Supplementary Material

1. Model description.
2. Stochastic values for parameters involved in the assessment of desertification risk.
3. Supplementary Figure 1. Evolution of the greenhouse land occupation in the Gualchos Stream basin.
4. Supplementary Table 1. Parameter values and reference values for some variables obtained from different sources.
5. Supplementary Table 2. Calibrated parameters and unknown parameters.
6. Supplementary Table 3. Alternative scenarios for *what if* questions.
7. References.

1. Model description

The model represents an unconfined coastal aquifer hydraulically connected to the sea where the dynamics of the saltwater–freshwater interface (SFI) determines the transmission (through the aquifer) and discharge of fresh groundwater to the sea. The rate of variation in the fresh groundwater stock is determined by the following four flow components (expressed per unit width): rainfall recharge, irrigation return, groundwater pumping and aquifer discharge to the sea:

Eq.1. Fresh Groundwater Stock [m^2]
= INTEG{Recharge + Irrigation Return – Groundwater Pumping – Fresh Groundwater Discharge}

where:
Recharge [$m^2 \cdot yr^{-1}$]; Irrigation Return [$m^2 \cdot yr^{-1}$]; Pumping [$m^2 \cdot yr^{-1}$]; Fresh Water Discharge [$m^2 \cdot yr^{-1}$].

Seasonal variation in rainfall recharge is emulated by means of a sine wave function centred on 1 and whose period is one year (Eq. 2). Instead of Time, the input of this function is Time + 0.25 to make years start when recharge is maximum. In this way, it can be assumed that years in the model roughly represent calendar years. The recharge rate (Eq. 3) simply expresses rainfall recharge per unit width of the aquifer.

Eq. 2. Rainfall Recharge [$m^3 \cdot yr^{-1}$]
= average rainfall recharge · (1 + SIN{2π · (Time + 0.25)})

Eq. 3. Recharge
= Rainfall Recharge / (aquifer width · 10^3)

where:
average rainfall recharge [$m^3 \cdot yr^{-1}$]; Time [yr]; aquifer width [km]; 10^3 [$m \cdot km^{-1}$]

The model imposes that there is a non-linear relationship between groundwater discharge and the fresh groundwater stock, as proposed by Coutagne (1948) [1] and Chapman (1999) [2]:

Eq. 4. Fresh Groundwater Discharge [m^2 yr^{-1}]
= Fresh Groundwater Stock$^{\text{aquifer geometry parameter}}$ / groundwater turnover time

where:
Fresh Groundwater Stock [m^2]; aquifer geometry parameter [1]; groundwater turnover time [yr]

The studied alluvial aquifer has a longitudinal shape, so the adopted aquifer geometry parameter is 1. This parameter may increase up to 2 for perfect circular aquifers [2]. In some coastal aquifers, a fraction of fresh groundwater can find preferential ways to discharge to the sea through geological structures (e.g., faults) or materials more transmissive than the sedimentary materials forming the alluvial aquifer. The model allows representing this possibility by including a parameter that specifies the fraction of the total fresh groundwater discharge that maintains the position of the SFI:

Eq. 5. Groundwater Discharge Affecting SFI [m^2 yr^{-1}]
= fraction of fresh groundwater discharge affecting SFI · Fresh Groundwater Discharge

where:
fraction of fresh groundwater discharge affecting SFI [1]; Fresh Groundwater Discharge [m^2 yr^{-1}]

Verruijt (1968) [3] arrives at the formulae giving the depth (that he call h_s) of the SFI below sea level (bsl) and the height (h_f) of the free groundwater surface above sea level (asl) as functions of the distance (x) from the coastline, the fresh groundwater discharge, and three constants, namely the coefficient of permeability, and the densities of fresh groundwater and seawater. Hence, for a given value of x, h_s and h_f will vary only if there is a change in the fresh groundwater discharge.

The model assumes, as a convenient simplification, that the depth bsl of all the pumping wells in the aquifer is the same, i.e. “wells depth bsl”. The variable “Seawater Intrusion” gives the distance of the line where the SFI intersects a horizontal plane at the bottom of the wells from the coastline. Thus, any well within the range of “Seawater Intrusion”, would pump seawater. For the sake of simplicity, cones of brackish groundwater or saltwater ascension are neglected.

“Seawater Intrusion” is obtained by equalling the Verruijt's h_s formulation to “wells depth bsl” and then solving for x. The resulting function is called VERRUIJT1. The complete expression of this function can be seen at the end of this description. However, a MIN function is added to avoid “Seawater Intrusion” exceeding the length of the aquifer:

Eq. 6. Seawater Intrusion [km]
= MIN{aquifer length,
VERRUIJT1{wells depth bsl, permeability coefficient, Groundwater Discharge Affecting SFI,
fresh groundwater density, seawater density}}

where:
aquifer length [km]; wells depth bsl [m]; permeability coefficient [m day^{-1}]; Groundwater Discharge Affecting SFI [m^2 yr^{-1}]; fresh groundwater density [kg m^3]; seawater density [kg m^3]

The model only makes use of the average height of the free groundwater surface (the water table in unconfined aquifers) a.s.l. (h_f is not a horizontal plane in the Verruijt's conceptualization). The expression giving this average, called VERRUIJT2, results from integrating the Verruijt's h_f formula between 0 and the length of the aquifer and then dividing the result by this length; see below for its complete expression.

Eq. 7. Average Height Free Groundwater Surface asl [m]
= VERRUIJT2{aquifer length, permeability coefficient, Discharge Affecting Interface,
fresh water density, sea water density}

where:
aquifer length [km]; permeability coefficient [$m\ day^{-1}$]; Groundwater Discharge Affecting SFI [$m^2\ yr^{-1}$]; fresh groundwater density [$kg\ m^3$]; seawater density [$kg\ m^3$]

The model assumes that a number of people own equally-sized pieces of land over the aquifer. These owners consider entering or leaving irrigated farming by comparing the average expected profit per irrigated farm ("Expected Profit") with their respective opportunity costs, i.e. with the expected returns from other alternative economic activities. It is additionally assumed that the opportunity cost follows a generalized Rayleigh distribution across owners, which is commonly used to analyse skewed data [4]. The CDF of this distribution is:

$$P(X \leq x) = 1 - EXP\{-x^2 / [\mu^2 \cdot (cv^2 + 1)]\} \qquad (1)$$

For us, X is the opportunity cost of an owner, and μ and cv are the mean and the coefficient of variation of the opportunity cost across owners, respectively. In this way, $P(X \leq \text{Expected Profit})$ gives the fraction of owners whose opportunity cost is less than the average expected profit per irrigated farm, i.e. the fraction of owners that regard irrigated farming as the most profitable alternative. However, given that they own equally-sized pieces of land, the same expression also gives the fraction of the potential irrigated area where irrigation agriculture is desired:

Eq. 8. Desired Irrigated Area [ha]
= potential irrigated area ·
· [1 – EXP{–Expected Profit^2 / [average opportunity cost^2 · (cv opportunity cost^2 + 1)]}]

where:

potential irrigated area [ha]; Expected Profit [€ farm^{-1} yr^{-1}]; average opportunity cost [€ farm^{-1} yr^{-1}]; cv opportunity cost [1]

It takes some time for farmers to carry out their plans. Therefore, change in the irrigated area is modelled as a first order exponential adjustment of the current towards the desired irrigated area. It is assumed that there is only one irrigated farm pumping groundwater from the aquifer at time zero. In this way, any model simulation will represent the expansion of irrigation agriculture in the area over the simulation period.

Eq. 9. Irrigated area [ha]
= INTEG{(Desired Irrigated Area – Irrigated Area) / irrigated area adjustment time}

Initial Irrigated Area = area of one farm

where:

Desired Irrigated Area [ha]; irrigated area adjustment time [yr]; area of one farm [ha]

Water in the modelled area has domestic and agricultural uses. The amount of water required for the former use is a model parameter. The amount for the latter equals irrigated area times the per hectare water requirements of crops:

Eq. 10. Water Requirements [m^3 yr^{-1}]

= domestic water requirements + Irrigated Area · crops water requirements

where:

domestic water requirements [$m^3\ yr^{-1}$]; Irrigated Area [ha]; crops water requirements [$m^3\ ha^{-1}\ yr^{-1}$]

Groundwater can only be used where wells do not pump seawater. The length of this area equals the length of the aquifer less "Seawater Intrusion" (Eq. 6). Hence, the fraction of the total water demand satisfied by groundwater is given by:

Eq. 11. Groundwater Demand Fraction [1]
= 1 – Seawater Intrusion / aquifer length

where:

Seawater Intrusion [km]; aquifer length [km]

The total demand for fresh groundwater is satisfied from the aquifer and from external sources. Such a demand equals total water requirements divided by the efficiency of the water distribution systems. For the sake of simplicity, the latter is assumed to be the same for both sources of water. Therefore, the allocation of the total demand for water is given by:

Eq. 12. Water Demand Aquifer [$m^3\ yr^{-1}$]
= Water Requirements · Groundwater Demand Fraction / water efficiency

Eq. 13. Water Demand Other Sources [$m^3\ yr^{-1}$]
= Water Requirements · (1 – Groundwater Demand Fraction) / water efficiency

where:

Water Requirements [$m^3\ yr^{-1}$]; Groundwater Demand Fraction [1]; water efficiency [1]

The groundwater pumping rate simply expresses the demand for groundwater per unit width:

Eq. 14. Groundwater Pumping [$m^2\ yr^{-1}$]
= Water Demand Aquifer / (aquifer width · 10^3)

where:

Water Demand Aquifer [$m^3\ yr^{-1}$]; aquifer width [km]; 10^3 [$m\ km^{-1}$]

The parameter "return flow coefficient" represents the fraction of the difference in irrigation water demand and the amount of water consumed by crops that returns to the aquifer. Therefore, the irrigation return flow (per unit width) is given by:

Eq. 15. Irrigation Return [$m^2\ yr^{-1}$]
= return flow coefficient · (1 – water efficiency) · Irrigated Area ·
· crops water requirements / (water efficiency · aquifer width · 10^3)

where:

return flow coefficient [1]; water efficiency [1]; Irrigated Area [ha]; crops water requirements [$m^3\ ha^{-1}\ yr^{-1}$]; aquifer width [km]; 10^3 [$m\ km^{-1}$]

Profit per hectare is the difference between total revenue and total costs per hectare. The former, which comes from the selling of agricultural production, is a model parameter. The latter equals the cost of water plus other costs. The cost of water results from multiplying the cost of a cubic meter of water and the per hectare demand for irrigation water, i.e. "crops water requirements" divided by "water efficiency".

Eq. 16. Profit per Hectare [€ $ha^{-1}\ yr^{-1}$]
= revenue per hectare – Water Cost per Cubic Meter · crops water requirements / water efficiency – other costs per hectare

where:

revenue per hectare [€ ha^{-1} yr^{-1}]; Water Cost per Cubic Meter [€ m^{-3}]; crops water requirements [m^3 ha^{-1} yr^{-1}]; water efficiency [1]; other costs per hectare [€ ha^{-1} yr^{-1}]

The cost of one cubic meter of water is a weighted average of the cost of pumping groundwater from the aquifer and the price of the water coming from external sources. The weights are the fractions of the total demand for water corresponding to both sources:

Eq. 17. Water Cost per Cubic Meter [€ m^{-3}]
= Groundwater Demand Fraction · Cost One Cubic Meter Groundwater +
+ (1 – Groundwater Demand Fraction) · price one cubic meter external water

where:

Groundwater Demand Fraction [1]; Cost One Cubic Meter Groundwater [€ m^{-3}]; price one cubic meter external water [€ m^{-3}]

The cost of a cubic meter of groundwater pumped from the aquifer combines the cost of the energy consumed, which depends on the average depth of the free groundwater surface and the price of energy, and other costs:

Eq. 18. Cost One Cubic Meter Groundwater [€ m^{-3}]
= energy price · energy to pump one cubic meter one meter ·
· (height land surface m.a.s.l. - Average Height Free Groundwater Surface m.a.s.l.) +
+ other water costs

where:

energy price [€ kwh^{-1}]; energy to pump one cubic meter one meter [kwh m^{-4}]; height land surface asl [m]; Average Height Free Groundwater Surface asl [m]; other water costs [€ m^{-3}]

The profit per irrigated farm results from multiplying the profit per hectare and the area of one farm. It is assumed that the expectation about such a profit is a moving average of past observed profits where weights exponentially decrease over time. This is the well-known exponential smoothing, that can be expressed as a first order linear negative feedback model [5].

Eq. 19. Expected profit [€ farm yr^{-1}]
= INTEG{(area of one farm · Profit per Hectare - Expected Profit) /
/ expectations adjustment time}

where:

area of one farm [ha]; Profit per Hectare [€ ha^{-1}]; expectations adjustment time [yr]

If, at a given time, the SFI would fix its position at some distance from the coastline, the average salinity of groundwater across the aquifer's length at the bottom of the wells would end up being the weighted average of the salinities of fresh and sea water, where the weights would be the lengths of the sections saturated with both kinds of water. However, given that the interface varies seasonally, and that it takes some time for fresh water to wash accumulated salts away, changes in average groundwater salinity are modelled as a first order exponential adjustment of the variable "Average Groundwater Salinity" towards the aforementioned weighted average, called "Target Groundwater Salinity" in the model:

Eq. 20. Target Groundwater Salinity [dS m^{-1}]
= Groundwater Demand Fraction · fresh water salinity +
+ (1 – Groundwater Demand Fraction) · sea water salinity

Eq. 21. Average Groundwater Salinity [dS m^{-1}]
= INTEG{(Target Groundwater Salinity – Average Groundwater Salinity) /
/ salinity adjustment time}

where:

Groundwater Demand Fraction [1]; fresh water salinity [dS m^{-1}]; sea water salinity [dS·m^{-1}]; salinity adjustment time [yr]

The model uses the electrical conductivity (dS m^{-1}) as a proxy of the content of salts, which is convenient in high-salinity, groundwater-dependent coastal agriculture areas.

Functions derived from Verruijt (1968) [3]

$$\mathrm{VERRUIJT1}\{d_w, k, Q, \rho_s, \rho_f\} = [365k\alpha(1+\alpha)d_w^2/(2Q\cdot 10^3)] - [(1-\alpha)Q/(2\cdot 365\alpha k\cdot 10^3)]$$

$$\mathrm{VERRUIJT2}\{l, Q, k, \rho_s, \rho_f\} = [8\alpha l Q\cdot 10^3/(9\cdot 365k(1+\alpha))]^{1/2}$$

where:

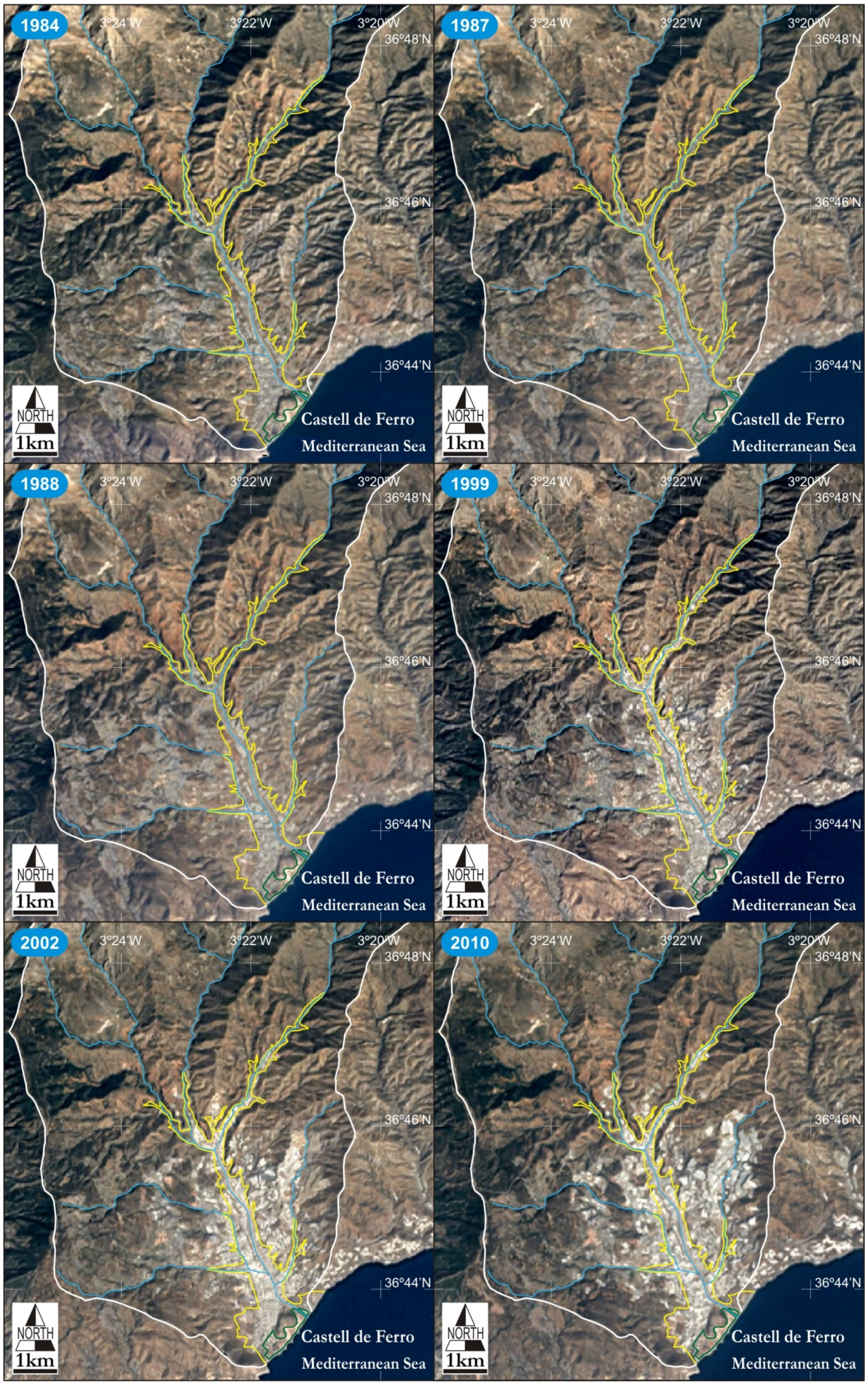
$\alpha = (\rho_s - \rho_f) / \rho_f$
d_w = wells depth bsl [m]; k = permeability coefficient [m day^{-1}]; Q = Groundwater Discharge Affecting SFI [m^2 yr^{-1}]; l = aquifer length [km]; ρ_s = seawater density [kg m^{-3}]; ρ_f = fresh groundwater density [kg m^{-3}]; 365 [day yr^{-1}]; 10^3 [m km^{-1}]

2. Stochastic values for parameters involved in the assessment of desertification risk.

The 200 alternative values to the baseline scenario (see Supplementary Tables 1 and 2) for the parameters "revenue per hectare" (Eq. 16) and "average rainfall recharge" (Eq. 2) are randomly sampled from two probability distributions. For the first parameter, the random sample comes from a normal distribution whose mean is the default parameter value (77,811 € ha^{-1} yr^{-1}), and whose standard deviation (11,189 € ha^{-1} yr^{-1}) is estimated from the tomato price series reported by the Price and Market Observatory of the Andalusian Regional Government over the period 2002/03–2021/21 [6]. Since tomato is the main crop in the area, such a series was deemed to be a good proxy for estimating the standard deviation of revenues, for which no time-series was found.

For "average rainfall recharge", a log-normal distribution was used because it reflects the typical skewness that characterizes precipitation in drylands [7,8]. The mean of the distribution is the default parameter value (1.85 m^3 yr^{-1}), and its standard deviation (0.6475 m^3 yr^{-1}) is estimated from the local precipitation time-series over the period 1980/81–2011/12 [9].

3. Supplementary Figure S1. Evolution of the greenhouse land occupation in the Gualchos Stream basin; source: https://earthengine.google.com/timelapse/. The yellow line is the Castell de Ferro alluvial aquifer.



4. Supplementary Table S1. Parameter values and reference values for some variables obtained from different sources.

Parameter	**Value**	**Source**
aquifer length [km]	5	(Pulido-Leboeuf, 2004) [10]
area of one farm [ha]	1.11	(Junta de Andalucía, 2015) [11]
average opportunity cost [€ $farm^{-1}$ yr^{-1}]	15,943[a]	(Instituto de Estadística y Cartografía de Andalucía, 2022) [12]
average rainfall recharge [m^3 yr^{-1}]	1.85	(Calvache and Pulido-Bosch, 1997) [13]
crops water requirements [m^3 ha^{-1} yr^{-1}]	4950	(Fernández et al,. 2012) [14]
domestic water requirements [m^3 yr^{-1}]	146,280	(INE, 2020) [15]
energy price [€ kwh^{-1}]	$7.6{\cdot}10^{-2}$	(Ministerio de Industria, 2022) [16]
energy to pump one cubic meter one meter [kwh m^{-3}]	$2.725{\cdot}10^{-3}$	(CottonInfo, 2015) [17]
fraction of groundwater discharge affecting SFI [1]	0.22	(Calvache and Pulido-Bosch, 1997) [13]
fresh groundwater density [kg m^3]	1,000	(Samper, 2013) [18]
fresh groundwater salinity [dS m^{-1}]	$5{\cdot}10^{-3}$	(Wikipedia, 2022) [19]
initial expected profit [€ ha^{-1} yr^{-1}]	35,508[b]	(Valera et al., 2016) [20]
potential irrigated area [ha]	626	(Junta de Andalucía, 2019)
price one cubic meter external water [€ m^{-3}]	0.61[b]	(Navarrete, 2014) [22]
revenue per hectare [€ ha^{-1} yr^{-1}]	77,811[b]	(Valera et al., 2016) [20]
seawater density [kg m^3]	1,025	(Samper, 2013) [18]
seawater salinity [dS m^{-1}]	50	(Wikipedia, 2022) [19]
water efficiency [1]	0.9	(WWF, 2009) [23]
Variable	**Value**	**Source**
Annual Fresh Groundwater Discharge [Mm^3 yr^{-1}][c]	0.14	(Calvache and Pulido-Bosch, 1997) [13]
Annual Irrigation Return [Mm^3 yr^{-1}][c]	0.26	(Calvache and Pulido-Bosch, 1997) [13]
Annual Water Cost per Hectare [€ ha^{-1} yr^{-1}][c]	1,875	(Valera et al., 2016) [20]
Annual Water Demand Aquifer [Mm^3 yr^{-1}][c]	1.97	(Calvache and Pulido-Bosch, 1997) [13]
Annual Total Costs per Hectare [€ ha^{-1} yr^{-1}][c]	45,732[b]	(Valera et al., 2016) [20]
Seawater Intrusion [km] (minimum)	1.5	(Calvache and Pulido-Bosch, 1997) [13]

[a] Average wage in Andalusia Region in 2020; [b] Adjusted for inflation (period 2014–2021) by means of INE’s on-line facility (Statistics Spain); [c] Annual values result from integrating the corresponding variable over one-year periods.

5. Supplementary Table S2. Calibrated parameters and unknown parameters.

Parameter	Value	Procedure
return flow coefficient [1]	0.75	These parameters fit Annual Groundwater Demand and Annual Irrigation Return.
pumping wells depth below sea level [m]	10	
aquifer geometry parameter [1]	0.6	These parameters fit Annual Fresh Groundwater Discharge and Seawater Intrusion.
groundwater turnover time [year]	0.2	
permeability coefficient [m day^{-1}]	180	Calvache (2002) estimated the permeability coefficient in the 60–250 range.
aquifer width [km]	0.6	Pulido-Leboeuf (2004) estimated the aquifer's area at 3 km^2 and its length at 5 km.
height land surface above sea level [m]	20	Field observation.
irrigated area adjustment time [yr]	6	This parameter makes the expansion of irrigated area to last for 35 years.
other costs per hectare [€ ha^{-1} yr^{-1}]	43,857	Annual Total Costs per Hectare less Annual Water Cost per Hectare.
other water costs [€ m^{-3}]	0.12	This parameter fits Annual Water Cost per Hectare.
initial average groundwater salinity [dS m^{-1}]	1.366	Equilibrium values reached by running the model with no irrigated area.
initial fresh groundwater stock [m^2]	38,488	
cv opportunity cost [1]	0.15	Unknown parameters. Their influence in model's behaviour is very weak.
expectations adjustment time [yr]	5	
salinity adjustment time [yr]	1	

6. Supplementary Table S3. Default scenario and alternative scenarios for implementing *what if* questions. Into parenthesis, the percentage change compared to the baseline scenario. In red, values different from the baseline scenario.

Parameter	**Scenarios**				
	I	**II**	**III**	**IV**	**Default**
average rainfall recharge	1.58 (↓14.4%)	1.35 (↓26.6%)	1.85	1.47 (↓20.5%)	1.85
energy price	0.076	0.076	0.139 (↑85%)	0.139 (↑85%)	0.076
price one cubic meter external water	0.61	0.61	0.82 (↑35%)	0.82 (↑35%)	0.61
other costs per hectare	43,857	43,857	59,246 (↑35%)	59,246 (↑35%)	43,857
revenue per hectare	77,811	77,811	77,811	105,045 (↑35%)	77,811

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