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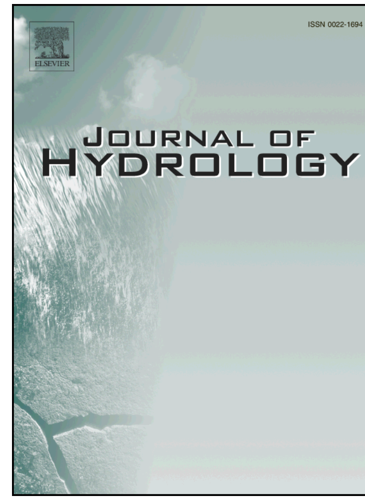

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Hydro-economic modeling with aquifer-river interactions to guide sustainable basin management

Mohamed Taher Kahil [a], **Frank A. Ward** [b], **Jose Albiac** [c,*], **Jack Eggleston** [d], **David Sanz** [e]

[a] Water Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[b] Department of Agricultural Economics and Agricultural Business, New Mexico State University, Las Cruces, New Mexico
[c] Department of Agricultural Economics, CITA-Government of Aragon, Saragossa, Spain
[d] US Geological Survey, New England Water Science Center, USA
[e] Institute for Regional Development, University of Castilla-La Mancha, Albacete, Spain

[*] Corresponding author: J. Albiac, Department of Agricultural Economics, Agrifood Research and Technology Center, CITA-Government of Aragon, Av. Montañana 930, 50059 Zaragoza, Spain (maella@unizar.es)

E-mail addresses: mt.kahil@gmail.com (M.T. Kahil); fward@nmsu.edu (F. Ward); maella@unizar.es (J. Albiac); jegglest@usgs.gov (J. Eggleston); David.Sanz@uclm.es (D. Sanz)

Abstract

Policymakers in arid and semiarid basins face hard choices on water policies needed for adaptation to climate change. Hydro-economic modeling is a state-of-the art approach that can be used to guide the design and implementation of these policies in basins. A major gap in developments of hydro-economic modeling to date has been the weak integration of physically-based representations of water sources and uses such as the interaction between ground and surface water resources, to inform complex basin scale policy choices. This paper presents an integrated hydro-economic modeling framework to address this gap with application to an important and complex river basin in Spain, the Jucar basin, for the assessment of a range of climate change scenarios and policy choices. Results indicate that in absence of adequate policies protecting water resources and natural ecosystems, water users will strategically deplete reservoirs, aquifers and river flows for short-term adaptation to climate change, disregarding the impacts on the environment and future human activities. These impacts can be addressed by implementing sustainable management policies. However, these policies could have disproportionate costs for some stakeholders groups, and their opposition may undermine attempts at sustainable policy. These tradeoffs among water policy choices are important guides to the design of policies aimed at basin-wide adaptation to climate change.

Keywords. Hydro-economic modeling, aquifer-river interactions, climate change, water policies

Highlights

- A hydro-economic model with aquifer-river interactions is developed
- The model integrates a spatially-explicit groundwater flow formulation
- The model is used to analyze the outcomes of various climate change scenarios and policy choices

1. Introduction

Policymakers in arid and semiarid basins face hard choices on water policy design for adaptation to climate change. Well-designed policies must account for complex environmental and economic tradeoffs, which point to the need for developing and using integrated tools capable to jointly address these tradeoffs based on sound science. Hydro-economic modeling is a state-of-the art tool to inform the design of integrated water policies at the basin scale. Hydro-economic models integrate the spatially distributed water sources, water storage and conveyance infrastructures, water-based economic activities, and water-dependent ecosystems into a unified framework. The advantage of this approach is the formulation of interrelationships among hydrologic, economic, institutional and environmental components for a comprehensive assessment of the tradeoffs among water policy choices (Harou et al., 2009).

Despite the significant advancement in hydro-economic modeling since the 1980s, several gaps remain unsettled in the literature, and progress in the development and application of hydro-economic models is needed to realize their full power to inform critical policy debates (Booker et al. 2012). One important gap not yet filled in the development of most hydro-economic models is the typically highly simplified modeling of interactions between groundwater and surface water flows. This linkage is important when aquifer systems are closely related to river flows making a sizable inflow or outflow contribution to basin resources. An earlier study by Burness and Martin (1988) suggests that the linkage between ground and surface water use requires detailed and careful attention to guide water policy design. They point out that the failure to account properly for river-aquifer linkage, when important, risks leading to misguided policy recommendations, either over-depleting or underusing basin water resources.

This paper presents the development of a fully-integrated (holistic) hydro-economic modeling framework capable to address the tradeoffs among water policy choices for climate change adaptation. The contribution of this paper relative to prior literature stems from a more unified treatment of basin dynamics and the explicit specification of the interactions between ground and surface water flows. The modeling framework is solved in its entirety, and information among the economic and hydrological components over all periods and locations is jointly and simultaneously determined. This framework is applied to the Jucar basin in Spain to identify the tradeoffs among policy choices and the hurdles facing the implementation of sustainable management under various climate change scenarios.

The paper is organized as follows. First, a literature review on the specification of river-aquifer interaction in hydro-economic models is presented in section 2, followed by the description of the modeling framework in section 3. Model application is presented in section 4, and the results in section 5. Finally, section 6 concludes with the summary and policy implications.

2. Literature review: hydro-economic modeling of river-aquifer interaction

This section reviews selected policy-oriented hydro-economic models at basin-level that include an economic objective function and representations of rivers and aquifers and the interaction between them. A more comprehensive literature review from hydraulic and hydrogeological views can be found in Sophocleous (2002), and Barthel and Banzhaf (2016).

Typically, aquifer dynamics and river-aquifer interactions have been simplified in hydro-economic models, because of the high level of complexity already involved in modeling whole river basins. Two simplifications are common. First, aquifers are mostly represented as simple single-tank units. Second, the linkage between aquifer and river flows is often represented using linear estimates relating the stream-aquifer flow with variables such as aquifer recharge, groundwater pumping, or water table levels. For example, Danskin and Gorelick (1985) present a combined ground and surface water economic management model that includes streamflow-recharge relationships based on field observations. McCarl et al. (1999) use regression-based forecasts of aquifer discharges that respond to recharge, pumping and water table levels. Cai et al. (2003) use a single-tank formulation and assume a linear relationship between aquifer discharge and water table levels. Ward and Pulido-Velazquez (2009) use single-tank formulation and estimate discharge as a proportion of recharge. Daneshmand et al. (2014) follow the same approach to optimize conjunctive management of water resources for mitigating impacts of droughts.

Some innovative studies in the hydro-economic literature have made progress in the representation of groundwater flow and river-aquifer interaction by incorporating spatially-distributed groundwater formulations into economic optimization frameworks. Pulido-Velazquez et al. (2008) present a holistic hydro-economic model with conjunctive ground and surface water use. They apply both the Eigenvalue and the Embedded Multi-reservoir methods to model groundwater dynamics and river-aquifer interactions. However, these methods have not been widely used in the literature. The study by Kuwayama and Brozovic (2013) develops an economic optimization model of agricultural groundwater use. It accounts for stream depletion using the Glover analytical solution, in order to test the effects of spatially differentiated groundwater pumping regulations. Although much work has been done to extend the applicability of analytical solutions to conditions that are typically found in the field, these solutions remain unable to address many practical applications, particularly basinwide analyses in which multiple users pump and divert water simultaneously and also numerous dimensions of water withdrawals, storage, and flows simultaneously yield economic benefits to a wide range of competing users (Barlow and Leake, 2012).

Several other studies have chosen to externally link separate hydrologic and economic sub-models. For example, Mulligan et al. (2014) evaluate groundwater management policies with coupled economic-groundwater hydrologic modeling. Medellin-Azuara et al. (2015) follow the same approach to analyze the effects of drought and groundwater overdraft, linking an economic model of agricultural production to a groundwater simulation model. Maneta et al. (2009) link an economic model of agricultural production to a detailed physically-based three-dimensional hydrodynamic model, to assess the effect of droughts. Dale et al. (2013) combine farmers' economic behavioral response functions and hydrological modeling to study conjuntive ground and surface water use. Although this approach brings in accurate hydrological details, it requires numerous iterations between the separate sub-models, together with simplified economic assumptions, which limit the comprehensiveness of the integrated environmental-economic analysis (Cai, 2008).

3. Modeling framework

An important contribution made by this paper is the development, application and use for policy analysis of a comprehensive multi-disciplinary modeling framework. This framework integrates several components including surface and groundwater hydrology, agronomy, land use, institutions, environment, and water-based economic activities. The framework is integrated, avoiding several of the simplified assumptions on both aquifer-river linkages and economic variables made in previous studies described above, as well as, bypassing iterations of temporary solutions passed among separate model elements. A description of each component of the framework as well as their integration is presented below. In all model equations, parameters are represented by lower case letters and variables are represented by capital letters.

3.1 Hydrology

The basin hydrology is represented by a node-link network based on the principle of water mass balance, defined in both flows and stocks. The flow variables tracked by the model are headwater inflow, streamflow, surface water diversion, groundwater pumping, water applied and consumed, return flow to streams and aquifers, stream-aquifer interaction, reservoir release, and reservoir evaporation. The stock variables tracked by the model are the reservoir and aquifer storage volume levels. The detailed formulation of the hydrological component is described in the Appendix.

One important component of basin hydrology, considered in this paper, is groundwater flow, calculated with a finite-difference groundwater flow equation based on the principle of water mass balance and Darcy's law. The formulation is a special case of the one used in the USGS MODFLOW groundwater flow model (McDonald and Harbaugh, 1988).

An aquifer system is divided into n (1 row, n columns and 1 layer) connected cells (sub-aquifers), aqf, which are linked to n connected reaches of a river, $river$. The aquifer head, $H_{aqf,t}$, in each sub-aquifer aqf in time t is defined by the following equation (see Appendix for details):

$$H_{aqf,t} = \left[1/\left\{\left(s_{y,aqf} \cdot a_{aqf}/\Delta t\right) + c_{aqf,aqf-1} + c_{aqf,aqf+1} + c_{river,aqf}\right\}\right] \cdot \left[r_{aqf,t} - Q_{aqf,t} + \left(s_{y,aqf} \cdot a_{aqf} \cdot H_{aqf,t-1}/\Delta t\right) + c_{aqf-1} \cdot H_{aqf-1,t} + c_{aqf+1} \cdot H_{aqf+1,t} + c_{river,aqf} \cdot H_{river,aqf}\right]; \; H_{aqf,0} = bz_{aqf,0} \quad (1)$$

Where $s_{y,aqf}$, a_{aqf}, and $r_{aqf,t}$ are specific yield, area, and recharge for sub-aquifer aqf, respectively. $c_{aqf,aqf-1}$ and $c_{aqf,aqf+1}$ represent hydraulic conductance between sub-aquifer aqf and adjacent sub-aquifers $aqf-1$ and $aqf+1$, respectively. $c_{river,aqf}$ is hydraulic conductance of river reach $river$ linked to sub-aquifer aqf. Δt is the time step. $bz_{aqf,0}$ is the initial head of sub-aquifer aqf, at $t=0$.

$H_{aqf,t-1}$ is the head of sub-aquifer aqf in the previous time period $t-1$. $H_{aqf-1,t}$ and $H_{aqf+1,t}$ are heads of adjacent sub-aquifers $aqf-1$ and $aqf+1$, respectively. $H_{river,aqf}$ is the head of the river reach $river$, linked to sub-aquifer aqf, and $Q_{aqf,t}$ is net groundwater pumping from sub-aquifer aqf, which are defined in equations (2) and (3) as follows:

$$H_{river,aqf} = bh_{river,aqf} \cdot (\sum_v b_{v,river,aqf} \cdot X_{v,t}) \quad (2)$$

$$Q_{aqf,t} = \sum_p b_{p,aqf} \cdot X_{p,t} - \sum_r b_{r,aqf} \cdot X_{r,t} \quad (3)$$

where $X_{v,t}$ is streamflow at each river gauge node, v; $X_{p,t}$ is gross groundwater pumping at each pumping node, p; and $X_{r,t}$ is return flows at each return flow node, r, in time t. $bh_{river,aqf}$ are coefficients defining the relationship between river head (river stage) and streamflow (discharge) for each river reach. This relationship depends on river features such as riverbed form and roughness coefficients. $b_{v,river,aqf}$, $b_{p,aqf}$ and $b_{r,aqf}$ are binary matrices linking river reaches to river gauge nodes, and sub-aquifers to pumping and return flow nodes, respectively.

The interaction between each sub-aquifer and the corresponding river reach is defined in the following equation:

$$X_{river,aqf,t} = c_{river,aqf} \cdot \left(H_{aqf,t} - H_{river,aqf,t}\right) \quad (4)$$

Equation (4) states that water flows between river reach $river$, and sub-aquifer aqf, $X_{river,aqf,t}$, depend on river and sub-aquifer heads and hydraulic conductance of river reach, with $X_{river,aqf,t}$ being positive if a sub-aquifer is discharging water to river reach. Water flows from cells of higher head to cells of lower head.

3.2 Land Use

For irrigated agriculture, land in production in each agricultural use node, ag (a subset of the set u that includes all use nodes in the basin), which produces irrigation water demand in that node, is defined in the following equations:

$$\sum_{j,k} L_{ag,j,k,t} \leq landavail_{ag,t} \quad (5)$$

$$L_{ag,per,k,t} \leq L_{ag,per,k,t-1} \quad (6)$$

Equation (5) states that the sum over crops (j) and irrigation technologies (k) of irrigated land in production, $L_{ag,j,k,t}$, at each agricultural use node in time t, cannot exceed land availability, $landavail_{ag,t}$, in that use node and time period. Equation (6) states that irrigated land in production $L_{ag,per,k,t}$, of perennial crops, per (a subset of j), at each agricultural use node in time t, cannot exceed perennial irrigated land for that use node in the previous time period $t-1$. This constraint guards against the high future loss of long-run capital investments in perennial crops like orchards and vines if farmers avoid irrigating those crops in the current time period.

3.3 Institutions and Environment

Water administration in arid and semiarid regions imposes several institutional and environmental constraints on water use and management, such as allocations rules, minimum supply requirements, and minimum environmental flows. The reasons are the need to satisfy human water needs, meet delivery obligations to downstream users, and protect valuable aquatic ecosystems, among others.

In this paper, several institutional and environmental constraints are specified depending on the climate and policy scenarios considered. A politically required lower bound constraint on urban water supply is protected in all scenarios in order to assure that a minimum amount of water, bx_{urb}^{min}, is delivered to urban use nodes, urb (a subset of u), in each time period t. This constraint is defined in the following form, which reflects a zero price elasticity of demand for urban use:

$$X_{urb,t} \geq bx_{urb}^{min} \tag{7}$$

3.4 Economics

Water has an economic value in all its competing uses. That value is determined by the total willingness to pay of users benefiting from it. For agricultural use, the economic value of water is measured by the contribution of water to farmers' net benefits. For urban use, it is measured by the sum of the consumer and producer surplus.

Net benefits, $NB_{u,t}$, at each use node u in time t is defined as follows:

$$NB_{u,t} = TB_{u,t} - TC_{u,t} \tag{8}$$

where $TB_{u,t}$ and $TC_{u,t}$ are the total benefits and costs at each use node u in time t, respectively.

For agricultural use nodes ag, total benefits, $TB_{ag,t}$, and total costs, $TC_{ag,t}$, in time t are defined by the following equations:

$$TB_{ag,t} = \sum_{j,k} \left(p_{ag,j} \cdot Y_{ag,j,k,t}\left(L_{ag,j,k,t}\right)\right) \cdot L_{ag,j,k,t} \tag{9}$$

$$TC_{ag,t} = \sum_{j,k}\left(pc_{ag,j,k,t} + WC_{ag,j,k,t}\right) \cdot L_{ag,j,k,t} \tag{10}$$

where $p_{ag,j}$ is crop prices; $pc_{ag,j,k,t}$ is non-water production costs, and $L_{ag,j,k,t}$ is crop area.

$Y_{ag,j,k,t}$ is the yield of each crop j equipped with irrigation technology k. Yield is specified as linear in the amount of land in production. The yield functions take the following form:

$$Y_{ag,j,k,t}(L_{ag,j,k,t}) = \alpha_{0,ag,j,k} + \alpha_{1,ag,j,k} \cdot L_{ag,j,k,t} \tag{11}$$

in which $\alpha_{0,ag,j,k}$ is the intercept of the function which depicts crop yield for the first unit of land brought into production, and $\alpha_{1,ag,j,k}$ is the linear term of the function which depicts the marginal effect of additional land on average yield. More details on crop production functions can be found in the Appendix.

$WC_{ag,j,k,t}$ is water costs which are defined as follows:

$$WC_{ag,j,k,t} = pw_{ag} \cdot \left(\sum_d b_{d,ag} \cdot X_{d,j,k}\right) + \left(cp_{0,ag} + cp_{1,ag} \cdot PD_{ag}\right) \cdot \left(\sum_p b_{p,ag} \cdot X_{p,j,k}\right) \tag{12}$$

where pw_{ag} is surface water price, $cp_{0,ag}$ is pumping cost not related to the level of the water table (investment, operation and maintenance of the well and pump equipment), and $cp_{1,ag}$ is pumping cost related to the water table level or energy costs of lifting water from the water table to land surface. PD_{ag} is the pumping depth, the difference between the water table level (aquifer head) and land surface elevation. $X_{d,j,k}$ and $X_{p,j,k}$ are the water applied to crops supplied with surface water and groundwater, respectively. $b_{d,ag}$ and $b_{p,ag}$ are vectors of coefficients that conform use nodes to diversion and pumping nodes, respectively.

For urban use nodes, urb, total benefits, $TB_{urb,t}$, and total costs, $TC_{urb,t}$, in time t are defined by the following equations:

$$TB_{urb,t} = \beta_{0,urb} + \beta_{1,urb} \cdot X_{urb,t} + \beta_{2,urb} \cdot X_{urb,t}^2 \tag{13}$$

$$TC_{urb,t} = \delta_{urb} \cdot X_{urb,t} \tag{14}$$

where equation (13) is the total benefits function with a quadratic specification (linear demand), with parameters $\beta_{0,urb}$, $\beta_{1,urb}$ and $\beta_{2,urb}$ for the constant, linear and quadratic terms, respectively. For urban use nodes, households use water first for high-valued uses such as indoor uses for drinking, sanitation and cooking, so that urban benefits rise quickly for initial supplies allocated to these uses. These high-value uses have few substitution possibilities, and therefore $\beta_{1,urb}$ is expected to be large and positive. However, urban marginal benefits fall rapidly for other additional low-value uses, such as outdoor uses for landscape irrigation, dust control, and car washing. Then $\beta_{2,urb}$ is expected to be large and negative. Equation (14) represents total urban supply costs, with δ_{urb} being the per unit cost of water supplied.

3.5 Objective Function

The model guides and informs policy debates and choices by maximizing the net present value of the economic net benefits over the planning horizon, subject to the basin's hydrological, land use, institutional, and environmental constraints. The model provides information on the optimized water flows and stocks, land use decisions, and economic outcomes. The objective function takes the following form:

$$Max\ NPV = \sum_{u,t} \frac{NB_{u,t}}{(1+r)^t} \tag{15}$$

where NPV is the net present value, $NB_{u,t}$ are the net benefits of each water use node u in time t, and r is the discount rate.

4. Model Application

The modeling framework is applied to evaluate the effects of several climate and policy scenarios in a semiarid basin in Southeastern Spain, the Jucar basin. This basin is a good experimental region for an integrated basin scale analysis. One reason is that the Jucar is at present under severe stress, showing acute water scarcity, significant ecosystem degradation, and a politically charged relationship between ground and surface water users. Another reason is that the foreseeable climate change impacts are expected to exacerbate water scarcity problems in the basin. Moreover, the Jucar basin has been choosen as one of the pilot basins for testing the implementation of the European Water

Framework Directive. However, the modeling framework is designed to be adaptable for any basin elsewhere.

4.1 Study Area: the Jucar Basin

The Jucar basin is located in the regions of Valencia and Castilla La Mancha in Southeastern Spain and extends over 22,300 km^2. The basin is a complex system including highly developed infrastructure and various competing uses with different priority rights, and a complex interaction between surface and groundwater resources. The Jucar basin presents a ratio of 0.84 between total water demand and average renewable water resources. This value highlights the strong pressure on water resources in the basin (Momblanch et al., 2014). A detailed description of the most important characteristics of the basin can be found in Kahil et al. (2015a and 2015b).

Irrigation development during recent decades in the basin has been quite important for the local economy, and irrigated agriculture remains an essential source of income and labor in the area. The expansion of irrigation has been driven especially by groundwater pumping from the Eastern La Mancha aquifer, the largest aquifer system in Spain (Esteban and Albiac, 2012). However, intensive groundwater pumping has caused a significant drop in the water table level reaching 80 m depth in some areas, producing large storage depletion fluctuating around 2,500 Mm^3 at present. In addition, the Eastern La Mancha aquifer is linked to the Jucar River stream, and was used to feed the river with about 200 Mm^3/year in the 1980s. Due to the depletion, aquifer discharges to the river have declined considerably over the past 30 years (Sanz et al., 2011). The consequence is that the lower Jucar is undergoing severe problems of low flows and water-quality degradation, with the riverbed in the middle Jucar being completely dry during recent droughts. A major challenge for policymakers in the Jucar basin is to find a balance between ground and surface water uses, upstream and downstream uses, and instream and offstream uses, in order to adapt to impacts of climate change.

The analysis undertaken in this paper focuses on irrigation activities in the major irrigation districts in the basin: Eastern La Mancha aquifer (EM), Canal Jucar-Turia (CJT), Escalona y Carcagente (ESC), Acequia Real del Jucar (ARJ) and Ribera Baja (RB), and urban demand in the major cities: Albacete, Valencia, and Sagunto. Water extractions by numerous small demand nodes are excluded from the model. Following the study by Sanz et al. (2011), the EM aquifer area is divided into three sub-aquifers: Northern Domain (NEM), Central Domain (CEM), and Southern Domain (SEM). In addition, the analysis includes the most important aquatic ecosystems in the Jucar basin: the groundwater-dependent ecosystems in the EM aquifer, the ecosystems linked to the Jucar River, and the Albufera wetland fed by irrigation return flows in the lower Jucar. Three indicator variables are used in order to quantify the environmental impacts of the climate and policy scenarios on these ecosystems: the change in the EM aquifer storage, outflows to the Mediterranean Sea, and inflows to the Albufera wetland.

The environmental benefits and damage costs for the three aquatic ecosystems in the basin are estimated. For the Albufera wetland, an environmental benefit function of the wetland from Kahil et al. (2015a and 2016) is used. For the Jucar River-dependent ecosystems, a benefit function is specified as linear in the amounts of water in the mouth flowing to the Mediterranean Sea. We relied on valuation studies from the literature that estimate the values of the ecosystem services provided by rivers (Hatton et al., 2011). For groundwater-dependent ecosystems in the EM aquifer, a damage cost function is specified as linear in the volume of depletion following the study by Esteban and Albiac (2012).

Figure 1 around here

The model of the Jucar basin consists of 8 headwater inflow nodes, 21 river gauge nodes, 8 diversion nodes, 4 pumping nodes, 11 return flow nodes, 3 stream-aquifer interaction nodes, 3 aquifer stock nodes, and 3 reservoir stock nodes (Figure 1). The model is formulated as a dynamic nonlinear problem that maximizes the basin's net present value (equation 15) for a 20 year time period with a discount rate of 5%. The GAMS software was used for model development and scenario simulation (Brooke et al., 1988). The model is available from the authors on request. Details on data sources and the calibration procedure of the model can be found in the Appendix.

Table 1 around here

4.2 Climate Change and Policy Scenarios

Two climate change scenarios are considered in this paper: mild and severe. These scenarios cover climate change impacts on potential evapotranspiration, surface runoff, and groundwater recharge. Impact estimates are taken from climate change projections for the Jucar basin by CEDEX (2010), which downscales to basin level the results of various global circulation models and emission scenarios as shown in table 1.

The modeling framework is used to assess the outcomes of two policy alternatives under the climate change scenarios presented above. The two policy alternatives are defined as follows:

Unsustainable management policy: This policy promotes a high use of water which is above renewable water availability. The policy is implemented in the model by placing no requirements on terminal reservoir or aquifer stocks, or on yearly streamflows. Reservoirs and aquifers can be run down as low as desired up to the last time period with no regard for future water uses or environmental damages caused by water resources depletion after the last period.

Sustainable management policy: This policy promotes the sustained use of water resources, accounting for long-term economic and environmental benefits. For the purpose of this paper, sustainable water management is defined as the water extractions that do not exceed the natural replenishment rate, and streamflows comply with minimum environmental flow thresholds. This policy is implemented in the model by requiring that all aquifers and reservoirs in the basin return to their starting levels by the end of the planning period, and that annual streamflows are greater or equal to the minimum flow thresholds set for the Jucar River.

These two policy alternatives do not necessarily replicate the current water management approach in the Jucar basin, but they provide a range of the possible future climate change impacts under different water policy choices. Several adaptation measures are considered under these scenarios such as the adjustment of water allocations, changing cropping pattern, fallowing of land, investment in more-efficient irrigation technologies (sprinkler and drip), and changes in urban water prices.

5. Results and Discussion

The results for the climate change and policy scenarios are compared to those of the current situation or baseline in terms of hydrologic, land use and economic outcomes. Results are presented by demand node, sector and basin location. The tables show average values for the analyzed planning period.

5.1 Baseline Scenario

Table 2 shows the outcomes of the baseline scenario. The hydrologic outcomes of this scenario indicate that total water demand is 799 Mm^3/year, divided between 690 Mm^3 for agricultural demand and 110 Mm^3 for urban demand. The surface water diversions are 483 Mm^3 covering the agricultural and urban demand, especially in the lower Jucar region of Valencia. These surface water extractions do not deplete reservoir storage, which increases by 10 Mm^3/year because inflows exceed releases and evaporation losses. Groundwater extractions are 317 Mm^3, and constitute the major sources for the irrigation districts located in the region of Castilla La Mancha in the upper Jucar (NEM, CEM and SEM).

Table 2 around here

Results show that under the current policy setting and climate conditions, the depletion of the basin's aquifers is around 39 Mm^3/year. Depletion occurs only in the CEM sub-aquifer while the other sub-aquifers increase their storage. Groundwater discharge to the river is around 46 Mm^3/year, which is very low compared to historical discharges above 250 Mm^3 before the escalation of pumping extractions in the 1980's and 1990's (Sanz et al., 2011; Perez-Martin et al., 2014). The annual water outflow to the Mediterranean Sea is 417 Mm^3, well above the environmental flow threshold required to achieve the "nominal" good ecological status of the Jucar River (63 Mm^3). However, the environmental flow is quite small throughout the year, except during flood events. The Albufera wetland receives about 89 Mm^3/year from irrigation return flows, which complies with the wetland water requirements to achieve a good ecological status (CHJ, 2014).

Land use outcomes show that the irrigated area is 123,000 ha/year, of which 53,500 ha are cereals, 16,000 ha vegetables, and 53,500 ha fruit trees. A considerable irrigated area is grown under high-efficient irrigation technologies (34% sprinkler and 44% drip), especially in the upper Jucar. About one fifth of the irrigated area is grown under low-efficient flood irrigation technology, especially in the lower Jucar.

Economic outcomes indicate that the basin net benefits are 706 million €. Agriculture, which is the major water user in the basin, produces only 15% of net economic benefits. Environmental uses generate 29% of net benefits, and the major share of net benefits accrues to urban uses, with about 56% of the total. This large share of urban benefits is reinforced by the low price elasticity of urban demand and its associated high consumer surplus. The economic outcomes reflect the intense competition for water among agriculture, urban and environmental uses.

The last two rows in table 2 show the economic value of an additional cubic meter of water (shadow price) for farmers and households. These shadow prices provide important information to policymakers on the willingness to pay for water by users. They could guide allocation decisions, and whether to invest in developing alternative sources of water such as desalination or water conservation measures. Results show that the shadow price of water is very high for urban uses compared to agricultural uses. These results explain why the main adjustments to water scarcity usually fall upon agriculture. The marginal values of irrigation water are higher in the upper Jucar, where groundwater resources are used in more intensive and profitable production activities, compared to those in the lower Jucar based mostly on surface water.

5.2 Mild Climate Change Scenario

Tables 3 and 4 show the outcomes of the mild climate change scenario for both the unsustainable and sustainable management policies. Under this climate scenario, headwater inflows are reduced by 30%. Aquifer recharge is reduced by 21 and 27% under the *unsustainable policy* and the *sustainable policy*, respectively. Total water demand falls by only 5% under the *unsustainable policy*, but by 19% under the *sustainable policy*.

The economic outcomes of this scenario indicate that the mild climate change scenario reduces net benefits between 85 and 91 million €/year (up to 13%) compared to *baseline*. However, contrary to expectations the *sustainable policy* achieves higher net benefits compared to the *unsustainable policy* because the environmental net benefit gains (+8%) outweigh the agricultural net benefit losses (-4%) for that policy. Urban net benefits for both policies remain almost unchanged under this climate change scenario compared to *baseline* because of the very small reduction in urban water supply. Urban water prices rise slightly under both the *unsustainable policy* (1%) and the *sustainable policy* (2%) compared to *baseline*.

The major impact of climate change falls upon agriculture and natural ecosystems, which bear the costs of adaptation. The reason rests with the cutbacks in allocations to agriculture together with depleted water stocks and river flows. Agriculture gets more benefits under the *unsustainable policy* because this policy increases both surface and groundwater extractions, drawing from the water stocks in reservoirs and aquifers, and river flows. Under the *unsustainable policy*, reservoir depletion is 10 Mm^3/year, and aquifer depletion is 65 Mm^3/year, with depletion occuring in all sub-aquifers.

The *sustainable policy*, which avoids water stock depletion and protects minimum river flows, achieves higher environmental net benefits (about 8%) compared to the *unsustainable policy*. The aquifer discharges to the river increase under the *sustainable policy* compared to both the *unsustainable policy* and *baseline*. This increase in aquifer discharges to the river enhances river flows available for water users downstream, and therefore reduces pressure on the water stocks in reservoirs that can be maintained.

Compared to *baseline*, the water flowing to the Mediterranean Sea decreases considerably under climate change, regardless of the policy (up to 76%), although this water flow is higher under the *sustainable policy* than under the *unsustainable policy*. Nevertheless, outflows to the sea under both policies comply with the very small minimum environmental flow threshold. Inflows to the Albufera wetland decrease under the mild climate change for the two policies compared to *baseline*. The wetland receives larger inflows under the *unsustainable policy* than the *sustainable policy*. The reason is that the Albufera wetland is fed by irrigation return flows in the lower Jucar, which are reduced under the *sustainable policy* as a result of the decline in water extractions.

Table 3 around here

Table 4 around here

5.3 Severe Climate Change Scenario

Tables 5 and 6 show the outcomes of the severe climate change for the alternative policies. Under this scenario, headwater inflows are reduced by 48%. Aquifer recharge is reduced by 43 and 52% under the *unsustainable policy* and the *sustainable policy*, respectively. Water demand falls by 19 and 43% under the *unsustainable policy* and *sustainable policy*, respectively.

The severe climate change scenario reduces basin net benefits between 133 and 147 million €/year (up to 21%) compared to *baseline*. *The sustainable policy* results in larger benefit losses compared to the *unsustainable policy* because the gains in environmental benefits (+15%) do not cover the agricultural benefit losses (-30%). Urban benefits from both policies remain almost unchanged because of the small reduction in urban water supply. Urban water prices rise slightly by 3 and 5% under the *unsustainable policy* and the *sustainable policy*, respectively.

The impacts of severe climate change on agriculture are considerable with benefits dropping between 15 and 40%, compared to *baseline*. The cost of achieving sustainability under severe climate change falls mainly on agriculture, with benefits falling 30% compared to the *unsustainable policy*. Without sustainability requirements, the depletion levels in reservoirs and aquifers are 10 and 92 Mm^3/year, respectively. The marginal value of irrigation water increases under severe climate change scenario, and it is even higher for the *sustainable policy* where less water is available for irrigation.

Policymakers in arid and semiarid regions worldwide are facing the challenge of designing policies to promote sustainable use of water resources. One class of sustainable management policies in developed countries such as Spain are targeted to reductions in overall basin extractions, rather than escalating investments in water technologies (Vörösmarty et al., 2010). The opportunity cost of such policies is measured by benefit losses sustained by stakeholders. For policy success, the costs of policies should be acceptable to stakeholders, possibly through compensation of losers. Otherwise, losing stakeholders groups bearing the costs of sustainable measures, will hinder the implementation of such measures.

Table 5 around here

Table 6 around here

Table 6 shows how the sustainability requirements can be met under severe climate change. The objective is finding water allocations with reasonable policy costs, measured by reductions in the present value of the stream of benefits. Results indicate that the best way to achieve that is by substantially reducing groundwater pumping in the upper Jucar, and increasing the share of surface water available to downstream users.

Pumping in the upper Jucar under the *sustainable policy* is reduced by 85% compared to the *unsustainable policy*, down to levels well below aquifer recharge. This occurs because the aquifer head rises when pumping is less than recharge, allowing larger discharges from the aquifer to the river. Therefore, higher amounts of water are available in the river satisfying environmental flows requirements, and at the same time providing water to downstream surface water users that are constrained from depleting the basin's reservoirs. Benefits of irrigation districts in the upper Jucar under the *sustainable policy* fall by 55% compared to the *unsustainable policy*. However, the benefits of irrigation districts in the lower Jucar are only slightly reduced under the *sustainable policy*, compared to the *unsustainable policy*. Water flowing to the sea decreases considerably under severe climate change, between 82 and 92% compared to *baseline*. Under the *unsustainable policy*, outflows are below the minimum environmental flow requirement, while the *sustainable policy* satisfies this requirement. Inflows to the Albufera wetland are also reduced under severe climate change compared to *baseline*. Inflows to the wetland are lower under the *sustainable policy* compared to the *unsustainable policy*, because the smaller water extractions reduce also the irrigation return flows feeding the wetland.

5.4 Tradeoffs Among Policies

The comparison between climate and policy scenarios shows the environmental and economic tradeoffs among policy choices. This information could guide the design of sustainable climate change adaptation policies at basin scale. Table 7 displays the present value of benefits for the different scenarios. Results indicate that climate change will have negative effects on the basin social benefits for all the climate and policy scenarios considered. Benefits decline between 13 and 21% under climate change. However, the losses of private benefits are less than 10%. The impacts vary by group of users, with urban users not very affected, and agricultural and environmental users bearing the largest damages.

Table 7 around here

Results show that the impacts of climate change depend on the policy choices. The adaptation of stakeholders can be economically efficient over the planning horizon, but this does not guarantee sustainable outcomes. In absence of regulations protecting the natural environment and the stock resources, water users will strategically deplete reservoirs, aquifers and river flows, given the common pool and public good nature of water, to better adapt to impacts of climate change (Booker et al., 2012). But this risks serious damages to water-dependent ecosystems and also threatens future human activities. Conversely, the inclusion of sustainability requirements within the adaptation policies reduces the climate change impacts on the environment by increasing river flows and avoiding the depletion of aquifers and reservoirs, and certainly reduces the impacts on future human activities, although these impacts are not explicitly investigated in this paper.

Still, sustainable management leads to costly impacts on current economic activities. For agriculture, there is a considerable gap between the benefits obtained under severe climate change and *sustainable policy* scenario, and all the other scenarios. This negative impact of combining severe climate change with sustainability is too detrimental to farmers, and the costs of the policy become high. Therefore, a mix of additional policy instruments is needed to assure the practical implementation of sustainable management. These instruments would compensate farmers for their large benefit losses such as providing them with compensation for the water released to support ecosystem services, subsidies to invest in water conservation measures, and technical advice. In addition, implementing sustainable management requires well-functioning water institutions and binding cooperative agreements among users within and across basin's regions. It is also important to mention that the combination of severe climate change and sustainable management results in a large decrease of irrigated area

(-70%) compared to all other scenarios, which may have negative impacts on food security and employment.

Figure 2 around here

Figure 2 displays the paths of groundwater stock variation, aquifer head and discharge from the aquifer to the river along the planning horizon for the different scenarios. It illustrates water users' management strategies of one type of common pool and public good resources under the different climate scenarios and policy choices. Results indicate that without sustainability requirements, groundwater net pumping (gross pumping minus return flows) in the upper Jucar exceeds aquifer recharge. On average, net pumping extractions amount to 98% of recharge for the *baseline*, but increase to 109% of recharge for mild climate change and *unsustainable policy* scenario, and to 131% of recharge for severe climate change and *unsustainable policy* scenario. The consequence of the *unsustainable policy* is the depletion of groundwater stock and a steady drop in both the water table level and the aquifer discharges to the river. The reason is that individual agents are unable to capture the environmental and future values of common pool and public good resources such as groundwater. Therefore, these resources in the absence of adequate regulation are heavily used for short term private benefits with little attention given to sustainable use, leading to a market failure situation. These results are consistent with the finding that a third of the world biggest groundwater systems are in distress, especially in arid and semiarid basins (Richey et al., 2015).

Under the *sustainable policy*, groundwater stock recovers, water table level rises, and discharges from the aquifer to the river increase, because of reduction in net pumping down to 74 and 25% of recharge for mild and severe climate change, respectively. The sustainable management of common pool and public good resouces such as groundwater calls for a wide-ranging overhaul of the current water policies, which mostly fail to align private short-term goals with societal long-term goals. These policies should reflect the full social costs and benefits of common pool and public good resources in order to achieve their sustainable use.

6. Conclusions

River basins in arid and semiarid regions worldwide face important water scarcity challenges, which stand to be aggravated by climate change in the coming decades. Solving these challenges requires improved and reliable analytical tools that could address the tradeoffs among policy choices and advance sustainable management. A key task is the integration of the complex interrelationships between hydrological, economic, institutional and environmental components in basins.

Hydro-economic modeling is one of the most important tools for implementing comprehensive basin scale analysis that could inform the unified and sound design of sustainable water management policies. However, hydro-economic models have to be capable to adequately account for the essential physical elements of the basin, with a physically-based representation of the different water sources and uses, including the interaction between surface water and groundwater, as well as the benefits and costs of alternative water allocations. This paper has addressed that challenge by developing an integrated hydro-economic model which is applied to the assessment of climate change scenarios and policy choices in the physically and institutionally complex Jucar basin of Spain.

The contribution of this paper compared to previous hydro-economic modeling efforts stems from a more unified treatment of the river basin dynamics. A groundwater flow formulation that is a special case of the USGS MODFLOW groundwater model is added to the standard hydro-economic framework of basins. This improved methodological approach simulates more accurately the spatial and temporal heterogeneity of real-world aquifers, and most important the linkages between aquifer systems and river flows. This paper presents a demonstration of the potential benefits of using such approach. However, as larger and more complex aquifer systems are modeled with this approach in future research, the advantages of doing so will be increasingly recognized and put to use in informing major policy debates.

Applying the modeling framework to the Jucar basin demonstrates the model capabilities to assess the effects of climate scenarios and policy choices, and also its potential for integrating the multiple dimensions of water resources. The results of the climate change and policy scenarios provide information on the spatio-temporal impacts of climate change on the hydrology, land use, economy and natural environment of the basin. Results illustrate how adaptation to climate change could be strategically undertaken at the basin scale, showing also the economic and environmental tradeoffs among the water policy choices. Such information, which could be provided only by hydro-economic models, is essential to guide policy debates and choices in arid and semiarid basins in the search for sustainable water management and policies.

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Author Contributions

Mohamed Taher Kahil, Frank Ward, Jose Albiac and Jack Eggleston designed the methodology. David Sanz provided the technical data on the river-aquifer interaction. All authors carried out the model setup, calibration and validation, as well as the simulation of water scenarios. Mohamed Taher Kahil, Jose Albiac and Frank Ward wrote the first draft of the manuscript, with further contributions from the rest of the authors.

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List of Figures

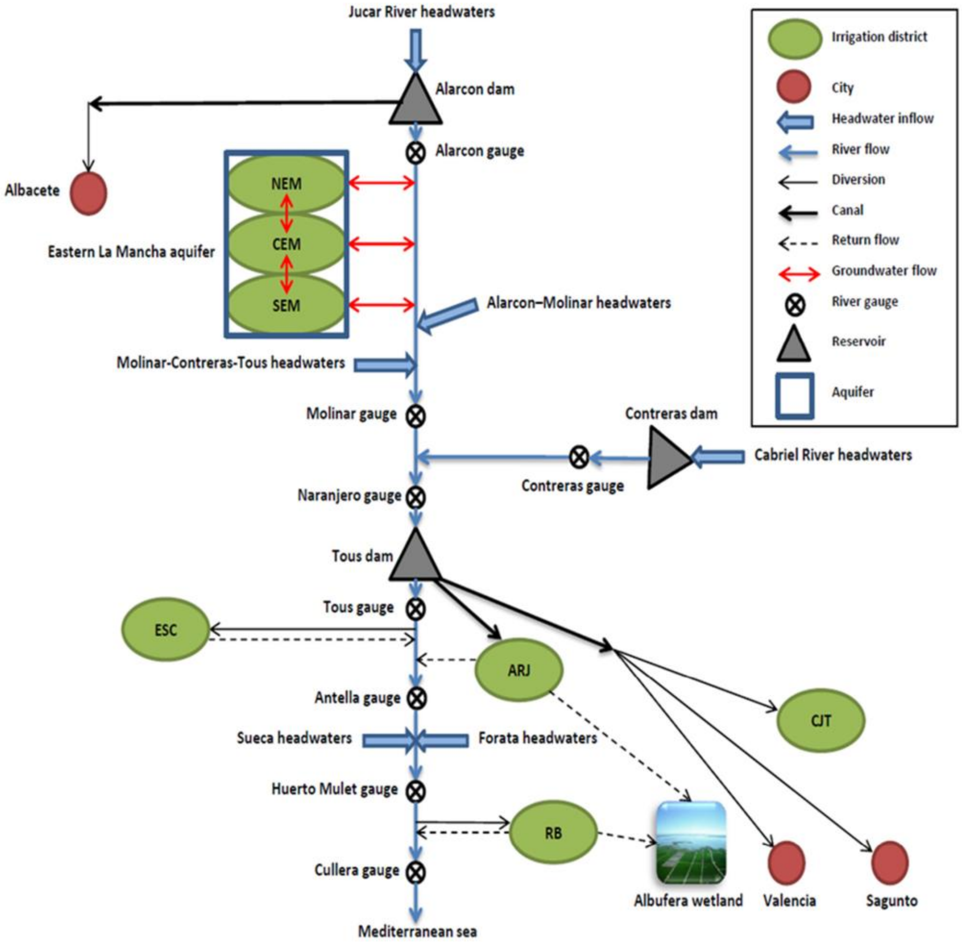
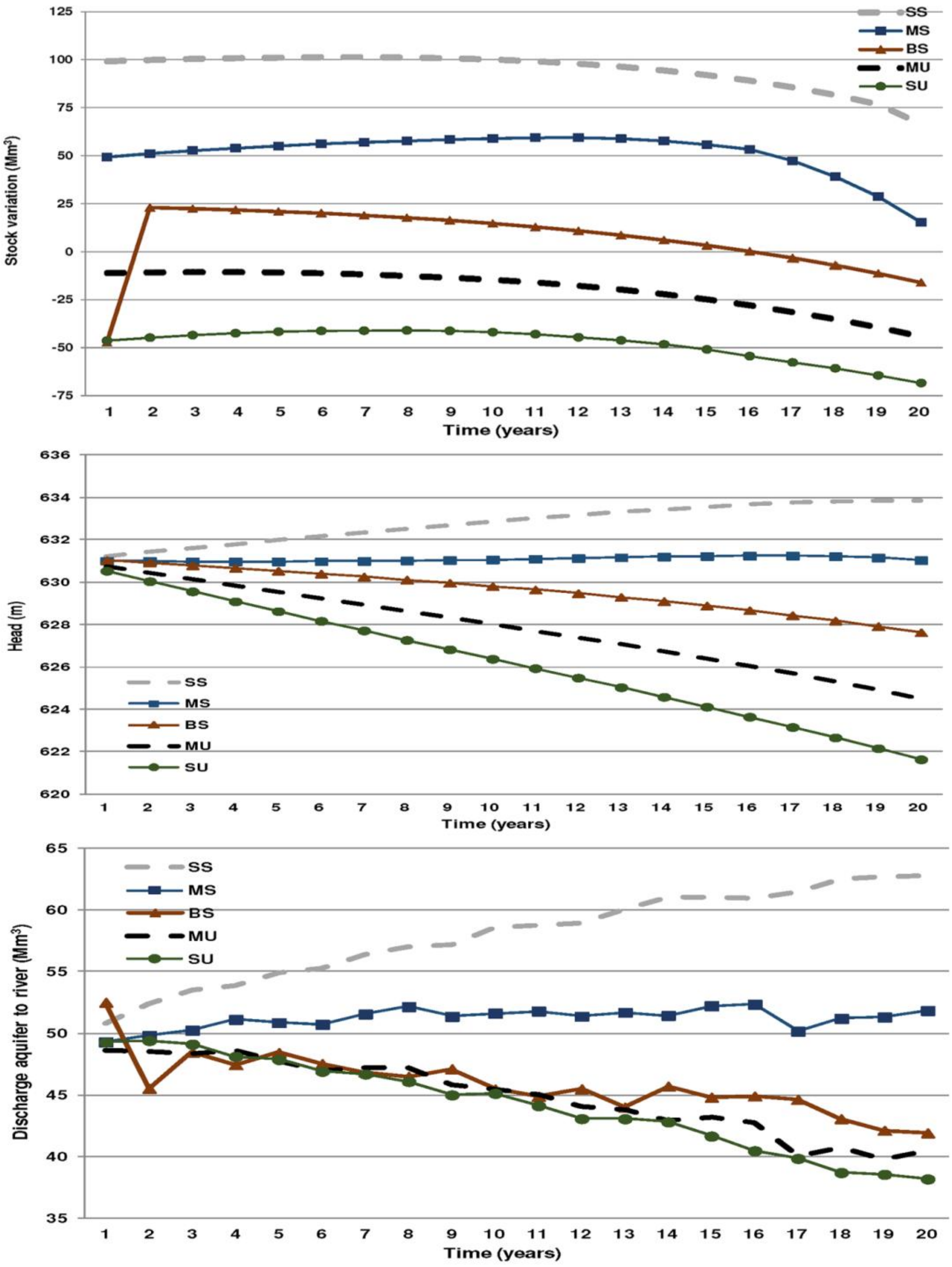


Figure 2. Groundwater stock variation (top), aquifer head (middle) and discharge to the river (down) under the climate and policy scenarios.



Note: *BS*=Baseline scenario; *MS*=Mild climate change and *sustainable policy; MU*=Mild climate change and *unsustainable policy*; *SS*=Severe climate change and *sustainable policy; SU*=Severe climate change and *unsustainable policy*. Stock variation is equal to recharge minus gross pumping plus return flows. Negative stock variation indicates stock depletion while positive stock variation indicates stock recovery. Aquifer head is an average value for the three sub-aquifers.

List of Tables

Table 1. Climate change impacts in the Jucar basin compared to current climate.

Climate scenario	Mild	Severe
Temperature (ºC)	+3.8	+4.4
Rainfall (%)	-1	-24
Potential evapotranspiration (%)	+13	+22
Surface runoff (%)	-27	-46
Groundwater recharge (%)	-22	-45

Note: The mild climate change scenario is the outcome of the downscaled climatic model ECHAM4-FIC forced by the B2 emission scenario. The severe climate change scenario is the outcome of the downscaled climatic model HadCM3-SDSM forced by the A2 emission scenario. Both scenarios present projections for the period 2071-2100 compared to current climate conditions.

Table 2. Hydrologic, land use and economic outcomes of baseline scenario.

Region/basin location	**Castilla La Mancha/Upstream**				**Valencia/Downstream**						**Basin**			
Sector	**Agriculture**			**Urban**	**Agriculture**				**Urban**		**Agriculture**	**Urban**	**Environment**	**Total**
Demand nodes	**NEM**	**CEM**	**SEM**	**Albacete**	**CJT**	**ESC**	**ARJ**	**RB**	**Valencia**	**Sagunto**				
Hydrologic outcomes (Mm³/year)														
Headwater inflows														1355.5
Aquifer recharge	67.7	133.6	65.8		56.0									323.1
Water demand	16.3	185.9	58.4	15.3	112.5	18.8	104.5	193.6	87.9	6.2	689.9	109.5		799.4
Surface water diversion	0.0	0.0	0.0	15.3	56.5	18.8	104.5	193.6	87.9	6.2	373.4	109.5		482.9
Groundwater pumping	16.3	185.9	58.4	0.0	56.0	0.0	0.0	0.0	0.0	0.0	316.5	0.0		316.5
Storage change (storage depletion if <0)														
Reservoirs														9.9
Aquifers	3.3	-48.3	5.8		0.0								-39.3	-39.3
Aquifer-river discharge (river gains if >0)	48.2	-4.0	1.7											45.9
Outflow to Mediterranean Sea													416.6	416.6
Inflows to Albufera wetland													88.6	88.6
Land use outcomes														
Irrigated area (1000 ha/year)*	6.8	45.9	17.1		19.2	3.4	15.3	15.3			123.0			123.0
Cereals	2.9	27.3	11.1		0.5	0.0	3.1	8.6			53.5			53.5
Vegetables	0.5	10.5	3.5		0.7	0.0	0.6	0.2			16.0			16.0
Fruit trees	3.4	8.1	2.6		18.0	3.4	11.6	6.4			53.5			53.5
Irrigation technology distribution (%)														
Flood	1.8	4.0	4.3		23.9	38.7	50.8	69.1			21.9			21.9
Sprinkler	42.6	59.5	64.6		0.1	0.0	0.5	0.1			33.7			33.7
Drip	55.6	36.4	31.1		76.0	61.3	48.7	30.9			44.4			44.4
Economic outcomes														
Gross benefits (million €/year)	11.1	96.8	32.5	75.1	94.4	16.8	66.8	49.2	430.9	30.6	367.4	536.6	205.6	1109.6
Production costs (million €/year)	7.1	60.0	20.3	19.8	71.0	13.4	51.5	38.1	113.4	8.1	261.4	141.3	1.3†	404.0
Net benefits (million €/year)	4.0	36.7	12.2	55.3	23.4	3.4	15.3	11.1	317.5	22.5	106.0	395.3	204.3	705.6
Marginal value of irrigation water (€/m³)	0.10	0.11	0.09		0.08	0.03	0.03	0.01			0.06			
Urban water price (€/m³)				1.29					1.29	1.29		1.29		

* Crops are aggregated into three representative groups: cereals: rice, wheat, barley, corn, other cereals; vegetables: garlic, onion, other vegetables and Fruit trees: citrus, grapes and other fruit trees.

† For the environment, production costs are equivalent to damage costs.

Table 3. Hydrologic, land use and economic outcomes of mild climate change and unsustainable policy.

Region/basin location	**Castilla La Mancha/Upstream**				**Valencia/Downstream**						**Basin**			
Sector	**Agriculture**			**Urban**	**Agriculture**				**Urban**		**Agriculture**	**Urban**	**Environment**	**Total**
Demand nodes	**NEM**	**CEM**	**SEM**	**Albacete**	**CJT**	**ESC**	**ARJ**	**RB**	**Valencia**	**Sagunto**				
Hydrologic outcomes (Mm^3/year)														
Headwater inflows														949.0
Aquifer recharge	53.4	105.7	52.5		43.7									255.2
Water demand	16.4	161.4	53.6	15.3	108.9	18.0	82.8	210.8	87.7	6.2	651.8	109.3		761.0
Surface water diversion	0.0	0.0	0.0	15.3	65.2	18.0	82.8	210.8	87.7	6.2	376.7	109.3		486.0
Groundwater pumping	16.4	161.4	53.6	0.0	43.7	0.0	0.0	0.0	0.0	0.0	275.1	0.0		275.1
Storage change (storage depletion if <0)														
Reservoirs														-10.1
Aquifers	-10.3	-51.5	-2.8		0.0								-64.7	-64.7
Aquifer-river discharge (river gains if >0)	47.3	-4.1	1.7											44.9
Outflow to Mediterranean Sea													98.1	98.1
Inflows to Albufera wetland													83.6	83.6
Land use outcomes														
Irrigated area (as % of baseline)	91	79	83		87	85	77	97			84			84
Cereals	84	70	79		45	-	40	96			75			75
Vegetables	92	89	89		91	-	87	99			90			90
Fruit trees	97	96	92		88	85	86	99			91			91
Irrigation technology distribution (%)*														
Flood	1.4	2.9	3.1		22.1	37.2	43.7	68.4			21.0			21.0
Sprinkler	39.3	52.8	61.5		0.1	0.0	0.3	0.1			29.6			29.6
Drip	59.2	44.3	35.4		77.9	62.8	56.0	31.5			49.4			49.4
Economic outcomes (as % of baseline)														
Gross benefits	95	90	91	100	92	90	88	99	100	100	92	100	60	90
Production costs	97	90	92	100	91	88	86	99	100	100	91	100	163	94
Net benefits	92	91	91	100	94	97	94	98	100	100	93	100	59	87
Marginal value of irrigation water	105	103	108		111	121	138	103			109			
Urban water price				100					101	101		101		

Note: see note to table 2.

* Irrigation technology distribution is shown as a percentage of irrigated area in each scenario.

Table 4. Hydrologic, land use and economic outcomes of mild climate change and sustainable policy.

Region/basin location	**Castilla La Mancha/Upstream**				**Valencia/Downstream**						**Basin**			
Sector	**Agriculture**			**Urban**	**Agriculture**				**Urban**		**Agriculture**	**Urban**	**Environment**	**Total**
Demand nodes	**NEM**	**CEM**	**SEM**	**Albacete**	**CJT**	**ESC**	**ARJ**	**RB**	**Valencia**	**Sagunto**				
Hydrologic outcomes (Mm^3/year)														
Headwater inflows														949.0
Aquifer recharge	51.5	93.9	47.8		43.7									236.9
Water demand	6.3	104.3	31.3	15.3	100.5	16.1	63.8	212.9	87.6	6.2	535.2	109.1		644.3
Surface water diversion	0.0	0.0	0.0	15.3	56.8	16.1	63.8	212.9	87.6	6.2	349.6	109.1		458.7
Groundwater pumping	6.3	104.3	31.3	0.0	43.7	0.0	0.0	0.0	0.0	0.0	185.7	0.0		185.7
Storage change (storage depletion if <0)														
Reservoirs														0.0
Aquifers	-8.3	-6.5	14.8		0.0								0.0	0.0
Aquifer-river discharge (river gains if >0)	53.5	-4.0	1.7											51.2
Outflow to Mediterranean Sea													148.9	148.9
Inflows to Albufera wetland													76.3	76.3
Land use outcomes														
Irrigated area (as % of baseline)	44	53	50		81	76	65	98			64			64
Cereals	10	33	38		18	-	9	97			42			42
Vegetables	57	77	71		87	-	79	99			76			76
Fruit trees	71	90	74		82	76	79	99			83			83
Irrigation technology distribution (%)														
Flood	0.0	0.8	0.5		21.0	36.1	37.8	68.6			23.3			23.3
Sprinkler	9.8	37.1	48.9		0.1	0.0	0.1	0.1			17.2			17.2
Drip	90.2	62.0	50.6		78.9	63.9	62.0	31.4			59.4			59.4
Economic outcomes (as % of baseline)														
Gross benefits	62	76	71	100	87	83	79	99	100	100	82	100	63	87
Production costs	55	68	63	100	85	80	77	99	100	100	79	100	0.0	86
Net benefits	76	88	86	100	93	94	89	98	100	100	90	100	64	88
Marginal value of irrigation water	140	104	113		118	133	159	101			122			
Urban water price				101					101	101		101		

Note: see note to tables 2 and 3.

Table 5. Hydrologic, land use and economic outcomes of severe climate change and unsustainable policy.

Region/basin location	**Castilla La Mancha/Upstream**				**Valencia/Downstream**						**Basin**			
Sector	**Agriculture**			**Urban**	**Agriculture**				**Urban**		**Agriculture**	**Urban**	**Environment**	**Total**
Demand nodes	**NEM**	**CEM**	**SEM**	**Albacete**	**CJT**	**ESC**	**ARJ**	**RB**	**Valencia**	**Sagunto**				
Hydrologic outcomes (Mm^3/year)														
Headwater inflows														706.5
Aquifer recharge	38.3	77.2	38.6		30.8									184.9
Water demand	15.9	137.7	48.6	15.3	86.7	12.5	49.2	185.4	87.3	6.2	536.1	108.8		644.9
Surface water diversion	0.0	0.0	0.0	15.3	55.9	12.5	49.2	185.4	87.3	6.2	303.0	108.8		411.8
Groundwater pumping	15.9	137.7	48.6	0.0	30.8	0.0	0.0	0.0	0.0	0.0	233.1	0.0		233.1
Storage change (storage depletion if <0)														
Reservoirs														-10.1
Aquifers	-24.4	-56.3	-11.7		0.0								-92.4	-92.4
Aquifer-river discharge (river gains if >0)	46.8	-4.3	1.7											44.2
Outflow to Mediterranean Sea													31.5	31.5
Inflows to Albufera wetland													63.5	63.5
Land use outcomes														
Irrigated area (as % of baseline)	85	65	72		66	56	48	83			67			67
Cereals	72	50	65		2	-	1	74			55			55
Vegetables	86	82	81		75	-	62	96			81			81
Fruit trees	95	93	88		67	56	60	95			75			75
Irrigation system distribution (%)														
Flood	1.1	1.6	1.9		18.8	32.1	32.5	64.4			17.4			17.4
Sprinkler	36.2	45.6	58.4		0.0	0.0	0.0	0.1			27.7			27.7
Drip	62.7	52.8	39.6		81.2	67.9	67.5	35.5			54.8			54.8
Economic outcomes (as % of baseline)														
Gross benefits	91	82	84	100	78	71	68	91	100	100	80	100	44	83
Production costs	94	81	85	100	75	67	65	90	99	99	77	99	237	86
Net benefits	87	84	84	100	87	87	80	93	100	100	85	100	42	81
Marginal value of irrigation water	110	104	114		128	159	189	128			121			
Urban water price				101					104	104		103		

Note: see note to tables 2 and 3.

Table 6. Hydrologic, land use and economic outcomes of severe climate change and sustainable policy.

Region/basin location	**Castilla La Mancha/Upstream**				**Valencia/Downstream**						**Basin**			
Sector	**Agriculture**			**Urban**	**Agriculture**				**Urban**		**Agriculture**	**Urban**	**Environment**	**Total**
Demand nodes	**NEM**	**CEM**	**SEM**	**Albacete**	**CJT**	**ESC**	**ARJ**	**RB**	**Valencia**	**Sagunto**				
Hydrologic outcomes (Mm^3/year)														
Headwater inflows														706.5
Aquifer recharge	35.8	56.3	32.8		30.8									155.6
Water demand	0.0	12.2	18.3	15.3	74.5	9.2	38.3	193.1	87.1	6.2	345.6	108.5		454.1
Surface water diversion	0.0	0.0	0.0	15.3	43.7	9.2	38.3	193.1	87.1	6.2	284.2	108.5		392.7
Groundwater pumping	0.0	12.2	18.3	0.0	30.8	0.0	0.0	0.0	0.0	0.0	61.4	0.0		61.4
Storage change (storage depletion if <0)														
Reservoirs														0.0
Aquifers	-24.5	48.0	12.8		0.0								36.2	36.2
Aquifer-river discharge (river gains if >0)	60.3	-4.0	1.7											58.0
Outflow to Mediterranean Sea													73.9	73.9
Inflows to Albufera wetland													61.3	61.3
Land use outcomes														
Irrigated area (as % of baseline)	0	5	26		57	42	38	86			31			31
Cereals	0	0	12		0	-	0	78			15			15
Vegetables	0	23	58		68	-	49	97			34			34
Fruit trees	0	0	41		58	42	48	96			46			46
Irrigation system distribution (%)														
Flood	0.0	0.0	0.0		17.2	27.2	28.0	65.3			32.7			32.7
Sprinkler	0.0	1.6	30.0		0.0	0.0	0.0	0.1			3.6			3.6
Drip	100.0	98.4	70.0		82.8	72.8	72.0	34.7			63.8			63.8
Economic outcomes (as % of baseline)														
Gross benefits	5	22	56	100	70	58	58	92	100	100	54	100	48	75
Production costs	5	16	46	100	66	53	53	92	99	99	52	99	0	68
Net benefits	5	30	73	100	83	76	73	94	100	100	60	100	49	79
Marginal value of irrigation water	238	156	127		136	178	213	124			170			
Urban water price				102					106	106		104		

Note: see note to tables 2 and 3.

Table 7. The present value of benefits by climate and policy scenario (million €).

Policy scenario	Climate scenario	Municipal	Agriculture	Environment	Total private benefits	Total social benefits
Baseline	Normal	5101.1	1389.6	2653.6	6490.7	9144.3
Unsutainable policy	Mild	5101.1	1285.7	1569.1	6386.9	7956.0
	Severe	5100.9	1162.1	1125.1	6263.0	7388.0
Sustainable policy	Mild	5101.1	1236.9	1714.6	6338.0	8052.6
	Severe	5100.7	792.2	1326.0	5892.9	7219.0

Note: Total private benefits are the sum of municipal and agricultural benefits, while total social benefits are the sum of private and environmental benefits.

Figures

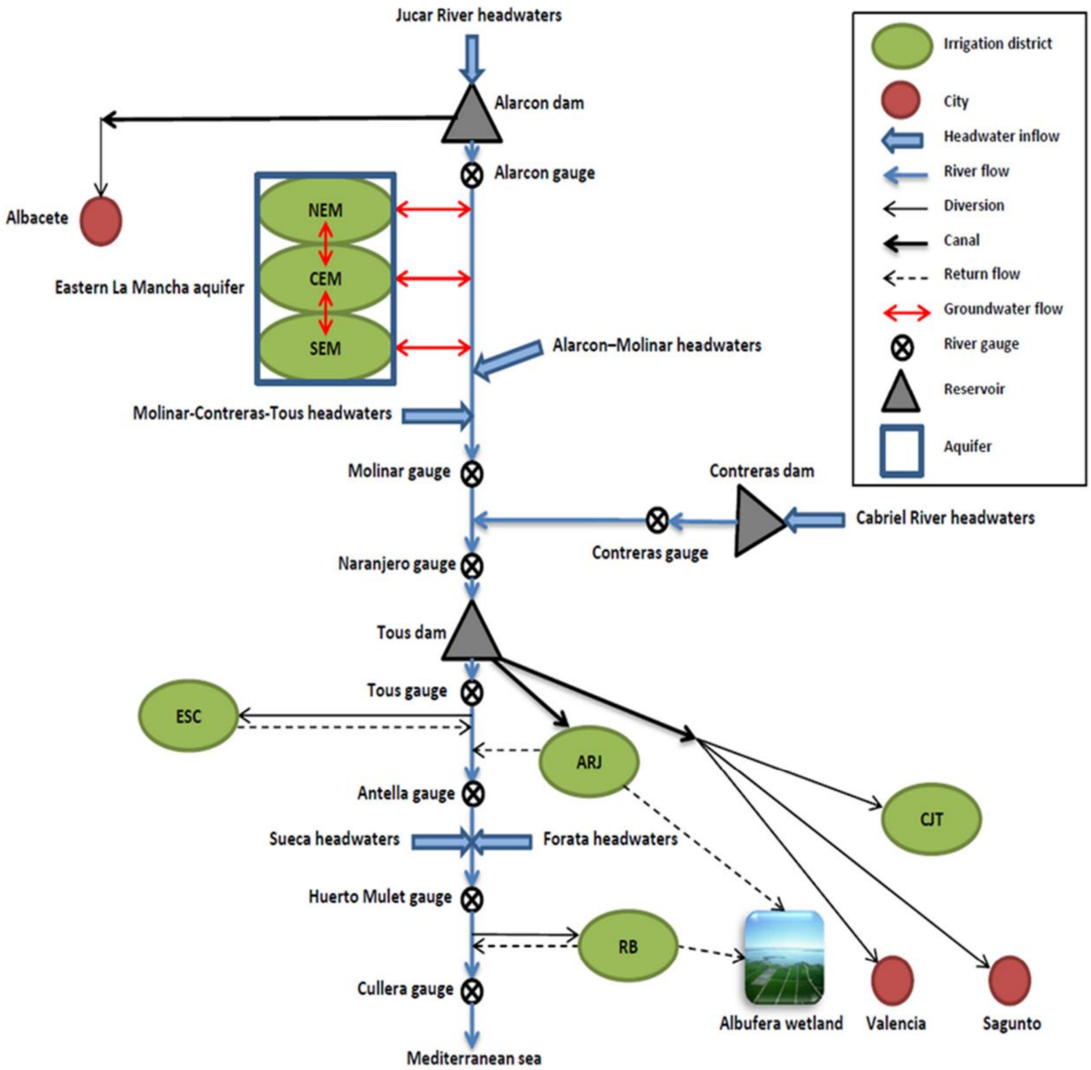


Figure 1. Network of the Jucar basin.

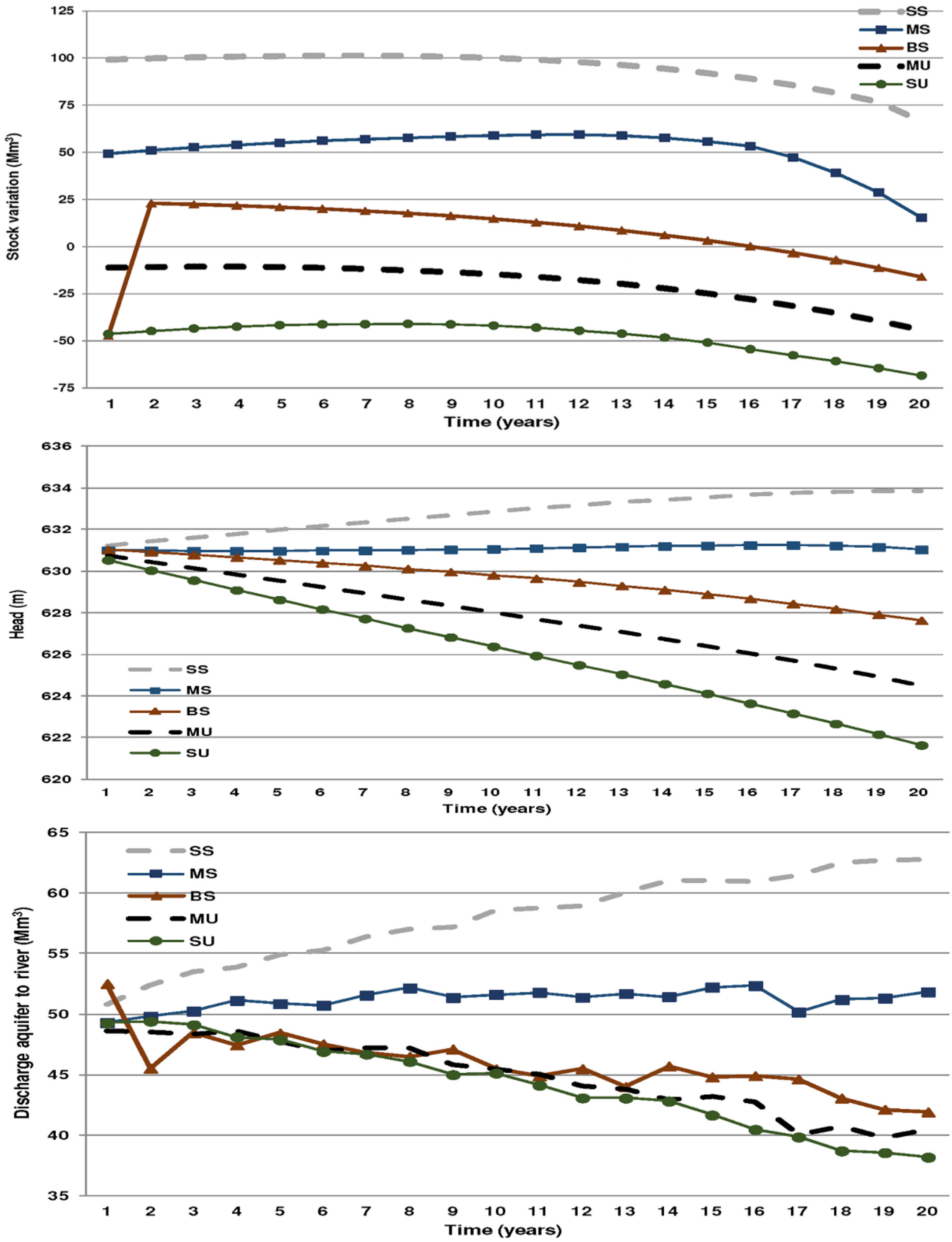


Figure 2. Groundwater stock variation (top), aquifer head (middle) and discharge to the river (bottom) under the climate and policy scenarios.

Note: *BS*=Baseline scenario; *MS*=Mild climate change and *sustainable policy; MU*=Mild climate change and *unsustainable policy*; *SS*=Severe climate change and *sustainable policy; SU*=Severe climate change and *unsustainable policy*. Stock variation is equal to recharge minus gross pumping plus return flows. Negative stock variation indicates stock depletion while positive stock variation indicates stock recovery. Aquifer head is an average value for the three sub-aquifers.

Appendix

1. Mathematical formulation of the hydrological component

The integrated hydro-economic modeling framework includes a simplified hydrological component based on the principle of water mass balance. The balances are defined for each flow, i, and each stock, s. The main flow variables, X_i, tracked by the model are headwater inflow, streamflow, surface water diversion, groundwater pumping, water applied and consumed, return flow to streams and aquifers, groundwater flow, stream-aquifer interaction, reservoir release, and reservoir evaporation. The stock variables, Z_s, tracked by the model are the reservoir and aquifer storage volume levels.

1.1 Surface water hydrology

1.1.1 Headwater inflows

Total surface water inflows to the basin are defined as the total annual flows at the different headwater gauges. The inflows, $X_{h,t}$, at each headwater gauge, h (a subset of i), in time *t* are equal to total source supplies, $source_{h,t}$:

$$X_{h,t} = source_{h,t} \tag{A1}$$

1.1.2 Streamflows

The streamflow, $X_{v,t}$, at each river gauge, v (a subset of i), in time *t* is equal to the sum of flows over any upstream node i whose activities impact that streamflow. These nodes include headwater inflow, river gauge, diversion, surface return flow, stream-aquifer interaction, and reservoir release. The streamflow at each river gauge, which is required to be nonnegative, is defined as follows:

$$X_{v,t} = \sum_i b_{i,v} \cdot X_{i,t} \tag{A2}$$

where $b_{i,v}$ is a vector of coefficients that links flow nodes i to river gauge nodes v. The coefficients take on values of 0 for non-contributing nodes, +1 for nodes that add flow, and -1 for nodes that reduce flow.

1.1.3 Surface water diversions

Water supply to basin's users can be met partially or totally by diversions from a stream. However, during drought spells, streamflow can be low or even zero. Therefore, a surface water diversion constraint is required in order to avoid that diversion, $X_{d,t}$, exceeds available streamflow at each diversion node, d (a subset of i), in time t. A diversion, which is required to be nonnegative, is defined as follows:

$$X_{d,t} \leq \sum_i b_{i,d} \cdot X_{i,t} \tag{A3}$$

where $b_{i,v}$ is a vector of coefficients that links flow nodes, i, to diversion nodes, d. The right hand side term represents the sum of all contributions to flow at diversion nodes from upstream sources. These sources include headwater inflow, river gauge, diversion, surface return flow, stream-aquifer interaction, and reservoir release. The b coefficients, take on values of 0 for non-contributing nodes, +1 for nodes that add flow, and -1 for nodes that reduce flow.

1.1.4 Reservoir stock and operation

Water stock, $Z_{res,t}$, at each reservoir, res (a subset of s), in time t is defined in the following equations:

$$Z_{res,t} = Z_{res,t-1} - \sum_L b_{L,res} \cdot X_{L,t} - \sum_e b_{e,res} \cdot X_{e,t} \tag{A4}$$

$$Z_{res,0} = bz_{res,0}$$
(A5)

$$Z_{res,t} \leq c_{res}^{max} \tag{A6}$$

$$Z_{res,t} \geq c_{res}^{min} \tag{A7}$$

where equation (A4) states that reservoir water stock, $Z_{res,t}$, is equal to its stock in the previous time period, $Z_{res,t-1}$, minus both the net release (outflow minus inflow) from the reservoir, $X_{L,t}$, and reservoir evaporation, $X_{e,t}$. Evaporation depends on reservoir features and climatic factors. Both sets of parameters $b_{L,res}$ and $b_{e,res}$ are binary matrices linking reservoir stock nodes to reservoir release and evaporation nodes, respectively. Equation (A5) defines initial reservoir water stock at $t = 0$, $bz_{res,0}$. Upper and lower bounds on reservoir water stock are defined in equation (A6) and (A7), respectively. Parameters c_{res}^{max} and c_{res}^{min} are reservoir maximum capacity and dead storage, respectively. Upper bound constraint guarantees that reservoir stock in each time period never exceeds its maximum capacity, while lower bound constraint states the capacity from which stored water in reservoir cannot be used.

1.2 Groundwater hydrology and stream-aquifer interaction

The groundwater flow equation is developed in a finite-difference form based on the principles of water mass balance and Darcy's law. Finite-difference is a numerical method used to obtain approximate solutions to the partial-differential groundwater flow equation. The formulation (equation 1) is a version of that used in the MODFLOW groundwater model (McDonald and Harbaugh 1988).

Equation (1) is derived by the following procedure:

For simplicity and without loss of generality, we assume that n aquifer cells or sub-aquifers are represented by 1 row, n columns and 1 layer, where the set aqf consists of n elements: $1,2,\ldots,n$. These aquifer cells are connected serially to each other and to n river reaches, $river$ (a set that consists of $1,2,\ldots,n$ elements), where every cell is connected only to one river reach. The water mass balance for each aquifer cell is defined by the following equation:

$$\Delta Z_{aqf,t} = r_{aqf,t} - Q_{aqf,t} + X_{aqf,t} + X_{river,aqf,t} \tag{A8}$$

where equation (A8) states that the sum of all flows into and out of sub-aquifer aqf in time t must be equal to the rate of change in storage within that sub-aquifer, $\Delta Z_{aqf,t}$, with $r_{aqf,t}$ is the recharge of that sub-aquifer, $Q_{aqf,t}$ is the net groundwater pumping from that sub-aquifer, $X_{aqf,t}$ is the water flow between that sub-aquifer and adjacent sub-aquifers, and $X_{river,aqf,t}$ is the water flow between that sub-aquifer and the corresponding river reach.

The rate of change in storage, $\Delta Z_{aqf,t}$, in each sub-aquifer is defined as a function of the sub-aquifer head as follows:

$$\Delta Z_{aqf,t} = s_{y,aqf} \cdot a_{aqf} \cdot \left(H_{aqf,t} - H_{aqf,t-1}\right)/\Delta t \tag{A9}$$

where parameters $s_{y,aqf}$ and a_{aqf} are specific yield and area of that sub-aquifer, respectively. Parameter Δt is the time step, and variables $H_{aqf,t}$ and $H_{aqf,t-1}$ are the head of that sub-aquifer in the current and previous time period, respectively.

The water flow between adjacent sub-aquifers $X_{aqf,t}$ is defined by equation (A10), and the water flow between sub-aquifers and the corresponding river reaches $X_{river,aqf,t}$ is defined by equation (A11). Equations (A10) and (A11) are formulated using Darcy's law as follows:

$$X_{aqf,t} = c_{aqf,aqf-1} \cdot \left(H_{aqf-1,t} - H_{aqf,t}\right) + c_{aqf,aqf+1} \cdot \left(H_{aqf+1,t} - H_{aqf,t}\right) \tag{A10}$$

$$X_{river,aqf,t} = c_{river,aqf} \cdot \left(H_{river,aqf,t} - H_{aqf,t}\right) \tag{A11}$$

where equation (A10) states that the water flows between the sub-aquifers aqf and adjacent sub-aquifers $aqf - 1$ and $aqf + 1$, depend on the sub-aquifer heads, H, and the hydraulic conductances between sub-aquifers, c, with $X_{aqf,t}$ being negative (positive) if water is flowing out of (in) sub-aquifer, aqf. Equation (A11) states that the water flow between the sub-aquifer, aqf, and the corresponding river reach, $river$, depends on the sub-aquifer and river heads, H, and the hydraulic conductance between the sub-aquifer and the river, c, with $X_{river,aqf,t}$ being negative (positive) if sub-aquifer is discharging water to (receiving water from) the river reach.

The mass balance equation (A8) can be rewritten using equations (A9), (A10) and (A11) as follows:

$$s_{y,aqf} \cdot a_{aqf} \cdot \left(H_{aqf,t} - H_{aqf,t-1}\right)/\Delta t = r_{aqf,t} - Q_{aqf,t} + c_{aqf,aqf-1} \cdot \left(H_{aqf-1,t} - H_{aqf,t}\right) + c_{aqf,aqf+1} \cdot \left(H_{aqf+1,t} - H_{aqf,t}\right) + c_{river,aqf} \cdot \left(H_{river,aqf,t} - H_{aqf,t}\right) \quad \text{(A12)}$$

Solving for $H_{aqf,t}$ yields the groundwater flow equation (equation 1 in the text):

$$H_{aqf,t} = \left[1/\left\{\left(s_{y,aqf} \cdot a_{aqf}/\Delta t\right) + c_{aqf,aqf-1} + c_{aqf,aqf+1} + c_{river,aqf}\right\}\right] \cdot \left[r_{aqf,t} - Q_{aqf,t} + \left(s_{y,aqf} \cdot a_{aqf} \cdot H_{aqf,t-1}/\Delta t\right) + c_{aqf-1} \cdot H_{aqf-1,t} + c_{aqf+1} \cdot H_{aqf+1,t} + c_{river,aqf} \cdot H_{river,aqf}\right] \quad \text{(A13)}$$

1.3 Hydrological relationships

1.3.1 Water application

Water applied, $X_{a,t}$, at each application node, a (a subset of i), in time t can come from two sources: stream diversion, $X_{d,t}$, and groundwater pumping, $X_{p,t}$. Water applied is defined as follows:

$$X_{a,t} = \sum_d b_{d,a} \cdot X_{d,t} + \sum_p b_{p,a} \cdot X_{p,t} \quad \text{(A14)}$$

where $b_{d,a}$ and $b_{p,a}$ are vectors of coefficients that link application nodes to diversion and pumping nodes, respectively. The coefficients take on values of 1 for application nodes withdrawing water from available sources, and 0 for not withdrawing water.

For each agricultural node in the basin, total water applied for irrigation is defined as follows:

$$X_{a,t}^{ag} = \sum_{j,k} b_{a,j,k} \cdot \left(\sum_u b_{u,a} \cdot L_{u,j,k,t}\right) \quad \text{(A15)}$$

Equation (A15) states that irrigation water applied to crops from both surface and groundwater sources, $X_{a,t}^{ag}$, is equal to the sum over crops (j) and irrigation technologies (k) of water application per ha, $b_{a,j,k}$, multiplied by irrigated area, $L_{u,j,k,t}$, for each crop and irrigation technology. $L_{u,j,k,t}$ is multiplied by a binary matrix, $b_{u,a}$, to conform nodes.

1.3.2 Water consumption

Consumptive use, $X_{u,t}$, at each use node, u (a subset of i), in time t is an empirically determined proportion of water applied, $X_{a,t}$. For irrigation, consumptive use is the amount of water used through crop evapotranspiration (ET). For urban uses, consumptive use is the proportion of urban water supply not returned through the sewage system. That use, which cannot be negative, is defined as follows:

$$X_{u,t} = \sum_a b_{a,u} \cdot X_{a,t} \tag{A16}$$

where parameters, $b_{a,u}$, are coefficients indicating the proportion of water applied that is consumptively used in each use node. For agricultural use nodes, water consumed is measured as:

$$X_{u,t}^{ag} = \sum_{j,k} b_{u,j,k} \cdot L_{u,j,k,t} \tag{A17}$$

Equation (A17) states that irrigation water consumed, $X_{u,t}^{ag}$, is equal to the sum over crops (j) and irrigation technologies (k) of empirically estimated ET per ha, $b_{u,j,k}$, multiplied by irrigated area, $L_{u,j,k,t}$, for each crop and irrigation technology.

1.3.3 Return flows

Return flows, $X_{r,t}$, at each return flow node, r (a subset of i), in time t is a proportion of water applied, $X_{a,t}$. These flows return to the river system or contribute to aquifers recharge. Return flows are defined as follows:

$X_{r,t} = \sum_a b_{a,r} \cdot X_{a,t}$ (A18)

where $b_{a,r}$ are coefficients indicating the proportion of total water applied that is returned to river and aquifers. For agricultural nodes, returns flows are defined as follows:

$X_{r,t}^{ag} = \sum_{j,k} b_{r,j,k} \cdot (\sum_u b_{u,r} \cdot L_{u,j,k,t})$ (A19)

Equation (A19) states that irrigation return flows, $X_{r,t}^{ag}$, are equal to the sum over crops (j) and irrigation technologies (k) of empirically estimated return flows per ha, $b_{r,j,k}$, multiplied by irrigated area, $L_{u,j,k,t}$, for each crop and irrigation technology. $L_{u,j,k,t}$ is multiplied by a binary matrix, $b_{u,r}$, to conform nodes. The sum of water consumed and returned must be equal to water applied at each demand node.

2. Data Sources

Data on historical headwater inflows to the basin, gauged water flows, and reservoir inflows, releases and evaporation have been obtained from the reports of the Jucar basin authority and the Spanish Ministry of Agriculture and Environment (CHJ, 2014; MAGRAMA, 2014). Information on the parameters of the EM sub-aquifers including area, recharge, hydraulic conductance and specific yield have been taken from Sanz et al. (2011). Headwater inflows and aquifer recharge are stochastically represented in the model with means and variances of historical inflows and recharge, respectively.

For agricultural uses, detailed information on crop yields and prices, subsidies, crop water requirements, irrigation efficiencies, water and production costs, and land availability in each irrigation district have been obtained from various data sources (INE, 2009; MARM, 2010). Irrigation water extractions in each district have been calculated using crop areas, irrigation technology use, and water requirements. The crops included in the model are rice, wheat, barley, corn, other cereals, garlic, onion, other vegetables, citrus, grapes and other fruit trees. Irrigation technologies are flood, sprinkler and drip.

For urban uses, a linear demand function is specified to characterize the demand for water in each urban demand node. The linear demand function results in the quadratic benefit function specified in equation (13). Parameter estimation requires three data items: the observed water price and quantity for a specific time period, and the price elasticity of water demand. Information on urban water supply, population growth rate, water prices and costs has been obtained from the Jucar basin authority reports (CHJ, 2014). The price elasticity of demand has been taken from Arbues and Barberan (2004).

3. Model Calibration

Integrated hydro-economic models typically require a detailed calibration procedure before they can be used. In this paper, both the hydrologic and the agricultural economic components of the Jucar model are calibrated. Calibration of the hydrologic component involves adjusting model parameters in order to reproduce the observed system states such as streamflows and aquifer heads under baseline conditions (Sophocleous et al., 1999). The agricultural economic component is calibrated using the Positive Mathematical Programming (PMP) procedure in order to reproduce observed land and water use under baseline conditions, and to address the problem of overspecialization in agricultural production (Howitt, 1995). Both components are calibrated for the year 2009, a normal flow year.

The hydrological component is calibrated so that the predicted gauged flows are broadly consistent with observed flows at each river gauge, where measurement data are available (8 gauges in the Jucar). To achieve this, the model is constrained to reproduce observed gauged flows, and to deliver the observed water supply to irrigation districts and cities. The calibration procedure involves introducing new variables that represent unmeasured sources or uses of water, which allow balancing supply and demand at each node. These variables include all possible sources or uses of water in the basin that are not measured with stream gauges.

Unmeasured sources include upstream headwater inflows, surface return flows, and aquifer discharge. Unmeasured uses include upstream demand nodes not included in the study, evapotranspiration of natural vegetation, evaporation from open water, and percolation. Additionally, the calibration procedure involves an adjustment of aquifer parameters including hydraulic conductance, specific yield and recharge in order to reproduce the observed aquifer heads and the stream-aquifer interaction. The calibration procedure requires a fair amount of experimentation since the model has to be calibrated node by node from upstream to downstream. Once the model calibration is satisfactory, all unmeasured sources and uses have to be held constant. Therefore any changes brought about by new policy scenarios will not change these unmeasured levels.

The agricultural economic component is calibrated using a variant of PMP developed by Dagnino and Ward (2012), in which parameters are estimated for a linear crop yield function (equation 11 in the text) based on the first-order conditions for profit maximization. This function represents a decreasing crop yield when additional land is assigned to crop production, based on the principle of Ricardian rent. For each crop and irrigation technology, the first lands brought into production have the highest yields, after which yields fall off as less-suitable lands enter production. The parameters of the linear yield function for each crop and irrigation technology are given in tables A1 and A2.

Table A1. Intercept of the yield function (maximum yield) by irrigation district, crop and technology (t/ha) ($\alpha_{0,ag,j,k}$).

Crop	Irrigation technology	Castilla La Mancha/Upstream			Valencia/Downstream			
		NEM	CEM	SEM	CJT	ESC	ARJ	RB
Rice	Flood	0.00	0.00	0.00	7.86	0.00	7.86	7.86
Wheat	Sprinkler	4.85	4.77	4.85	0.00	0.00	0.00	0.00
Barley	Sprinkler	5.25	5.22	5.25	0.00	0.00	0.00	0.00
Corn	Sprinkler	11.45	11.41	11.45	0.00	0.00	0.00	0.00
Other cereals	Flood	0.00	0.00	0.00	11.48	0.00	11.48	11.48
	Sprinkler	21.87	22.59	21.88	12.45	0.00	11.66	11.53
Garlic	Drip	8.68	8.66	8.68	0.00	0.00	0.00	0.00
Onion	Drip	92.64	92.37	92.60	0.00	0.00	0.00	0.00
Other vegetables	Flood	4.48	4.70	4.21	51.55	0.00	51.55	51.55
	Drip	5.17	5.48	4.89	54.10	0.00	52.31	51.92
Citrus	Flood	0.00	0.00	0.00	26.37	26.37	26.37	26.37
	Drip	0.00	0.00	0.00	26.95	26.54	26.56	26.46
Grapes	Drip	10.27	10.19	10.27	0.00	0.00	0.00	0.00
Other fruit trees	Flood	0.00	0.00	0.00	13.61	13.61	13.61	13.61
	Drip	2.41	2.40	2.42	14.00	13.70	13.71	13.66

Table A2. Linear term of the yield function (marginal yield) by irrigation district, crop and technology (Δ(t/ha)/Δha) ($\alpha_{1,ag,j,k}$).

Crop	Irrigation technology	Castilla La Mancha/Upstream			Valencia/Downstream			
		NEM	CEM	SEM	CJT	ESC	ARJ	RB
Rice	Flood	0.00	0.00	0.00	-4.52	0.00	-0.57	-0.20
Wheat	Sprinkler	-0.74	-0.06	-0.19	0.00	0.00	0.00	0.00
Barley	Sprinkler	-0.77	-0.06	-0.17	0.00	0.00	0.00	0.00
Corn	Sprinkler	-4.64	-0.20	-0.55	0.00	0.00	0.00	0.00
Other cereals	Flood	0.00	0.00	0.00	-17.80	0.00	-12.49	-14.38
	Sprinkler	-7.15	-0.69	-1.75	493	0.00	-21.04	-133.87
Garlic	Drip	-22.13	-1.00	-3.27	0.00	0.00	0.00	0.00
Onion	Drip	-162.69	-7.82	-25.72	0.00	0.00	0.00	0.00
Other vegetables	Flood	-5.59	-0.23	-0.67	-61.37	0.00	-104.34	-272.18
	Drip	-20.33	-0.63	-1.72	-31.66	0.00	-27.68	-70.05
Citrus	Flood	0.00	0.00	0.00	-1.41	-3.19	-0.94	-2.26
	Drip	0.00	0.00	0.00	-0.40	-2.21	-0.80	-0.99
Grapes	Drip	-0.81	-0.34	-1.93	0.00	0.00	0.00	0.00
Other fruit trees	Flood	0.00	0.00	0.00	-3.74	-240.91	-21.39	-62.32
	Drip	-3.84	-0.46	-0.30	-1.77	-27.43	-2.44	-15.76

Highlights

- A hydro-economic model with aquifer-river interactions is developed
- The model integrates a spatially-explicit groundwater flow formulation
- The model is used to analyze the outcomes of various climate change scenarios and policy choices