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Combining economic policy instruments with desalinisation to reduce overdraft in the Spanish Alto Guadalentín aquifer

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Abstract

This paper analyses the cost-effectiveness of combining several economic policy instruments to address the problem of non-renewable pumping in the Alto Guadalentín aquifer in southeastern Spain, one of the most extreme cases of aquifer depletion in Europe. Our results show that all instruments have significant economic impacts. However, the future availability of desalinisation would notably mitigate these impacts, as farmers can substitute groundwater with desalinised water. Although a complete ban on non-renewable pumping and an environmental tax on withdrawals imply the lowest level of public expenditure, they are very unpopular and have a large political cost. The buyback of groundwater rights and the subsidisation of desalinisation in exchange for reducing withdrawals are likely to be much better received by farmers, as their cost would be charged to the public budget. A combination of instruments would split the cost of aquifer recovery between farmers and the administration and would therefore possibly not meet with as much opposition from stakeholders.

Keywords: Desalinised seawater; Groundwater; Irrigation; Mathematical programming; Water demand; Water economics

Introduction

Aquifer overdraft is a major environmental and water management problem in Mediterranean semi-arid areas, such as the Segura basin in southeastern Spain. Although it receives external water resources from central Spain through the Tagus-Segura Transfer (TST), the expansion of intensive horticulture since the 1980s has put water resources under huge pressure. This is at the root of a structural water deficit that positions the Segura as one of the most water-stressed basins in Europe.

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In the case of groundwater, depletion has reached alarming rates in many aquifers. This jeopardises the possibility of reaching the environmental objectives set in the Basin Management Plan to comply with the Water Framework Directive (Gómez-Limón & Riesgo, 2012). Apart from the severe environmental impacts on groundwater-dependent ecosystems, aquifer overdraft also poses threats to the sustainability and resilience of agricultural production itself. Groundwater is not only a major water source for the agricultural sector of the basin, one of the most profitable in Europe, but it is also a strategic resource for coping with droughts.

It was not until the 1990s that the Spanish Water Authorities started to implement policies to address the problem of groundwater depletion. A major instrument has been the establishment of management plans for depleted aquifers to control unauthorised pumping and reduce abstractions by establishing quotas on water withdrawals and zoning. In some cases, water authorities resorted to payments to reduce consumption and, exceptionally, to the buyback of water rights and concessions (Carmona *et al*., 2011; Garrido *et al*., 2013). Management plans raised considerable social opposition at the local level and compliance was generally poor (Carmona *et al*., 2011). Consequently, they were unsuccessful because of politicians' unwillingness and farmers' uncooperativeness (Esteban & Albiac, 2011; De Stefano & Lopez-Gunn, 2012). Experiences of implementing payments to farmers for reducing consumption had some success in the short run. However, in the absence of proper control mechanisms, they created an incentive for additional unauthorised pumping.

The public purchase of groundwater rights has been used and was relatively successful in a few significant cases. The 1999 Water Law Reform allowed for the creation of public water exchange centres, similar to the public water banks operating in countries like the USA (Garrido *et al*., 2013). Although centres were set up in the Guadiana, Segura and Júcar basins in 2004, they were only operational during the 2005 to 2008 drought to achieve environmental objectives with relative and limited success (Rey *et al*., 2014).

Unlike the case of other depleted aquifers in Spain where there are no alternative sources of water supply, the recent development of desalinised seawater resources along the Mediterranean coast provides an opportunity to address this problem in this area at a lower social and economic cost. Over the last decade, the Spanish Government has built several large desalinisation plants intended to serve as a major source of water supply and tackle water scarcity in southeastern Spain. In practice, its relatively high cost initially restricted its use to domestic users, although irrigated areas have increasingly resorted to its use, especially during drought periods. However, desalinisation plants remain to a large extent underused.

Some studies have analysed the potential of desalinised resources to address irrigation water scarcity problems in southeastern Spain. Albiac *et al*. (2006) show that the most cost-effective alternatives combine the control of illegal abstractions with water trading and desalinisation, whereas pumping restrictions and water pricing have large impacts in terms of farm income, raising social opposition and resulting in failure. Martínez-Granados & Calatrava (2014) analyse alternative policy instruments to eliminate non-renewable pumping in several aquifers of the Segura basin and show that the availability of desalinised water alone may not be effective for reducing groundwater withdrawals, as its price is greater than the cost of groundwater. Therefore, desalinised water resources would have to be heavily subsidised if they are to be a substitute for groundwater.

While Martínez-Granados & Calatrava (2014) consider the separate application of instruments, this study analyses the economic impact of combining several instruments that can be used to eliminate overdraft in the Alto Guadalentín aquifer, one of the most severe cases of groundwater depletion in Europe.

These include the public purchase of groundwater rights, an environmental tax on groundwater and the substitution of groundwater with subsidised desalinised resources. We analyse the cost-effectiveness of combining these instruments to achieve the objective of eliminating overdraft, their trade-offs and their impact in terms of public expenditure, farm income, agricultural production and employment. We also identify and discuss the efficient combinations of instruments that are compatible with the objectives of containing public expenditure and minimising the impact on farm income.

Irrigation and groundwater depletion in the Alto Guadalentín aquifer

The Alto Guadalentín aquifer is located in the Guadalentín sub-basin within the semi-arid Segura basin in southeastern Spain (Figure 1). The Guadalentín is one of the most productive agricultural areas of Spain because of its climate, which ranges from the semi-arid to Mediterranean, making it

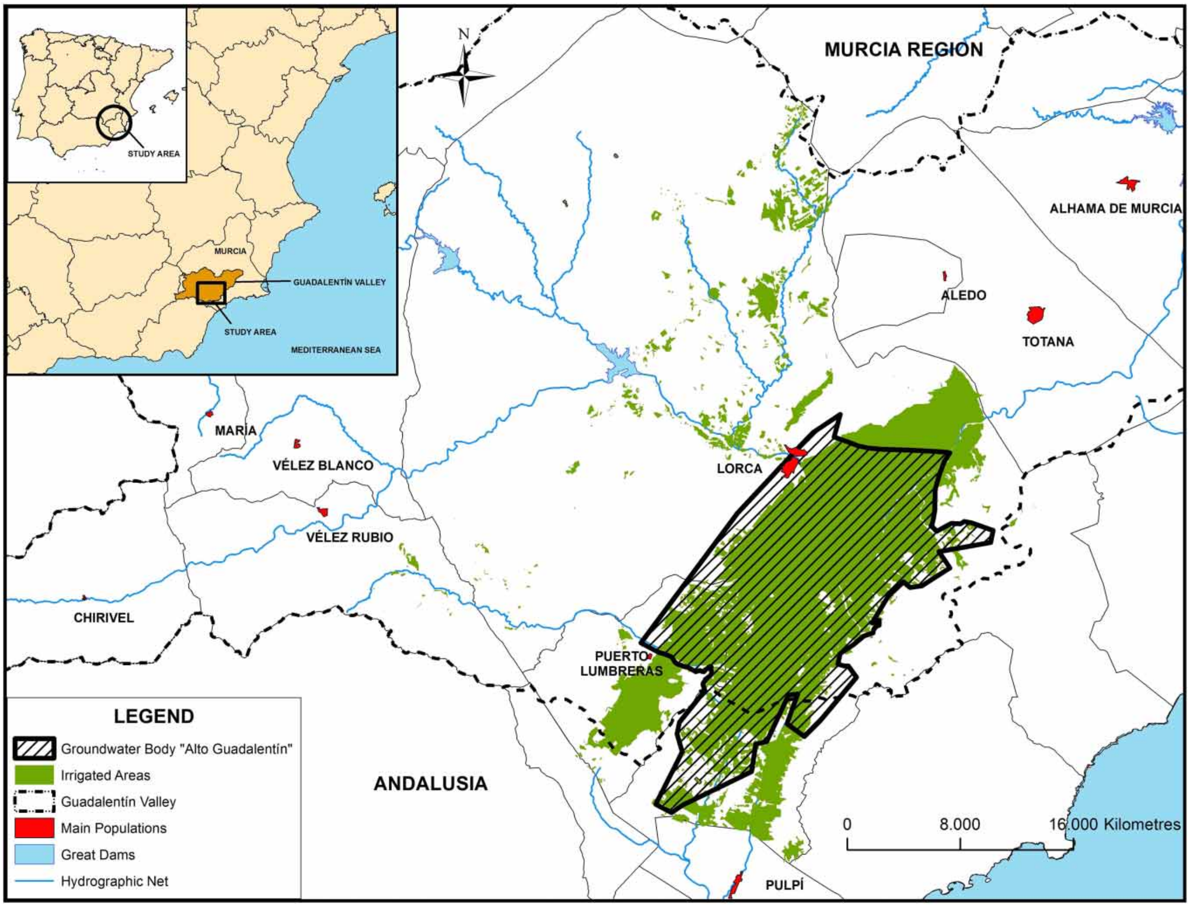

Fig. 1. Location of the Alto Guadalentín aquifer in SE Spain. *Source:* Own elaboration from data from the Segura River Basin Authority GIS (https://www.chsegura.es).

an ideal setting for export-oriented out-of-season horticulture. On the other hand, average annual precipitation is below 350 mm.

Structural water scarcity is especially severe in this area. According to our own estimates using data from the Segura River Basin Authority (SRBA), the total surface of the irrigated areas above the Alto Guadalentín aquifer (including infrastructures and unproductive land) accounts for 36,026 hectares, of which 21,107 hectares can be irrigated. According to the current cropping patterns and crop water requirements, agricultural water demand in the area accounts for 116.42 hm^3/year, whereas existing water rights and concessions for the different sources of supply account for 94.26 hm^3/year (second column in Table 1). In actual fact, the unbalance between supply and demand is even greater.

In practice, the availability of renewable resources has decreased by 20% since the 1980s and the TST only supplies, on average, 60% of its maximum annual transferable water allotment for irrigation. Available resources do not include desalinised resources, which are not yet available to farmers, as water transportation infrastructures are being built. Considering current availability, renewable resources (46.75 hm^3/year) would account for only 40% of agricultural water demand, i.e. a 60% water deficit (third column in Table 1). This deficit is partly accounted for by deficit crop irrigation, a reduction in the crop area and non-renewable groundwater withdrawals.

The resources actually used are estimated at 74.35 hm^3/year (fourth column in Table 1) and constitute about 64% of agricultural water demand. Groundwater currently supplies nearly half of the area's used water resources. Most of these resources correspond to historical private groundwater rights and to non-renewable withdrawals. Specifically, 27.6 out of 74.35 hm^3/year of water resources used in the area correspond to non-renewable groundwater pumping (CHS, 2013), which is caused by the overallocation of rights in the past and a progressive reduction in the rate of recharge of the aquifer.

The massive use of groundwater over the last few decades has caused the severe depletion of the Alto Guadalentín aquifer. Based on average aquifer depth and piezometric levels, we estimate that accumulated non-renewable withdrawals over the last 30 years account for approximately 60% of the aquifer capacity. In addition, as piezometric levels have substantially decreased, pumping costs have notably increased over the last few decades.

To address aquifer overdraft in the Alto Guadalentín, the SRBA proposed a management plan to control pumping over the quotas established in rights and concessions and to reduce water quotas for withdrawal. However, the SRBA postponed compliance with the objective of eliminating

Table 1. Available water resources and water costs in the Alto Guadalentín aquifer.

Source of water supply	Existing water rights (hm^3/year)	Available water resources (hm^3/year)	Used water resources (hm^3/year)	Cost of water (€/m^3)
Surface water	13.90	11.10	11.10	0.05
TST	37.16	22.25	22.25	0.127
Treated wastewater	4.70	4.70	4.70	0.08
Groundwater	38.50	8.70	36.30	0.24
TOTAL (*)	94.26	46.75	74.35	
Desalinised water	–	28.00		0.45

Source: Own elaboration using data from the SRBA GIS (https://www.chsegura.es), Confederación Hidrográfica del Segura (CHS, 2013) and data from a survey conducted in 2012/13 in the local irrigation districts.

*Not including public desalinised resources that are expected to be available from 2017 onwards.

non-renewable pumping to 2027 because of its large expected economic impact and the legal and institutional complexity of restricting private groundwater rights. Alternatively, it proposed the gradual substitution of groundwater with desalinised resources.

Analysed management measures

In this study we consider several economic policy instruments that are all capable of achieving an environmental objective (eliminating non-renewable abstractions) but have different implications in terms of their impact on the economy and the public/private distribution of the costs of attaining the above goal. The first analysed instrument is water pricing, chosen because it is one of the most analysed policy options in the literature. The Water Framework Directive prioritises reforming water tariffs as an instrument for managing water resources. A volumetric tax on groundwater abstractions would increase the cost of pumping for farmers and eventually would reduce groundwater withdrawals and their environmental impacts. However, water pricing is rarely used as a groundwater management tool. A notable exception is France where a levy on water abstractions from all sources is in place (Montginoul *et al.*, 2015). In fact, in 2011, the Netherlands revoked the environmental tax on groundwater pumping established in 1994 because it did not meet the objectives of raising tax revenues and improving groundwater conditions (Schuerhoff *et al.*, 2013). In the case of Spain, water pricing is rather viewed as a tool for cost recovery. Thus groundwater users, who abstract water themselves and do not benefit from public water infrastructures, do not pay any water tariffs (Calatrava *et al.*, 2015).

It is generally held that irrigation water demand is very inelastic in the short term, at least for low water tariffs, reduced water availability or more profitable crops (Bazzani *et al.*, 2005; Scheierling *et al.*, 2006; Molle & Berkoff, 2007; Wheeler *et al.*, 2008; Kahil *et al.*, 2016). The relative inelasticity of agricultural water demand reduces the potential for water saving, especially in intensive agricultural systems as in southeastern Spain, because more profitable crops can withstand higher water prices (Bazzani *et al.*, 2005). Moreover, intensive irrigated agricultural systems have largely substituted capital for water by adopting water-saving irrigation technologies to combat reduced water availability, and thus there is a limited potential for further water saving. Increasing current water prices would thus reduce farmers' income rather than their water use.

In any case, levying an environmental tax on groundwater withdrawals is a very unpopular measure, and water users are uncooperative in this respect. Virtually all analyses of the effects of price increases in irrigation predict that the agricultural sector would be severely hit by higher water prices (Mejías *et al.*, 2004; Riesgo & Gómez-Limón, 2006; Giannoccaro *et al.*, 2010; Balali *et al.*, 2011; Gallego-Ayala *et al.*, 2011; Giraldo *et al.*, 2014; Kahil *et al.*, 2016). Irrigated agriculture is very important in rural areas of southern Europe, and the social impacts of water pricing on rural economies are likely to be high (Gómez-Limón & Riesgo, 2012) and to raise local opposition. In any case, should water pricing be applied in the area of study, a very high tax would have to be levied to promote sustainable groundwater use because of the high profitability of irrigation, which would likely reduce the political feasibility of this measure. However, although we recognise that it is hard to implement, we consider this instrument because it does not put pressure on public expenditure and because it can complement other less conflictive measures.

A second instrument is the purchase of groundwater rights to reduce pressures on the aquifer. The buyback of water rights has been selected because it has already been applied in other Spanish aquifers, has the advantage of permanently reducing withdrawals and is less conflictive than consumption quotas and other command-and-control policies. However, it requires a high level of public expenditure and may have significant impacts on the economy and labour market of the affected rural areas (Carmona *et al*., 2011). Previous water rights purchasing experiences had limited success. In the Upper Júcar and Segura basins, purchased resources were used to maintain environmental river flows, but the budgets were not fully spent because the purchase price was not attractive for farmers (Rey *et al*., 2014). In the case of the Upper Guadiana, the largest-scale experience to date in Spain, the budget was spent but purchased rights were reallocated to other users in the form of new public concessions, and withdrawals were hardly reduced at all (Garrido *et al*., 2013). Unlike other areas where this instrument has been used, there are several complementary sources of water in the Alto Guadalentín that may mitigate the negative impact of groundwater buybacks. In any case, previous experiences show that the bid price should be high enough to be attractive for farmers.

One such complementary water source is desalinisation. The massive construction programme of desalinisation plants along the Spanish Mediterranean coast over the last decade has created a large desalinisation capacity that is currently underused. Desalinisation mostly serves domestic consumption, as farmers have been reluctant to use it because of its relatively high price and have resorted to it mostly during drought periods. However, its use for irrigation is increasing as the Spanish Government is promoting this water source to serve undersupplied irrigated areas. In the case of the Alto Guadalentín, desalinisation is not yet available for farmers, as transportation infrastructures are still being built.

The SRBA considers desalinised seawater as an option to substitute groundwater to reduce aquifer overdraft. However, it might not be an effective alternative, as its price is greater than the cost of groundwater pumping. Even if agriculture can bear the cost of desalinised resources, there is a large incentive to continue with groundwater pumping at a lower cost (0.24 €/m^3 compared to 0.45 €/m^3). It is thus very unlikely that farmers will substitute groundwater with a more expensive resource without having any incentive to do so. We have thus considered as a third instrument a subsidy for desalinisation conditional upon a reduction in groundwater pumping. This alternative has an advantage over the other instruments: it does not reduce water use and therefore does not have any impact on the agricultural sector in terms of production and employment.

Last, we have also analysed the alternative of restricting groundwater abstraction to its renewable fraction by establishing pumping quotas. This option has been considered by the SRBA but never implemented in the area because of its high economic impact and political cost. It is institutionally complex, as a sizeable share of groundwater rights are private. Contrarily to the case of public concessions, private groundwater rights explicitly indicate the water flow that can be legally pumped, so restricting pumping associated with this type of rights is legally complex and, in any case, would require compensating the right holders. It is obviously less conflictive to purchase water rights or provide alternative external resources, which is the preferred policy option. However, we have included this instrument in our study in order to measure the economic impact of banning overdraft pumping and not because we consider it to be a potentially successful policy option.

Whatever the economic instrument considered, one of the prerequisites for successful implementation is the monitoring of groundwater withdrawals to assure that sustainable pumping rates are respected. This requires cooperation and collective action on the part of stakeholders (Esteban & Albiac, 2011). Currently all groundwater rights and concessions in the area are registered by the SRBA which monitors withdrawals and water use and sanctions illegal pumping. In addition, the number of right and concession holders in the area of study is relatively small and some of them are large users. This makes water use easier to control. According to data sourced from the SRBA, there are 75 holders of groundwater rights or concessions in the area of study, including 22 water user associations that distribute 52% of groundwater from their communal wells, seven large horticultural enterprises (25%) and 46 individual right holders (25%). The organised cooperation of water users is a more complex issue. Even with less troublesome approaches, such as public purchases of rights, cooperation is a key element for success, as the Upper Guadiana experiences show.

Economic assessment of the impact of policy instruments

The economic impact of the analysed policy instruments is assessed using a non-linear mathematical programming model that maximises agricultural net margin derived from using the different sources of water supply available for irrigation in each area under different water availability scenarios. This model can simulate the impact of different economic instruments. The objective function of the model is:

$$Max\ MN(wu) - \sum_{o}(pw_o \times wu_o) - ta \times wu_{subt} + pc \times wv_{subt} + sd \times wu_{desal\ subv} \tag{1}$$

Expression (1) is subject to the following constraints:

$$wu = \sum_{o} wu_o \tag{2}$$

$$wu_o \leq dot_o \quad \forall o = \text{surface, Tajo} - \text{Segura Transfer, treated wastewater} \tag{3}$$

$$wu_{subt} + wv_{subt} + wu_{desal\ subv} \leq dot_{subt} \tag{4}$$

$$wu_{desal} + wu_{desal\ subv} \leq dot_{desal} \tag{5}$$

$$wu_o \geq 0 \quad \forall o \tag{6}$$

$$wv_{subt} \geq 0 \tag{7}$$

where o denotes each source of water supply (surface water, TST, treated wastewater, groundwater, desalinised water, subsidised desalinised water); wu is the amount of water used in the area from all the sources of water supply o (measured in hm^3/year); $MN(wu)$ is a function that relates the amount of water used in the area with the farm net margin generated in that area, not including the cost of acquiring water resources (measured in euros); pw_o is the average cost of water from each source of supply o (measured in euros/m^3/year); wu_o is the amount of water used in the area from the source of water supply o (measured in hm^3/year); ta is the environmental tax on groundwater withdrawal (measured in euros/m^3/year); pc is the purchase price for groundwater rights and concessions (measured in euros/m^3/year); wv_{subt} is the quantity of groundwater rights purchased by the SRBA in the area (measured in hm^3/year); sd is the subsidy for desalinised water (measured in euros/m^3/year); $wu_{desal\ subv}$ is the amount of desalinised water whose price is subsidised in exchange for reducing groundwater pumping from the aquifer (measured in hm^3/year); and dot_o is the amount of irrigation water available from each source of water supply o. The decision variables in the programming model are the amount of water used in the area from each source of water supply o (wu_o and thus wu) and the quantity of groundwater rights that farmers sell to the basin authority (wv_{subt}).

Objective function (1) maximises the farm net margin derived from using the different sources of water supply available for irrigation in the area of study. Constraint (2) calculates the total amount of irrigation water used (wu) as the sum of the amount of water used from each source of supply (wu_o). The set of constraints (3) restricts the amount of water that can be used from surface, transferred and wastewater to their availability. Constraint (4) is related to the availability of groundwater and assures that sold groundwater rights are not used and that subsidised desalinised water substitutes groundwater pumping. Farmers can use unsubsidised desalinised water but they must reduce groundwater pumping in exchange for subsidised prices. Constraint (5) restricts the amount of desalinised water (subsidised or unsubsidised) to the availability of desalinised water in each area. Finally, expressions (6) and (7) are two sets of non-negativity constraints for the decision variables of the model (wu_o and wv_{subt}, respectively).

The model calculates, from the optimal values of the decision variables, the reduction in groundwater pumping, as well as several economic indicators (value of agricultural production, agricultural employment, farm net margin and public expenditure) that are computed as follows:

$$\text{Value of agricultural production: } PFA(wu*) \tag{8}$$

$$\text{Agricultural employment: } MO(wu*) \tag{9}$$

$$\text{Net margin: } MN(wu*) - \sum_{o} (pw_o \times wu_o^*) - ta \times wu_{subt}^* + pc \times wv_{subt}^* + sd \times wu_{desal\ subv}^* \tag{10}$$

$$\text{Cost for the basin authority: } pc \times wv_{subt}^* + sd \times wu_{desal\ subv}^* - ta \times wu_{subt}^* \tag{11}$$

where *PFA(wu)*, *MO(wu)* and *MN(wu)* are three functions that relate the amount of water used in the area (hm^3/year) to the value of generated agricultural production (euros/year), the total net margin obtained by farmers not including the cost of acquiring water resources (euros/year) and the resulting agricultural employment (working days/year), respectively. The source of these three functions is another mathematical programming model developed by Martínez-Granados *et al*. (2011) that simulates crop and water allocation in the irrigated agriculture of the Segura basin and generates economic indicators of water use[1].

We use the above non-linear programming model (expressions (1)–(7)) to simulate the impact of different combinations of the analysed policy instruments (represented by the model parameters *ta*, *pc* and *sd*) and obtain the value of the above indicators (8)–(11) for each combination of instruments (*ta*, *pc*, *sd*). Based on water values in the area of study, the ranges of values considered to build the

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[1] To obtain these three functions, we solved an updated version of the model developed by Martínez-Granados *et al*. (2011) for different values of water availability and computed the corresponding values of farm net margin, value of agricultural production and agricultural employment. Then we have estimated fourth-order polynomial functions that relate these three indicators with the total amount of irrigation water used in each area.

(ta, pc, sd) combinations are 0–0.50 €/m^3 for both pc and ta and 0–0.45 €/m^3 for sd. These obviously include the non-intervention alternative ($ta = pc = sd = 0$) and the separate application of each instrument. Once every combination of instruments has been assessed, we identify the set of efficient combinations that eliminate overexploitation of the Alto Guadalentín aquifer. Finally, we also consider the alternative of restricting groundwater pumping to the level of the aquifer's natural recharge by taking $ta = pc = sd = 0$ and substituting constraint (4) for $wu_{subt} \leq dot_{subt} - nonrenew$, where $nonrenew$ is non-renewable groundwater pumping (hm^3/year).

Results and discussion

First we discuss the results for the separate application of the different policy instruments. We then report the results for the combinations of instruments, which we discuss considering different policy decision criteria in order to identify the optimal policy mix that eliminates non-renewable groundwater pumping under each of these criteria. Note that, to allow comparing the purchase of rights with the other instruments, the price and cost of the purchase of rights are expressed in terms of their annual equivalent cost, not in terms of the single compensation to be paid to farmers. The cost of this measure would thus be equivalent to the annual compensation to be paid to farmers for stopping non-renewable withdrawals.

Separate instruments

First of all, we present the results for the *'non-intervention' scenario* (second column in Table 2), in which we assume that desalinised resources are already available for farmers and that any policy is implemented to reduce groundwater pumping. Despite their comparatively high price, about a quarter of the desalinised resources (7.44 out of 28 hm^3) would be used when they are available in this scenario because of the high demand for irrigation water in the area of study. However, this increased use of desalinised seawater does not result in a reduction of groundwater withdrawals because of the severe water scarcity and high water demand in the area. In this scenario, the value of generated agricultural production is approximately 202 million euros/year, farm net margin is 64.6 million euros/year and agricultural employment is 1,263 million days per year. This scenario is taken as the reference to assess the impact of the analysed policy instruments.

The *prohibition of non-renewable pumping* to restrict withdrawals to the aquifer recharge level has a lower than expected impact (third column of Table 2), as farmers can partly substitute unused desalinised resources for groundwater. This alternative reduces agricultural production by 12.5 million euros/year (a 6.2% reduction), farm net margin by 6 million euros/year (a 9.2% reduction) and agricultural labour by 1,149 million days per year (a 9% reduction) with respect to the 'non-intervention' scenario. The availability of desalinised water partly offsets the negative impact that banning non-renewable pumping would have for the agricultural sector.

Again, the *purchase of groundwater rights* has a lower than anticipated impact on agricultural production and employment, as farmers can substitute desalinised resources for the sold groundwater rights (fourth column of Table 2). A bidding price of 0.38 euros/m^3/year, measured in terms of the annual equivalent cost of the purchase price, would be required to buy back enough water rights to eliminate non-renewable pumping in the aquifer. The impact in terms of agricultural production and labour is

Table 2. Economic impact of eliminating overdraft in the Alto Guadalentín aquifer using each instrument separately.

	Non-intervention scenario	Prohibition of non-renewable pumping	Purchase of rights (0.38 €/m^3/year)*	Environmental tax (0.38 €/m^3/year)	Subsidy for desalinised water (0.38 €/m^3/year)
Total water use (hm^3/year)	81.88	74.44 (−9.1%)			
Reduction in groundwater use (hm^3/year)	0.00	27.60			
Desalinised water use (hm^3/year)	7.44	27.60 (271%)			
Subsidised desalinised water use (hm^3/year)	0.00	0.00			27.60
Agricultural production (million euros/year)	201.97	189.51 (−6.2%)			
Farm net margin (million euros/year)	64.59	58.62 (−9.2%)	69.11 (7%)	55.30 (−14.4%)	69.11 (7%)
Agricultural employment (10^4 working days/year)	126.26	114.87 (−9%)			
Public expenditure (million euros/year)	0.00	0.00	10.47*	−3.33	10.47

Source: Own elaboration. Proportional change with respect to the non-intervention scenario is shown in brackets.
*The price and the cost of the purchase of rights are expressed in terms of their annual equivalent cost.

the same as in the previous case, as the total amount of water used is identical. On the other hand, the purchase of water rights does not reduce but increases farm net margin by 4.5 million euros/year (7.6%) with respect to the 'non-intervention' scenario at a cost of 10.5 million euros/year in public expenditure (measured in terms of the annual equivalent cost of purchasing the rights).

As expected, a high *environmental tax on groundwater withdrawal* (as high as 0.38 euros/m^3/year) would be required to eliminate non-renewable pumping because of the low water demand elasticity in the area. The tax has the same impact in terms of foregone agricultural production and employment (fifth column of Table 2) as the buyback of rights. However, unlike the buyback, it reduces farmers' net margin substantially (14.4%). On the other hand, public revenue from the tax is 3.33 million euros per year. In addition, the water tax has a greater impact on farm profitability than the prohibition of non-renewable pumping.

Last, *subsidising desalinised water in exchange for reducing groundwater pumping* has an identical impact to the purchase of rights, regardless of the analysed economic indicator (sixth column of Table 2). If desalinisation were only available for those farmers that reduce withdrawals, this instrument would have the advantage of not reducing water use and thus not reducing production and employment. However, as desalinised water will be available to farmers in any case, all instruments have the same impact on agricultural production and employment because farmers could use these resources (either subsidised or not) to substitute for the reduced groundwater withdrawals.

The potential of this last instrument is limited by the fact that farmers may use unsubsidised desalinised water and continue depleting the aquifer. In principle, the subsidy should cover the price differential between desalinisation and groundwater (0.21 €/m^3/year). However, our results show that it must be at least 0.38 €/m^3/year to completely stop non-renewable extractions. For subsidies between 0.21 and 0.38 €/m^3/year (subsidised desalinisation cheaper than groundwater), there is an incentive to use some unsubsidised desalinised water and maintain some level of non-renewable withdrawals. As a result, farmers can use more water than if all non-renewable withdrawals were stopped.

Combinations of instruments

As discussed above, all the instruments considered above for eliminating the Alto Guadalentín aquifer overdraft have a significant economic impact, which is, however, notably mitigated by the greater availability of expensive desalinised seawater resources. Turning now to look at the combinations of two or more instruments, we get similar results.

The horizontal line at the top of Figure 2 shows the relation between the value of agricultural production and public expenditure for the set of efficient combinations of instruments that eliminate aquifer overdraft, whereas the bottom line shows the relation between farmers' net margin and public expenditure. The two isolated spots show the same relations for the baseline scenario of non-intervention (202 million euros/year of agricultural production, 64.6 million euros/year of farmers' net margin and no public expenditure).

The efficient combinations of instruments range from the separate application of an environmental tax on the far left, with a negative public cost (i.e., a positive tax revenue), to the exclusive application of one of the other two instruments (purchase of rights or subsidisation of desalinisation, without any environmental tax) on the far right. All these combinations are characterised by the fact that their sum (value of the tax plus purchase price of rights plus subsidy to desalinised water) adds up to 0.38 €/m^3, which is the marginal value of water at the point where overexploitation is eliminated and desalinised resources are used[2]. The instruments have the same impact on water demand, reducing the use of groundwater either because its cost is increased (tax), because the sale of groundwater rights is encouraged or because a subsidy is given to substitute desalinised resources for groundwater. All the combinations of instruments result in the same level of water use as in the case of the separate application of instruments shown in Table 2[3]. As a result, the value of agricultural production is the same for all the efficient combinations (189.5 million euros/year), as shown in Figure 2. Thus, the choice of the policy mix would have no implications for these two variables.

On the contrary, the impact in terms of farmers' net margin and public expenditure varies with each combination of instruments, and there is a direct relationship between both indicators (Figures 2 and 3). Figure 3 shows the relation between farmers' net margin and the three components of the public expenditure (tax revenue, cost of purchasing rights and cost of subsidising desalinisation). The variation in net margin ranges from −9.29 to +4.57 million euros/year, while public expenditure ranges from −3.33 to +10.47 million euros/year. As we move to the right, the combinations are based on an increasing purchase price or an increasing subsidy to desalinisation and a decreasing environmental tax, and thus both public expenditure and farmers' net margin increase. As we move to the left, combinations are based on an increasing tax and a decreasing purchase price or a decreasing subsidy to desalinisation, and thus the burden of the policy is shifted from the government to the farmers' budget. The total cost of the

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[2] If desalinised resources were unavailable, the marginal value of water at the point where overdraft is eliminated would be 0.71 €/m^3. The availability of desalinised resources means that groundwater can be substituted with desalinised seawater, resulting in a lower marginal value of water. This mitigates the economic impact of eliminating overexploitation and reduces both the private and public cost of the policies.

[3] The set of efficient combinations of instruments includes the cases in which each instrument is used separately.

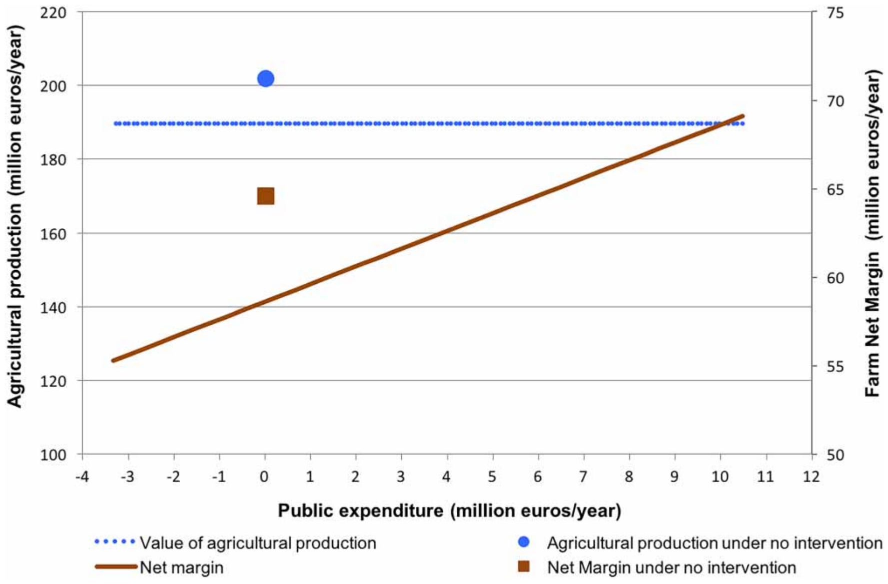

Fig. 2. Public expenditure versus net margin and agricultural production for those combinations of instruments that eliminate overexploitation. *Source:* Own elaboration.

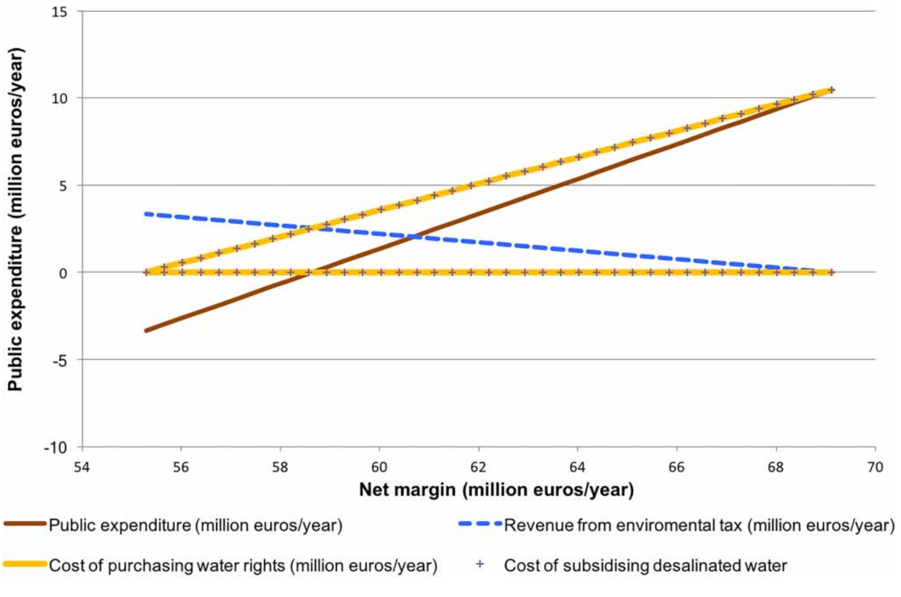

Fig. 3. Scatter diagram of farmers' net margin versus public expenditure for the set of efficient combinations of instruments that eliminate non-renewable pumping. *Source:* Own elaboration.

intervention is 5.9 million euros/year (public expenditure plus variations in net margin), equivalent to the 0.21 €/m^3/year resulting from the cost difference between groundwater and desalinisation. This cost is shared by farmers and the administration depending on the chosen policy mix.

The choice of the optimal combination of instruments (policy mix) will depend on the relative importance given by the policy maker to each criterion (in this case, the impact on public expenditure and the impact on farmers' profitability). We now comment on the optimal combinations according to different decision-making criteria. Figure 4 shows the relationship between public expenditure and farmers' net margin for different criteria, whereas Table 3 shows the values of the instruments according to each criterion and their impact in terms of economic and water use indicators.

Let us first consider that the administration's budget is unlimited. In this case, the optimal solution would be the right end of Figure 4, where no environmental tax is levied. As part of this solution, either a purchase price of groundwater rights or a subsidy to desalinised water of 0.38 €/m^3 should be set. This would increase farmers' net margin by 7% and result in a maximum public expenditure of 10.47 million euros per year (second and third column in Table 3). On the contrary, if the decision criterion was to maximise the collected tax revenue (i.e. minimising public expenditure), the optimal solution would be to establish a tax of 0.38 €/m^3 (left end of Figure 4), with a 14.4% reduction in farmers' net margin and an annual tax revenue of 3.33 million euros (fourth column in Table 3). Depending on which criteria we consider, the optimal decision will move towards one of these two extreme solutions.

Let us assume that the decision criterion is zero public expenditure (both public expenditure and tax revenue). This would require setting an environmental tax of 0.29 €/m^3 and either a purchase price or a subsidy for desalinisation of 0.09 €/m^3, with a 9.3% reduction in farmers' net margin (empty triangle in Figure 4 and fifth and sixth columns in Table 3). The tax revenue would finance the public cost of the

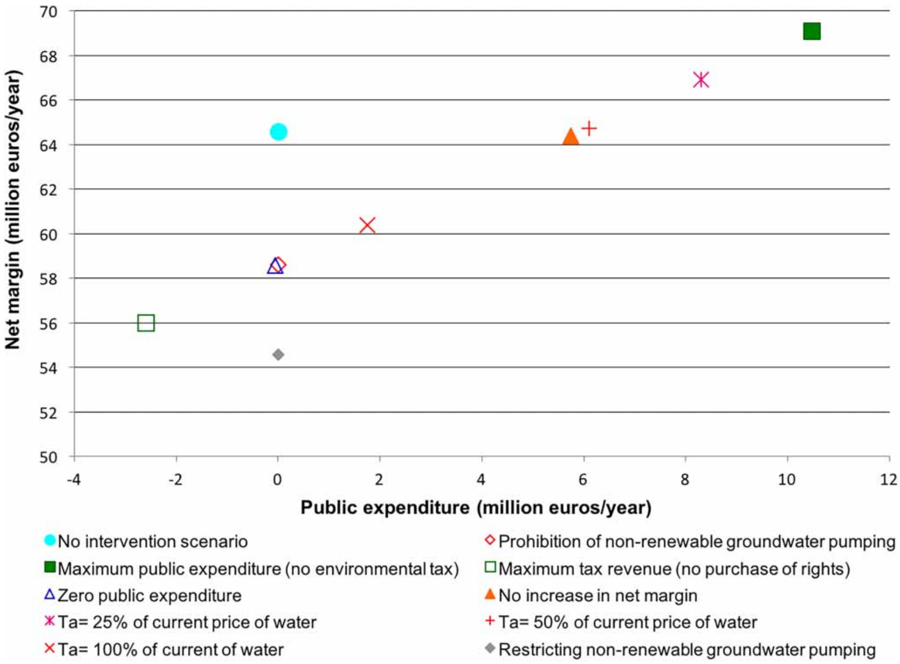

Fig. 4. Trade-off between farmers' net margin and public expenditure for different decision criteria, pumping restrictions and non-intervention scenario. *Source:* Own elaboration.

Table 3. Economic impact of eliminating non-renewable groundwater withdrawals considering different decision-making criteria.

	Possible Criteria											
	Maximum public expenditure		Maximum tax revenue	Zero public expenditure		No change in net margin		Ta = 25% of current water price		Ta = 50% of current water price		Ta = 100% of current water price
Purchase of groundwater rights (€/m^3/year)	0.00	0.38	0.00	0.00	0.09	0.00	0.25	0.00	0.32	0.00	0.26	0.00	0.14
Environmental tax (€/m^3/year)	0.00	0.00	0.38	0.29	0.29	0.13	0.13	0.06	0.06	0.12	0.12	0.24	0.24
Desalinated water subsidy (€/m^3/year)	0.38	0.00	0.00	0.09	0.00	0.25	0.00	0.32	0.00	0.26	0.00	0.14	0.00
Total water use (hm^3/year)	74.44 (−9.1%)												
Reduction in groundwater use (hm^3/year)	27.60												
Groundwater rights purchased (hm^3/year)	0.00	27.56	0.00	0.00	27.56	0.00	27.56	0.00	27.56	0.00	27.56	0.00	27.56
Use of desalinised water (hm^3/year)	0.00	27.60	27.60	0.04	27.60	0.04	27.60	0.04	27.60	0.04	27.60	0.04	27.60
Use of subsidised desalinisation (hm^3/year)	27.60	0.00	0.00	27.56	0.00	27.56	0.00	27.56	0.00	27.56	0.00	27.56	0.00
Agricultural production (million euros/year)	189.51 (−6.2%)												
Farm net margin (million euros/year)	69.11 (7%)	69.11 (7%)	55.30 (−14.4%)	58.57 (−9.3%)	58.57 (−9.3%)	64.59 (0.0%)	64.59 (0.0%)	66.92 (3.6%)	66.92 (3.6%)	64.74 (0.2%)	64.74 (0.2%)	60.39 (−6.5%)	60.39 (−6.5%)
Agricultural employment (10^4 days/year)	114.87 (−9%)												
Cost of purchasing rights (million euros/years)	0.00	10.47	0.00	0.00	2.48	0.00	6.89	0.00	8.82	0.00	7.16	0.00	3.86
Tax revenue (million euros/year)	0.00	0.00	3.33	2.54	2.54	1.14	1.14	0.52	0.52	1.05	1.05	2.11	2.11
Cost of desalinated water (million euros/year)	10.47	0.00	0.00	2.48	0.00	6.89	0.00	8.82	0.00	7.16	0.00	3.86	0.00
Public expenditure (million euros/year)	10.47	10.47	−3.33	−0.06	−0.06	5.75	5.75	8.30	8.30	6.11	6.11	1.75	1.75

Note: When one criterion has two columns, these represent the extremes of the combinations of instruments that comply with such a criterion.

measure, and thus there would only be a private cost for farmers. However, environmental taxation on groundwater is a conflictive issue, not only in Spain. There are few examples of its use across Europe, and even the Netherlands derogated it after 17 years of implementation. Should a tax be levied on groundwater, it is unlikely that such a high and unpopular one could be set.

In this sense, a potentially more balanced and popular solution would be the choice of a combination that does not reduce farmers' net margin below the non-intervention level (64.6 million euros per year), while at the same time does not increase farmer's income above that level. In this case, the optimal solution would be to establish an environmental tax of 0.13 €/m^3 and either a purchase price or a subsidy for desalinisation of 0.25 €/m^3, with an annual public cost of 5.75 million euros and no impact on farmers' profit (full triangle in Figure 4 and seventh and eighth columns in Table 3). This could still be considered a high tax, as it is equivalent to a 50% increase in the average cost of water in the area. Setting a lower environmental tax would be less unpopular but more costly for the administration (far right of Figure 4 and ninth and tenth columns in Table 3).

Conclusions

We have analysed different economic policy instruments that can be used to eliminate non-renewable pumping in the Alto Guadalentín aquifer, one of the most profitable agricultural areas in Europe. Unlike other depleted aquifers in Spain where there are no alternative sources of water supply, the availability of desalinised seawater in the area in the near future provides an opportunity to address this problem at a lower social and economic cost. To assist in the choice of which instruments to apply, we assess their economic impact in terms of agricultural activity, social impact and public expenditure.

Our results show that demand for desalinised resources is relatively small because of its high price for farmers. In addition, in the absence of any policy intervention, groundwater withdrawals will not be reduced by merely giving farmers access to desalinised resources because of the high water demand and severe water scarcity in the area of study.

The application of any of the analysed instruments reduces groundwater withdrawals and creates incentives for farmers to make use of desalinised resources to substitute for non-renewable ones. At the point where non-renewable withdrawals are eliminated, farmers would use almost all of the available desalinised water. Overall, the availability of desalinisation would notably mitigate the significant economic impact of eliminating aquifer overdraft using any of the instruments, as farmers can substitute groundwater with desalinised water.

Although a complete ban on non-renewable pumping and a tax on withdrawals would result in the lowest level of public expenditure, they are very unpopular and have a large political cost. We should not overlook the fact that the success of any policy largely depends on the cooperation of users. It is unlikely that a tax of more than a few euro cents could be levied or that pumping could be restricted without any type of compensation, as the experiences in other Spanish basins have shown (Esteban & Albiac, 2011; Garrido *et al.*, 2013).

The buyback of water rights and the subsidisation of desalinisation in exchange for reducing groundwater pumping have the same impact on agricultural production and employment as the tax, but are likely to be much better received by farmers. Their disadvantage is that the cost of reducing withdrawals shifts from farmers to the public budget. The solution could be a combination of instruments that would split the cost of aquifer recovery between farmers and the government.

The combinations of instruments that eliminate aquifer overexploitation range from the separate application of an environmental tax at one end of the spectrum and the exclusive application of one of the other two instruments (buyback of rights or subsidisation of desalinisation) at the other. The impact on the rural economy, in terms of agricultural production and employment, is the same for all efficient combinations. Thus, the choice of the policy mix would only have implications for farmers' profitability and public expenditure.

There is thus a trade-off between public expenditure and farmers' net margin. Both of them increase when the combinations of instruments are based on a higher purchase price (or a larger subsidy for desalinisation) and a lower environmental tax. When combinations are based on a higher tax and a lower purchase price (or a smaller subsidy for desalinisation), the burden of the policy intervention shifts from the government to the farmers' budget.

The choice of the optimal policy mix will therefore depend on the relative importance given by policy makers to each criterion (impact on public expenditure and impact on farmers' income). However, this choice will depend on the stronger or weaker opposition that each measure receives from stakeholders. A high tax on groundwater should be levied to eliminate non-renewable withdrawals, which makes this option politically unfeasible. However, lower taxes can complement less conflictive measures by raising revenue to offset the public cost of financing them. On the other hand, more popular policies to recover the aquifer can be controversial as they may improve farmer's income at the expense of the public budget.

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