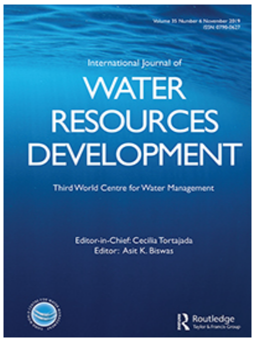

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Water buybacks to recover depleted aquifers in south-east Spain

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ABSTRACT

This article assesses the economic impact of implementing a public buyback of groundwater rights to eliminate non-renewable pumping in the Murcia Plateau of the Spanish Segura basin, home of some of the most depleted aquifers in Europe. We find that, regardless of the policy instrument applied, stopping non-renewable extraction would severely hit the agricultural sector. The buyback of rights would not prevent this impact but the cost of reducing extraction would be borne by the government instead of farmers, making it a potentially more successful alternative. However, the estimated cost for the public budget is very large and probably unaffordable.

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Groundwater; Segura basin; public water purchases; water markets; water banks; economic impact

Introduction

The unsustainable exploitation of aquifers is one of the most pressing water management and environmental problems in the Mediterranean (Scheidleder et al., 1999). As in many other areas around the world, over-appropriation of water resources, weak enforcement of water rights regimes and illegal pumping from aquifers are major factors behind the depletion of groundwater resources (Marchiori, Sayre, & Simon, 2012; Skurray & Pannell, 2012). In the Segura River basin in south-eastern Spain, one of the most profitable agricultural areas in Europe, the expansion of irrigation over the last four decades has put groundwater bodies under huge pressure and caused depletion to reach alarming rates in many aquifers (Martínez-Granados & Calatrava, 2017). As in other Spanish basins, farmers and agricultural water users' associations (WUAs) have led the development of agricultural groundwater use, with very little participation or control from water authorities, which has led to the current situation of aquifer depletion (Fornés, De La Hera, & Llamas, 2005). This jeopardizes the possibility of reaching the environmental standards set for 2027 in the Segura River Basin Management Plan (CHS, 2014) to comply with the objectives of the EU Water Framework Directive (WFD) (Berbel & Expósito, 2018).

With some notable exceptions, the Spanish water authorities had barely addressed this problem before the implementation of the WFD (EU, 2000) and the elaboration of the 2009–2015 river basin hydrological plans. The most relevant initiative was the development of management plans for those aquifers that were legally declared as depleted. These plans aimed at improving the definition and registration of water rights,

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establishing abstraction quotas and monitoring water pumping, paying special attention to the control of unauthorized withdrawals. Aquifer management plans, where implemented in the past, were strongly opposed by farmers and other local stakeholders (Carmona, Varela-Ortega, & Bromley, 2011). The lack of political willingness to enforce the management plans, together with the little cooperation between water authorities and water users, resulted in the failure of most initiatives (De Stefano & Lopez-Gunn, 2012; Esteban & Albiac, 2011; Fornés et al., 2005). The need to comply with the WFD by 2027 will hopefully encourage greater efforts at political compromise.

In some exceptional cases, Spanish water authorities have implemented payment schemes to reduce groundwater abstraction or used public water banks to buy back groundwater rights (Carmona et al., 2011; Garrido, Rey, & Calatrava, 2013; Marchiori et al., 2012; Montilla-López, Gómez-Limón, & Gutiérrez-Martín, 2018). In the 1990s, the Guadiana River Basin Authority implemented a system of agri-environmental payments to farmers for reducing abstraction from the over-exploited Western La Mancha aquifer (Carmona et al., 2011). Initially, this initiative had some success, but in the absence of effective monitoring mechanisms, it created incentives for additional pumping (Esteban & Albiac, 2011). With this precedent in mind, the Guadiana River Basin Authority implemented the Special Plan for the Upper Guadiana (Law 13/2008), which included the public purchase of groundwater rights from the Western La Mancha aquifer.

The public purchase of water rights is being increasingly used in some of the most mature water economies, like the United States (Garrick, Siebentritt, Aylward, Bauer, & Purkey, 2009; Ghosh, Cobourn, & Elbakidze, 2014; Hadjigeorgalis, 2009; Loomis, Quattlebaum, Brown, & Alexander, 2003) and Australia (Adamson & Loch, 2018; Bark, Kirby, Connor, & Crossman, 2014; Crase, O'Keefe, & Kinoshita, 2012; Docker & Robinson, 2014; Garrick et al., 2009; Wheeler, Garrick, Loch, & Bjornlund, 2013; Wittwer & Dixon, 2013), to reallocate water resources to environmental uses. Water authorities buy back water rights from water users, generally farmers (Marchiori et al., 2012). In contrast to payments for reducing extraction, this instrument has the advantage of permanently reducing abstraction.

The evidence from water buyback experiences in other countries is mostly positive. Buybacks are more cost-effective in recovering water resources for public uses than investments to improve water infrastructure or subsidies to water-saving irrigation technologies (Adamson & Loch, 2018; Bark et al., 2014; Crase et al., 2012). The introduction of water buybacks has also provided individual risk-management opportunities for farmers (Crase et al., 2012). However, water buybacks may increase water prices, reduce agricultural production and employment, and compromise the efficiency and financial profitability of irrigated districts (Bark et al., 2014). In fact, Crase et al. (2012) report some stakeholders in Australia opposing buyback schemes based on social concerns. Another drawback is that the environmental outcomes of buybacks are not guaranteed (Crase et al., 2012). In Spain, the public purchase of water for the environment has been used with relative success in a few significant cases. Apart from the permanent purchase of groundwater rights within the Special Plan for the Upper Guadiana Basin (Law 13/2008), the water authorities of the Júcar and Segura basins temporarily leased water rights during the 2005–2008 drought to meet environmental demands (Rey, Garrido, & Calatrava, 2014).

One of the most severe examples of aquifer overdraft in Europe can be found in the Murcia Plateau (Altiplano de la Región de Murcia), in the north-east of the Segura basin (Molina et al., 2009), an important wine- and fruit-producing area (Calatrava & Martínez-Granados, 2012). Irrigation in this area is served almost exclusively from groundwater resources, 61% of which are non-renewable (CHS, 2013). As in many other areas of south-eastern Spain, aquifer overexploitation in the Murcia Plateau is caused by both past over-allocation of groundwater rights and the progressive reduction of the aquifers' recharge rate.

The Segura River Basin Authority (SRBA) has not clearly defined the measures that will be applied to face this problem. The establishment of pumping quotas to reduce extraction has been delayed because of its institutional complexity (most groundwater resources correspond to private rights rather than public water concessions) and because of its severe economic impact and thus opposition at the local level. The alternative of substituting external water resources for groundwater has been proposed, but without identifying those external resources. Moreover, this alternative is not currently available. Unlike in other depleted aquifers in Spain, which do have alternative sources of water, the Murcia Plateau is not connected by water transportation infrastructure to the rest of the basin, leaving groundwater as its only natural source of water. The public purchase of groundwater rights appears as a less conflictive and costly alternative to eliminate aquifer overdraft in the area.

This article evaluates the economic impact of stopping non-renewable pumping from the aquifers of the north-east plateau of the Spanish Murcia Region through the public purchase of groundwater rights, against the alternative of restricting extraction quotas. It also considers the fact that right holders can enter into water trading through formal temporary lease contracts. Water trading is expected to minimize the private economic damage caused by a reduction in water availability (Kahil et al., 2016), for example due to limits on groundwater withdrawal. The impact of these policy alternatives is assessed using a non-linear agro-economic model that simulates land and irrigation-water allocation in the area for different economic, policy and water availability scenarios. This economic model provides results in terms of marketed agricultural production, farm labour and public expenditure.

This study makes several contributions. First, it assesses the direct costs of stopping non-renewable pumping from one of the most depleted aquifers in Europe. Second, it quantifies the implications of relying on the public purchase of groundwater rights to reach this objective. Third, it evaluates the cost of purchasing rights under alternative calculation assumptions. Last, it provides information relevant to the design of public buyback strategies. The effectiveness of public water purchase programmes is highly dependent on the ability of water agencies to place attractive bids that incentivize farmers' participation (Crase et al., 2012). The Júcar and Segura water purchase offers during the 2005–2008 drought were not fully successful because, among other reasons, the price set by water authorities was not attractive enough for farmers. As water trading data are usually not available, or market prices are not representative due to market thinness and lack of transparency (Calatrava & Martínez-Granados, 2018), water agencies have to rely on other methods for estimating compensation. The model used here enables a more realistic assessment, as the estimated value of irrigation water changes with water availability.

The article continues with a description of the situation of water resources in the study area and a discussion of the different policy options considered for tackling aquifer depletion. Then the methodology of the analysis is presented. The article concludes by presenting and discussing the most relevant results of the study.

Irrigated agriculture and groundwater use in the Murcia Plateau

The Murcia Plateau is in the north-east of both the Murcia Region and the Segura River basin, in south-east Spain. It is a tableland, at an altitude of about 600 m, formed by wide valleys surrounded by small mountain ranges. The tableland is scored by many creeks with scarce and intermittent flows, often of a torrential nature, that are tributaries of the Segura River. Water infrastructure in the area is not connected to the rest of the Segura River basin and thus does not receive water from other areas, being exclusively supplied from several aquifers (Figure 1).

Agricultural production in the area is specialized in classical Mediterranean crops, such as wine grapes, almonds and olives, but also fruits (pears, table grapes and, to a lesser extent, peaches, apricots and prunes). Despite farm profitability being far below that of intensive horticulture in other areas of the Segura basin, water productivity and profitability are still above the basin's average (Calatrava & Martínez-Granados, 2012). This is because a large share of the irrigated area is planted with traditionally rainfed crops that notably increase their yields with relatively small applications of irrigation

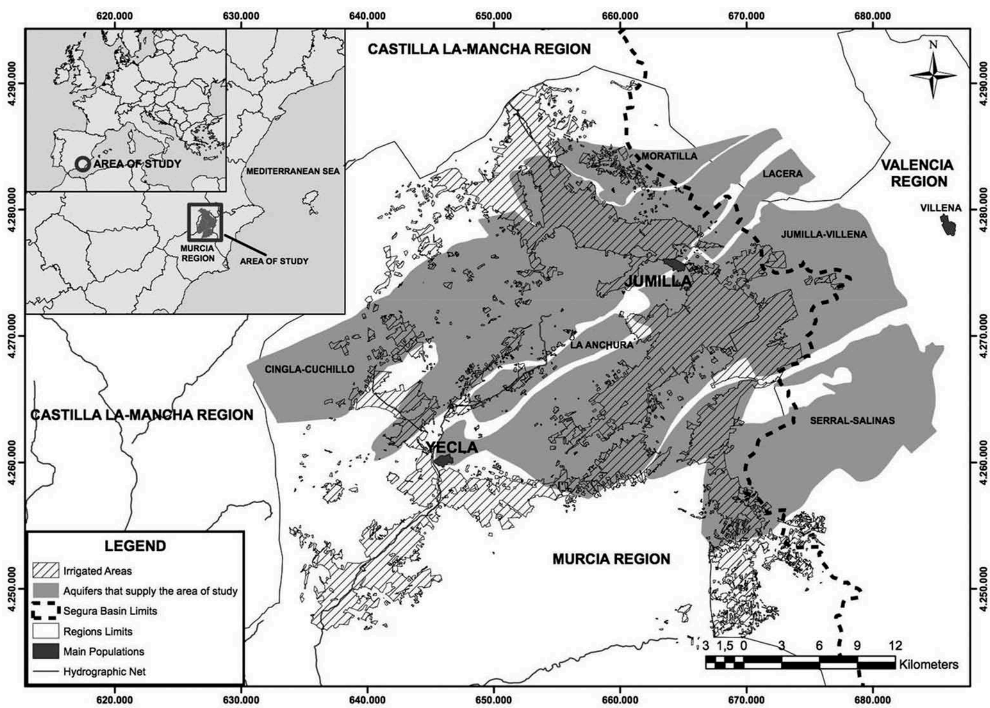

Figure 1. Location, irrigated areas and aquifers of the Murcia Plateau in south-east Spain.

water. In addition, wine and pear production have Protected Designation of Origin brands, which increases the profitability of these two crops.

According to the SRBA Geographical Information System (https://www.chsegura.es), the total irrigable area in the Murcia Plateau is 33,175 hectares. In practice, the annual area effectively irrigated averages 24,483 hectares. Agricultural water demand in the area is estimated at 67 Mm^3/y (CHS, 2013). If we consider urban uses (5.49 Mm^3/y), total water demand in the area is 72.49 Mm^3/y, whereas existing water rights and concessions account for 75.18 Mm^3/y (Table 1). In fact, demand is far from being balanced with supply.

In practice, the renewable groundwater resources (27 Mm^3/y) are very small compared to the existing rights (72 Mm^3/y). Overall, groundwater rights and concessions exceed renewable resources by 45 Mm^3/y. Including treated wastewater, total available resources satisfy only 41.6% of the existing water demand. Part of this deficit is accounted for by the application of regulated deficit irrigation techniques, but most of it is covered by non-renewable groundwater extraction. Specifically, 42.31 out of 72.49 Mm^3/y of water used in the Murcia Plateau corresponds to non-renewable groundwater withdrawal (CHS, 2013). The difference between 45 Mm^3/y (overallocation of groundwater rights) and 42.31 Mm^3/y (current estimated non-renewable pumping) corresponds to currently unused water rights.

Unlike other areas in Spain and around the world, the overdraft problem in the Murcia Plateau does not come only from the lack of control over groundwater rights and pumping rates. In fact, groundwater rights are included in a public registry, and the SRBA monitors extraction and punishes illegal pumping. This control is favoured by the small number of right holders, most of which are relatively large users. According to data sourced from the SRBA, there are only 43 groundwater right holders in Murcia Plateau, including 31 WUAs, which distribute 87% of the groundwater used in the area from their communal wells, and 12 enterprises and agricultural cooperatives, which use 13% of the groundwater. This makes water use easier to control and fulfils an obvious prerequisite for the successful implementation of whatever policy instrument is considered. The main causes of aquifer overexploitation in the area are the massive overallocation of rights during the twentieth century and the reduction in the rate of recharge of the aquifers. Despite this level of aquifer depletion, the pumping cost is still below the marginal value of irrigation water. Under these circumstances, the relatively high profitability of irrigation creates an incentive to continue using groundwater resources in an unsustainable manner.

Policy alternatives for the study area

The most straightforward way to tackle aquifer overdraft is establishing pumping quotas to restrict abstraction to its renewable fraction. The 1985 Spanish Water Act (Law 29/1985) established that, when an aquifer is legally declared to be over-exploited, water right holders must constitute WUAs to jointly manage the aquifer's resources. A management plan regulating and restricting extraction from the aquifer should then be implemented. In addition, the WFD established the obligation to reach a good quantitative and qualitative status of all water bodies, which in practice implies eliminating aquifer overdraft.

As mentioned, management plans have been developed for many aquifers in Spain but have been only implemented in some cases, and with very limited success, due to the high political cost of strong local opposition. Regulatory approaches, such as modifying water concessions to restrict extraction, are a low-cost alternative that is administratively simple to implement (Bark et al., 2014; Crase et al., 2012). However, they are usually unpopular because they impact existing property rights (Bark et al., 2014). In fact, in Australia they have only been used with relatively small volumes of water and small numbers of affected right holders (Crase et al., 2012). In the Spanish case, there are additional institutional and legal difficulties because about 80% of groundwater resources correspond to historical private groundwater rights.

Public water rights (water concessions) are valid for a limited time (30 years for new ones) but can be modified or revoked by water authorities if necessary to adapt to changing hydrological conditions or water policy needs. They usually give a right to a maximum volume of water, but the annual volumes of water effectively allocated to the existing water concessions are established annually by water authorities based on the water availability in each area, but without clearly defined criteria (Calatrava & Martínez-Granados, 2018). In contrast to public concessions, private groundwater rights are valid indefinitely and give holders the right to legally abstract the water volume/flow indicated in it. They are considered private property that can form part of the assets of companies or cooperatives, and as such can be sold, leased or rented, although subject to specific restrictions (Rey et al., 2014). They can be also taken from their holders by the state through a compulsory purchase order for reasons of public interest. Consequently, restricting groundwater extraction should follow a slow legal process that would, in principle, require compensating the right holders. However, the 1985 Water Act (Law 29/1985) explicitly states that restrictions on groundwater pumping from aquifers legally declared over-exploited should be applied equally to both public water concessions and private water rights. Despite this legislation, there is still a legal debate on whether restrictions can be applied to private water rights without compensating the owners.

In the case of the Murcia Plateau, the 2009–2015 Segura River Basin Hydrological Plan (CHS, 2014) set the environmental objective of balancing extraction and recharge in the aquifers of the area and established aquifer management plans to reduce water extraction quotas in this and other areas of the basin with similar problems. However, in view of its large expected economic impact ('disproportionate cost' in the WFD jargon), it postponed compliance with this objective by 2027. It also proposed gradually substituting desalinized seawater for groundwater. Over the last 15 years, the Spanish government has developed a large seawater desalination capacity along the Mediterranean coast that serves both urban and agricultural users. Due to the relatively high profitability of agriculture in the Segura basin, the demand for desalinized resources is significant (Alarcón Luque & Juana Sirgado, 2018).

The current Segura River Basin Hydrological Plan (2015–2021) maintains the same philosophy but proposes replacing non-renewable groundwater pumping with unspecified 'external resources' (CHS, 2015). Published studies in other areas with similar aquifer depletion problems have proposed providing alternative resources to substitute for groundwater, such as desalinized seawater in the cases of the Aguilas, Upper Guadalentín and Lower Guadalentín aquifers in the Segura basin itself (Martínez-Granados, 2015; Martínez-Granados & Calatrava, 2014, 2017) or surface resources in the Medina del Campo and Los Arenales aquifers in the Spanish Duero basin (CHD, 2015). However, this option is not always available. There is presently no infrastructure connecting the Murcia Plateau with the rest of the basin. Without that, this seems an unfeasible alternative, at least in the medium run. Similarly, the 2012 reform of the 1985 Spanish Water Law (Law 11/2012) established the possibility of recharging aquifers from external resources to achieve good quantitative status, which is also unfeasible for the same reasons. The only currently available alternative resources come from the purification of urban wastewater. However, the potential for water reuse in the area of study is almost fully developed, and farmers are already using all the available reclaimed water from local urban wastewater treatment plants.

Nor is reducing water demand through investments in the modernization of water infrastructure or in water-saving irrigation technologies viable. Currently, all irrigated areas in the Murcia Plateau have modern infrastructure for water distribution to farmers, and all the irrigated area is equipped with pressurized irrigation systems, as is common in groundwater-supplied irrigated areas in southern and eastern Spain.

An alternative instrument to reduce pressures on groundwater bodies is the buyback of water rights by the government. In contrast to payments for reducing extraction, an option unsuccessfully applied in some isolated cases in Spain, the buyback of groundwater rights permanently reduces abstraction. It is also less conflictive than reducing pumping rates and other command-and-control policies. In the Australian experience, water buybacks have been in most cases positively received by farmers (Crase et al., 2012). They may have a significant impact on the rural economy of the affected areas, but this impact would be smaller than for the outright restriction of groundwater withdrawal. However, it requires great public expenditure to buy back the rights. Experiences in Spain show that the price bid should be attractive enough for farmers (Calatrava & Martínez-Granados, 2018; Carmona et al., 2011).

The effectiveness of buyback schemes depends on both the existing level of over-allocation of water rights and the enforcement of the water rights regime (Garrick et al., 2009; Marchiori et al., 2012). As in any other type of surface or groundwater trading, effective monitoring of water use and potential negative and environmental impacts is essential for successful implementation (Garrick et al., 2009; Skurray & Pannell, 2012). Of special relevance is the control of illegal abstraction, as the purchase of rights creates an incentive to increase illegal pumping, which could make the reduction in water consumption smaller than the volume of purchased rights (Marchiori et al., 2012). As mentioned, the monitoring of groundwater use in the area of study can be considered good, so this issue is not considered relevant to the present analysis. In any case, there have been several experiences of buyback or leasing of water rights in Spain, which shows the feasibility of this type of instrument in the Spanish water legal and institutional framework, as the following section will illustrate.

Public water rights purchase offers in Spain

To provide flexibility to the Spanish system of public water use rights (concessions), increase the economic efficiency of water use and reduce the economic impact of scarcity, in 1999 the Spanish Parliament passed the Water Law Amendment (Law 46/1999), which legislated and regulated the operation of water markets in Spain. This law allowed, subject to application to and authorization by the corresponding river basin authority, voluntary water trading between concession holders entering into a private contractual agreement to temporarily lease their water use rights for a price, or 'compensation' (Calatrava & Martínez-Granados, 2018). Before this reform, only private groundwater rights could be leased or sold (Rey et al., 2104).

Apart from the legal concept of lease contracts between users, the 1999 Water Law Amendment offered the possibility of basin authorities setting up water use rights exchange centres (WURECs). Through WURECs, basin authorities could make public water rights purchase offers to holders interested in temporarily or permanently transferring their concessions, which they were then to transfer to other interested right holders (Calatrava & Gómez-Ramos, 2009). The original spirit of the law was that WURECs would operate as a means of connecting water sellers with buyers, in the manner of the water banks operating in the US (Garrido et al., 2013; Hadjigeorgalis, 2009; Loomis et al., 2003). On this ground, WURECs were not allowed to retain any of the purchased rights. Their role was, therefore, limited to that of middlemen.

The first WURECs were set up in the Guadiana, Júcar and Segura River basins by a decision of the Council of Ministers dated 15 October 2004, whereby the respective river basin authorities were authorized to make public water rights purchase offers. But the centres did not enter into operation until the start of the 2005–2008 drought, when Law 9/2006 reinforced their effectiveness and they were allowed to cater to other, primarily environmental, demands (Montilla-López, Gutiérrez-Martín, & Gómez-Limón, 2016). In particular, apart from transferring resources to other users (the original goal set in the 1999 Water Act), the centres were also able to use the purchased rights to target environmental uses or transfer rights to the regional governments in each river basin to implement their water policies.

The Special Plan for the Upper Guadiana (Law 13/2008) included the largest water rights purchase offers to date in Spain, aimed at raising water tables in a severely overexploited aquifer (López-Gunn, Dumont, & Villarroya, 2013). Three offers were launched in 2006/07, and the large budget allocated was fully spent. The average price paid to right holders was 0.12 €/m^3 (Palomo-Hierro, Gómez-Limón, & Riesgo, 2015). It was a relatively successful experience, as the purchased rights were converted into new public concessions and transferred to other users, and groundwater pumping was hardly reduced at all (Garrido et al., 2013; Montilla-López et al., 2016).

The objective of the Júcar water rights purchase offers in 2006/07 and 2007/08 was to reduce abstraction in the Upper Júcar aquifer to increase environmental flows in the lower Júcar basin during the 2005–2008 drought (Garrido et al., 2013; Palomo-Hierro et al., 2015). Farmers could participate in the purchase offers by leasing out their water rights for a year for compensation that depended on the location of the water seller in the basin. Average compensation paid was 0.19 €/m^3 in 2006/07 and 0.25 €/m^3 in 2007/08 (Montilla-López et al., 2016). The two purchase offers did not meet their objectives, as the purchased water did not reach half of the targeted volumes.

In the case of the Segura River basin, the SRBA issued a public water rights purchase offer in 2007 with the aim of first satisfying urban demand and second setting up a strategic reserve in the headwaters of the basin to guarantee environmental flows in the Segura and Mundo Rivers (CHS, 2007). In practice, this environmental objective limited participation to concession holders in the basin headwaters in the province of Albacete. Holders of consumptive use rights, both concession and private groundwater right holders, were entitled to participate in the public water rights purchase offer only if the resources covered by the use rights had been used in at least one of the irrigation seasons prior to the public water rights purchase order (CHS, 2007). Subject to prior consent from the corresponding WUA, their individual member farmers were also entitled to participate. Also, on accepting the offer, participating users had to transfer all the resources of the hydrologic year to which they were entitled. This was tantamount to the cessation of water use on the signature of the agreement, save justified exception (CHS, 2007).

The 2007 public water rights purchase offer in the Segura basin had a budget of €700,000, and the maximum price to be paid was 0.18 €/m^3. The SRBA sustained the costs of transporting water from the catchment areas. Finally, 41 offers by smallholders, totalling 371.5 hectares, were accepted. The purchased volume was 2.93 Mm^3, at an average price of 0.168 €/m^3 and with a budgeted cost of €495,000. All the purchased flows were allocated to environmental uses (Calatrava & Martínez-Granados, 2018). The offer was repeated in 2008 under identical terms and with similar outcomes (Calatrava & Gómez-Ramos, 2009). As in the Júcar basin, the Segura public water rights purchase offers were only moderately successful; the original budget was not used up, because there were not enough suppliers that met the requirements (Garrido et al., 2013; Rey et al., 2014). According to Calatrava and Martínez-Granados (2018), the price was not attractive, as it was only slightly above the marginal value of water in the area of origin.

Likewise, none of the WURECs in Spain have operated as purchasers of water or of water rights that have been sold on to other users (Garrido et al., 2013). In fact, the purchased resources have been transferred to other users as new concessions (in the case of the Guadiana) or have been used to maintain ecological flows in times of drought (in the cases of the Segura and Júcar) (Rey et al., 2014). Therefore, the sole purpose of the centres has been environmental protection, as in the public water banks in California, Australia and Canada (Docker & Robinson, 2014; Hadjigeorgalis, 2009; Loomis et al., 2003; Wheeler et al., 2013). None of these WURECs has operated again since.

Methodology

The economic impact of the analyzed policy measures was assessed using a non-linear mathematical programming optimization model that simulates the economic use of irrigation water in the Segura River basin. The model simulates land and water allocation among crops and computes several economic indicators (cultivated area, marketed agricultural production, on-farm labour and farmers' net margin). The mathematical structure of the model and its calibration process is the same as in Martínez-Granados, Maestre-Valero, Calatrava, and Martínez-Alvarez (2011). However, all the technical and economic parameters of the model have been updated, including irrigable and irrigated areas; crop yields, prices, production costs and water requirements; efficiency losses in storage, transportation and distribution; existing water rights; and water use and non-renewable water availability.

The objective function of the model maximizes the sum of the net margin for all the irrigated crop activities selected in each irrigated area, subject to a number of constraints that represent the availability of irrigated land and irrigation water. In a stylized manner, the model for each irrigated area is given by

$$\text{Maximize} \sum_i \sum_j \sum_k \left[s_{ij} \left(p_j \, q_{ij} - c_{ij} \right) - w_{ik} \, pw_{ik} \right] \tag{1}$$

subject to the following constraints:

$$\sum_j s_{ij} \leq \text{SF}_\text{i} \qquad \forall i \tag{2}$$

$$w_{ik} \leq A_{ik} \qquad \forall i, k \tag{3}$$

$$\sum_j \left[\frac{s_{ij} \, a_{ij}}{\text{eff}_\text{i}} \right] \leq \sum_k w_{ik} \quad \forall i \tag{4}$$

$$s_{ij}, w_{ik} \geq 0 \quad \forall i, j, k \tag{5}$$

where i is a set that denotes the irrigated area; j is a set that denotes the crop; k is a set that denotes the source of irrigation water (surface water, groundwater, reclaimed wastewater, etc.); s_{ij} is a decision variable that represents the area allocated to crop j in irrigated area i (ha); p_j is the price of crop j (€/kg or €/unit); q_{ij} is the average yield of crop j in irrigated area i (kg/ha or units/ha); c_{ij} is the average production cost per hectare for crop j in irrigated area i (€/ha), excluding water charges; w_{ik} is a decision variable that represents the volume of water used from source k in irrigated area i (m^3); pw_{ik} is the unitary water charge paid for water source k in irrigated area i (€/m^3); SF_i is the irrigable land in irrigated area i (ha); A_{ik} is water availability from source k in irrigated area i (m^3); a_{ij} is the water application per hectare to crop j in irrigated area i (m^3/ha); and $eff_i$is a coefficient that represents the efficiency of water transportation, distribution and on-farm storage for each irrigated area.

The constraint in Eq. (2) prevents more land than available from being irrigated. The constraint in Eq. (3) prevents the volume of water used from a given source in an irrigated area from exceeding the water supply available from that source in that irrigated area. The constraint in Eq. (4) prevents the total volume of water used in a given irrigated area from exceeding the total water supply available for that irrigated area. Finally, non-negativity constraints in Eq. (5) prevent the model from assigning negative values to the decision variables. As mentioned, all the irrigated area is equipped with pressurized irrigation systems, and water application rates to crops are already adjusted to the minimum because of the low water availability in the area, so the model does not consider the option of shifting to more efficient irrigation systems or reducing water application to crops.

The technical and economic coefficients used in the model were taken or calculated using data from official statistical databases and from interviews with irrigating farmers in the Segura basin conducted between 2013 and 2017. Average crop prices (p_j) for 2006–2015 were calculated using data from the Murcia Regional Statistic databases (CREM, 2015), which are considered representative of the area of study. Average crop yields (q_j), production costs (c_j) and water application to crops (a_j) were obtained from the mentioned interviews with farmers and validated with official data. Specifically, crop yields were validated with statistics on crop yields at the province level (MAGRAMA, 2015a), while average water applications to crops were validated with those considered in the Segura River Basin Management Plan (CHS, 2014). Average per hectare production costs (c_j) were calculated based on a technical and economic characterization of standard crop production processes in the study area using data obtained from the interviewed farmers. Following the methodology used by the Spanish Ministry of Agriculture (MAGRAMA, 2015b), farm net margin was calculated by subtracting direct costs, machinery costs, labour costs, indirect costs and asset depreciation from farm revenue. The water charges paid for each source of irrigation water were obtained from the interviewed farmers and agree with those provided by the SRBA (CHS, 2014). Average production costs (c_{ij}) do not include water charges. The observed distribution of crop activities in each irrigated area of the area of study was obtained by crossing the observed crop areas by municipality (from CREM, 2015) with the distribution of the irrigated areas per municipality. Both the irrigable area (SF_i) and water availability per source (A_{ik}) for each irrigated area were obtained from the SRBA's geographical information system (www.chsegura.es) and CHS (2013), as indicated in Table 1. Lastly, the efficiency coefficient (eff_i) was calculated for each irrigated area using data from CHS (2014) and Martínez-Granados et al. (2011).

The model was calibrated for 2015 using positive mathematical programming (PMP), which is the most commonly used calibration method in agro-economic models (Graveline, 2016). PMP uses observed data on the farmers' cropping patterns to obtain quadratic cost or yield functions for each crop activity. The calibrated model provides results that are consistent with the real observed crop allocation decisions made by farmers. PMP calibration thus makes the model a more accurate representation of the real modelled system when no data are available at a very detailed level (Martínez-Granados et al., 2011). Specifically, the PMP calibration approach proposed by Röhm and Dabbert (2003) was used to obtain a quadratic cost function for each crop and irrigated area. In the calibrated model, these non-linear cost functions replace c_{ij} in expression (1). Once calibrated, the model can be used to analyze the outcome of technological, economic and institutional changes. But it must be noted that, as PMP calibration is based on observed cropping patterns, the simulation results do not consider new crop alternatives that could be available to farmers in the future.

The calibrated model determines the optimal irrigated area allocated to each crop and the optimal volume of water used from each supply source in each irrigated area of the study area. From the optimal crop allocation and mix of water sources, the model computes the market value of agricultural production, the net margin and farm labour use in each irrigated area, and the marginal value of irrigation water.

The model allows assessing the economic impact of changes in its technical and economic parameters. Specifically, in this study, it was used to simulate the economic impact of changes in water availability (restricting groundwater pumping) and water

Table 1. Available water resources and water costs in the Murcia Plateau.

Source of water supply	Existing water rights (Mm^3/y)	Available water resources (Mm^3/y)	Used water resources (Mm^3/y)	Cost of water for farmers (€/m^3)
Groundwater	72.00	27.00	69.31	0.16
Treated wastewater	3.18	3.18	3.18	0.03
TOTAL	**75.18**	**30.18**	**72.49**	

Source: Elaborated from data from the SRBA GIS (https://www.chsegura.es) and CHS (2013).

allocation (water trading). Thus, four different scenarios are considered in the analysis: (1) the current situation or 'no intervention'; (2) the current situation plus water trading between right holders; (3) elimination of non-renewable extraction; and (4) elimination of non-renewable extraction with water trading between right holders. Scenario 1 is taken as the reference to assess the impact of the other ones.

To simulate the 'elimination of non-renewable extraction' scenarios, A_{ik} (water availability per source) in Eq. (3) was restricted to its renewable fraction. To simulate the 'water trading' alternative, a price endogenous modelling approach was taken (Calatrava & Garrido, 2005). More specifically, Eq (3) was replaced by Eq. (6) for the case of groundwater resources:

$$\sum_i w_{ik} \leq \sum_i A_{ik} \quad \forall k = \text{groundwater} \tag{6}$$

In Eq. (6), the different irrigated areas' groundwater availability constraints are replaced by one groundwater availability constraint for the whole area of study, as in Kahil, Connor, and Albiac (2015), to cite a recent application. This implies enabling the optimal reallocation of groundwater among irrigated areas. The market equilibrium price for water was derived as the dual value of the water availability constraint (6) and used to compute the market outcome from the optimal reallocation established by the spatial equilibrium price endogenous model, as in Calatrava and Garrido (2005) and Rinaudo, Calatrava, and Vernier De Byans (2016). No transportation losses from water trading are considered, as groundwater trading consists of exchanging the right to abstract a given water volume rather than the water volume itself. Water is not transported; only the abstraction point changes. To simplify the analysis, we assumed zero transaction costs and no barriers to trade. Consequently, the outcome of the water-trading scenario would represent a maximum level of gains from trade. However, a major advantage of water banks is that they significantly reduce transaction costs, especially those related to contracting (Montilla-López et al., 2016). Consequently, transaction costs are not expected to be relevant in this case. In addition, based on the experience of the 2007–08 water bank in the SRB, it can be assumed that they would be borne by the Basin Authority.

The outcome of the water buybacks was calculated by adding the annual compensation to farmers for relinquishing their groundwater rights to the outcome of the 'elimination of non-renewable extraction' scenario. It is therefore assumed that the volume purchased in the buyback is equal to the level of non-renewable extraction to be eliminated (the policy objective). The annual equivalent cost of purchasing the rights was calculated by multiplying the unitary annual compensation by the volume of water rights purchased. The unitary annual compensation to be paid to farmers for relinquishing their groundwater rights through a public water rights purchase offer was calculated under two alternative assumptions: (a) all rights are purchased at the marginal value of water at the point where non-renewable pumping is eliminated (market clearing price); and (b) the compensation for the purchase of rights is equal to the foregone farm income. Alternative (a) resembles the way the Spanish water agencies implement public water buybacks. According to Law 9/2017, which regulates contracts in the Spanish public sector, launching a water rights public purchase offer requires first defining a budget for the bid invitation, that is, a maximum price bid. In the offers launched in

Spain between 2006 and 2008, farmers were asked to post bids to lease their rights with a maximum bid price. The average price paid by basin agencies was close to that maximum. Alternative (b) more resembles a closed first-price auction. In the Spanish case, it would require launching several consecutive public purchase offers with independent budgets and increasing maximum prices. The total public cost of purchasing the rights was calculated by capitalizing the annual equivalent cost of purchasing rights using the legal interest rate to be applied for the calculation of compensation for compulsory public purchase orders in Spain (2.65% for 2018).

Results and discussion

First of all, under the current policy scenario ('no intervention', second column in Table 2), the value of irrigated agricultural production is approximately 147 million €/y, generating an annual farm net margin of €52 million and agricultural employment equivalent to 4651 full-time jobs, out of a registered area population of 59,399 inhabitants in 2016 (INE, 2016).

The third column in Table 2 shows the implications of reallocating water among groundwater right holders through lease contracts in the 'no intervention' scenario. First, water trading would result in the mobilization of unused groundwater rights, which would increase water withdrawal from aquifers and irrigation water use (5.3%). As expected, water trading increases agricultural production (3.5%), farm income (1.2%) and on-farm labour (5.6%).

The fourth column in Table 2 shows the economic impact of eliminating non-renewable pumping by means of, for example, a reduction in water quotas. In the absence of alternative water resources, restricting extraction to the aquifers' recharge rate will have a large impact on the agricultural economy of the area, as non-renewable water withdrawal accounts for nearly two-thirds of the water available for irrigation. Specifically, if non-renewable pumping is to be eliminated by 2027, the irrigated area would be reduced by 60% with respect to the current area, reducing agricultural production by 81.5 million €/y (a 55.3% reduction), farm net margin by 26.7 million €/y (a 51.3% reduction) and agricultural labour by 2855 full-time-equivalent jobs (a 61.4% reduction) with respect to the current situation.

Water trading only slightly reduces the negative economic impact of restricting groundwater pumping (fifth column in Table 2). Gains from water trading are modest, 3% to 4.5% depending on the economic indicator considered. This is because the differences in the marginal value of water between right holders are small. The largest gains from water trading arise when users are heterogeneous and have different economic values for water (Calatrava & Garrido, 2005; Hadjigeorgalis, 2009; Pujol, Raggi, & Viaggi, 2006).

If non-renewable extraction is eliminated through the public buyback of groundwater rights, or any other policy instrument that could be considered, the economic impact would be the same in terms of irrigated area, agricultural production and employment and farm net margin, as the total volume of water used would be the same. However, in contrast to the case of the restricting of water quotas, the cost of balancing extraction and recharge would shift from farmers to the government. Table 3 presents the distribution of the cost of eliminating non-renewable pumping between farmers and

Table 2. Economic impact of eliminating non-renewable groundwater extraction in the Murcia Plateau under different policy scenarios.

	No intervention	No intervention with water trading	Without non-renewable pumping	Without non-renewable pumping but with water trading
Agricultural groundwater rights that correspond to renewable resources (Mm^3/y)	21.51	21.51	21.51	21.51
Groundwater rights that correspond to non-renewable resources (Mm^3/y)	45.00	45.00	45.00	45.00
Non-renewable pumping from agriculture (Mm^3/y)	41.52	45.00 (+8.38%)	0.00 (−100%)	0.00 (−100%)
Treated wastewater used for irrigation (Mm^3/y)	3.18	3.18	3.18	3.18
Total agricultural water use (Mm^3/y)	66.21	69.69 (+5.26)	24.69 (−62.71%)	24.69 (−62.71%)
Purchased water rights (Mm^3/y)	0.00	0.00	45.00	45.00
Volume of water traded (Mm^3/y)	0.00	10.99	0.00	6.10
Marginal value of water (€/m^3)	0.27	0.1985	0.65	0.68
Value of agricultural production (million €/y)	147.28	152.50 (+3.54%)	65.79 (−55.33%)	67.80 (−53.97%)
Farm net margin (million €/y)	51.99	52.62 (+1.21%)	25.30 (−51.34%)	26.46 (−49.11%)
Irrigated area (ha/y)	24,483	24,483 (0)	9,826 (−59.87%)	9,466 (−61.34%)
Agricultural employment (labour units per year)	4,651	4,910 (+5.57%)	1,796 (−61.38%)	1,860 (−60.01%)

Source: Own elaboration. Figures in parentheses are the proportional change with respect to the non-intervention scenario.

Table 3. Share of the public and private costs of eliminating aquifer overdraft in the Murcia Plateau through the public purchase of groundwater rights (under alternative calculation assumptions).

Calculation assumption	Indicator	No inter-vention	No intervention with water trading	Without non-renewable pumping	Without non-renewable pumping but with water trading
All rights are purchased at the market-clearing price (marginal value of water)	Unitary compensation for the purchase of rights (€/m^3 per year)*	–	–	0.65	0.68
	Public expenditure (million €/y)*	0.00	0.00	1985.25	30.60
	Farm net margin (million €/y)	51.99	52.61 (+1.19%)	25.30 (−51,34%)	26.46 (−49,11%)
	Farm net margin plus compensation (million €/y)	51.99	52.61 (+1.19%)	54.55 (+4.92%)	57.06 (+9.75%)
Compensation is calculated as lost farm net margin	Average compensation for the purchase of rights (€/m^3 per year)*	–	–	0.59	0.58
	Public expenditure (million €/y)*	0.00	0.00	26.69	26.15
	Farm net margin (million €/y)	51.99	52.61 (+1.19%)	25.30 (−51.34%)	26.46 (−49.11%)
	Farm net margin plus compensation (million €/y)	51.99	52.61 (+1.19%)	51.99 (+0.00%)	52.61 (+1.19%)

Source: Own elaboration. Figures in parentheses are the proportional change with respect to the non-intervention scenario.
*Compensation per m^3 and cost of the purchase of rights are expressed in terms of their annual equivalent cost.

the government under the two alternative assumptions considered for the calculation of the compensation for the purchase of water rights.

First, the compensation to farmers for selling their rights is estimated assuming that all rights are purchased at a price equal to the marginal value of water at the point where non-renewable pumping is eliminated (market clearing price). Under this assumption, as much as 0.65 €/m^3 per year should be paid to buy back enough water rights to eliminate unsustainable pumping rates in the aquifers. Note that, to allow comparisons, the price and cost of the buyback of rights are expressed in terms of their annual equivalent cost, not in terms of the single compensation to be paid to farmers, as in Martínez-Granados and Calatrava (2017). This cost is equivalent to the annual payment that should be given to farmers in compensation for stopping non-renewable extraction. As a result, the purchase of groundwater rights would increase farm net margin by 2.56 million €/y (4.9%) with respect to the 'no intervention' scenario. This happens because each water right, except the last one, is purchased for more than its marginal value. The annual equivalent cost in public expenditure would be 1985.25 million €/y. The total public cost of purchasing the rights would be €1104 million (capitalized value of the annual equivalent purchase cost). Water trading increases the marginal value of water from 0.65 to 0.68 €/m^3 per year, increasing the cost of purchasing groundwater rights. Water exchanges thus benefit farmers in two ways: increasing their income through trading and increasing the compensation required to make selling their rights a profitable option.

On the other hand, if the compensation to be paid to farmers for relinquishing their water rights is calculated as the lost farm net margin, the resulting average bid price is 0.59 €/m^3 per year. In this case, each water right is purchased at a price equal to its marginal value, and farmers are left as in the reference scenario (current situation). As a result, the cost in terms of public expenditure is significantly less than under the previous calculation assumption: 26.69 million €/y. The effect of water trading is not very significant. Under this second calculation assumption, the capitalized value of the cost of purchasing the rights is €1007 million. As mentioned, we think that the first estimate is more realistic, according to the Spanish legal procedure for launching public purchase offers. The real cost can be expected to be between the two estimates but significantly closer to the first one.

A previous study estimated the cost of agricultural water buybacks in the Segura River basin using a multi-attribute mathematical programming approach for model calibration (Pérez-Blanco & Gutiérrez-Martín, 2017). However, it is very difficult to directly compare its results with those presented here, as the authors did not link their results to specific environmental objectives (e.g. increasing river flows, or reducing groundwater extraction) or specific areas of the basin. Instead, they computed the total cost of different levels of water buybacks for the whole basin, without differentiating between types of water resources or areas. Nevertheless, their average results and model calibration parameters suggest that their results might be of a similar magnitude to ours.

Conclusions

The Murcia Plateau, in the south-eastern Segura basin of Spain, is one of the most severe cases of aquifer overdraft across Europe. Water users in this area are almost exclusively served from groundwater sources. The increased use of groundwater since the 1980s, together with the decline in the rates of aquifers' recharge, has severely depleted the aquifers in this area. Against other command-and-control policy measures, such as outright restrictions on withdrawals, one of the alternatives used in Spain to face this problem is the public buyback of groundwater rights. In this study, we assessed the economic impact of stopping non-renewable groundwater pumping in the Murcia Plateau through a public water rights purchase offer in terms of agricultural activity and employment and public expenditure.

Regardless of the policy instrument used to reduce agricultural groundwater use, and in the absence of alternative resources, eliminating non-renewable water withdrawal from the Murcia Plateau aquifers will have a large economic impact on its farming sector. The studies by Martínez-Granados and Calatrava (2014, 2017) and Martínez-Granados (2015) showed that the availability of desalinized seawater would partly offset the economic losses caused by the elimination of aquifer overdraft in the Guadalentin basin, also located in the Segura basin. In the Murcia Plateau, where aquifers are the main source of irrigation water and no alternative resources are available, it is virtually impossible to comply with the environmental objectives set for 2027 without causing severe damage to the agro-food sector. In this case, water markets only provide modest gains from trade and barely mitigate the impact of reducing groundwater pumping.

Despite its high cost for the public budget, the public buyback of groundwater rights permanently solves the problem without reducing farmers' income, as they are compensated for relinquishing their rights. However, it still has the same notable impact as the ban on non-renewable pumping in terms of lost agricultural production and employment. The difference is that in the former case the cost of reducing withdrawal is borne by the public budget, while in the latter it is borne by farmers. The complete restriction of non-renewable pumping is obviously a very unpopular and potentially conflictive measure that would have a large political cost. The success of any water policy largely depends on the cooperation of the affected users (Marchiori et al., 2012), who in this case would be more likely to accept the option of the public buyback. Moreover, experiences in other Spanish basins suggest that it is unlikely that groundwater pumping could be restricted without compensating right holders (Esteban & Albiac, 2011; Garrido et al., 2013).

However, the estimated cost for the public budget (about €1000 million) is very large and probably unaffordable. To adequately frame the above figure, consider that, during the 2000s, the Spanish government allocated a total of €800 million in the Upper Guadiana aquifer, where agriculture is far less profitable than in the Segura, to reduce extraction by 200 Mm^3/y (Law 13/2008). Despite the advantages of water buybacks, it is not realistic to think of it as the only solution for aquifer overdraft in the study area. An intermediate solution could combine some restrictions on pumping with some degree of public purchase of rights to split the cost between the farmers and the public budget and mitigate the economic impact of restricting non-renewable extraction, which is the policy objective.

Major limitations of the presented analysis are those inherent in the methodology used for the economic assessment of water use in agriculture. However, these are compensated by the sound level of accuracy that they allow for a basin-scale assessment and by the use of official hydrologic and ad hoc developed economic data at the local level. The methodology used in this study can be easily applied in other similar geographical contexts.

This study raises some issues for future research. First, it must be taken into account that the economic impact of aquifer recovery goes beyond agricultural production, due to multiplier effects. As in many rural areas in south-eastern Spain, in the Murcia Plateau there is tight integration between agricultural production and the food industry, especially with the wine industry, which is protected under two Protected Designation of Origin brands. Also, a large share of the employment in the area is directly or indirectly linked to agricultural production. On the other hand, the environmental benefits of recovering the aquifers have not been considered. The environmental benefit considered is the reduction in non-renewable groundwater withdrawal, which is the environmental indicator used by the SRBA. But it must be noted that the spatial distribution of environmental assets may not coincide with the distribution of water rights (Crase et al., 2012), and thus the environmental benefits may not be directly correlated with the volume of water purchased (Garrick et al., 2009). Similarly, groundwater trading alters the spatial distribution of extraction points, which may have relevant environmental impacts (Skurray & Pannell, 2012).

Second, a relevant issue in the design of water buybacks is the possible interaction with other water policies (Marchiori et al., 2012). Third, in this study we assumed a comparative statics approach, as our aim was to assess the economic impact and the public cost of eliminating non-renewable extraction in the area of study. However, aquifer management is dynamic. Reduction in groundwater withdrawal has consequences for the water table level and the pumping costs that would require a dynamic modelling approach (Kahil et al., 2016; Koundouri, Roseta-Palma, & Englezos, 2017), should the aquifer dynamics be relevant to the study objectives. Fourth, climate change projections include a notable reduction of renewable water resources in south-east Spain (Calatrava, García-Valiñas, Garrido, & González-Gómez, 2015), which is likely to exacerbate the aquifer depletion problem and increase the cost of addressing it. Last, although the preferred option for policy-makers is still to provide alternative external resources to the area, these resources have not been identified. An assessment of possible alternatives and the cost of making them available in the Murcia Plateau would allow comparison with other policy measures such as the ones assessed in this study.

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