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ORIGINAL ARTICLE

Hydro-economic modeling of water scarcity under global change: an application to the Gállego river basin (Spain)

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Abstract Integrated approaches are needed to assess the effects of global changes on the future state of water resources at regional scales. We develop a hydro-economic model of the Gállego catchment, Spain, to assess how global change and policy options affect the catchment's water scarcity and the economic implications to the agricultural sector. The model couples physical processes (hydrology) and regulatory and economic processes (agricultural water demand, reservoir operation). Five scenarios, covering currently ongoing changes in climatic conditions, agriculture and hydrological planning, are evaluated. Our results suggest that the scenarios' impacts on water resources and regional agricultural income are significant. Policy responses such as investments in modernization of irrigation technology would mitigate the negative impacts of climatic change on the agricultural sector, but the implementation costs outweigh the extra regional agricultural income. Also, a planned reservoir extension project appears ineffective, even considering effects of climatic change. Although our results are site-specific, our methodology is relevant to other areas that face comparable problems of water scarcity.

Keywords Hydro-economic modeling · Irrigated agriculture · Hydrology · Climatic change · Spain

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Introduction

Increasing water demands due to population growth and economic development put more and more pressure on decreasing good-quality water resource availability, among others due to the effects of climatic change (Vorosmarty et al. 2000). Societies need to respond to this pressure. In Europe, for instance, the Water Framework Directive (WFD) requires the use of scenarios to assess the future state of water resource systems in the medium term (European Commission 2000). Hydrological, climatic and socioeconomic characteristics imply that such assessments cannot be easily transferred between regions. The assessment of global change impacts on water resource systems should therefore be done at a regional scale and requires local biophysical and socioeconomic characterizations of the system including the comprehension on driving forces.

The objective of this paper is to develop a hydro-economic model that allows us to assess the effects of global change—climatic, socioeconomic and policy changes—on the agricultural sector and water scarcity in the Gállego catchment, a tributary of the Ebro River in Spain. However, it accounts only for agricultural land changes and not for other land cover type changes (mainly forest) that could also influence hydrology. Notice that this assumption does not limit the relevance of our modeling exercise since López-Moreno et al. (2011) showed that in the lower reaches of the Ebro river, water yield is mainly affected by water consumption and diversions for agricultural activities.[1]

In this catchment, as in the Ebro basin, water is seasonally scarce and agricultural water demand is high. In addition, salinity of soils is a problem for downstream water resources, because salts are leached in return flows and groundwater. Moreover, scarcity of water resources is constraining cropping decisions by farmers. Projected climatic change effects in the Iberian Peninsula (decreasing precipitation and increasing temperature) are expected to worsen this situation (Fowler et al. 2007). Policy responses, currently under discussion, include the modernization of irrigation technology (per hectare water demand reduction) and the extension of water storage reservoirs.

Hydro-economic modeling allows us to assess such responses by an integrated analysis of climatic change, water quantity, water quality and farmers' behavior, explicitly linking water uses both spatially and temporally. Heinz et al. (2007), Brouwer and Hofkes (2008) and Harou et al. (2009) provide detailed reviews on hydro-economic modeling. Two modeling approaches coexist: the compartment and the holistic approach. The compartment approach (see e.g., Lefkoff and Gorelick 1990) keeps the biophysical and economic aspects in separate models but allows the output of one model to be used as input in the other, while the holistic approach fully integrates both aspects in one integrated model (cf. Rosegrant et al. 2000; Cai et al. 2003). The choice for either of the two approaches is a trade-off between information transfer difficulties in the compartment approach and the simplification of hydrological and economic modeling often requested by the holistic approach (McKinney et al. 1999). In addition, the holistic approach allows for optimization in addition to simulation. Other recent models include Cai and Wang (2006), Draper et al. (2003), Graveline et al. (2007), Iglesias and Blanco (2008), Jenkins et al. (2004) and Pulido-Velazquez et al. (2004, 2008).

Two economic models have been applied to the issues of water scarcity and salinity in the Ebro basin. Albiac et al. (2007) analyzed several policy instruments to reduce pollution and water use. Esteban and Albiac (2007) extend this analysis by assessing taxes, tax-subsidy schemes and group fines on salinity emissions.

Based on the trade-off between simplification and information transfer, we develop a hydro-economic model based on the compartment approach. Our model is based on detailed field work and data collection, which backs up the assumptions used in the model compartments and the scenarios. It allows both a robust modeling of farm behavior and application of a sophisticated hydrological model, in the context of changing policies and climatic change.

The contribution of our paper lies in developing a policy-oriented framework at river basin scale that uses a large amount of local information in order to capture the regional biophysical and economic characteristics. Some studies have looked at the impact of global change on the agricultural sector (e.g., Henseler et al. 2009) but without the impact on water resources, while other explore the impact of drought scenarios on hydrology and agriculture with hydro-economic modeling (e.g., Maneta et al. 2009), but without considering climatic change scenarios. In this paper, we add to these studies by explicitly including the role of both reservoirs and irrigation technology as means to mitigate the effects of climatic change on water resources at a regional scale.

The remainder of this paper is organized as follows. In the second section we present background information and a conceptual model of the Gállego catchment. In the third section we describe the hydro-economic model. In the fourth section we introduce the scenarios and their policy relevance. In the fifth section we present and discuss the results before concluding in the last section.

The Gállego catchment

The Gállego catchment covers 4,009 km^2 and is located in the northern part of the Ebro basin in the Communidad Autonoma de Aragon, Spain (see Fig. 1). Its source lies in the Pyrenees, and it flows into the Ebro near the city of Zaragoza, with an average annual flow volume of 1,090 hm^3. Its climate is arid to semiarid. Aragon is one of the most important regions of Spain in terms of agriculture. Since 1960, large reservoirs have been constructed in the Gállego catchment in order to increase water storage capacity in the basin and extend the area of irrigated agriculture. Nowadays, irrigated agriculture represents 94 % of the water demand (excluding hydropower demand CHE 2007), largely supplied by dams, and large amounts of water are transferred to the eastern Cinca basin for irrigation.

The total hydropower potential of the Gállego is 242,090 Kw at a production of 745 Gw per year and is produced by about 20 reservoirs in the basin. To optimize water use through storage and release by reservoirs, a complex management infrastructure has been set up by the basin authority, the "Confederacion Hidrografica del Ebro" (CHE). Individual dam regulations ("normativas") include security norms, priority, flood and drought management rules.

[1] This assumption would not be completely valid in headwater catchments characterized by moderate human activities.

Fig. 1 Situation map of the Gállego: a catchment of the Ebro basin (source: Instituto Nacional de Estadística (Spain) and CHE)

Irrigated areas in the catchment cover 20,726 ha and are mainly located in Violada (9,004 ha) and Bajo Gállego (11,722 ha) districts, both of which are irrigated with surface water. Furthermore, the Monegros district, which is located within the Cinca catchment, is also partially supplied by the Gállego through the Monegros channel (see Fig. 2a). The irrigation associations ("Communidades de regantes"), supervised by the CHE, control and distribute water according to specified historical rights and demands. Water rights range from 2,500 m^3/ha in the upper humid parts to 10,851 m^3/ha in the lower dryer parts, and depend on irrigation techniques. The main technique is flood irrigation (80 % in La Violada to 95 % in Bajo Gállego), and the remaining area (20 % in La Violada and 5 % in Bajo Gállego) is equipped with sprinkler irrigation. Lecina et al. (2010) and Barros et al. (2011) provide a detailed analysis of the irrigation efficiency in this area.

The main irrigated crops in the region are alfalfa, corn, wheat, barley and sunflower. Cereals account for more than 90 % of the total irrigated area. A regional characteristic is the production of rice, which is cultivated because it can be grown on soils that are affected by salinization, whereas other crops would be less productive on those soils. The remaining 10 % of irrigated agriculture includes fruits, olives and vineyards (Albiac et al. 2007).

The Gállego catchment is affected by high concentrations of salts in soils due to salt-rich geological formations. Downstream water bodies are affected by irrigation return flows with high salt concentrations (Causapé et al. 2004a).[2] The water quality of upstream surface water is not affected by salinity and does not affect agricultural production.

[2] Export of salts in the Ebro (79 T/km^2) are far above European (49 T/km^2) and world averages (35 T/km^2, see Meybeck 1979).

Hydro-economic model

Model overview

We designed a conceptual model of the water supply and demand system whose main features are presented in Fig. 2a. Two irrigation districts are considered: Violada and Bajo Gállego. The La Sotonera dam is the main reservoir associated with the Violada irrigation district. The Bajo Gállego is supplied by four main channels, Camarena, Candevania, Raval and Urdan, that collect water from the Ardisa dam. Nodes (see Fig. 2b) have been selected for modeling purposes: They correspond to a stream gauge, a reservoir, a point of connection between the river and a diversion channel, or a section where the hydrological balance is performed and data are exchanged between models. The principle of the model is as follows, and the connections between compartments are illustrated in Fig. 3.

On March 1, the expected amount of available water for agriculture is assumed to be known. Then, associations recalculate and inform smaller associations on the quantity of water they can expect for the irrigation period. This information enables farmers to plan their cropping patterns according to water availability and water requirements per crops. Then, according to the real cropping patterns of farmers, water is released "on demand" from the reservoirs. This structure of water supply and demand explains the need for a two-step modeling approach: (1) The hydrological model provides the information on water availability and (2) subsequently, this availability is used in the economic model to determine cropping patterns that provide the real water demand from agriculture, and thereby the amount of water to be released at the reservoir levels. The reservoir operation module reproduces decisions to store or deviate water according to both hydrological conditions and water demand. The economic model maximizes regional farming profits.

The compartments communicate via input and output data. The technical implementation of the coupled modeling system can be summarized in five steps.

Step 1: Based on different levels of water availability for agriculture, economic model runs have been performed in order to create a library of responses able to provide the input data for the hydrological model and the reservoir operation compartment (i.e., monthly water demand based on selected cropping pattern). The optimization time horizon was fixed at 1 year, with each month being simulated separately.[3]

[3] Note that climate parameters only enter the hydrological compartment and do not enter the agro-economic compartment. This limits the applicability of our results to the impacts of reduced irrigation water availability without considering the likely reduction in rainwater availability.

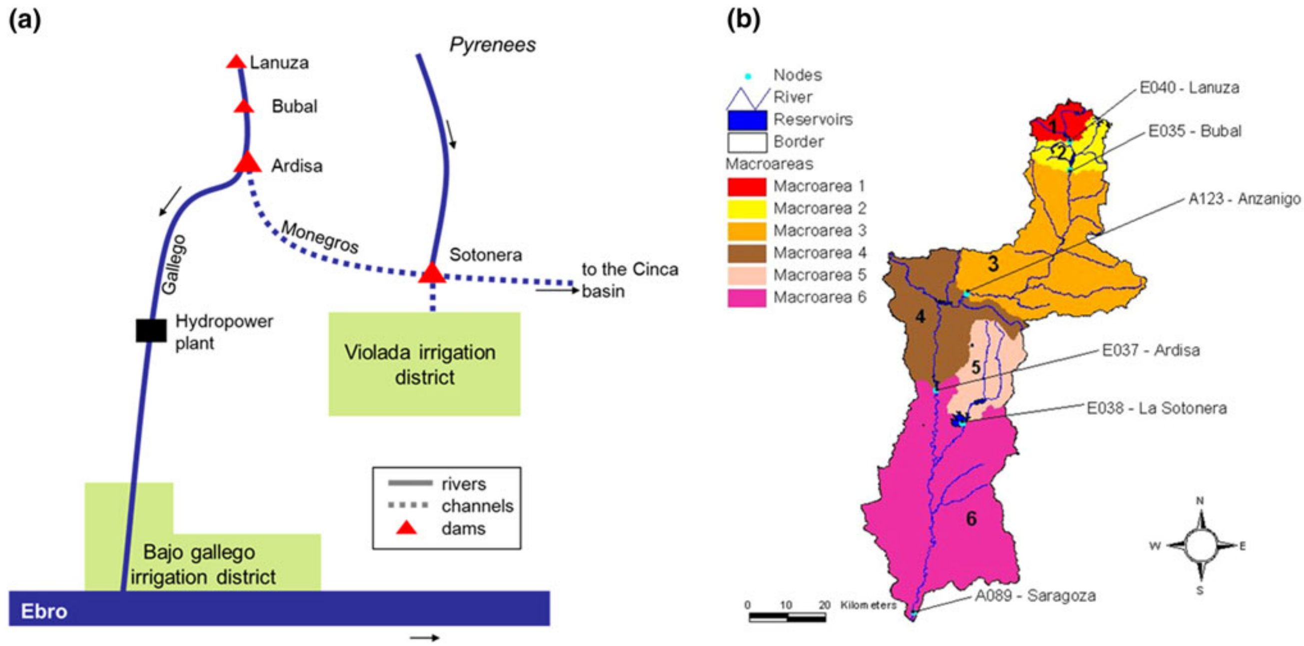

Fig. 2 **a** Conceptual model of the Gállego catchment and **b** the subdivision of the catchment into six different macroareas adopted for the hydrological simulations

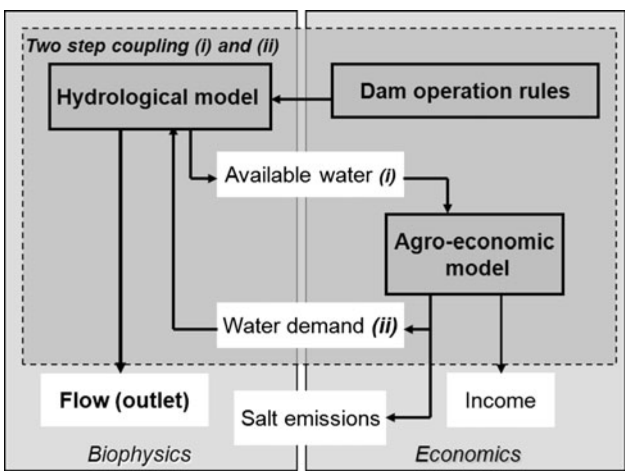

Fig. 3 Overview of the model and major links in the integrated model

Step 2: Based on the monthly water demands derived in Step 1 and on the reservoir management rules, expected withdrawals from reservoirs and water supplies to rivers and irrigation districts are fixed at daily timescale by the reservoir operation compartment.

Step 3: Based on output from Step 2, hydrological model runs are performed with a daily time step, which provides data of water fluxes and water storage in selected nodes.

Step 4: Based on aggregated yearly values of water supplied as output from Steps 2 and 3, the economic model provides irrigated area, crop yields, regional agricultural income and salt emissions.

Step 5: Coupling of the models is realized by iterating Steps 2, 3 and 4 over the simulation period in which the hydrological model updates yearly values of water availability together with the input data provided by the agro-economic library and the dam management compartment.

The hydro-economic model is used to simulate the impacts of scenarios that we introduce in "Scenarios" section. Before doing so, we describe the three model compartments in detail.

Hydrological model

The hydrological model GEOTRANSF, detailed in Majone et al. (2005), has been adapted to the Gállego catchment. GEOTRANSF is a semidistributed modeling system for basin-scale hydrology that accommodates an accurate description of the main mechanisms controlling runoff. It includes snow accumulation and melting, infiltration, evapotranspiration, subsurface flow generation and channel routing. The core of the approach is a nonlinear relationship between the subsurface flow and the soil water content (Majone et al. 2010). The model is related to the external climatic forcing through a suitable mass balance and is able to take into account reservoirs, artificial channels for hydropower or irrigation purposes and spatially and temporally varying water uses.

The GEOTRANSF model has been applied to the Gállego catchment by subdividing the basin into six macroareas, with streamflow computed at six nodes located at the outlet of each macroarea (see Fig. 2b). Particular attention was given to the integration of reservoirs in the model. A suitable balance equation was applied in order to reproduce the observed volumes during the reference period.

Calibration and validation of GEOTRANSF model has been conducted by matching streamflow data for the reference period 2001–2005 at the nodes. This 5-year period shows wide variations in the hydrological regime with two extremely dry years (2002 and 2005) and thus can be considered a severe test of the model. Data and details on validation are given in "Appendix 1".

Reservoir management

Six major reservoirs are used to provide water for irrigation and hydropower and to manage flood protection. In the model, four dams with the highest storage capacity (i.e., the Ardisa, Bubal, Lanuza and La Sotonera dams) as well as the hydropower station "Marracos" are considered (see Fig. 2a). The reservoir management rules have been assessed through expert interviews and a review of the technical literature on reservoir management in the Ebro basin. For dams with an irrigation purpose, two main periods are distinguished. The "refilling period" lasts from October to March, when there is no agricultural demand, with the minor demand for drinking water and industry being almost constant throughout the year. Dam management maximizes the total volume of water in the basin through the storage of rain and snowmelt. The storage capacity is limited by both dam capacity and its related security margins for flood prevention. The overall basin strategy is to store the water in dams as downstream as possible. Releases of water correspond to the demand for drinking water, industry and hydropower according to existing concessions and the minimum flow requirements which are mandatory to the WFD and integrated in the basin hydrological planning.

The irrigation period lasts from March to October. In this period agricultural water demand is the main demand. Drinking water has priority over all other uses. Agriculture has priority over hydropower, with a few exceptions for particular hydropower stations that run throughout the year. In general, however, hydropower is a nonconsumptive water use and thereby compatible with agricultural water demand.

There are several particular reservoir management rules. First, the prior use of the Ardisa dam is to deliver water to the lower Gállego. Only if there is sufficient water, it is channeled to La Sotonera dam. When La Sotonera is full, the water is channeled to the Gállego. The minimum volume is kept at 1.2 hm^3 in order to safeguard fish habitats. The Ardisa dam fills when the income flow is higher than the maximum flow capacity of the channel feeding the La Sotonera dam (90 m^3/s). Second, the Marracos hydropower station has priority over the irrigation districts and has a right to 15 m^3/s throughout the year. Third, traditional farms with prior rights can be found downstream on the shores of the Ebro. In the lower Gállego, the channels of Camarena and Candevania and the channels of the Raval and Urdan have priority over other water uses because they supply traditional irrigation areas. Fourth, there is a minimum flow requirement, fixed at 10 % of the mean annual flow (for instance, it is 1.2 m^3/s for the Bubal dam) or 5 % if this mean flow is above 80 m^3/s. This requirement has to be respected only when there is sufficient inflow.

As an example of the capability of the model to simulate the volume stored in the reservoirs, Fig. 4a shows the observed (blue line) versus simulated (pink line) daily water volumes for the La Sotonera reservoir during the period 2001–2005. Note that the monthly reservoir management rules provided by the reservoir management compartment are able to reproduce the observed volumes both for the storage and for the irrigation periods and thereby provide a further validation of our methodology.

Economic model

The economic model represents the farmers' behaviors in terms of cropping pattern and water use given climatic and policy conditions. In wet years, farmers may choose more water-demanding crops, leading to high water use and increasing return flows. In dry years, farmers are faced with a water constraint; they may irrigate a smaller area and will choose crops with low water requirements, for example, wheat or barley.

The economic model is a mathematical programming model that is well suited to model farmers' decisions when changing conditions affect input parameters (e.g., water) because it uses production functions that explicitly link input with output parameters. We specify a linear relationship between input (land) and output (quantities) parameters as we consider a small modeling scale with limited heterogeneity, the municipality, and consider several soil types to distinguish quality of soils. The major alternative approach is positive mathematical programming (PMP) (Howitt 1995), which accommodates decreasing marginal yields or increasing marginal costs (e.g., to account for spatial heterogeneity in assets), which are models that are more realistic at the regional scale and enable perfect calibration (Mérel et al. 2011). One of the main advantages of PMP is that it yields smoother responses.[4] However, the drawback of PMP is that the problem is

[4] However, we did not intend to model the dynamics of gradual adjustment to, for example, policy shocks or climatic change from the reference period up to 2100. This is why we do not value having smooth responses to such changes.

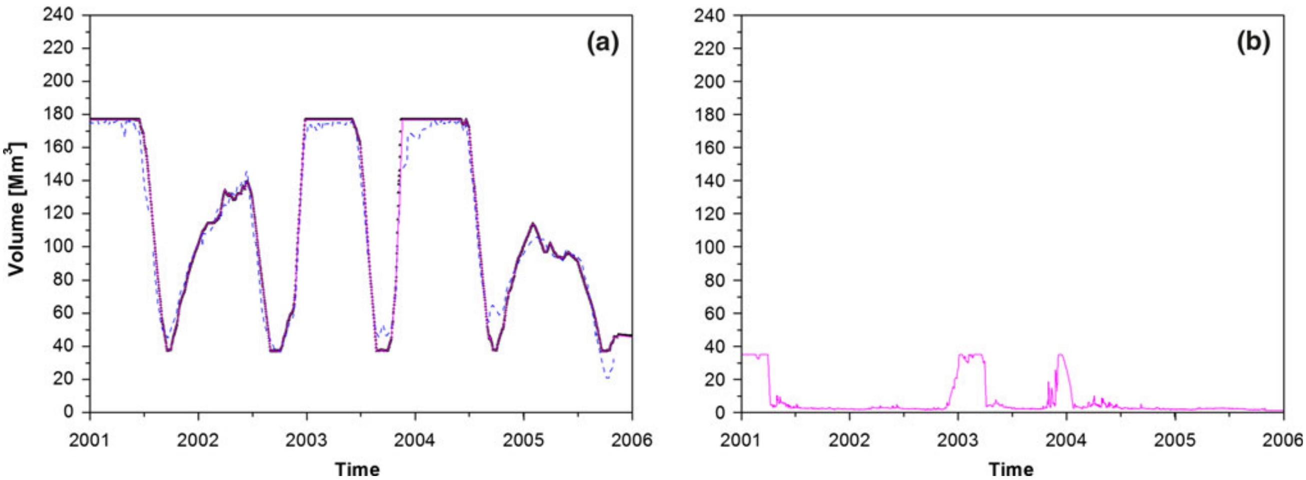

Fig. 4 **a** La Sotonera reservoir simulated volumes (reference period 2001–2005). The *black dotted line* refers to the case in which the Biscarrués reservoir is realized, while the *pink line* is related to the case in which the storage capacity is not modified (data provided by Majone et al. 2012). The *blue dashed line* shows the observed volumes for the reservoir. **b** Ardisa and Biscarrués dam simulated volume (reference period) (color figure online)

underdetermined and that arbitrary assumptions have to be made or that rare data have to be available (e.g., supply elasticities). Other recent studies dealing with agricultural water use have also made the choice for linear programming (e.g., Bazzani et al. (2004), Graveline et al. (2009, 2012) and Acs et al. (2010)).

We develop a linear programming (LP) model (Hazell and Norton 1986) for irrigated agriculture that we apply to 13 municipalities in the two irrigation districts. Each of the 13 municipalities is characterized by land availability, available irrigation technique and soil type. Crops considered are alfalfa, corn, wheat, barley, sunflower and rice; fallow is also an option. Irrigation techniques considered are flooding and sprinkler irrigation. Based on expert and farmer interviews when farmers are planning their cropping pattern, they generally prefer to switch crops rather than to irrigate below the crop water requirements of a given crop (Van Duinen 2008). We model water as the scarce resource in a Von Liebig-style yield function. This implies that there is no substitute to irrigation water (such as fertilizers or pesticides) to increase yield levels. We assume, based on interviews with local farmers, that either a crop is grown using a fixed amount of water or it is not grown at all. The combined choice of an irrigation technique with a crop is modeled as a land use system. We model six different crops with two irrigation techniques, and because rice cannot be grown with sprinkler irrigation, our model contains 11 different land use systems.

The model and data sources are explained in detail in "Appendix 2". The optimization problem is solved using the software GAMS. Comparing the model output with actual crop choice in this period, we conclude that the model is well capable of reproducing crop choice in Violada. Note that linear programming models used for regional-level agricultural modeling are generally not calibrated to historical data in the conventional sense (Buysse et al. 2007). Nevertheless, our model is able to almost exactly reproduce the observed crop choices in the reference period. For Bajo Gállego, the model slightly overestimates the area of sunflower production and fallow land and underestimates alfalfa production. An explanation for the overestimation of fallow land is that farmers in the area were found to prefer growing crops over fallowing in case of negligible gross margins. An example comparison of observed land use and simulated land use in 2003 for Violada and Bajo Gállego jointly is provided in Fig. 5 while comparisons for other years show similar results and are not presented here for the sake of brevity.

Scenarios

We construct five scenarios based on currently ongoing developments in the catchment to simulate their impact on water uses and flows. The first scenario relates to climatic change impacts, while the second and the third refer to socioeconomic developments concerning irrigated agriculture. The fourth and fifth global change scenarios consider different combinations of the first three scenarios.

Climatic change scenario

Climatic change effects on temperature, precipitation, evaporation and soil moisture are expected to have a large impact on the hydrological cycle and river flow in particular throughout Europe (IPCC 2007). In the present study,

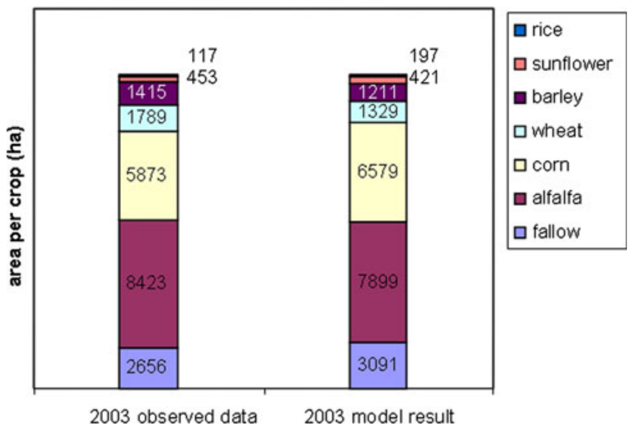

Fig. 5 Comparison of observed and modeled land use in 2003 for both Violada and Bajo Gállego (in hectares)

climate simulations for the Iberian Peninsula were recovered from results by the PRUDENCE EU project (Christensen et al. 2007). These projections indicate increased temperatures, predominantly in summer, decreased summertime precipitation and a small increase in winter precipitation (Fowler et al. 2007). Notwithstanding uncertainties, these impacts are expected to increase water scarcity problems in the Gállego.

This first scenario is constructed by downscaling projections from the PRUDENCE simulations representing a stationary climate for the three timeslices 2011–2040, 2041–2070 and 2071–2100. In particular, we consider a regional climate model (RCM) corresponding to the A2 emissions scenario of IPCC (2007) from the six different macroareas adopted by Majone et al. (2012). Projected precipitation and temperature data were downscaled from the RCAO (Rossby Centre regional Atmosphere–Ocean, Jones et al. 2004) RCM driven by boundary conditions derived from the Global Circulation Model ECHAM4/OPYC3 (Roeckner et al. 1996), which has proved to be the driest and hottest regional climate model for the Gállego river basin. Furthermore, RCAO projections for precipitation and temperature adopted in the present study show similar patterns to those presented by López-Moreno et al. (2011), where climate simulations for the Ebro basin were extracted from the ENSEMBLES EU-project RCM dataset (van der Linden and Mitchell 2009) and by Barrera-Escoda and Cunillera (2011) where dynamical downscaling technique was employed to generate projections over the Catalunya region based directly on the outputs of an atmosphere–ocean global model.

Increase in water storage capacity and irrigated land extension scenario

The national and basin hydrological plans suggest infrastructure development, water transfers and dam construction in order to extend the amount of irrigated area to improve the agriculture competitivity. This scenario corresponds to an increase in water storage capacities in the Gállego catchment, which is meant to supply an additional 5,800 m^3/ha water to an extension of 6 000 ha of irrigated agriculture northeast of the Violada area. The scenario implies the construction of a new dam, the Biscarrués dam, or an equivalent series of smaller dams. The original plans contemplated an additional storage capacity of 192 hm^3 with the infrastructure being located just above the Ardisa reservoir. This project faced a lot of opposition among the local communities, and a new project with a reduced storage capacity of 35 hm^3 was then discussed and estimated at € 138 million (Arrojo 2011), see "Increase in reservoir capacity" section.

Modernization of irrigation technique scenario

Besides infrastructure development, hydrological plans also envision modernization of irrigation techniques in order to improve the agriculture competitivity. This scenario concerns the modernization of irrigation technology in both irrigation districts in order to increase water use efficiency (see e.g., Perry et al. 2009). In the reference period, flood irrigation accounts for 80 % of irrigated area in Violada and 95 % in Bajo Gállego. In this scenario, 50 % of all irrigated area will be equipped with sprinkler irrigation, which requires about 20 % less water per hectare. This scenario loosens the water scarcity constraint to farmers and is thereby expected to increase farm profits. The investment cost of modernization is estimated to be around € 3,330 per ha.[5]

Global change scenarios

The two global change scenarios, GC1 and GC2, are combinations of the scenarios described above. Their characteristics are shown in Table 1. GC1 combines the climatic change scenario, the increase of 35 hm^3 in the water storage capacity and modernization of irrigation technique for 50 % of irrigated land. GC2 is similar to GC1 but does not include the increase in water storage capacity. This scenario enables us to evaluate the marginal effects of the proposed dam construction in terms of mitigating climatic change effects.

Results

The hydro-economic model was used to simulate water scarcity, salinity and agricultural profits for each of the five

[5] Depending on field characteristics and required network adaptations (http://www.riegosdelaltoaragon.es).

Table 1 Main characteristics of the global change scenarios

	Reference	Global change scenario 1	Global change scenario 2
Reservoir capacity	261 hm^3	261 + 35 hm^3 (Biscarrués dam)	261 hm^3 (no extension)
Irrigation technology	80 % flood irrigation in Violada and 95 % in Bajo Gállego	50 % sprinkler irrigation and 50 % flood irrigation in both Violada and Bajo Gállego	
Hydrology	Reference period 2001–2005	Rossby Centre regional Atmosphere–Ocean model 2071–2100	

Table 2 Overview on impacts of scenarios on main indicators (average values for either the reference period 2001–2005 or the 30-year period 2071–2100 for the climatic change and global change scenarios)

	Reference	Climatic change (%)	Dam extension (35 hm^3) (%)	Modernization (50 %)	GC1 (%)	GC2 (without reservoir extension) (%)
Irrigated area (ha)	15.550	−3	0	+4	+1	+1
Total water delivery (million m^3/year)[a]	415	−4	0	−2	−3	−4
Average regional agricultural income (€ million)	9.40	−8	0	+27	+22	+22
Salt emissions (1,000 T/year)	248	−4	0	+7	+4	+4

[a] This estimate includes water channeled to Cinca basin by means of the Monegros channel

scenarios, using the coupling procedure described in "Model overview" section. The reservoir extension and modernization scenarios have been simulated for different levels of climatic conditions, corresponding to the reference period 2001–2005, whereas the climatic change and the global change scenarios have been simulated over the 30-year period, 2071–2100. A summary of the main results is reported in Table 2.

Climatic change scenario

The water inflow in the Sotonera dam shows a decreasing trend over time, and the threshold level of water below which water becomes a constraining factor to farmers (421 hm^3 at La Sotonera dam) is harder to meet over time. This may occur even if the total annual water inflow in the La Sotonera dam is above this value due to a higher concentration of rainfall during winter than during summer. For an extended discussion on hydrological results see Majone et al. (2012).

Irrigated area decreases by 3 % on average, while water delivery to agriculture decreases by 4 % compared with the reference scenario (see Table 2). Overall, the climatic change scenario implies for the 2071–2100 period a decrease in average regional agricultural income of 8 % compared to the reference period, because farmers are constrained by limited water availability.

More land is fallowed, production of corn and alfalfa decreases, and only wheat shows an increase in production. This scenario seems to have a small positive impact on salt emissions which reduce by 4 % as a consequence of the decrease in both irrigated area and water use.

Increase in reservoir capacity

Model simulations show that the increase in storing capacity (35 hm^3) has negligible effects on agriculture as irrigated area and water supply remain largely unchanged (see Table 2). Water, rather than land, remains the limiting factor in agricultural production so that the aim of land extension is not realized by the increase in water storage capacity. The additional storage capacity is not able to increase significantly the water volume stored in the La Sotonera dam (see Fig. 4a). Indeed, the simulated water volume (black dotted line) is not distinguishable from the reference case simulation (pink line). This is particularly evident for the dry years 2002 and 2005 when the Biscarrués dam is completely depleted (see Fig. 4b).

This result shows that the construction of the new dam cannot prevent income losses due to water shortage in years with low precipitation. The reservoir management rules which control the transfer of water to the La Sotonera dam allow the Biscarrués dam to be filled only when incoming flows exceed a value of 105 m^3/s which accounts for the 90 m^3/s capacity of the artificial channel connecting the two reservoirs (see Fig. 2a) and the streamflow of 15 m^3/s diverted to the Marracos power plant. As a consequence, the Biscarrués dam will only be filled during important flood events.

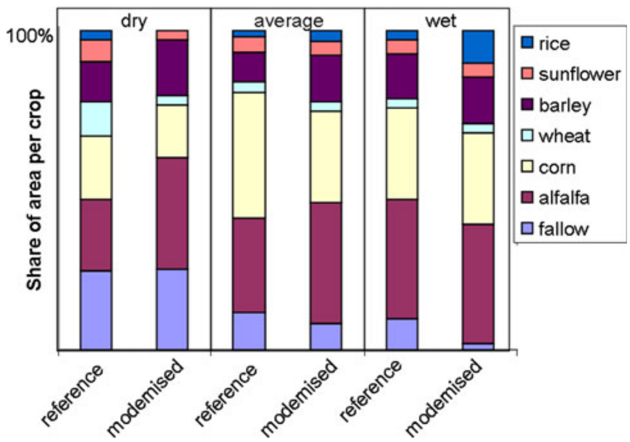

Fig. 6 Cropping pattern in Violada before (reference) and after modernization to 50 % sprinkler irrigation. Dry, average and wet refer to climatic conditions in a typical dry, average and wet year as measured by water availability from the La Sotonera dam

The infrastructure cost estimated to about € 6.2 million per year (Arrojo 2011) is not compensated by any increase in regional agricultural income.

Modernization of irrigation techniques

Modernization of irrigation technology enables us to decrease water use per crop and per hectare by increasing the efficiency of each water drop at the field scale. The total water use decreases by 2 %, while the irrigated area increases by 4 % (see Table 2). Despite the small increase in irrigated area, modernization does not enable land extension beyond currently available irrigable land. Nevertheless, this scenario has a significant impact on the cropping pattern in both irrigation districts. In Fig. 6, this impact is illustrated for the Violada irrigation district for three climatic conditions, dry, average and wet, corresponding to water availability from the La Sotonera dam, respectively, 300, 400 and 450 hm^3.[6] Two impacts deserve attention. First, for all conditions, modernization causes an increase in the area planted with alfalfa and barley and a decrease in corn and wheat, because the former two crops become relatively cheaper to produce when water use efficiency increases. Related to this, modernization does not necessarily imply less land being fallowed (only under average and wet conditions). Second, except for a difference in the number of hectares planted with rice, the cropping pattern for wet and average years is identical under modernization. This indicates that water scarcity for these conditions is not a major constraining factor. When there is no water scarcity, more efficient irrigation techniques will not significantly change the cropping pattern; here it enables to grow more rice and reduce the area of fallow land. In the Bajo Gállego, the effects are only slightly different, because there is an effect on both average and dry years: The cultivated area increases due to less water application per hectare compared with flood irrigation. Modernization of Bajo Gállego has a larger impact, mainly because 20 % of Violada has already been modernized in the reference period compared with 5 % for Bajo Gállego.

Average regional agricultural income increases by 27 % due to increased cultivated area and more flexibility in cropping patterns. Modernization leads to a 7 % increase in salt emissions on average over the reference period.[7]

All in all, modernization appears to imply lower levels of water use, mainly in wet years. In dry years, farmers use all the water that is available. Because water use and salt emissions are positively related, a decrease in water use leads to a decrease in salt emissions (per hectare). This effect, however, is offset by the switch from flood irrigation to sprinkler irrigation. Sprinkler irrigation causes a higher salt concentration in the irrigation return flow than flood irrigation. As a consequence, there is a trade-off between quantity of return flow and salt concentration; water use has to be sufficiently high to have sprinkler irrigation emits less salt than flood irrigation. This result corresponds to results found by Lecina et al. (2010) and Causapé et al. (2004b) in the Ebro river basin and the analysis of Mema (2006), although he did not specify the effects on cropping patterns and the trade-off between salt concentration and water use for flood irrigation and sprinkler irrigation.

The cost of modernization amounts to around € 3 million per year for the whole modernization (50 % of the fields, i.e., around 10,000 ha); they are not completely covered by the extra income provided by the modernization.

Global change scenarios

In line with the results obtained under the reservoir extension scenario detailed in "Increase in reservoir capacity" section, the effect of reservoir extension in the presence of climatic change (GC1) is negligible compared to the climatic change scenario. As a result, the outcomes of both global change scenarios are almost identical. In GC1 and GC2, and similar to the climatic

[6] Note that these conditions are only presented as an illustration; in our calculations the corresponding cropping patterns for each level of water availability have been determined.

[7] If 80 % (instead of 50 %) of all irrigated area is equipped with sprinkler irrigation, the irrigated area would increase by 8 % (compared to 4 % in the 50 % modernization case). Average regional agricultural income increases by 38 % (compared with 27 %).

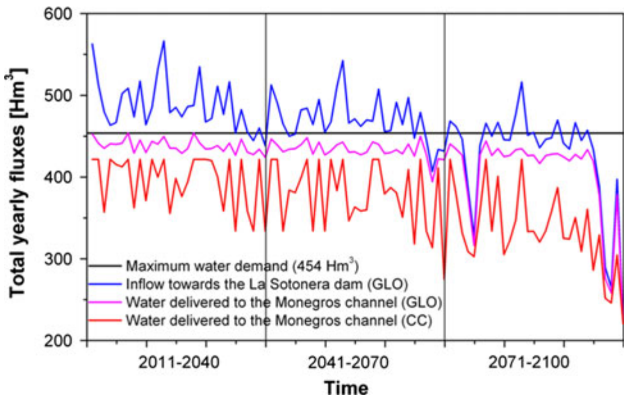

Fig. 7 GC1 scenario total yearly inflow toward the La Sotonera dam (*blue dashed line*) compared to the water delivered from the dam to the Monegros channel (*pink line*) under the same GC1 scenario. The *green symbols* present the water delivered from the dam to the Monegros channel for the GC2 scenario, while the *horizontal black line* represents the constant value of 454 hm^3 (maximum water required from the irrigation system with modernization) (color figure online)

change scenario, the total inflow in the dam (see the blue dashed line in Fig. 7 for the case of GC1) shows a decreasing trend over the 2011–2100 period accompanied by an increase in the frequency of dry years where the annual inflow is below the maximum water demand of the agricultural districts connected to the dam (see the horizontal black line in Fig. 7). This reduction in total annual inflow to the dam coupled with the change in seasonality of meteorological forcing explains why the water delivered from the La Sotonera dam is often lower than the maximum water demand of agriculture, though the annual incoming fluxes are above this threshold. They both have a positive outcome for the agricultural sector as they lead to an extension of 1 % of the irrigated areas and an increase in regional agricultural income by 22 % compared with the reference scenario. This result is achieved despite a decrease in average water delivery due to climatic change. This decrease equals 3 % for GC1 and 4 % for GC2.

The effect of the global change scenarios on salt emissions by agriculture districts is an increase by 4 % compared with the reference scenario (recall that in the climatic change scenario there was a decrease in salt emissions by 4 %).

The comparison between the global change and the climatic change scenarios shows that modernization can mitigate the negative effects of climatic change-induced water scarcity, whereas the storage extension of 35 hm^3 has only a negligible effect. Modernization offsets water reductions by improving field water efficiency and changing cropping patterns, thereby increasing regional agricultural income, similar to the modernization scenario.

Again, the cost of the dam is not outweighed by the increased regional agricultural income. The modernization thus appears to cover almost, but not totally, the costs of its implementation (the net cost is € 0.2 million). However, this does not account for the impact of salinity.

Conclusions

The hydro-economic model presented in this paper was used to simulate the effects of several realistic scenarios on the hydrology and the agricultural sector of the Gállego catchment. We find that our compartment model allows us to derive very specific results on the expected changes in cropping patterns, regional agricultural income and hydrology.

Our first main result is that modernization is able to reduce the reduction in water availability for the farming sector caused by climatic change even if its costs are significant. A second main result is that modernization of irrigation technology has a very positive outcome on regional agricultural income, but at high implementation costs (that are not totally covered by the extra income) and at the expense of increased pressure on the environment through increased salinity. Finally, the planned reservoir extension appears to have no effect on water supply for extra irrigated land and cannot mitigate the negative effects of climatic change on water availability. This result is of high relevance to local decision-makers. Our results, like Ward and Pulido-Velazquez (2008) and Molden et al. (2010), show that field water savings do not necessarily induce basin-scale water savings.

Our model could be extended, for instance, by modeling the downstream reuse of return flows from upstream inefficient irrigation systems. We name four other possible extensions. First, reservoir management rules could be made contingent on changing conditions. Second, both onsite and off-site effects of salinity could be modeled explicitly. Third, the model could be extended with variable output prices of the agricultural sector, combined with risk aversion in farm behavior (e.g., Graveline et al. 2012). Fourth, uncertainty in the model chain could be analyzed to assess the robustness of results presented in this study and, in general, with similar hydro-economic modeling approaches.

The practical relevance of our model is twofold. First, the model enables us to combine different factors of change in one scenario in order to simulate possible future outlooks. Such outlooks can assist decision-makers in river basin planning by providing them a view of the basin with ongoing climatic change effects as well as policies to adapt to these effects. This possibility is especially relevant in the context of ongoing developments following the Water

Framework Directive and its requirements for water bodies; second, our model can be used to test particular policies or impacts in order to assess their individual (marginal) effects on hydrology and agriculture, and this is of particular interest for climatic change impact studies. Indeed, if current policies do not suffice to meet good ecological status of water bodies, extra measures will have to be implemented and their effectiveness evaluated on a ex-ante basis. The framework and model presented in this paper are appropriate to do so.

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Appendix 1: Details on the GEOTRANSF model (hydrology)

Daily precipitation and temperature at 32 rain gauges and 26 temperature stations within the catchment were available from CHE (2007) during the period 2001–2005. Daily precipitation was distributed spatially by using the Ordinary Kriging method and considering the eight nearest stations to the interpolation point, which in our scheme corresponds to the center of mass of each subcatchment. Temperature was computed for each subcatchment by linear interpolation with elevation. The interpolation was performed by using the six closest temperature stations, and the subcatchment was assigned the temperature corresponding to its mean elevation. Potential evapotranspiration has been calculated with the method of Hargreaves and Samani (1982) which depends only on the mean, maximum and minimum daily temperatures of the subcatchments. Notice that potential evapotranspiration was transformed into actual evapotranspiration by means of a linearly varying water stress reduction function following the approach proposed by Rodríguez-Iturbe and Porporato (2004, chap. 2.1.5). Land use and geology information available for the Gállego catchment have been used in order to apply the Soil Conservation Service Curve Number model (SCS-CN, Michel et al. 2005) which is the method present in the infiltration module of GEOTRANSF.

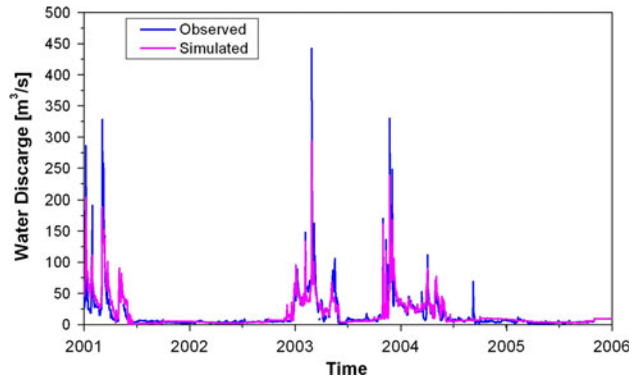

Fig. 8 Observed (*blue line*) versus simulated (*pink line*) daily streamflow during the period 2001–2005 computed at node 6 and obtained by calibrating the model on the year 2003 (color figure online)

Calibration and validation

The classical Nash–Sutcliffe (NS) efficiency coefficient (Nash and Sutcliffe 1970) was adopted to evaluate the performances of hydrological modeling. According to this metric, NS equals 1 when the match between the model and the observed data is perfect, while when NS < 0 the model should be disregarded because its predictions are worse than approximating all the observational data with their sample mean. As an example, with reference to the Saragoza node, the set of parameters obtained by calibrating the model to the year 2003 produced a relatively high NS value of 0.81 and NS ranging from 0.51 to 0.8 when applied in the validation of the remaining years. This is evidence that the set of parameters obtained by calibrating to the year 2003 provides a good reproduction of the streamflow recorded in other periods as also shown in Fig. 8. In particular, the model has performed well and has been able to predict correctly the magnitude and timing of storm events (see Fig. 8) and also the shape of the stormflow recessions both in dry and in wet periods, although peak flows are sometimes underestimated. Notice that similar results were also obtained for the other nodes.

A more detailed description of the implementation of GEOTRANSF model to the Gállego catchment and of the calibration and validation procedure can be found in the work of Majone et al. (2012). It presents an assessment of the projected impacts of climatic change on streamflow and water resources of the catchment by adopting an ensemble of future climate experiments (one of which is used in the present work) and provides a robust validation of the whole modeling framework (i.e., hydrological modeling and reservoir operation model) by also verifying the model performances during a much longer time period, that is, 1961–1990.

Appendix 2: Details to the economic model

Model

The agro-economic model maximizes regional profits Π as follows (for ease of notation, a subscript to denote years is not included):

$$\Pi = \sum_{n \in N} \sum_{g \in G} \left(q_{ng} \cdot p_g\right) - \left(w_{ng} \cdot r\right) - t_{ng} + s_{ng} \tag{1}$$

with $q_{ng} = \sum_{j \in G} x_{nj} \cdot y_j$, $w_{ng} = \sum_{m \in M} \sum_{j \in G} x_{nj} \cdot u_{jm}$, and $t_{ng} = \sum_{j \in G} x_{nj} \cdot c_g$, where $q_{ng} \geq 0$ is the production of crop $g \in G$ in municipality $n \in N$, $p_g \geq 0$ is the crop price, $w_{ng} \geq 0$ is water use, r is the water price, t_{ng} is the total remaining production costs, and s_{ng} is a subsidy. x_{nj} is the area cultivated with Land use system $j \in J$ (defined by crop g and irrigation technique i) in municipality n, $y_j \geq 0$ is the yield, $u_{jm} \geq 0$ is the water use of Land use system j in month $m \in M$, and $c_g \geq 0$ are crop-specific costs. The following constraints hold:

$$\sum_{j \in I} x_{nj} \leq l_{ni} \tag{2}$$

$$\sum_{n \in N} \sum_{g \in G} w_{ng} \leq a \tag{3}$$

$$\gamma_{ng} = \sum_{z \in Z} \gamma_{ngz} b_z \tag{4}$$

Constraint (2) is a land constraint, saying that the total cultivated area in municipality n should not outweigh total available land l_n in municipality n, subdivided by irrigation type $i \in I$. Water constraint (3) says that water use over all municipalities should not outweigh total water availability a. Constraint (4) assures a convex combination of historical crop mixes, where γ_{ng} denotes current crop choice in municipality n, γ_{ngz} denotes the historical crop mix in year z, and $b_z \geq 0$ is a variable that denotes the share of each historical crop mix in the solution with $\sum_{z \in Z} b_z = 1$. This constraint assures that the solution is a convex combination of historical crop mixes, in the sense that it prevents the model from choosing crop mixes that lay beyond the boundaries of crop mixes that have been chosen in the past. Doing so, this constraint prevents unrealistic crop mixes, thereby implicitly accounting for crop rotation and other practices that affect crop choice (McCarl 1982; Chen and Önal 2012). Because the reference years have a large variation in terms of water availability, this constraint allows the model to provide realistic output in simulated drought years caused by climatic change. The drawback of this approach is that an aggregation bias might occur, in the sense that the model is not capable of producing sensible crop choices when water availability (or some other model input) has a value outside the range of its historical levels.

Table 3 Data used in the economic model: prices and costs of the six crops included in the model

Crop	Output price (EUR/kg)	Production costs (EUR/ha)
Alfalfa	0.12	658.72
Corn	0.12	947.86
Wheat	0.13	658.27
Barley	0.12	446.31
Sunflower	0.21	328.00
Rice	0.26	879.65

Source: Mema (2006)

In our results, we did not find strong effects of this drawback, mainly because of the large variation in water availability in the reference period, and that changes implied by climatic change are largely within this range.

An extension to our economic model allows estimating salt emissions from agricultural activities. Salt levels in irrigation return flows are closely related to cropping patterns, irrigation techniques and management, irrigation time and period, soil characteristics, land levelling, annual climatic characteristics and adaptation to climatic conditions. These are roughly the same factors that contribute to irrigation efficiency at the field level (e.g., Causapé et al. 2006). We do so by using salt emission functions and parameter values based on Esteban and Albiac (2007). These salt emission functions calculate the salt emission e_n in municipality n as a function of water use:

$$e_n = \sum_{g \in G} \beta_0 + \beta_1 w_{ng}$$

Esteban and Albiac (2007) calibrated β_0 and β_1 on the neighboring Bardenas area, and we corrected these values for differences in irrigation efficiency and techniques.[8] We remark that a specific transport module for salt emissions is not included in the hydrological model and thus the effect of downstream reuse of water with high concentrations is not considered.

Data

Crop price data, cost data, subsidy data and yield data are taken from Mema (2006) for the year 2005 (see Table 3). Water price data are taken from Esteban and Albiac (2007). Water use data, irrigation technique data, land availability

[8] As soil characteristics and water use are not exactly the same, we compared results given by the function with salt loads provided by Causapé et al. (2006) and corrected the coefficients in order to consider moderate presence of gypsum soils.

data and historical crop mix data are obtained from the research institute Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), Spain. Finally, water availability is calculated on irrigation district level using a database that registers the water outflow from the La Sotonera dam (CHE Web site).

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