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Optimisation of water procurement decisions in an irrigation district: the role of option contracts*

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Water supply instability is one of the main risks faced by irrigation districts and farmers. Water procurement decision optimisation is essential in order to increase supply reliability and reduce costs. Water markets, such as spot purchases or water supply option contracts, can make this decision process more flexible. We analyse the potential interest in an option contract for an irrigation district that has access to several water sources. We apply a stochastic recursive mathematical programming model to simulate the water procurement decisions of an irrigation district's board operating in a context of water supply uncertainty in south-eastern Spain. We analyse what role different option contracts could play in securing its water supply. Results suggest that the irrigation district would be willing to accept the proposed option contract in most cases subject to realistic values of the option contract financial terms. Of nine different water sources, desalination and the option contract are the main substitutes, where the use of either depends on the contract parameters. The contract premium and optioned volume are the variables that have a greater impact on the irrigation district's decisions.

Key words: Segura Basin, stochastic recursive programming, water markets, water supply option contract, water supply risk.

1. Introduction

Water supply uncertainty results from climate variations that affect water resources availability and reduce agricultural production. In water-scarce areas, hydroclimatic uncertainty is also costly in terms of irrigation decision efficiency (Griffith *et al.* 2009). Very often farmers have to make crop and management decisions without knowledge of how much water will be available in the season (Calatrava and Garrido 2005a; Iglesias *et al.* 2007).

Irrigation district boards in water-scarce areas aim not only to efficiently distribute water to their members but also to manage water supply risks. For

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example, Mesa-Jurado *et al.* (2012) found that farmers in southern Spain would be willing to increase the water tariffs they pay from 10 to 20 per cent, as well as accept a 30 per cent reduction in their average water supply concession in return for increased water supply reliability.

A well-defined water planning strategy can help irrigation districts' boards to reduce both water delivery risks and procurement costs. According to Kidson *et al.* (2013), water supply reliability increases with access to a pool of resources. Previous research (some applied to Australian cases) has demonstrated that a water planning portfolio that considers option contracts and/or spot purchases can reduce costs and risks for an urban water supply agency (Michelsen and Young 1993; Jenkins and Lund 2000; Gómez-Ramos and Garrido 2004; Characklis *et al.* 2006; Page and Hafi 2007; Byrnes *et al.* 2009; Kirsch *et al.* 2009; Leroux and Crase 2010), for environmental purchases (Hafi *et al.* 2005; Hollinshead and Lund 2006) and for irrigation districts (Calatrava and Garrido 2005b).

Voluntary water exchanges among users reduce risk exposure (Easter *et al.* 1998), providing flexibility and water supply reliability in the face of hydrological uncertainties (Calatrava and Garrido 2005a,b; Bjornlund 2006; Cheng *et al.* 2011). In Spain, agricultural water right holders often rely on different strategic water sources to deal with scarcity situations, including groundwater, spot water markets and, more recently, desalinated sea water. Here, we focus on the role of water supply option contracts as an alternative to other water sources for irrigation districts.

Water supply option contracts give the holder the right (not the obligation) to buy or sell the underlying asset (Williamson *et al.* 2008; Cui and Schreider 2009; Cheng *et al.* 2011). They have a greater potential for reducing risks than spot purchases as they lower the supply and price uncertainty risks for both buyers and sellers of water (Howitt 1998; Hollinshead and Lund 2006; Brown and Carriquiry 2007; Ranjan 2010). Besides, option contracts allow the holder to put off water purchase decisions until more information is available (Characklis *et al.* 2006; Kasprzyk *et al.* 2009). By giving the right holder the entitlement to access additional water resources in drought years, water supply option contracts are a potential cost-minimising strategy for managing water supply variability (Michelsen and Young 1993; Gómez-Ramos and Garrido 2004).

Despite all their advantages, option contracts have attracted more interest within academia than practical implementations. However, option contracts have been used to a degree in the water markets of several countries. In the USA, water options have been used in Colorado, California and Texas, generally contracted by urban water agencies to augment water supplies in drought conditions (Hafi *et al.* 2005; Hansen *et al.* 2008; Tomkins and Weber 2010; Hansen *et al.* 2014).

Water option contracts with agricultural users have been proposed in Australia to meet urban (Page and Hafi 2007) and environmental demands (Heaney *et al.* 2004; Hafi *et al.* 2005) during drought periods. Nonetheless, water options have received limited attention in Australia, often on the ground that they will eventually be implemented when the water market expands and matures (Leroux and Crase 2010), and current trading practice has not grown to develop option mechanisms. The separation of water use rights and entitlements and the existence of water rights with different reliability levels may have provided some risk-transfer potential and partially substituted options as a risk management mechanism.

Despite this, there is growing interest in Australia in the potential for more flexible trading mechanisms involving the development of secondary markets, such as option contracts and derivatives, which are one of the instruments proposed by the Australian Government (NWC 2013). According to Schreider (2009), the introduction of option contracts in the Australian water market would have both positive and negative impacts, and this should be taken into account when they are implemented.

Although water option contracts do not currently exist in Spain, they have been previously evaluated for urban supply by Gómez-Ramos and Garrido (2004) and Cubillo (2010), among others. There have also been a couple of recent trading experiences between users in the Tagus and Segura basins, which have some features in common with water option contracts. As the most water-stressed areas in Spain meet the conditions identified by Michelsen and Young (1993) for water supply option contracts to function, they are, after recent legal changes, likely to be an attractive risk management alternative for irrigation districts.

The aim of this study was to analyse the potential of an option contract for securing water supply for an irrigation district[1] that has access to different water sources but is subject to a high degree of uncertainty. We present an original stochastic recursive mathematical programming model that determines the optimal water procurement program of an irrigation district in a context of water supply uncertainty. The analysis focuses on decisions to enter into and exercise option contracts in interaction with other supply alternatives. The model is applied to a large irrigation district in south-eastern Spain, one of the driest and most arid regions of Europe.

The article is organised as follows. Section 2 describes the case study. Section 3 contains a description of the proposed option contract. Section 4 presents all the specifications of the optimisation model. Section 5 reports the model results. Section 6 outlines the main conclusions of this research.

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[1] Spanish irrigation districts operate like water users associations. Farmers belonging to a district share a common water right (or rights when the district has access to more than one source of water). Irrigation districts manage more than two-thirds of irrigation water in Spain. The irrigation district's boards are responsible, among many other things, for water purchasing decisions. In this article, all references to decisions made by the irrigation district should be construed as decisions made by the district's water management board. However, our analysis is equally applicable to a single farmer choosing between a set of available sources of water supply.

2. Case study and data collection: the Lorca irrigation district

The optimisation model is applied to the Lorca irrigation district in the Segura Basin (south-eastern Spain, Figure 1), one of the most water-stressed basins in Europe (EEA (European Environment Agency) 2009). This irrigation district is located in the valley of the Guadalentín River, a major tributary of the Segura River. It comprises an area of 12,116 hectares and has 8300 farmers, whose farm size is mostly relatively small. It stands as one of the largest and most productive irrigation districts in Spain. Farmers grow primarily high-value horticultural crops, such as lettuce, artichoke and broccoli.

Traditionally, irrigated areas were supplied with scarce and highly variable surface resources, which were allocated to farmers through auctions. With the intense development of groundwater use and the Tagus-Segura Transfer (TST), the irrigated area was enlarged, new distribution infrastructures were built and the water allocation system changed from an auction-based mechanism to a per-hectare proportional rule.[2] The TST serves a large share of the district's water needs but is subject to a high degree of interannual variability. At the same time, groundwater resources are becoming increasingly scarce. This increasingly risky scenario has driven the district's board to search for additional sources to secure water supply for farmers.

Currently, the Lorca irrigation district has access to a range of nine different water sources (Table 1). This portfolio has broadened as new water supply sources became operational. The most recent additions are desalinated

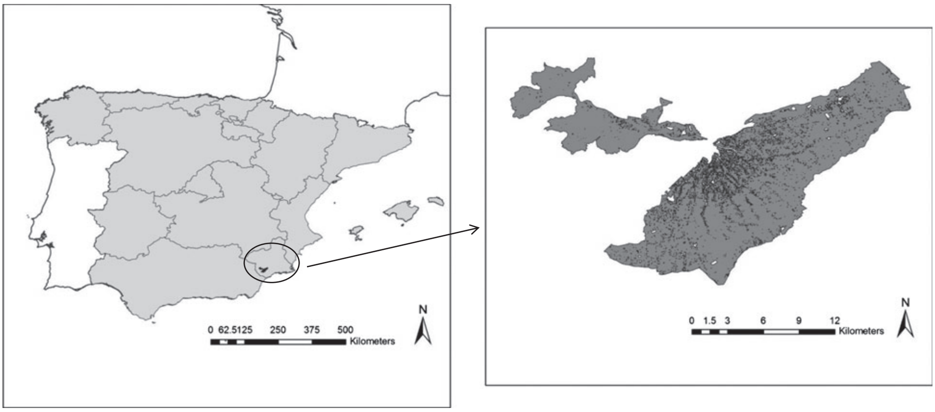

Figure 1 Location of the Lorca irrigation district

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[2] Under the proportional water allocation rule, water entitlements are defined as the share of available water supplies (Brennan and Scoccimarro 1999; Freebairn and Quiggin 2006). In Spain, water allotments are predominantly set according to the proportional allocation doctrine by granting all irrigators the same volume per irrigated hectare (Calatrava and Garrido 2005a).

Table 1 Current water supply sources for the Lorca irrigation district

Water source	Characterisation of water availability	Water available to the district (hm^3/year)				Water effectively used by the district (hm^3/year)	
		Volume set in the concession	Minimum	Average	Maximum	Average	Maximum
'Puentes' reservoir	Variable	14	3.68	6.42	9.34	6.42	9.34
Tagus-segura transfer	Variable	29.06	1.31	18.25	36.85	18.25	36.85
Segura basin regulation system	Variable	4.20	0.73	2.20	5.19	2.20	5.19
District's own wells	Freely available up to a maximum value	10.4	–	–	10.40 (3†)	3‡	4.40‡
Wastewater treatment plant	Freely available up to a maximum value	2.50	0.62	2.15	2.0	2.15	2.30
'Aguilas' desalination plant	Freely available up to a maximum value	8	8	8	8	0§	0§
Purchase from private wells	Freely available up to a maximum value	–	–	–	8.20	7.40†	8.20
Basin authority's drought wells	Only available in drought periods	–	–	1.17	1.17	1.17	1.17
Interbasin spot purchases	Only available in drought periods upon authorisation	–	–	2.03	2.03	2.03	2.03

Source: Author calculations based on information provided by the irrigation district.

†According to the district, maximum availability has declined over the last 20 years and is currently three hm^3/year.

‡In the past 10 years.

§There is no historical water use record because these resources have only been available since 2013.

sea water, intermittent use of groundwater (the so-called drought wells[3]), treated wastewater, and spot interbasin water purchases from the Tagus Basin.

For the water availability characterisation, we rely upon data provided by the district's board. Our initial database contains annual irrigation district water availability from each water source for the 1994–2012 period. This period includes two drought episodes (1994–1995, 2005–2008). Our water sources database has been processed to build data series that represent the current water availability situation for the district.

Surface water resources come from the following: (i) a concession[4] of 14 hm^3 per year from the 'Puentes' Reservoir; (ii) a 29.06 hm^3/year concession from the TST; and (iii) a 4.2 hm^3/year concession from the Segura River Regulation System. The original data consist of annual water availability series from each source that have been detrended, as necessary, to produce a stationary series. These three series exhibited a significant ($P < 0.05$) downward trend, illustrating how the availability of water resources for the Lorca irrigation district has decreased over time. In practice, average water availability values from each source are below the water volume set in the concession (8, 18.25 and 1.58 hm^3/year, respectively, according to Table 1).

Groundwater resources are an important source of water for this irrigation district. Groundwater data include annual extraction series from each source. The original series have also been detrended (all are significantly downward, $P < 0.05$). Pumped volume increases in dry years but decreases in wet years with more surface water availability. For this reason, we have not characterised groundwater availability as stochastic; instead, we have considered the maximum value as the maximum water volume that the irrigation district can currently use from each source according to the district's own availability estimates.

Regarding unconventional resources, the Lorca irrigation district has a concession of 2.5 hm^3/year from the local wastewater treatment plant and, since 2013, another concession of up to 8 hm^3/year of desalinated water from a coastal sea water desalination plant.

During drought periods, other relatively minor water sources are available. First, the Segura River Basin Authority has developed a strategic set of drought wells used only in scarcity situations to guarantee supply to small municipalities and provide some water for irrigated areas. The irrigation

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[3] Each basin in Spain has a drought management plan. This plan determines all the actions aimed at reducing the impacts of the drought period (Estrela and Vargas 2012), including drought wells: wells owned and managed by the river basin authority that can be used during drought periods in order to meet water users' most urgent needs (e.g. emergency water applications to tree crops).

[4] Water volumes in this article are expressed in cubic metres (m^3) and hectometres (hm^3). One cubic metre is equal to a thousand litres; 1 million cubic metres (1 hm^3) is equal to a thousand megalitres (ML).

district received an average of 1.17 hm^3/year, with slight variations, during the last drought period (2005–08). Secondly, legislative changes during that period allowed for interbasin water exchanges in drought periods through the water market (Garrido *et al.* 2012). Together with the other agricultural water users of the TST, the Lorca irrigation district participated in an interbasin program to purchase water from users in the Tagus Basin. This program was renewed annually throughout the 4 years of the above drought period (the Lorca irrigation district received 2.034 hm^3 each year). After the redefinition of the TST operating statute and rules[5] in 2013, option and spot contracts across basins can be approved. Our model assumes that drought wells and interbasin spot purchases are available to the district when water availability from the TST is below a certain threshold.

To characterise water supply uncertainty, we use the above characterisation of water availability and consider each of the 19 years spanning 1994–2012 as a single state of nature with an equal probability of occurrence.

The Lorca irrigation district is exposed to a high variability of available water. The black line (Figure 2, right axis) shows total water availability under each state of nature. Bars represent the percentage share of each water source in the total water volume for each scenario. Note that TST is the main

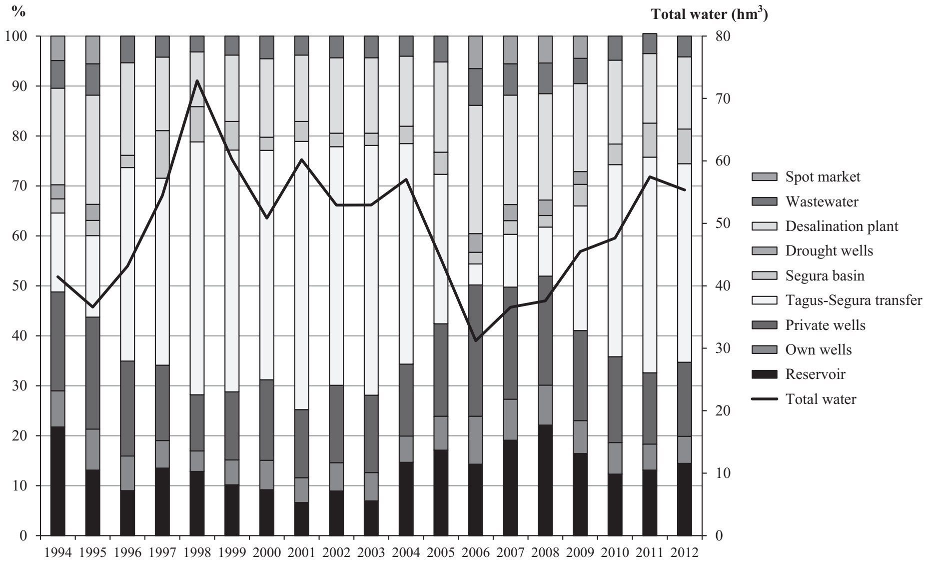

Figure 2 Characterisation of Lorca irrigation district's current water availability from each source (hm^3) under each state of the nature

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[5] Apart from modifying the TST management rules, one of the aims of the Memorandum of Understanding on the Tagus-Segura Transfer (2013) is to make exchanges of water rights using the Tagus-Segura Aqueduct infrastructure more flexible and efficient. This memorandum was included in the Spanish Environmental Impact Assessment Law (Law 21/2013), which is available in Spanish at https://www.boe.es/boe/dias/2013/12/11/pdfs/BOE-A-2013-12913.pdf.

Table 2 Current water prices for each water source paid by the irrigation district (€/m^3; distribution costs not included)

Water source	€/m^3
'Puentes' reservoir	0.100
Tagus-segura transfer	0.127
Segura basin regulation system	0.100
District's own wells	0.140
Purchase from private wells	0.253
Wastewater treatment plant	0.100
'Aguilas' desalination plant	0.450
Segura river basin Authority's drought wells	0.270
Interbasin spot purchases from the Tagus	0.205

Source: Author calculations based on information provided by the irrigation district.

water source in 14 out of the 19 considered states of nature (from 29 to 53 per cent), but it is also the major source of variability. With reduced deliveries from the TST, the irrigation district would rely more on desalinated water and purchases from private wells.

Facing this set of possible scenarios (hydrological years), the Lorca irrigation district will have to decide how much water to use from which sources, taking into account the available water from stochastic sources and water prices (shown in Table 2).

These prices are quite stable over time. Desalination is by far the most expensive water source in the pool. If the objective of the irrigation district were to minimise water procurement costs, the strategy would be to purchase water from the cheapest to the most expensive water until the irrigation district's water needs are fulfilled. However, cost must be weighed against reliability.

3. Proposed water option contract

Several examples of water option contract schemes, with different features and conditions, can be found in the literature. Michelsen and Young (1993) first proposed water option contracts in dry years, transferring the water from agricultural users to urban water suppliers. Researchers such as Hafi *et al.* (2005), Page and Hafi (2007), Byrnes *et al.* (2009) and Leroux and Crase (2010) later applied the water option contracts valuation method that Michelsen and Young (1993) developed.

Jenkins and Lund (2000) studied the potential of the use of dry-year option contracts in combination with other water supply reliability strategies for an urban water supplier to acquire water during water scarcity periods. Kirsch *et al.* (2009) worked on the optimisation of long-term (10-year) water supply portfolios, evaluating multiyear option contracts which provide the holder with year-to-year flexibility, while still offering long-term contractual security without annual renegotiations. Gómez-Ramos and Garrido (2004) evaluated 18 different four-year option contracts between an urban supply agency and an irrigation district in Spain with different volumes and triggering conditions. In our research, the proposed option contract aims at reducing the risk faced by an irrigation district in terms of water availability.

The proposed option contract is intended to provide another flexible water source to reduce irrigation district supply risk. This contract would give the irrigation district access to the optioned volume at the maturity date in return for payment of the exercise price to the seller. As defined in this study, the option holder could acquire all or part of the optioned volume at the maturity date. In return for the right to purchase this volume, the irrigation district would have to pay the seller an annual premium.

The option contract is a two-stage scheme. In the first stage, assuming there is an interested counterparty, the irrigation district would have to decide, based on the irrigation district manager's risk preferences and water supply reliability, whether to sign the contract to protect against the water supply uncertainty to which it is exposed. In the second stage, when the supply is no longer uncertain, and provided the contract trigger condition is met, the irrigation district would have to decide whether to exercise the previously contracted option.

Most examples of optioning water rights are subject to a condition or trigger. The trigger is an external condition that should be met in order to exercise the option. In this particular case, the trigger is related to the water volume received through the TST. When the volume is below the set threshold, the irrigation district could exercise the option. The reason behind the choice of this trigger is that the TST is the main water source for this irrigation district, and it is a good indicator of the irrigation district's potential water availability in a given year. The rationale of using a trigger is to ensure that the other party to the contract uses the water when there is a normal or abundant supply (Gómez-Ramos and Garrido 2004; Hafi *et al.* 2005; Leroux and Crase 2010). It thus works as a risk-transfer mechanism between two water users with different supply reliability needs or risk aversion levels.

4. Optimisation model

An optimisation model has been formulated to analyse the Lorca irrigation district water procurement decisions. The objective function of the model minimises the irrigation district's water procurement costs in order to meet the water requirements of irrigators, taking into account availability and cost of each water source. The model yields the optimal water procurement strategy, including the possible signing of an option contract.

It is a two-stage recursive stochastic model. In the first stage, when there is uncertainty regarding water availability, the irrigation district has to decide whether or not to sign the option contract. In the second stage, when the available volumes from each source are known, the model identifies the optimal water sourcing strategy, including the decision on whether or not to exercise the option (if contracted in the first stage and if the trigger condition holds) and acquire the optioned volume.

In order to assess the benefits derived from the existence of the option contract in the water source pool, we have also considered the case when the option contract for water is not available. This is the baseline scenario used to compare the costs and the water reliability with and without an option contract in the pool of water sources.

4.1. First-stage stochastic decision model

The decision variables are as follows:

Q: binary variable (0 when the irrigation district decides not to sign the option contract, 1 otherwise)

$W_{i,k}$: water used by the irrigation district from each water source in each state of nature (hm^3).

The first-stage decision is modelled as follows:

$$\min C = \sum_i \sum_k ((P_i \times W_{i,k} + \mathrm{OP} \times A_{\mathrm{opt,k}} \times Q)\mathrm{Prob}_k), \tag{1}$$

subject to:

Water needs (the target water volume required by the district):

$$\sum_i \sum_k (W_{i,k} \times \mathrm{Prob}_k) \geq N \tag{2}$$

Water use constraint (the irrigation district cannot use more water than is available):

$$W_{i,k} \leq A_{i,k} \tag{3}$$

Water use constraint for the option contract (the trigger must be met for the option holder to acquire the optioned volume):

$$W_{\mathrm{opt,k}} \leq A_{\mathrm{opt,k}} \times Q \quad \text{if } A_{\mathrm{TST,k}} < T \tag{4}$$

$$W_{\mathrm{opt,k}} = 0 \quad \text{if } A_{\mathrm{TST,k}} \geq T$$

Non-negativity constraint:

$$W_{i,k} \geq 0 \tag{5}$$

C is the total water procurement cost for the irrigation district (€ million) with:

i (1,. . .,10): water source (all water sources shown in Table 1, plus the option contract), where the subscript ‘opt’ refers to the option contract; ‘TST’ refers to the water volume that comes from the Tagus-Segura Transfer;

k (1,…,19): states of nature, where each year spanned by the database (1994–2012) is considered as a state of nature[6], $k = 1$ is the state of nature with the lowest water availability, and $k = 19$ the one with the highest water availability for this irrigation district,

and the parameters are as follows:

P_i: price of each water source (€/m^3)
OP: option contract premium (€/m^3)
$A_{i,k}$: maximum water availability for each water source in each state of nature (hm^3)
Prob$_k$: probability of each state of nature, all of which have the same probability of occurrence (1/19)
N: irrigation district water needs (hm^3)
T: option contract trigger (hm^3).

4.2. Second-stage deterministic decision model

Based on the first-stage decision (whether or not to sign the option contract), the second-stage model defines the optimal water procurement decisions for each state of nature. In this stage, decisions are made when water availability is no longer uncertain.

The first-model decision variable Q is introduced into this second-stage model as a parameter ($R = Q$). The objective function is

$$\min C = \sum_i \sum_k (P_i \times X_{i,k} + \mathrm{OP} \times A_{\mathrm{opt,k}} \times R), \tag{6}$$

where X_i is the water volume obtained from each source for each state of nature,
s.t.:

$$X_{i,k} \le A_{i,k} \tag{7}$$

$$\sum_i X_{i,k} \ge N \tag{8}$$

$$X_{\mathrm{opt,k}} \le A_{\mathrm{opt,k}} \times R \qquad \text{if } A_{\mathrm{TST,k}} < T$$

$$X_{\mathrm{opt,k}} = 0 \qquad \text{if } A_{\mathrm{TST,k}} \ge T \tag{9}$$

$$X_{i,k} \ge 0. \tag{10}$$

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[6] The years spanned by the original database (1994–2012) have been reordered based on water availability: $k1$ (2006); $k2$ (2007); $k3$ (1995); $k4$ (2008); $k5$ (1994); $k6$ (1996); $k7$ (2005); $k8$ (2009); $k9$ (2010); $k10$ (2000); $k11$ (2002); $k12$ (2003); $k13$ (1997); $k14$ (2012); $k15$ (2004); $k16$ (2011); $k17$ (2001); $k18$ (1999); and $k19$ (1998).

4.3. Baseline model

If we do not consider the option contract, the decisions are all made at once for each state of nature. There is no uncertainty related to water availability.

$$\min C = \sum_i \sum_k (P_i \times W_{i,k}) \tag{11}$$

s.t:

$$W_{i,k} \leq A_{i,k} \tag{12}$$

$$\sum_i W_{i,k} \geq N \tag{13}$$

$$W_{i,k} \geq 0, \tag{14}$$

where $W_{i,k}$ is the water volume obtained from each source i in each state of nature k.

The optimal solution was yielded by mixed integer programming using GAMS (General Algebraic Modelling System).

4.4. Parameterisation of the option contract

A wide range of parameters (premium, exercise price, optioned volume and trigger) have been used to assess the conditions that make the option contract an attractive supply source for the district.

The average parameter values were obtained from records of previous trading experiences involving irrigators in the Segura Basin (Garrido *et al.* 2012). We tried to consider a realistic set of values, taking into account that there are no previous water option contract experiences.[7] Water prices in formal lease contracts in the Segura Basin are within the range of 0.03 to 0.30 €/m^3, whereas prices in interbasin trading during the last drought period were 0.21 €/m^3. In total, we examined 375 cases, combining five exercise price levels, five premium levels, five contracted volumes and three triggers (Table 3).

As the objective of the model is to yield the required water volume at minimum cost, these parameterisations will influence the option contract costs and hence the irrigation district's water procurement decisions.

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[7] In Spain, water option contracts are not a common type of exchange, but there was one experience of a multiyear contract resembling an option contract between water users in the Tagus and the Segura basins during a drought period: *Canal de Estremera* irrigation district in the Tagus Basin and SCRATS (Central Association of Tagus-Segura Aqueduct Irrigators) in the Segura Basin signed a water trading contract for 31.05 million m^3/year that was renewed annually for 4 years. The average price was 0.21 €/m^3.

Table 3 Parameterisation of the option contract conditions (number of cases $5 \times 5 \times 5 \times 3 = 375$)

P_{opt} (€/m^3)	OP (€/m^3)	$A_{\text{opt},k}$ (hm^3)	T (hm^3)
0.06	0.02	3	10
0.12	0.04	6	15
0.18	0.06	9	20
0.24	0.08	12	–
0.30	0.10	15	–

P_{opt}: exercise price; OP: premium, $A_{\text{opt},k}$: optioned volume, T: trigger.

Figure 3 compares the total option contract price (in €/m^3, the premium plus the exercise price) with the prices of other water sources. The range of option contract parameters covers the whole spectrum of water prices from other sources. Desalinated water is the most expensive water source. Thus, the irrigation district would always prefer the option contract to desalinated water. However, desalinated water would be used when the option cannot be exercised because the trigger condition is not met or when the irrigation district needs more water.

Figure 3 shows that the cost-effectiveness of the option contract with respect to other sources is totally dependent on its economic parameters, and they, of course, depend on the willingness of the counterparty to enter into such an agreement.

5. Results

The analysis focuses on the decisions related to the option contract: whether the irrigation district would sign the contract in the first stage, whether the

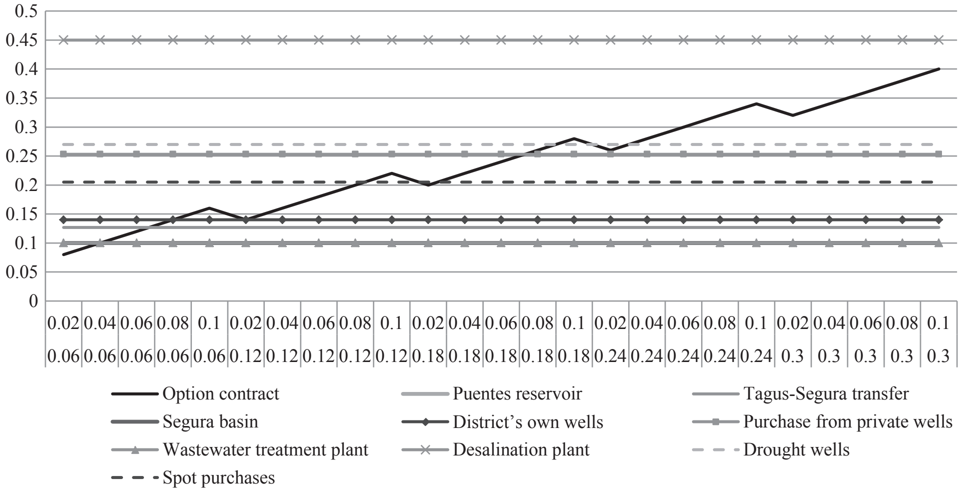


Figure 3 Water prices for the different water sources. For the option contract, all the parameterisations (€/m^3) of the premium (OP) and the exercise price (P) are taken into account

irrigation district would exercise the option (if previously contracted) and the circumstances determining both decisions.

5.1. First-stage decision results

At this stage, the irrigation district has to decide whether to sign the option contract (Q in the model). Whether or not the irrigation district would find the option contract to be an attractive option depends on its parameter values. The district will consider the possibility of not meeting its target supply with its water sources and will weigh the cost of purchasing the option against the relative cost of the alternative sources. Results show that the irrigation district would sign the option contract ($Q = 1$) in 48.3 per cent of the considered cases, taking into account all the parameterisations (see Figure 5).

Table 4 disaggregates the distribution of the optimal Q in all 375 possible cases, depending on the option contract parameter values. The premium and optioned volume are the parameters that will have most bearing on the decision to sign the contract. For high premium and optioned volume values, the irrigation district would not sign the contract because the costs of the contract would be higher than other available alternatives. There is a trade-off between the optioned volume and the contract premium. Greater optioned volumes require lower annual premiums for the district to enter into the option contract.

The decision to sign the option contract is analysed by means of logistic regression accounting for all 375 parameterisations. The results of this regression (Table 5) show what influence each parameter has on the decision to sign the option contract (binary variable; 0,1).

All the variables, except exercise price (associated P-value = 0.162), are statistically significant. The premium (€/m^3) and the option volume (hm^3/year) determine the costs of signing the option contract. This explains why the value of their coefficients is negative. On the contrary, a higher trigger increases the probability of signing the contract, as it makes it more appealing to the district's managers.

The marginal effects show the impact that a change in each variable has on the probability of signing the option contract. For example, if the trigger increases from 15 hm^3/year to 16 hm^3/year, ceteris paribus, the probability of purchasing the option increases by four per cent.

This logistic regression yields the average probability of signing the option contract depending on the parameter values. As shown in Figure 4, the probability for a premium of 0.02 €/m^3 is close to 90 per cent, dropping to <10 per cent when the premium is 0.1 €/m^3. For the highest premium (0.1 €/m^3) and the highest optioned volume (15 hm^3), the irrigation district would never sign the contract because of its high fixed

Table 4 Decision to sign the option contract depending on parameter values

Premium (OP) (€/m^3)	Price (P_{opt}) (€/m^3)	Optioned volume ($A_{\text{opt},k}$) (hm^3)														
		3			6			9			12			15		
		Trigger (T) (hm^3)			Trigger (T) (hm^3)			Trigger (T) (hm^3)			Trigger (T) (hm^3)			Trigger (T) (hm^3)		
		20	15	10	20	15	10	20	15	10	20	15	10	20	15	10
0.02	0.06	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	0.12	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	0.18	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	0.24	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	0.3	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
0.04	0.06	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	▨	□	□
	0.12	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	□	□
	0.18	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	□	□	□
	0.24	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□
	0.3	▨	▨	▨	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□
0.06	0.06	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□	□	□	□
	0.12	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□	□	□	□
	0.18	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□	□	□	□
	0.24	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□	□	□	□
	0.3	▨	▨	▨	▨	▨	▨	□	□	□	□	□	□	□	□	□
0.08	0.06	▨	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□
	0.12	▨	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□
	0.18	▨	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□
	0.24	▨	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□
	0.3	▨	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□
0.1	0.06	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□	□
	0.12	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□	□
	0.18	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□	□
	0.24	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□	□
	0.3	▨	▨	□	□	□	□	□	□	□	□	□	□	□	□	□

Grey: the irrigation district would sign the option contract ($Q = 1$).
White: the irrigation district would not sign the option contract ($Q = 0$).

Table 5 Logistic regression results for the contract decision (Q)

Explanatory variable	Coef.	SE	z	$P > \|z\|$	Marginal effects†
P_{opt}	−4.234	3.028	−1.40	0.162	−1.02
$A_{\text{opt},k}$	−1.682	0.344	−4.89	0.000	−0.40
OP	−278.430	53.028	−5.25	0.000	−66.76
T	0.168	0.065	2.58	0.010	0.040
Intercept	29.678	6.192	4.79	0.000	
Observations	375	–	–	–	–
Pseudo R^2	0.81	–	–	–	–
% of correctly classified	93.60	–	–	–	–
% of correctly predicted ‘0’	94.85	–	–	–	–
% of correctly predicted ‘1’	92.27	–	–	–	–

P_{opt}: exercise price; OP: premium, $A_{\text{opt},k}$: optioned volume, T: trigger.
†The marginal effect of each variable has been calculated by holding all other model variables at their means.

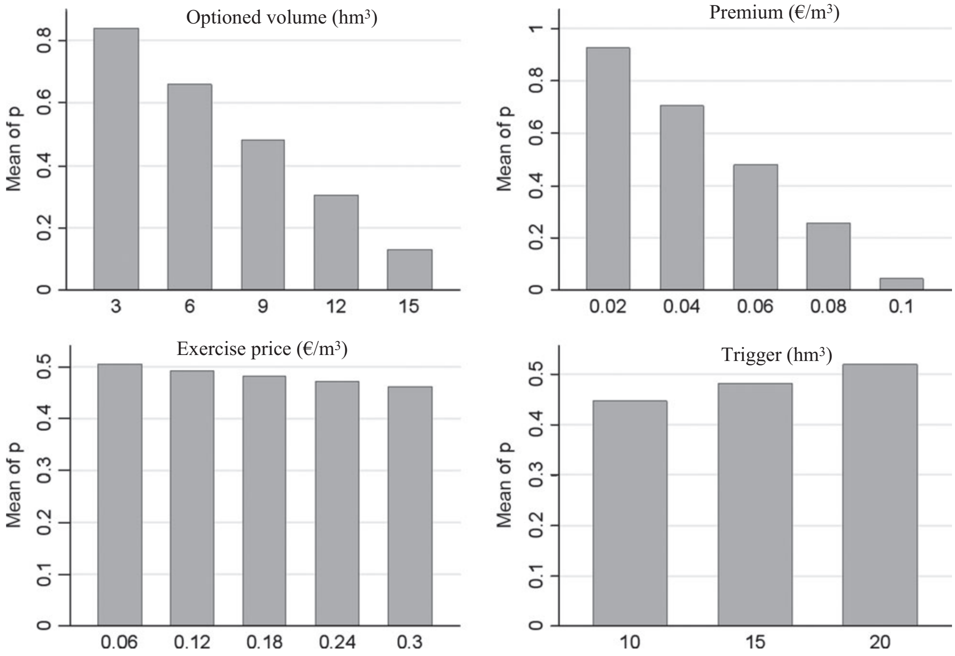


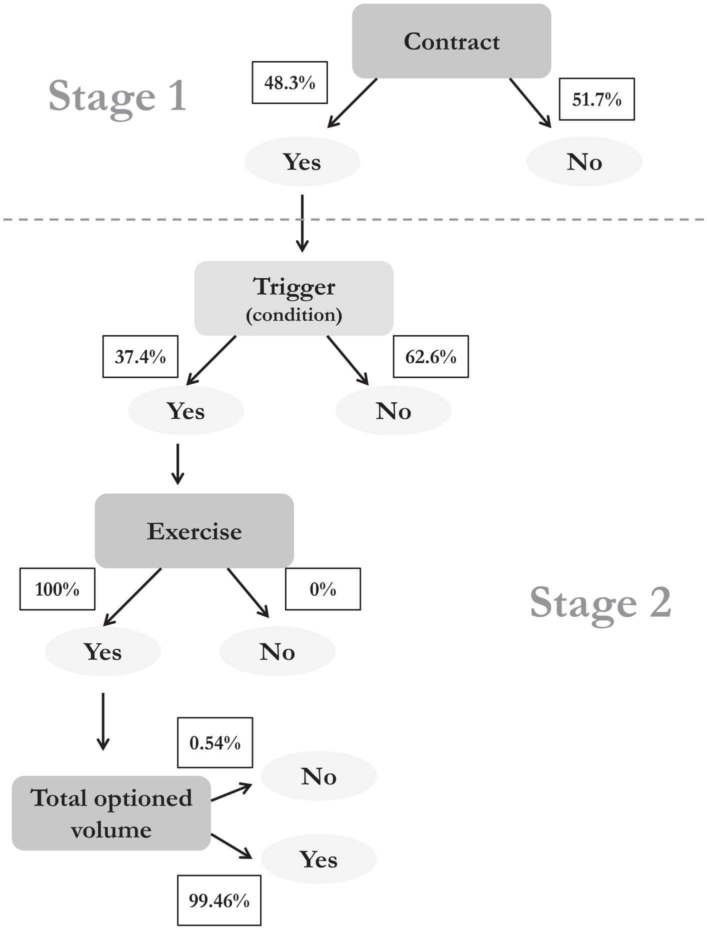
Figure 4 Average probability of signing the option contract for each parameter’s value

costs. Obviously, if the irrigation district has other alternatives and cheaper water sources, a contract with that premium will not be attractive. The conclusions regarding the optioned volume are similar. The exercise price will not have a significant impact on the probability of signing the contract.

5.2. Second-stage decision results

At this stage, the decision is taken in the absence of uncertainty. The irrigation district has to decide whether or not to exercise the option depending on the available water volume from other sources, that is, determined by the state of nature, *k*, and contingent on the trigger condition being met.

Our results show that, if the irrigation district signed the option contract in the first stage and if the trigger condition holds, the irrigation district would always exercise the option in the second stage. When the irrigation district exercises the option, the optioned volume is purchased in full in 99.46 per cent of the cases (see Figure 5). The probabilities of meeting each of the considered triggers (i.e. the probability of being able to exercise the option) are as follows: nine out of 19 states of nature for the 20 hm^3 trigger; seven out



Whether the trigger is met is not a decision of the ID, but a condition imposed by the option contract itself.

Figure 5 Option contract decision tree (all the parameterisations are taking into account to calculate the probabilities of each step)

Table 6 Comparison of water procurement costs and total water volume for the irrigation district with and without the option contract (average values for all possible states of nature)

Statistics	With option contract			Without option contract		
	Total volume (hm^3)	Total costs (million €)	Average Cost (€/m^3)	Total volume (hm^3)	Total costs (million €)	Average costs (€/m^3)
Mean	46.51	8.46	0.19	45.47	8.22	0.18
Standard deviation	5.13	1.14	0.04	6.04	1.00	0.04
Variation coefficient	0.11	0.14	0.19	0.13	0.12	0.20
5th percentile	36.57	6.26	0.13	31.20	5.90	0.12
25th percentile	43.59	7.60	0.15	41.45	7.39	0.15
Minimum	31.20	5.86	0.12	31.20	5.90	0.12
Maximum	50.00	12.54	0.27	50.00	9.51	0.25

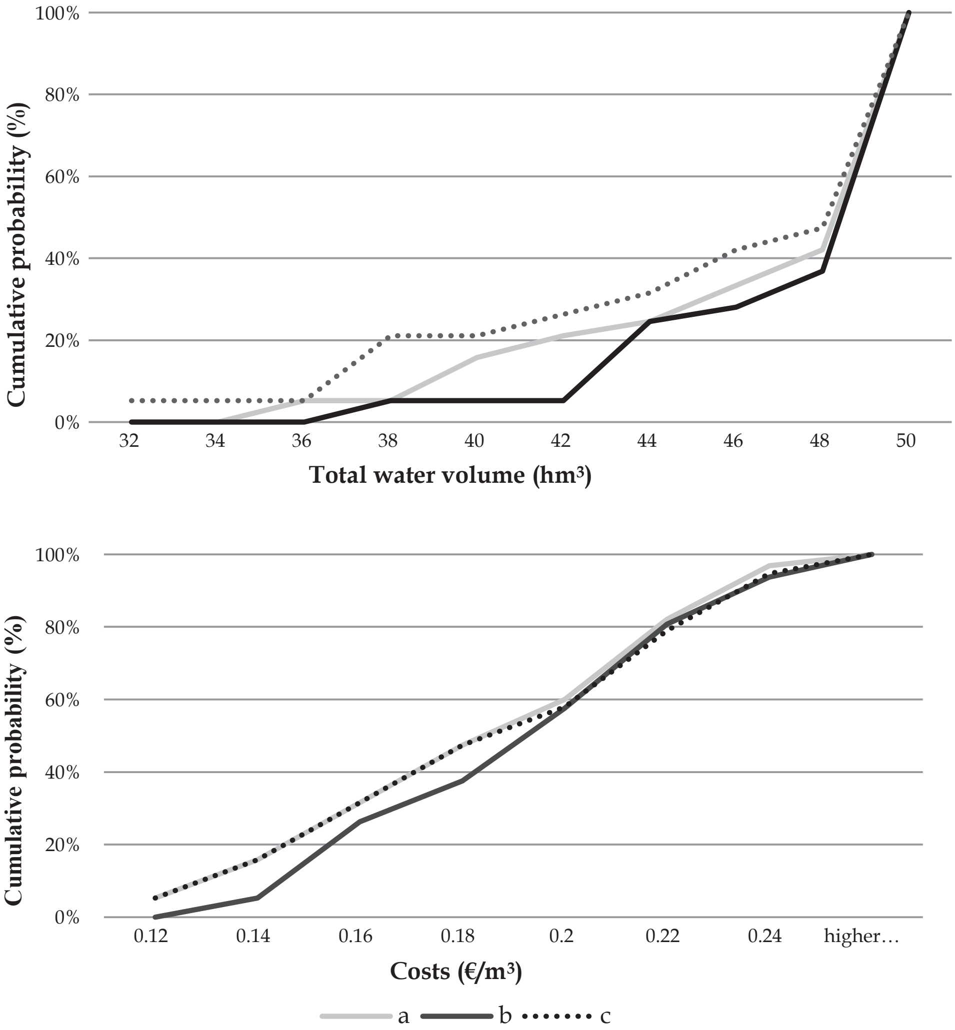
of 19 for the 15 hm^3 trigger; and five out of 19 for the 10 hm^3 trigger. For states of nature with high water availability ($k > 9$), none of these triggers are met because the water volume received from the TST is greater than 20 hm^3.

Table 6 reports the main statistics for the total costs and total water volume with and without the option contract (baseline scenario). If the proposed option contract is added to Lorca irrigation district's pool of water sources, average annual water availability increases slightly due to access to the optioned volumes. However, the biggest advantage of this contract is its risk-reduction effect. It reduces the water availability variation coefficient and the probabilities of the left tail of the water availability. Although the average effect is small, the impact is quite significant under scarcity situations. Water volumes for both the fifth and 25th percentile are greater with than without the option contract (see also Figure 6).

However, the irrigation district incurs costs by signing the option contract in the first stage and exercising the option in the second stage, which increase the total water procurement costs slightly (on average by 0.01 €/m^3).

Figure 6 shows the cumulative probability distribution of water use and unitary water cost for two specific option contracts and the baseline scenario. Figure 6 (top) shows that water availability is always lower without ('c') than with ('a' and 'b') the option contract. In the baseline scenario ('c'), the probability of meeting the irrigation district's water demand (50 hm^3) is lower than with the option (52 per cent without the contract, and 57 and 63 per cent for cases 'a' and 'b', respectively). Of the two scenarios with the option contract ('a' and 'b'), scenario 'b' gives the irrigation district access to more water under the contract, but the total costs for this water volume would be higher. Regarding the costs per m^3, scenario 'a' would have the lowest costs per m^3.

A relevant issue is the water volume that the irrigation district will obtain from each source. Specifically, we focus on which water sources are substitutes for each other, for example whether the water option contract is used instead of another water source, and vice versa.



a: premium= 0.02 €/m^3 and optioned volume =3 hm^3; b: premium = 0.06 €/m^3 and optioned volume = 6 hm^3; c: without contract.

Figure 6 Cumulative ascending probability distribution of total water volume (hm^3) and costs (€/m^3) in the irrigation district for three scenarios (a and b, with option contract; c without option contract)

Figure 7 shows that desalinated water and the option contract are substitutes. As the water volume specified in the option contract increases, the average volume of desalinated water purchased is reduced and substituted by water from the option seller. Average water volumes procured from groundwater sources (private wells and drought wells) are also reduced when the irrigation district has access to the largest optioned volume. However, this reduction only applies for total option prices <0.27 €/m^3 (the price of water from emergency drought wells). Table A1 (Appendix) shows more detailed

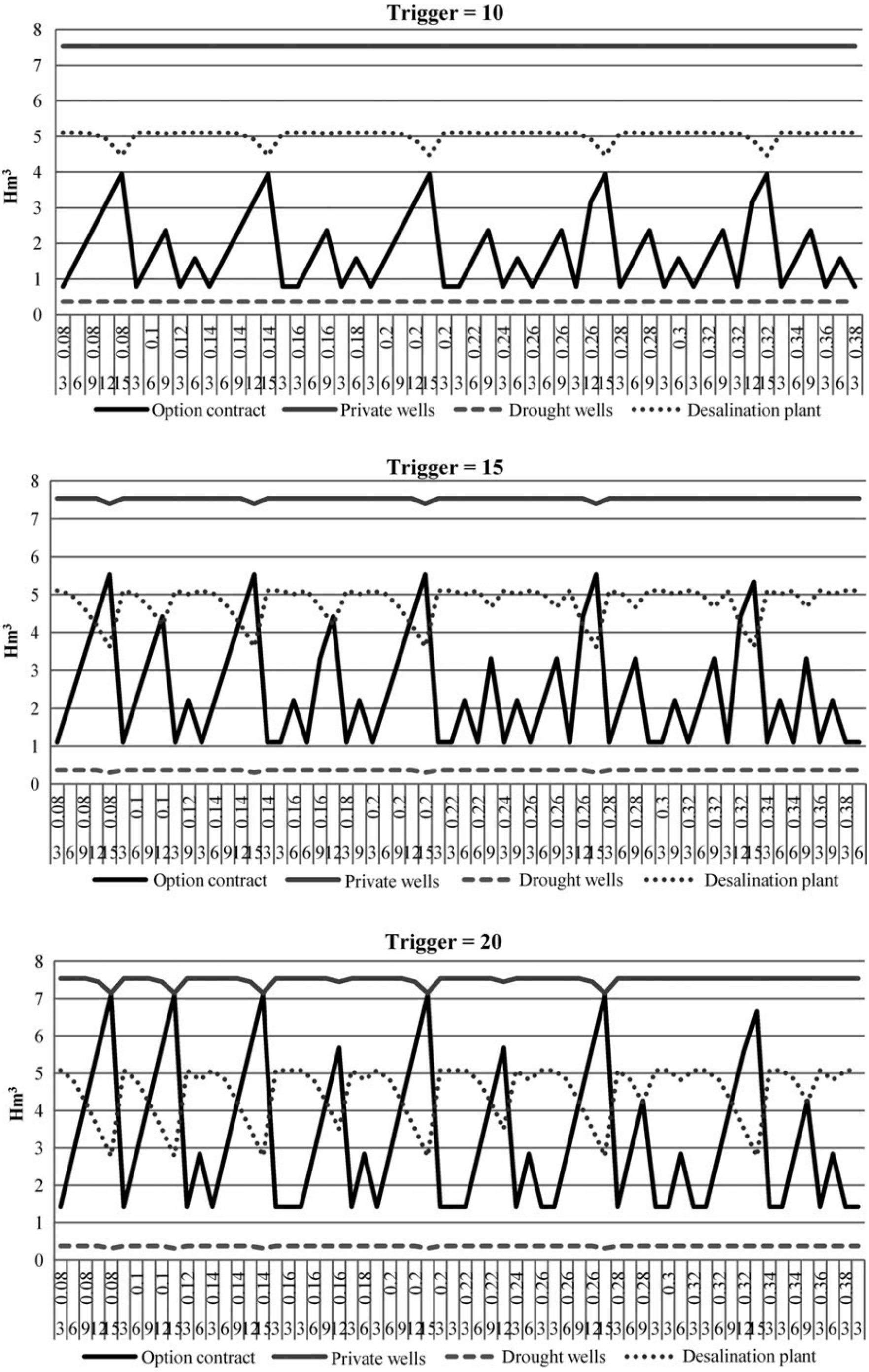


Figure 7 Water volumes from different sources, for each parameterisation of the option contract (only those cases when the option is signed are shown in the graph). Volumes represent the mean of the purchased volumes in the 19 states of nature (X-axis, unitary costs of the option contract (€/m^3) and optioned volume below (hm^3)).

results about the water volume procured from different sources for several states of nature. When the optioned volume is not available (because the trigger is not met or because the contract was not signed in the first stage), the irrigation district would purchase the maximum volume from the desalination plant (8 hm^3) (not shown in Figure 7).

6. Conclusions

Irrigators have to make key production decisions when there are uncertain prospects about how much water will be available during the season. Reducing this uncertainty improves farm planning and promotes economic efficiency. Collective organisations (irrigation districts or communities) manage water for more than two-thirds of the irrigated area in Spain (3.5 million hectares). Optimising water procurement decisions can help irrigation districts to reduce costs and water availability risks and improve the efficiency of their growers. We have developed a model to represent the water procurement decisions of an irrigation district when different water sources are available, including water supply option contracts. This model is applicable to any other irrigation district that relies on multiple water sources.

During drought periods, water users can rely on spot water markets to get the water volume that they need to meet their demands. Under these conditions, however, it might be difficult to find a water seller and prices are normally high. Option contracts can avoid this situation and may well have an important risk-reducing potential. Option contracts allow option holders to secure access to a specified water volume for a given price in the future in exchange for the payment of an annual premium. As our model shows, option contracts can be combined with other sources, adding more flexibility to the entire source pool.

As expected, an irrigation district would be more interested in signing the option contract when the associated costs (exercise price, premium) and the conditions (optioned volume and trigger) are more favourable to its business. The most relevant variables for this decision are the optioned volume and the premium, that is the cost of contracting the option. The district's board might consider the probability of not meeting its target supply with the other available water sources and weight the cost of purchasing the option against the relative cost of the alternative water sources. In other words, the district's board assesses whether or not the value of the contract, that is the difference between the costs of the option and of the most likely alternative water supply (Michelsen and Young 1993), is positive. Our results show that the district would be interested in signing nearly half of the option contracts for the considered option parameter values and that greater optioned volumes require lower annual premiums for the district to sign the contract. Besides, when the irrigation district signs the option contract and the trigger condition is met, the irrigation district would always exercise the option.

The benefits in terms of reduced risk exposure of the contract option at an average unitary cost of 0.01 euro per cubic metre highlight its advantages for irrigation districts in water-scarce areas. Moreover, our case study considers an irrigation district that, despite being subject to a high degree of supply variability, is relatively well endowed compared with other districts in southern Spain which rely on a more restricted pool of water sources. The potential benefits of water option contracts for more vulnerable districts are thus likely to be much greater.

The irrigation district's decisions are in practice more complex than our model implies. The main complication not addressed in the study is finding the contract counterparty. Traditionally, water sellers in Spain are agricultural users who use their resources in normal years and sell them in dry years and not right holders who have water trading as their main economic activity. There has been one large multiyear lease contract between irrigation associations that resembled an option contract, so there are, in theory, some potential option sellers. Still, the results are an indication of the potential of option contracts for an irrigation district facing an uncertain water supply. Our model can be further developed to include several interesting aspects, including varying levels of irrigation district risk tolerance. Besides, we assume here that the spot water price is known in the first stage when there is uncertainty regarding water availability. However, the spot price would depend on the hydrological situation and increase sharply in drought periods. Lastly, under extreme and sustained circumstances in which the high procurement cost of water makes the farming activity unprofitable, the cultivated area could be drastically reduced, eventually leading to shutting down the irrigation district. In our case study, with the availability of relatively cheap, although not very abundant, sources of surface water, shutting down the district seems beyond consideration at the moment.

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Appendix

Table A1 Optimisation results for several states of nature (k) under different parameterisations of the option contract

OP (€/m^3)	$A_{\text{opt},k}$ (hm^3)	P_{opt} (€/m^3)	T (hm^3)	k	Total volume (hm^3)	Volume from different sources (%)			
						Option contract	Desalinated water	Ground water†	Other sources
0.08	3	0.06–0.3	10;15;20	1	34.20	8.77	23.39	36.17	31.67
			10;15;20	3	39.59	7.58	20.21	31.25	40.97
			10	7	44.29	0	18.06	25.29	56.65
			15; 20		47.29	6.34	16.92	23.68	53.06
			10;15;20	13	50.00	0	7.14	22.40	70.44
			10; 15; 20	18	50.00	0	0	17.90	82.10
0.06	6	0.06–0.3	10;15;20	1	37.20	16.13	21.51	33.25	29.11
			10;15;20	3	42.59	14.09	18.78	29.04	38.08
			10	7	44.29	0	15.42	25.29	56.65
			15; 20		50.00	12.00	15.42	22.40	50.18
			10;15;20	13	50.00	0	7.14	22.40	70.44
			10;15;20	18	50.00	0	0	17.90	82.10
0.04	9	0.06–0.3	10;15;20	1	40.2	22.39	19.90	30.77	26.94
			10;15;20	3	45.59	19.74	17.55	27.13	35.58
			10	7	44.29	0	18.06	25.29	56.65
			15;20		50.00	18.00	9.42	22.40	50.18
			10;15;20	13	50.00	0	7.14	22.40	70.44
			10;15;20	18	50.00	0	0	17.90	82.10
0.02	12	0.06–0.3	10;15;20	1	43.2	27.78	18.52	28.63	25.07
			10;15;20	3	48.59	24.67	16.461	25.46	33.38
			10	7	44.29	0	18.06	25.29	56.65
			15;20		50	24.00	3.42	22.40	50.18
			10;15;20	13	50	0	7.14	22.40	70.44
			10;15;20	18	50	0	0	17.90	82.10
0.02	15	0.06–0.3	10;15; 20	1	46.20				
			10;15;20	3	50	30.00	12.82	24.74	32.44
			10	7	44.29	0	18.06	25.29	56.65
			15;20		50	30.00	0	19.82	50.18
			10;15;20	13	50	0	7.14	22.40	70.44
			10;15;20	18	50	0	0	17.90	82.10

P_{opt}: exercise price; OP: premium, $A_{\text{opt},k}$: optioned volume, T: trigger; k: state of nature.
†Groundwater sources: private wells, drought wells and irrigation district's own wells.