adequate quality and quantity of freshwater (Distefano and Kelly 2017). The world's population is growing, and conse-

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quently the demand for food is increasing, leading to a rise in water extraction and global consumption (FAO 2012). In the Mediterranean and semi-arid climate regions, where irrigated agriculture is prevalent and water consumption for crop irrigation has increased, the closure of river basins has become a common practice. A basin is considered closed when it is not possible to increase the water supply to meet new demands (Molle et al. 2010).

Furthermore, because of global warming and climate change, there has been a general reduction in water availability around the world (IPCC 2018). In any given mature water economy, there is thus insufficient water to supply the increasing and competing uses of water, meaning that new demands can only be satisfied through a reduction in existing ones (Molle 2009). Therefore, to reduce the amount of water used, it is necessary to implement different demand-management instruments and economic policies such us water pricing, water markets, technologies, and user-based reallocation (Gómez et al. 2018; Lago et al. 2015). It is often difficult to implement these instruments, either because legislation or regulation does not allow them or because there are too many obstacles and a lack of acceptance by society, as is the case with water markets (Giannoccaro et al. 2013). Similarly, the Water Framework Directive (WFD) (European Commission 2000) has encouraged the use of economic instruments to bring about changes in water demand and to reduce water pollution (Art. 9).

Water allocation rights are a key tool for managing water resources in closed basins, where water availability is limited, and use must be carefully controlled and regulated. In a closed basin, water allocation rights are granted to users based on the availability of water and the needs of different users. These rights establish how much water can be extracted from the basin by each user (Molle 2009; Molle et al. 2010). Water allocation rights can be granted in the form of concessions or water extraction permits and can be assigned for a specific period or permanently. In some cases, these rights are transferable, which means that users can buy and sell their water rights on the market.

There are two main alternative approaches to rationing irrigation water allocations (quotas) in the event that there is not enough water to satisfy all water rights holders: those based on the proportional rule and others based on priority rule (OECD 2016). The proportional rule is the best known and most widely used rationing method for irrigation water allocation (Gómez-Limón et al. 2020a). This rule consists of all water rights holders receiving an amount of water proportional to their water rights so that the total demand equals the total supply (OECD 2015). Conversely, under the priority rule, irrigation rights holders are divided into priority classes, and their water rights are allocated according to those priority levels. In this way, the demands of the rights holders deemed highest priority are satisfied first, and when these demands have been fully met, the remaining resource is allocated to the corresponding rights holders according to the criterion of diminishing priority (Gómez-Limón et al. 2020a).

Water pricing is another well-known economic instrument aimed at promoting efficient water use and conservation. According to the European Environmental Agency (EEA) glossary, water pricing is defined as “the application of a rate or monetary value at which water can be bought or sold” (European Environment Agency 2013). The WFD (Art. 9) states that “[…] water pricing policies provide adequate incentives for users to use water resources efficiently, and thereby contribute to the environmental objectives of this directive. However, European Environment Agency (2013) points out that the application of pricing in the EU has been slow, including in the agricultural sector. Thus, more than 20 years after the adoption of the WFD, not a single Southern European member state has implemented an agricultural water pricing reform that incorporates the principles of cost recovery, polluter-pays, and affordability as set out in the WFD (Rey et al. 2018).

Many authors have conducted in-depth studies of water pricing in the agricultural sector. Some of these publications examined the impact of the WFD on the sustainability of irrigation systems in agriculture (Bazzani et al. 2004; Berbel and Gutiérrez Martín 2005). Others have analysed water pricing experiences in different countries such as Australia, Brazil, Mexico, Italy, France, and China, among others (Dinar et al. 2015; Doppler et al. 2002; Grové et al. 2023; Massarutto 2003; Molle 2009; Mu et al. 2024). However, few authors have based their research on regional economic models using multi-model joint frameworks involving various mathematical programming methods (Pérez-Blanco et al. 2016; Sapino et al. 2020).

In Spain, which is the focus of this case study, research on water pricing is of great interest. Some of the most recent contributions have analysed the effect of water pricing using a case study in a particular area (Aldaya et al. 2023; Montilla-López et al. 2017). Some authors have applied various methods and simulation models using mathematical programming to simulate and quantify the impact of water pricing on the agricultural sector (Gallego-Ayala et al. 2011; Iglesias and Blanco 2008). It is worth noting the relative scarcity of evaluations of regional impacts at basin level, and very few studies have incorporated water pricing into hydro-economic models (Kahil et al. 2016; Martínez-Dalmau et al. 2023a).

Previous research on water pricing has not considered the full welfare effect of a tax reform (with a few exceptions, such as Gómez-Limón et al. 2019, 2020b; Martínez-Dalmau et al. 2023b). This can be accounted for by a “price” per unit of tax revenue (González-Páramo 2003a), known as the marginal cost of public funds (MCF). The MCF represents the shadow price that society pays for each of the monetary units invested in public spending policies (Dahlby 2008). There are other monetary measurements of the cost of the distortions that taxes introduce into the economic system, such as the excess burden of taxation (González-Páramo 2003a), which measures the monetary loss caused by the introduction of a tax as the difference between the total economic loss and the revenue collected. In addition, it is important to take into account that the agricultural sector not only generates wealth through its activity, but also indirectly benefits the rest of the economy through its interrelation with and spillover effects on the agri-food chain and other sectors. Some authors have examined the spillover effects in Spain, measured as an effect on the overall economy through a multiplier (Cansino Muñoz-Repiso et al. 2013; Gómez-Ramos and Pérez 2012; Rodríguez-Chaparro 2013). In other studies, the effects of water pricing on the economy as a whole have been assessed using a general equilibrium model (Pérez-Blanco et al. 2016).

Against this background, this paper aims to analyse the outcomes of water pricing and quotas in the agricultural sector and to determine how each of these policies affects the welfare of farmers and society as a whole. To this end, the Guadalquivir River Basin (GRB) is used as a case study to determine which policy could be more effective in the current context of scarce water resources. As a novel contribution, the economic inefficiency of water pricing is analysed through two public accounting indicators, the marginal cost of public funds and the excess burden of taxation.

The next two sections introduce the case study and the methodology. The fourth section describes the results, while the fifth section analyses and compares them with findings previous studies. Finally, the last section is devoted to the main conclusions, study limitations, and avenues for further research.

2 Case Study

The Guadalquivir River Basin in southern Spain covers an area of 57,679 km^2 that extends over 12 provinces belonging to four administrative regions, with Andalusia representing more than 90% of the demarcation area. The river basin area is home to a population of more than 4.4 million people. This region has a typical Mediterranean climate with a heterogeneous precipitation distribution and frequent episodes of hydrological drought. The annual average temperature is 16.1ºC, and the annual average precipitation is 561 mm (CHG, 2022). The availability water in the basin amounts to approximately 3720 hm^3 per year, of which about 3207 hm^3 per year is used to meet the demands of irrigated agriculture (representing 86% of the total water demand in the basin) (CHG, 2022).

Agricultural water rights are associated with ownership of irrigated land, but they are temporarily (for one season) transferable to other water users. Agricultural water use (along with all other economic uses, such as industry and energy) has a lower level of priority than domestic uses. The basin is closed to new demands or users because it is not possible to increase water supply. The main crop in the basin is rainfed and irrigated olive.

As can be seen in Fig. 1, the river basin has been divided into three zones (Upper Basin, Middle Basin, and Lower Basin) according to the characteristics of each of agricultural region and the crops there. The Upper Basin is characterized by the presence of perennial

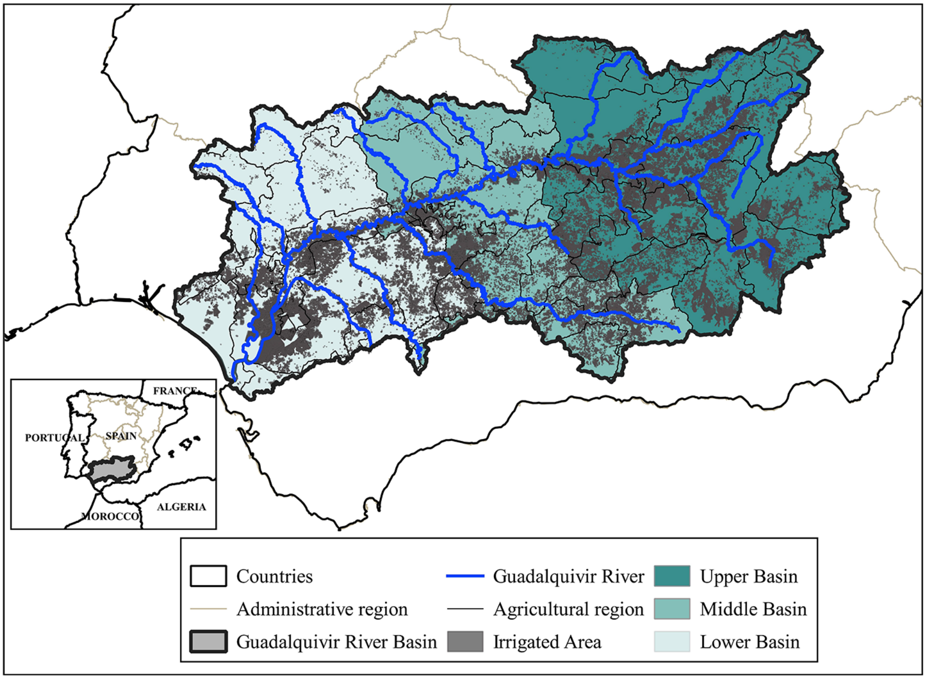

Fig. 1 Case study

Table 1 Summary of the main crops per zone

Area (ha)

	Upper Basin	Middle Basin	Lower Basin	Basin
Olive	269,143 (88%)	91,721 (57%)	68,455 (26%)	429,319
Other perennials	10,256 (3%)	18,640 (12%)	40,434 (15%)	69,330
Cereals	11,793 (4%)	18,607 (12%)	27,612 (11%)	58,012
Cotton	4592 (1%)	4652 (3%)	39,289 (15%)	48,533
Rice	0 (0%)	0 (0%)	37,083 (14%)	37,083
Other crops	11,155 (4%)	26,834 (17%)	48,950 (19%)	86,939
Total	306,939 (100%)	160,454 (100%)	261,824 (100%)	729,218

Table 2 Data of the main crops in the basin

Crop	Total area (ha)	Yield (kg/ha)	Price (EUR/kg)	Cost (EUR/ha)	Subsidy (EUR/ha)	Water needs (m^3/ha)	Gross Margin (EUR/ha)
Wheat	53,710	3973	0.205	670		1900	145
Rice	37,083	8560	0.284	1874	117	10,500	674
Corn	13,280	12,124	0.189	1940		5000	351
Cotton	48,533	3008	0.452	1492	967	4500	835
Orange tree	55,695	25,457	0.186	3587		5400	1148
Olive tree	429,319	5050	0.473	1553		1500	836

crops (91% of the total area of this zone), with the main crop being olive groves, representing 88% of the total surface area (see Table 1). However, in the Middle Basin, the percentage of perennial crops drops to 69% of the total crops in the zone, with olive groves still being the main crop (56%) followed by cereals (12%). Finally, in the Lower Basin, less than half of the cultivated area is dedicated to perennial crops (41%), with olive groves being the main perennial crop, followed by orange trees (10%). In this zone, crops such as cereals, cotton, rice, or vegetable crops play a fundamental role, representing about 49% of the total crops grown in the area. Due to the unavailability of economic information on some crops, the area considered in this study is 85% of the total basin area and includes all the main crops.

Regarding the data source used in the analysis, area (ha), yield (kg/ha) and price (EUR/kg) have been obtained from the Yearbook of Agricultural Statistics of the Spanish Ministry of Agriculture while cost (EUR/ha) and water requirements (m^3/ha) have been compiled of Costs and Income Studies of Farming Operations (ECREA) and Basin Management Plan, respectively. Data are at the scale of administrative region or provinces, meaning they have had to be estimated at the scale of the agricultural region (agricultural county) using the Spanish Plan for productive regionalization (BOE 2002).

Table 2 shows data on area, yield, price, costs, subsidy, water needs and gross margin for some of the most important crops in the basin. In each region, each crop has a different initial data value, so these data are provided as a weighted average for the basin.

3 Methodology

This section describes the model developed based on Positive Mathematical Programming (PMP) and the rationale for calculating the loss of economic efficiency through the marginal cost of public funds and the excess burden of taxation.

3.1 The Model

We develop a PMP model which maximizes total gross margin as a proxy for short-term profit. For the most part, only irrigated crops have been taken into account in the simulations of water scarcity, although some rainfed alternatives have been included. The decision unit is the agricultural region, which is an agriculturally homogeneous unit below province or NUTS3 level, following the European Union nomenclature. Finally, the results are aggregated for each of the basin zones considered and for the basin as a whole.

PMP models describe and analyse the behaviour of economic agents, such as farmers, in response to prevailing economic incentives and market conditions (Heckelei et al. 2012). These models are designed to maximize profits subject to physical and economic constraints. Therefore, they are descriptive models that attempt to explain how the real world operates by calibrating the objective function according to the observed situation. PMP models are based on non-linear programming, a mathematical optimization technique that maximizes a non-linear objective function subject to a set of constraints.

There are many approaches that can be used to calibrate the parameters needed to reproduce the baseline scenario when the objective function is maximized. PMP was formally proposed by Howitt (1995), although some earlier studies had already applied it empirically. Despite the development of new approaches that overcome some of the problems with Howitt's work, the original approach is still widely used. Our model is based on the standard approach developed by Howitt (1995), which involves estimating a quadratic cost function. One of the problems of the standard approach is that the calibration parameters are underdetermined. To avoid this underdetermination, the average cost approach (Heckelei and Britz 2000) has been used, assuming a quadratic variable cost function for each crop c ($cost_c = \alpha_c \cdot X_c + 1/2 \cdot \beta_c \cdot X_c^2$), with α_c and β_c being parameters that need to be determined in order to replicate the precise levels of activity for each farm type in the reference year while X_c represents the area for each crop. This approach ensures that the cost resulting from the quadratic cost function when the base scenario is reproduced matches the average cost of the crop. Then, the set of calibrating parameters is defined as follows:

$$\alpha_{c,f} = avgcost_c - \mu_c \tag{1}$$

$$\beta_{c,f} = \frac{2\mu_c}{X_c^{obs}} \tag{2}$$

where $avgcost_c$ is the observed average variable accounting cost of crop c, X_c^{obs} the observed crop area of c in the reference year and μ_c the dual values of the calibration constraints that replicate the baseline scenario.

Finally, the objective function is the maximization of the total gross margin calculated as the sum of the individual gross margin of each crop, where P_c and Y_c are the price and yield of each crop, respectively.

$$TGM = \sum_c \left[P_c \cdot Y_c - \left(\alpha_c + \frac{1}{2}\beta_c \cdot X_c \right) \right] \cdot X_c \tag{3}$$

The cost component of the gross margin corresponds to the sum of direct costs, machinery, and hired labour. As an example, the gross margin for wheat in one of the zones is determined from input data and after applying the PMP (according to Eq. 3) as the difference between total income and costs. In this way, if the price is 0.205 EUR/kg, yield 3468 kg/ha and cost 587.98 EUR/ha, the total gross margin is 123 EUR/ha for input data. Alternatively, applying the PMP methodology with the same price and yield, α of 551, and β of 0.13 and an initial area of 569 ha, the total gross margin is also 123 EUR/ha.

The model includes constraints on land use and water use, as well as constraints on permanent crops. Some permanent crops have rainfed alternatives, such as olive and almond trees, while others —such as orange trees—do not. Orange is an important crop in the basin that cannot survive without water, so the possibility of using the minimum level of irrigation to ensure survival in the event that there is not enough water has been included in the analysis. Apart from this option for reducing water use in orange groves, there are no other intensive margin adjustments, so the farmers' only possible responses to pricing or water restrictions are changes in cropping patterns, opting for less water-intensive crops (extensive margin adjustment) and rainfed crops (super-extensive margin adjustment). In fact, the adjustment for orange trees also lies within the extensive margin, as we do not know the water response function. Thus, 'normal' orange trees are replaced with 'survival' orange trees (an extensive margin adjustment).

We conduct two types of simulations aimed at reducing water use. For the water pricing simulations, the cost of water will be increased by up to 1 EUR/m^3 in increments of 0.01 EUR/m^3. The second group of simulations are water restrictions or water quotas. In this case, water availability will be reduced by 1% increments until no water is available. It should be noted that above a certain level of restriction there may not be a feasible solution in every region if there are permanent crops that cannot be replaced by rainfed crops in the short term.

The model has been programmed with the latest version of GAMS (Bussieck and Meeraus 2004) using the CONOPT solver.

3.2 Cost of Public Funds

The concepts of the MCF and excess burden have become increasingly crucial in the field of public economics. They play a significant role in the assessment of tax reforms, public expenditure initiatives, and other public policies, ranging from tax enforcement to the privatization of public enterprises (Dahlby 2008). The excess burden of a tax system can be defined as the difference between the monetary value of the well-being reduction caused by the taxation system and the amount of tax revenue generated (Dahlby 2008). The MCF indicates the total welfare effects of a tax reform, in the form of a "price" per unit of tax revenue (González-Páramo 2003a).

These indicators were developed to evaluate public investment projects that involve raising public funds. Most related empirical studies are based on the analysis of changes in income tax, considering effects on the market and prices. However, our study is based on a microsimulation model used to examine the effects of an increase in the water tariff without knowing the allocation of the revenue or possible effects on prices paid to farmers. Therefore, based on the theoretical framework of public accounting, we have developed some indicators to calculate the losses of economic efficiency after the implementation of the irrigation water tariff. One of the proposed indicators measures the loss of efficiency in absolute terms, the excess burden, while other indicators measure the relative loss, namely the average relative cost of public funds ($AvgRCF$) and the marginal relative cost of public funds ($MgRCF$).

In the case of the excess burden, it has been calculated as the difference between the changes in welfare, measured as absolute losses of total gross margin after the implementation of water pricing, and the total revenue, according to the following equation:

$$EB = Changes\,in\,welfare\,(losses\,of\,total\,GM) - Total\,tax\,collected \tag{4}$$

The average relative cost of public funds would be the “price” of raising one euro, which can be calculated using the following equation:

$$AvgRCF = \frac{Changes\,in\,welfare\,\,(losses\,of\,total\,GM)}{Total\,tax\,collected} \tag{5}$$

Similarly, the marginal relative cost of public funds measures the relative cost of the last unit collected, and is calculated using the following equation:

$$MgRCF = \frac{Changes\,in\,welfare\,\,(losses\,of\,marginal\,GM)}{Marginal\,tax\,collected} \tag{6}$$

However, these indicators differ depending on the applied irrigation tariff, so they are analysed using some basic statistics.

In addition, the spillover effects on the agri-food chain from the implementation of water pricing have been approximated for the above-mentioned indicators, based on estimated values reported by other authors. For example, the multiplier factor for the effects on the rest of the agri-food chain has been estimated by Rodríguez-Chaparro (2013) at 1.3, while other authors such as Cansino Muñoz-Repiso et al. (2013) and Gómez-Ramos and Pérez (2012) have estimated it at 1.5 and 1.4, respectively. In the case at hand, an intermediate value of 1.4 has been used.

4 Results

4.1 Water Use and Gross Margin Losses Due to Water Pricing and Water Quotas

Results vary across the three distinct zones of the basin, depending on the ability of the crops to adjust to a reduced volume of water due to water pricing or water quotas.

Figure 2 represents the water use with the application of water pricing (solid line) and water quotas (dashed line) in each of the zones into which the basin has been divided, as well as in the basin as a whole. The curve corresponding to water quotas is linear because it represents the water used when water availability is reduced proportionally. In other words, as the availability of water decreases, the amount used will also decrease uniformly and proportionally, thus being represented by a straight line. The water use due to water pricing represents a typical water demand curve, and after aggregating the different zones, the total basin result is smoother. This curve contains two distinct sections. The first section is elastic up to 0.25 EUR/m^3 and there are continuous decreases in water use because of changes in cropping patterns made by the farmer as the price of water increases. This first elastic phase means that crops are very susceptible to water price increases, and the first increments especially affect important crops in the Lower Basin, such as rice, which need a large amount of water and have a low marginal value for water. Thus, farmers cut back on water-demanding crops and replace them with those that use less water. Nevertheless, this elastic section appears mostly in the Lower Basin and to a lesser extent in the Middle Basin, while the Upper Basin has a more inelastic first section in its water use curve because of the prevalence of olive trees. The second part of the water use curve (>0.25 EUR/m^3) of the total basin does not allow water saving, thus presenting very inelastic behaviour; it remains almost constant even if the price of water increases.

Figure 3 illustrates total gross margin losses for each water policy. Figure 3a not only shows gross margin losses but also the monetary amount collected with the tariff. Thus, this figure shows that as the price of water increases, total gross margin losses increase and, in general, the total revenue collected by water authorities. However, it is observed that the implementation of a rate or price for irrigation water always implies a loss of profit (measured as total gross margin losses), while some decreases in revenue are observed as the rate increases. This is due to the change in cropping patterns, which leads to less water usage in response to a higher water tariff, negatively affecting revenue collected. It can be seen that from 0.18 EUR/m^3 and up, the difference between total gross margin losses and the total revenue collected increases. Consequently, much more is lost than is collected, leading to an increase in economic inefficiencies.

Nevertheless, with the application of water pricing, gross margin losses are more than proportional (above the diagonal) for the first tariff increases. That is, a 1% increase in the water tariff leads to higher percentage losses. This is due to the fact that the water tariff results in changes in the cropping pattern, leading to more than proportional losses and producing economic inefficiencies, as will be discussed below. From 0.50 EUR/m^3 and above,

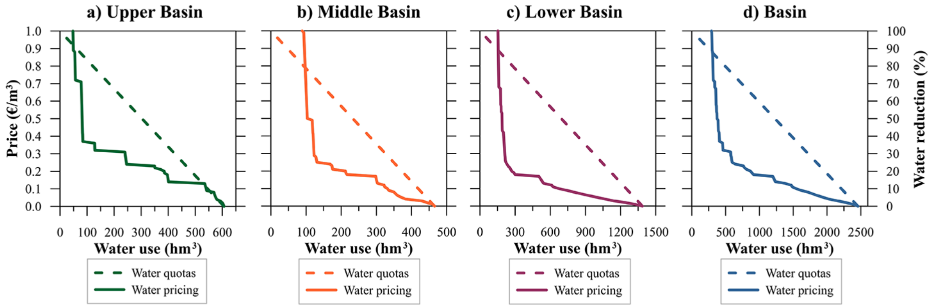

Fig. 2 Water use

losses become less than proportional. Figure 3b shows how the reduction in allocations through water quotas also reduces private gross margin. On the contrary, with the application of reductions in water allocations, losses are always less than proportional (below the diagonal). That is, a 1% reduction in water availability leads to proportionally lower losses.

4.2 Losses of Gross Margin According to Water Policy

Figure 4 builds on the previous two figures by relating water use (Fig. 2) to the gross margin losses (Fig. 3) caused by the implementation of each of the water policies, allowing a comparison of the two policies. Figure 4 depicts how private gross margin losses are impacted by the implementation of water pricing and water quotas that reduce the use of water. The figure also displays the gross margin losses incurred by society if revenue from tax is taken into account. Since the revenue from the water tariff is a transfer from the farmers to the water authority, it is not regarded as a loss to society.

Based on the results of this case study, from a private perspective, using water quotas rather than water pricing is the best option due to the lower economic losses for high and medium levels of water availability. When water use falls below a certain level (approximately 27% of full allocation), private gross margin losses due to water pricing become roughly equal to losses incurred for a proportional reduction in allocations. However, from a social perspective, the water pricing policy is less damaging if one also considers revenue collection, as overall losses are lower than those incurred through water restrictions. This implies that revenue collected can be used for other purposes and contribute to the welfare of society. That said, it is important to note that implementing water pricing always results in a greater loss than revenue collected, leading to economic inefficiencies. Otherwise, the sum of private gross margin loss and collected fees would remain at 100% of the total gross margin.

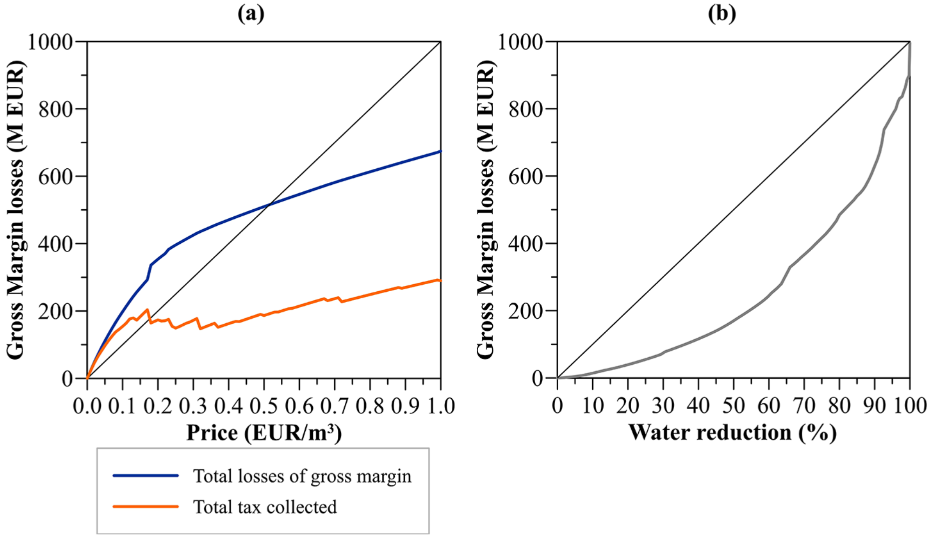

Fig. 3 Total gross margin losses by water policy

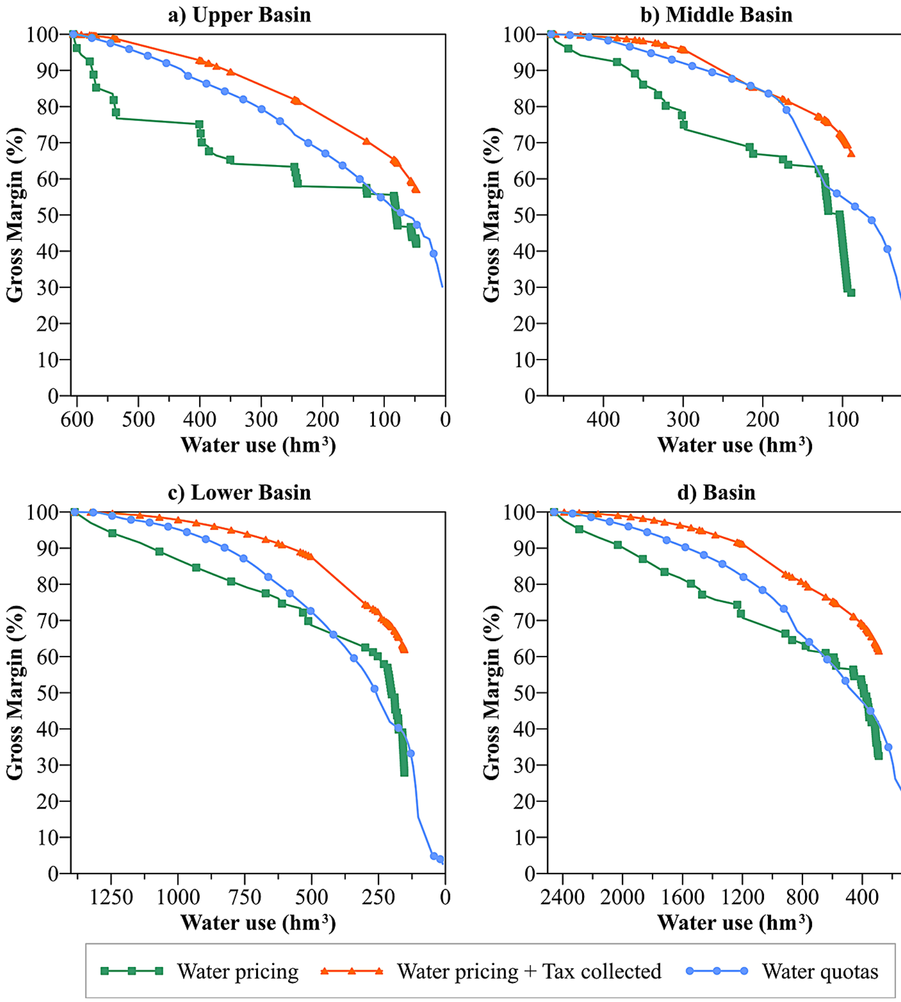

Fig. 4 Percentage of gross margin losses by water policy

However, the results differ by basin zones. In the Upper Basin it is observed that despite experiencing more pronounced losses during initial reductions in water use with the application of tariffs, it is the most resilient zone. Similarly, with a 100% water restriction, this region maintains 30% of the gross margin. This is due to the adaptation of the olive groves, the main crop in the area, to rainfed farming.

In the Middle Basin, it can be seen that the water restriction and pricing plus revenue policies have very similar outcomes, with both producing relatively smaller gross margin losses than in other zones. This result suggests that the water use restriction policy would be preferable to pricing, as it produces the same level of losses for society but would not have such a negative effect on farmers.

In the Lower Basin, we observe a narrower gap between water pricing and water quotas. In general, this zone experiences the smallest gross margin losses from the water tariff, indicating fewer economic inefficiencies caused by water pricing. This outcome is partly due to rice, which is highly sensitive to reductions in water allocation as well as to water pricing because of its high water requirements and low marginal value. It is worth mentioning that the area dedicated to rice cultivation drops to zero with the first 0.10 EUR/m^3 increase in water price, reducing the water consumption in this zone by half.

4.3 Costs of Public Funds

As mentioned above, indicators based on a public accounting framework have been adapted to calculate economic efficiency losses. In this context, Fig. 5a, constructed from Fig. 3a, shows the excess burden, measured as the difference between total gross margin losses caused by the application of an irrigation water tariff and the total amount revenue collected. Furthermore, the spillover effects on the agri-food chain have been taken into account. Thus, the impact of reducing irrigation water due to water pricing can be extrapolated to the agri-food chain, as for every euro lost in the primary sector, an additional 0.4 euros are indirectly lost.

The average relative cost of public funds (Fig. 5b) has been also calculated from Fig. 3a. This indicator provides a relative measure of the economic efficiency losses caused by the implementation of water pricing. It is important to note that this indicator is calculated as the ratio of total gross margin losses to total revenue, providing average data. The values range from 1 (for the first cost increment) to 3 euros (when the price of water reaches 0.37 EUR/m^3). The average value for this ratio is 2.30 without taking into account the spillover effect on the agri-food chain. If these spillover effects are considered, it can reach a maximum of 4.2 and an average of 3.22.

Having analysed the effects in average terms, we proceed to the analysis in marginal terms. This means assessing the cost of collecting an additional euro. In Fig. 6a, marginal gross margin losses are depicted, along with the spillover effects caused by the losses. Figure 6b illustrates marginal revenue. It can be seen that both marginal gross margin losses and revenue follow a downward trend in response to increasing water prices, until the point where they stabilize and no significant changes in the trend are observed. Significant peaks

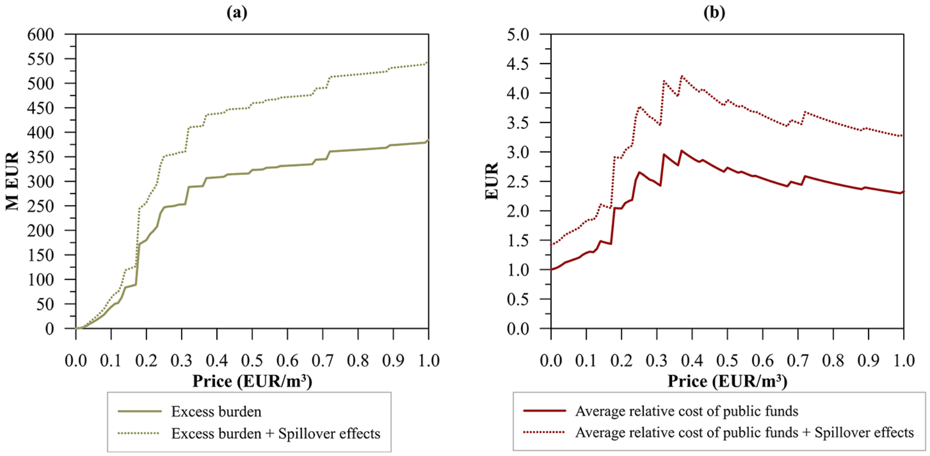

Fig. 5 Excess burden and average relative cost of public funds

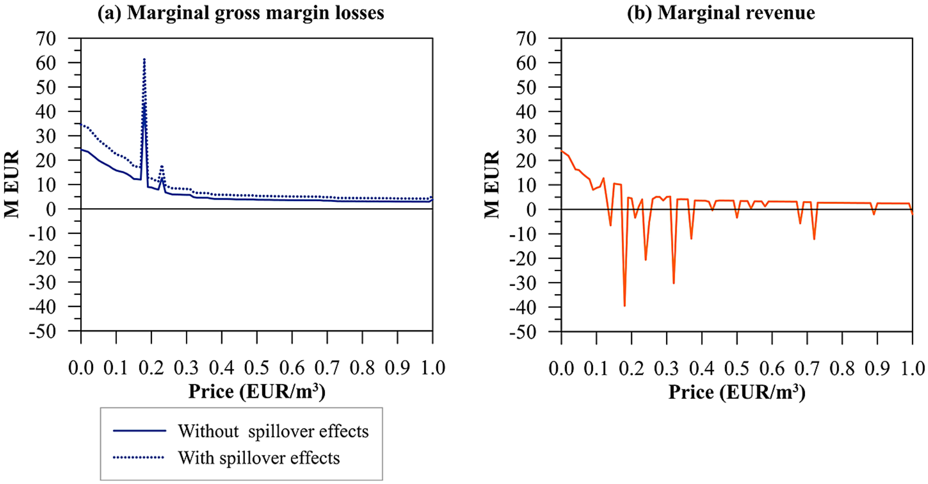

Fig. 6 Marginal gross margin losses and marginal revenue

can be observed in both marginal gross margin losses and marginal revenue at certain price levels, influenced by variations in cropping patterns. Whenever a crop is totally replaced or transformed into rainfed crop in response to a 0.01 EUR/m^3 increase in the tariff, the amount collected decreases sharply, and in some cases the gross margin losses also hit a peak.

From the results of marginal gross margin losses and marginal revenue (Fig. 6), the marginal relative cost of public funds is constructed (Fig. 7) as the ratio between these two values. We observe an increasing trend from 0.01 EUR/m^3 to 0.09 EUR/m^3, because marginal losses (although decreasing) are greater than marginal revenue (also decreasing). The extreme values presented in Fig. 7 may be due to deviations in the numerator (gross margin loss) or in the denominator (revenue). However, as Fig. 6 shows, most of the deviations are due to decreases in marginal revenue caused by a reduction in irrigated area in response to the increase in water cost. After the initial increasing trend, this indicator remains stable, with an average value of 1.09 and a most frequent value (mode) of 1.19.

5 Discussion

The analysis of the effect of water pricing and quotas on water demand and other economic indexes such as farm incomes has been extensively studied, but the social perspective requires a deeper analysis and the comparison with water quotas should be further explored. Below, we compare the evidence reported in the literature with the results obtained in this work.

First of all, it should be noted that the existence of three differentiated sections in the irrigation water demand curves—a first inelastic section for low water prices, a second elastic section, and then another inelastic section for higher water prices—has been evidenced in many previous works (Molle and Berkoff 2007; Varela-Ortega et al. 1998; Wheeler et al. 2008). However, this was not found to be the case in our study. The Lower and Middle Basin, and to a lesser extent the Upper Basin, show very elastic curves from the beginning.

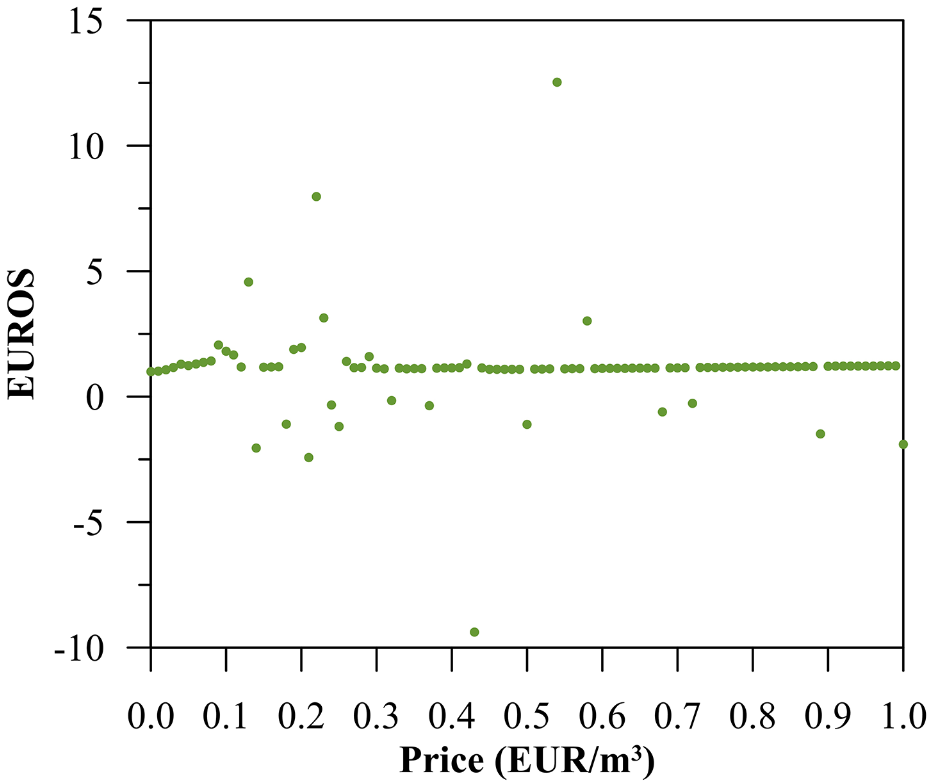

Fig. 7 Marginal relative cost of public funds

The usual first inelastic section is explained by the fact that the initial increases in the price of water do not lead to a reduction in the area under cultivation, as the marginal value of water is higher than its cost. This implies that all the area under the same crop is homogeneous and therefore the marginal value of water used is the same. However, PMP is based on the principle of Ricardian rent, which means that the first reductions in area of a given crop correspond to land with lower productivity, where yields are lower, or costs are higher. This leads to a reduction in the area under cultivation even for the first price increases. These results are in line with those of other authors who use PMP to analyse water pricing (Martínez-Dalmau et al. 2023a). Thus, in the elastic section, low value crops in terms of water productivity are replaced by others with higher value when possible or replaced by rainfed crops. When water became very scarce, there is an inelastic section where water saving is low for increases in water price. The shape of the irrigation water use curve shown in this paper and corroborated by much of the existing literature suggests that water pricing could be an effective management tool for both surface water and groundwater if we only focus on the water saving (Kahil et al. 2016).

However, the results show that water pricing is the worst option from the farmers' point of view, as for the same water reduction, the economic losses are higher than with the allocation of lower water quotas. In contrast, the combination of water pricing plus tax collection yields higher gains for society as a whole, although these gains fail to compensate for the private sector losses. Additionally, it is essential to note that, as a simulation, it is feasible to set a certain price for water use to decrease by a certain amount. For example, a reduction from 2500 hm^3 to 2000 hm^3 would require a price of 0.04 EUR/m^3. However, determining such a precise price in real life is challenging and setting the wrong price could lead to undesirable results. This, added to the fact that, for small reductions in water use, the differences between water pricing plus tax collected and water quotas are minimal, the application of water quotas instead of water pricing proves to be a simpler and probably better approach.

Other authors have compared the impact of water pricing and water quotas, as we do in this paper. Molle (2009) explains that reduced water allocations are usually applied uniformly across users. Nevertheless, there are situations where some water rights are less affected, either for economic reasons (e.g., trees versus annual crops) or social reasons (areas with historic water rights). Thus, in the study by Molle (2009), even in the rare cases where water is scarce and the conditions are in place to regulate demand through water pricing, supply is invariably managed through quotas or water rights. There are many reasons for the prevalence of quotas: equity, simplicity of supply, adaptation of water use to the continuous variation in available resources, and more limited overall revenue loss (as compared to water pricing), among others (Molle 2009). In fact, one outcome of price regulation is increased financial pressure on users, forcing out those with less adaptability and capital. In other words, when there is less water supplied than demanded, say 30% less, the implementation of water quotas means reducing the supply per customer by 30%, whereas water price regulation means raising prices until the least “economically efficient” farmers reduce their total demand by 30%. But raising prices also reduces the incomes of the more efficient users and means a transfer of wealth from farmers to the public purse (Molle 2009). Latinopoulos (2005) studied the reaction of Greek farmers to increased water prices, revealing elasticity for price levels that caused a significant drop in income. The study also noted that quotas were a “more natural and effective way” (p. 332) to achieve similar outcomes without a drastic reduction in income. Thus, as in our study, Molle (2009) and Latinopoulos (2005) show that from a private point of view, quotas lead to smaller losses for farmers than the application of water pricing.

It is worth stressing that the analysis of the socio-economic impacts of agricultural water pricing, in terms of loss of farm income, has previously been undertaken by Berbel and Gutiérrez Martín (2005); Iglesias and Blanco (2008); Riesgo and Gómez-Limón (2006); Varela-Ortega et al. (1998), and more recently by Kahil et al. (2016); Martínez-Dalmau et al. 2023a); Pérez-Blanco et al. (2016). These studies show that the increase in the price of agricultural water produces changes in cropping patterns that entail losses in farm incomes, as well as a reduction in direct employment generated by the irrigation sector. This is a consequence of both the increase in variable costs due to the tariff, and the substitution of high value-added and water-consuming crops for others that have lower water requirements. As for public revenue from water pricing, previous studies mentioned above have also shown that, in the elastic sections of the water demand curve, there is a decrease in public revenue from tariffs due to drastic changes in cropping patterns. Indeed, when demand enters an elastic phase, the percentage reduction in water consumption is much higher than the percentage increase in the water price, leading to a decrease in public revenue.

This study has developed indicators based on public economics that allow a measurement of the efficiency loss that would occur if a tariff were applied to irrigation water in the Guadalquivir River Basin. These indicators reveal an average relative cost of revenue of around 2.30 and a marginal relative cost of 1.09 EUR, both measured in average values, but with maximum values of 3 EUR for every euro collected in the case of the average relative cost, and a most frequent value of 1.19 in the case of the marginal relative cost. These results are important because they provide a measure of the economic inefficiency that occurs when introducing a water tariff aimed at ensuring the rational and sustainable use of the resource. With regard to the marginal relative cost, it should be determined whether our value is lower than the one estimated by Alonso-Carrera and Manzano (2002); González-Páramo and Sanz Sanz (2003b). However, the results are not directly comparable because our case study focuses on a specific tariff with few secondary effects, while the aforementioned studies are conducted on the overall economy, typically affecting income tax.

6 Conclusions

The novel contribution examines the economic inefficiency of water pricing by adapting two public accounting indicators, the marginal cost of public funds and the excess burden of taxation. In this manner, the indicators of a discipline enable the comprehension of the economic inefficiency of water pricing at the microeconomic level.

The results show that the best option from a private point of view is the use of water quotas rather than water pricing, since the economic losses are lower. However, from a social perspective, the use of water pricing together with the amount of revenue collected by the basin authority is more beneficial for society as a whole. This implies that the proceeds can be used for other purposes to improve the welfare of society in general.

Thus, for water pricing to have a dissuasive effect on water consumption, the water use curve must be elastic. However, even in the elastic section of the curve, we find that losses of economic efficiency appear as the losses of agricultural income exceed public revenue. Our results indicate that water pricing should be implemented alongside other measures or in combination with other economic instruments that promote flexibility in water allocation and minimize economic losses.

Therefore, water quotas are often preferred over purely economic regulation, such as water pricing, for several reasons. They are equitable (water quotas ensure that each user receives a fair share of the available water, regardless of their ability to pay), transparent (they are easier to understand and implement than water pricing, which can be complex and difficult to communicate to users) and effective (water quotas can be more effective than water pricing in matching demand to supply, as they provide a clear signal to users about how much water they can use).

Nevertheless, these economic instruments should be considered as part of a package of other economic tools, such as water banks and markets to provide flexibility in water allocation. This is the only way to quantify the economic, social, and environmental impacts of these instruments in the long term, and thus ensure the preservation of water resources and the compatibility of their economic uses.

Several limitations should be highlighted, which could be addressed in future studies. One limitation of the study is the reliance on taxes collected. If these taxes are invested in projects that subsequently generate benefits for society, there could be an overall improvement in societal welfare. Depending on the extent of this improvement, the use of water pricing may be preferable to water quotas, as the social improvement would help offset the private losses. Another related limitation, beyond the scope of this study but potentially addressed by linking to a general equilibrium model, is the indirect effects on the rest of the economy. Potential losses due to these indirect effects would be proportionate to the losses in the sector, necessitating consideration of tax collection and subsequent investment.

Additionally, another limitation is the failure to consider the possible price variation caused by the decrease in production. The greater the reduction in supply, the more significant the theoretical increase in prices. Therefore, it can be observed that, with the same reduction in water use, both policies lead to a similar reduction in irrigated area. However, the water quota policy results in a greater reduction in olive production (a shift to rainfed with lower production), which is the main crop in the basin. Given that the Guadalquivir basin is the primary area for olive grove production in Spain, one would expect an increase in prices that could partially or completely offset the economic losses due to the reduction in production.

On one hand, it could be concluded that this would have a positive effect (on average) from a private standpoint, making the establishment of water quotas a better solution. On the other hand, it would have a negative effect on society, which would have to bear higher prices. Further investigation is required to delve deeper into these possible effects by linking with general equilibrium models to quantify the changes in prices and assess both private and social benefits.

Further research is needed to explore (i) the combination with other instruments, (ii) hydrological impacts, and (iii) the effects on the rest of the economy. This could be achieved with a hydro-economic model that can be linked to a general equilibrium model or an input-output model.

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

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Declarations

Competing Interests The authors declare no conflict of interests.

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