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Hydro-economic modeling with aquifer-river interactions for sustainable basin management

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Abstract

Water demands for irrigation, urban and environmental uses in many arid and semiarid regions continue to grow, while freshwater supplies from surface and groundwater resources are becoming scarce and are expected to decline because of climate change. Policymakers in these regions are faced with hard choices on water management and policies. Hydro-economic modeling is the state-of-the arts tool to assist policymakers in the design and implementation of sustainable water management policies in basins. The strength of hydro-economic modeling lies in its capacity to integrate key biophysical and socio-economic components within a coherent framework. A major gap in developments of hydro-economic models to date has been the difficulty of integrating surface and groundwater flows based on the theoretically correct Darcy equations used by the hydrogeological community. The hydro-economic model presented here specifies a spatially-explicit groundwater flow element. The methodological contribution to previous modeling efforts is the explicit specification of the aquifer-river interactions, which are important when aquifer systems make a sizable contribution to basin resources. This advanced framework is applied to the Jucar basin (Spain) for the assessment of different climate change scenarios and policy choices, specially the hydrologic, land use and economic outcomes. The response to scenarios integrates the multiple dimensions of water resources, allowing results to provide valuable information on the basin scale climate change adaptation paths to guide alternative policy choices using sound science.

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

1. Introduction

Water resources are key critical assets to support human societies and natural ecosystems. Despite their paramount importance, many freshwater systems are threatened because of the affordable expansion in water extractions, coupled with large pollution loads that impair water quality. The rate of growth of water extractions has almost doubled population growth during the last century. This expanded human access to water has been driven by urbanization, industrialization and land use changes, with a large deployment of engineering waterworks such as dams, irrigation schemes, inter-basin transfers, and extensive well drilling.

Costs to ensuing damages to ecosystems and biodiversity in river basins are undervalued by private markets when there are public good characteristics of these natural assets. The environmental benefits and services provided to society are "market externalities" and the market failure that are corrected with water policies and regulations can produce a more economically efficient allocation of water resources (Dasgupta and Heal, 1979).

The situation in river basins located in arid and semiarid regions is even worse because in these regions human activities already maximize the extraction of water from the natural environment. The water scarcity problem could become quite serious, threatening both human activities and natural ecosystems. The forthcoming impacts from climate change would further exacerbate the current water scarcity situation in arid and semiarid regions having sizable impacts on irrigated agricultural production, as indicated by global model results (Schewe et al. 2014; Elliot et al. 2014).

The current drought in California and much of the southwestern United States and the recent millennium drought in the Murray-Darling basin of Australia illustrate vividly the severity of water scarcity problems. Another indicator is the finding that a third of the world biggest groundwater systems are in distress, especially in arid and semiarid basins (Richey et al. 2015). The long-term sustainability of groundwater systems requires new aquifer management models in order to address the current groundwater management challenge (Gorelick and Zheng 2015).

This widespread mismanagement of water resources in basins demonstrate the need for better analytical tools that could support more sustainable water management and policies. An important emerging tool for the analysis of sustainable management options in basins is hydro-economic modeling. Hydro-economic models (HEM) integrate the spatially distributed water systems, water storage and conveying infrastructures, water-based economic activities, and water-dependent ecosystems into a coherent model (Harou et al. 2009). The advantage of this approach is the inclusion of interrelationships between the hydrologic, economic, institutional and environmental components for an accurate assessment of sustainable management and policy options (Cai et al. 2003). Booker et al. (2012) analyze the evolution in concepts, methods and application of hydro-economic modeling, stressing its capability for addressing system wide impacts. They indicate that hydro-economic modeling requires further advances in the dynamic and stochastic model dimensions, and also in the accurate understanding of interdependencies between the hydrologic, economic, institutional and environmental components. Despite these achievements, an important gap not yet closed in the development of most hydro-economic models is the theoretically weak connection of the linkages between groundwater and surface water activities. While the Darcy equation approach is the widely-recognized and correct approach to modeling groundwater flows, few if any hydro-economic modeling applications in the water resources literature properly account for the Darcy equation approach for groundwater, mass balance for surface water, and economic principles properly applied for a complete optimization framework.

This paper's unique contribution is to present the development and application of a hydro-economic modeling framework that addresses the gap described above. The issue addressed in this paper is the improvement of the river basin dynamics in modeling, by including the linkage between aquifer systems and river flows. This linkage is important when aquifer systems are closely related to river flows making a sizable inflow or outflow contribution to the basin resources. Overall, the aquifer dynamics and stream-aquifer interactions have been simplified in hydro-economic models, given the level of complexity already involved in modeling whole river basins. First, aquifers are represented as simple single-tank units. Second, the linkage of aquifers and river flows, either inflows or outflows, is usually represented with linear estimates relating the stream-aquifer flow, with variables such as aquifer recharge, water pumping, or water table levels.

For example, Cai et al. (2003) assume a linear relationship between aquifer discharges and water table levels. McCarl et al. (1999) use regression-based forecasts of aquifer discharges that respond to recharge, pumping and water table heights. Ward and Pulido-Velazquez (2009) estimate discharge using a simple proportion of recharge. The study by Schoups et al. (2006) deals with the conjunctive use of surface water and groundwater in irrigation, stressing the need to account for interactions between surface and groundwater systems. Although the model includes water extractions and returns to the aquifer from irrigation, it does not include an explicit aquifer-river interaction.

The approach to the aquifer-river interaction taken here is much more elaborated, avoiding both the single-tank assumption, and overly simple assumptions on the aquifer-river linkages. When these linkages are important, these simplifying assumptions may result into wrong policy recommendations (Brozovic et al. 2010). The groundwater flow formulation used in this paper is similar to the one used in MODFLOW groundwater model, which is able to simulate the spatial and temporal heterogeneity of real-world aquifers and the linkage between aquifer system and river flow (McDonald and Harbaugh 1984). The model is applied to the Jucar basin in Spain, where the river-aquifer linkage is important for the sustainable management of the basin.

2. Modeling framework

This paper presents an integrated basin-scale hydro-economic modeling framework that could be used to assess the impacts of future climate change scenarios and to analyze the economic and biophysical outcomes of adaptation policies. This framework is a comprehensive tool that integrates several components including surface and groundwater hydrology, agronomy, land use, institutions, environment, and economic activities, covering the main water uses. The mathematical formulation of each component is presented below.

2.1 Hydrology

Basin hydrology is based on the principle of water mass balance, defined for each flow, i, and each stock, s. The main flow variables, X_i, tracked by the model include headwater flow, streamflow, surface water diversion, groundwater pumping, water applied and consumed, return flow to streams and aquifers, stream-aquifer interaction, and reservoir release and evaporation. The stock variables, Z_s, tracked by the model are the reservoir and aquifer volume levels.

2.1.1 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, $source_{h,t}$:

$$X_{h,t} = source_{h,t} \tag{1}$$

2.1.2 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:

$$X_{v,t} = \sum_i B_{i,v} \cdot X_{i,t} \tag{2}$$

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.

2.1.3 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:

$$X_{d,t} \leq \sum_i B_{i,d} \cdot X_{i,t} \tag{3}$$

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.

2.1.4 Water applied

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:

$$X_{a,t} = \sum_d B_{d,a} \cdot X_{d,t} + \sum_p B_{p,a} \cdot X_{p,t} \qquad (4)$$

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:

$$X_{a,t}^{ag} = \sum_{j,k} B_{a,j,k} \cdot \left(\sum_u B_{u,a} \cdot L_{u,j,k,t}\right) \qquad (5)$$

Equation (5) 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 an identity matrix, $B_{u,a}$, to conform nodes.

2.1.5 Water consumed

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:

$$X_{u,t} = \sum_a B_{a,u} \cdot X_{a,t} \qquad (6)$$

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:

$$X_{u,t}^{ag} = \sum_{j,k} B_{u,j,k} \cdot L_{u,j,k,t} \qquad (7)$$

Equation (7) 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.

2.1.6 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:

$$X_{r,t} = \sum_a B_{a,r} \cdot X_{a,t} \tag{8}$$

where parameters, $B_{a,r}$, 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:

$$X_{r,t}^{ag} = \sum_{j,k} B_{r,j,k} \cdot (\sum_u B_{u,r} \cdot L_{u,j,k,t}) \tag{9}$$

Equation (9) 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 an identity matrix, $B_{u,r}$, to conform nodes. The sum of water consumed and returned must be equal to water applied at each demand node.

2.1.7 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:

$$Z_{res,t} = Z_{res,t-1} - \sum_L B_{L,res} \cdot X_{L,t} - \sum_e B_{e,res} \cdot X_{e,t} \tag{10}$$

$$Z_{res,0} = B_{res,0} \tag{11}$$

$$Z_{res,t} \leq C_{res}^{max} \tag{12}$$

$$Z_{res,t} \geq C_{res}^{min} \tag{13}$$

where equation (10) 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 identity matrices linking reservoir stock nodes to reservoir release and evaporation nodes, respectively. Equation (11) defines initial reservoir water stock at $t = 0$, $B_{res,0}$. Upper and lower bounds on reservoir water stock are defined in equation (12) and (13), 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.

2.1.8 Aquifer stock and stream-aquifer interaction

The groundwater flow is calculated with a finite-difference groundwater flow equation based on the principle of water mass balance and Darcy's law. The formulation is similar to that used in MODFLOW groundwater model (McDonald and Harbaugh 1984). Assume an aquifer system divided into n (1 row and n columns) connected cells (sub-aquifers), aqf (a subset of s), which are linked to n connected reaches of a river, $river$ (a subset of i). The aquifer head, $H_{aqf,t}$, in each sub-aquifer, aqf, in time, t, is defined in the following equation (see the mathematical appendix for further details on the groundwater flow equation):

$$H_{aqf,t} = \left[1/\left\{\left(S_{aqf} \cdot A_{aqf}/\Delta t\right) + C_{aqf,aqf-1} + C_{aqf,aqf+1} + C_{river,aqf}\right\}\right] \cdot \left[R_{aqf,t} - Q_{aqf,t} + \left(S_{aqf} \cdot A_{aqf} \cdot H_{aqf,t-1}/\Delta t\right) + C_{aqf-1} \cdot H_{aqf-1,t} + C_{aqf+1} \cdot H_{aqf+1,t} + C_{river,aqf} \cdot H_{river,aqf}\right] \; ; \quad H_{aqf,0} = B_{aqf,0} \tag{14}$$

where parameters S_{aqf}, A_{aqf}, and $R_{aqf,t}$ are specific yield, area, and recharge for sub-aquifer, aqf, respectively. Parameters $C_{aqf,aqf-1}$ and $C_{aqf,aqf+1}$ represent hydraulic conductance between sub-aquifer, aqf, and adjacent sub-aquifers, $aqf-1$ and $aqf+1$, respectively. Parameter $C_{river,aqf}$ is hydraulic conductance of river reach, $river$, linked to sub-aquifer, aqf. Parameter Δt is the time step. Parameter $B_{aqf,0}$ is the initial head of sub-aquifer, aqf, at $t = 0$. Variable $H_{aqf,t-1}$ is the head of sub-aquifer, aqf, in the previous time period. Variables $H_{aqf-1,t}$ and $H_{aqf+1,t}$ are heads of adjacent sub-aquifers, $aqf-1$ and $aqf+1$, respectively. Variable $H_{river,aqf}$ is the head of the river reach, $river$, linked to sub-aquifer, aqf, and variable $Q_{aqf,t}$ is net groundwater pumping from sub-aquifer, aqf, which are defined in equations (15) and (16) as follows:

$$H_{river,aqf} = BH_{river,aqf} \cdot \left(\sum_{v} B_{v,river,aqf} \cdot X_{v,t}\right) \tag{15}$$

$$Q_{aqf,t} = \sum_{p} B_{p,aqf} \cdot X_{p,t} - \sum_{r} B_{r,aqf} \cdot X_{r,t} \tag{16}$$

where variables $X_{v,t}$ 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. Parameters $BH_{river,aqf}$ are coefficients defining the relationship between river head (or river stage) and streamflow (or discharge) for each river reach. This relationship depends on river features such as riverbed form and roughness coefficients. Parameter sets $B_{v,river,aqf}$, $B_{p,aqf}$ and $B_{r,aqf}$ are identity 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:

$$X_{river,aqf,t} = C_{river,aqf} \cdot \left(H_{river,aqf,t} - H_{aqf,t}\right) \tag{17}$$

Equation (17) 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 negative if sub-aquifer is discharging water to river reach.

2.2 Land use

For irrigated agriculture, land in production in each agricultural use node, (a subset of u), which derives water demand in that node, is defined in the following equations:

$$\textstyle\sum_{j,k} L_{u,j,k,t} \leq Tland_{ut} \tag{18}$$

$$L_{u,per,k,t} \leq L_{u,per,k,t-1} \tag{19}$$

Equation (18) states that the sum over crops (j) and irrigation technologies (k) of irrigated land in production, $L_{u,j,k,t}$, at each agricultural use node in time, t, cannot exceed land availability, $Tland_{ut}$, in that use node and time period. Equation (19) states that irrigated land in production, $L_{u,per,k,t}$, 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 reflects the possible future loss of long-run capital investments in perennial crops if farmers decide to not irrigate those crops in the current time period.

2.3 Institutions and environment

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

In this paper, several institutional and environmental constraints are included depending on the climate and policy scenarios considered. A constraint on urban water supply is maintained in all scenarios in order to assure that a minimum amount of water, B_a^{min}, is delivered to urban application nodes, a, in each time period, t. This constraint is defined in the following form:

$$X_{a,t}^{urb} \geq B_a^{min} \tag{20}$$

2.4 Economics

Water has an economic value in all its competing uses, which 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:

$$NB_{u,t} = TB_{u,t} - TC_{u,t} \tag{21}$$

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, total benefits, $TB_{u,t}^{ag}$, and total costs, $TC_{u,t}^{ag}$, in time, t, are defined by the following equations:

$$TB_{u,t}^{ag} = \sum_{j,k}\left(P_{u,j} \cdot Y_{u,j,k,t}\right) \cdot L_{u,j,k,t} \tag{22}$$

$$TC_{u,t}^{ag} = \sum_{j,k}\left(PC_{u,j,k,t} + WC_{u,j,k,t}\right) \cdot L_{u,j,k,t} \tag{23}$$

where parameters $P_{u,j}$ is crop prices; $Y_{u,j,k,t}$ is crop yields, and $PC_{u,j,k,t}$ is non-water production costs, and variable $L_{u,j,k,t}$ is crop area. Variable $WC_{u,j,k,t}$ is water costs which is defined as follows:

$$WC_{u,j,k,t} = PW_u \cdot \left(\sum_d B_{d,u} \cdot X_{d,j,k}\right) + \left(CP_{0,u} + CP_{1,u} \cdot PumpDepth_u\right) \cdot (\sum_p B_{p,u} \cdot X_{p,j,k}) \tag{24}$$

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

For urban use nodes, (a subset of u), total benefits, $TB_{u,t}^{urb}$, and total costs, $TC_{u,t}^{urb}$, in time, t, are defined by the following equations:

$$TB_{u,t}^{urb} = \beta_{0,u} + \beta_{1,u} \cdot X_{a,t}^{urb} + \beta_{2,u} \cdot X_{a,t}^{urb\,2} \tag{25}$$

$$TC_{u,t}^{urb} = \delta_u \cdot X_{a,t}^{urb} \tag{26}$$

where equation (25) is the total benefits function with a quadratic specification, with $\beta_{0,u}$, $\beta_{1,u}$ and $\beta_{2,u}$ are the parameters for the constant, linear and quadratic terms, respectively. For urban use nodes, households utilize water first for high-value uses such as indoor uses for drinking, sanitation and cooking, so that urban benefits rise quickly for supplies allocated to these uses, starting from a position of no use. These high-value uses have few substitution possibilities, and therefore β_{1u} is expected to be large and positive. However, urban marginal benefits fall rapidly for other additional low-value uses, such as outdoor uses for garden irrigation and car washing. Then β_{2u} is expected to be large and negative. Equation (26) represents total urban supply costs, with δ_u being the per unit cost of water supplied.

2.5 Objective function

The model objective is maximizing the net present value of the economic net benefits over a planning horizon, subject to the basin's hydrological, land use, institutional, and environmental constraints. The model provides information on the optimal water flows and stocks, and cropping patterns under different climate and policy scenarios predefined by the modeler. The objective function takes the following form:

$$Max\ NPV = \sum_{u,t} \frac{NB_{u,t}}{(1+r)^t} \tag{27}$$

where NPV is the net present value, $NB_{u,t}$ are the net benefits, and r is the discount rate.

3. Model application

The modeling framework described previously in section 1 is applied to an arid and semiarid basin in Southeastern Spain, the Jucar basin. This basin is a good experimental field for an integrated basin scale analysis. One reason is that the Jucar is at present under severe stress with acute water scarcity and significant ecosystem degradation. Another reason is that the foreseeable climate change impacts are expected to exacerbate water scarcity problems in the basin. However, the modeling framework is designed to be adaptable for any basin elsewhere.

3.1 Study area: the Jucar basin

The Jucar basin is located in the regions of Valencia and Castilla La Mancha in Southeastern Spain. It extends over 22,300 km^2 and covers the area drained by the Jucar River and its tributaries, mainly the Magro and Cabriel Rivers. The basin is a complex system including 13 reservoirs and numerous competing uses with different priority rights, and with a complex relationship 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).

Urban and industrial extractions are 270 Mm^3 to supply households, industries, and services in an area with more than one million inhabitants. This population is located mostly in the cities of Valencia, Sagunto and Albacete. Extractions for irrigated agriculture are nearly 1,400 Mm^3 to irrigate 190,000 ha. The main crops are rice, wheat, barley, corn, garlic, onion, grapes, and citrus. There are three major irrigation areas, the Eastern La Mancha irrigation area (EM) located in the upper Jucar; the traditional irrigation districts of Acequia Real del Jucar (ARJ), Escalona y Carcagente (ESC), and Ribera Baja (RB) located in the lower Jucar; and the irrigation area of the Canal Jucar-Turia (CJT) located in the bordering Turia Basin (CHJ 2014).

The Jucar basin includes the Albufera wetland, which is one of the most important aquatic ecosystems in Europe. The Albufera is catalogued in the RAMSAR list, and it is a natural park and a special protected area for birds. It receives water mainly from the return flows of the ARJ and RB irrigation districts. Other flows originate from the neighboring Turia basin, and from the discharge of urban and industrial wastewaters in the adjacent municipalities (Sanchis, 2011).

Irrigation development during recent decades in the basin has been quite important for the local economy, and irrigated agriculture remains an important source of income and labor in the area. The expansion of irrigation has been driven especially by groundwater pumping from the EM aquifer, which is the largest aquifer system in Spain (Esteban and Albiac 2012). However, the intensive groundwater pumping has caused a significant drop in the water table level reaching 80 m in some areas, and resulting in large storage depletion fluctuating around 2,500 Mm^3 at present. In addition, the EM aquifer is linked to the Jucar River stream, and it 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 desiccated during recent droughts.

A major challenge for policymakers in the Jucar basin is the design of sustainable adaptation strategies to the upcoming effects of climate change, which is expected to reduce the freshwater supplies and increase the demand for water. Climate change projections for the end of the twenty-first century in the Jucar basin under a range of climatic and emission scenarios indicate a reduction of surface and groundwater availability between 11 and 46%, and an increase of evapotranspiration between 12 and 22% (CEDEX, 2010).

The hydro-economic modeling framework is applied to the Jucar basin in order to address adaptation to climate change. The analysis undertaken in this paper focuses on irrigation activities in the major irrigation districts (EM, CJT, ESC, ARJ and RB) and urban demand in the major cities (Albacete, Valencia, and Sagunto). Following the study by Sanz et al. (2011), the EM irrigation district is divided into three sub-areas of the aquifer, 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 Albufera wetland, the ecosystem linked to the Jucar River and its tributaries, and the groundwater-dependent ecosystems in the EM aquifer. Three proxy variables are used in order to quantify the environmental impacts of the climate and policy scenarios on these ecosystems: the inflows to the Albufera wetland, the outflows to the Mediterranean Sea, and the change in the EM aquifer storage. 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, 1 environmental demand node, 3 reservoir release nodes, 3 reservoir stock nodes, and 3 aquifer stock nodes. Figure 1 presents the hydrological network of the basin, including the sources and uses of water.

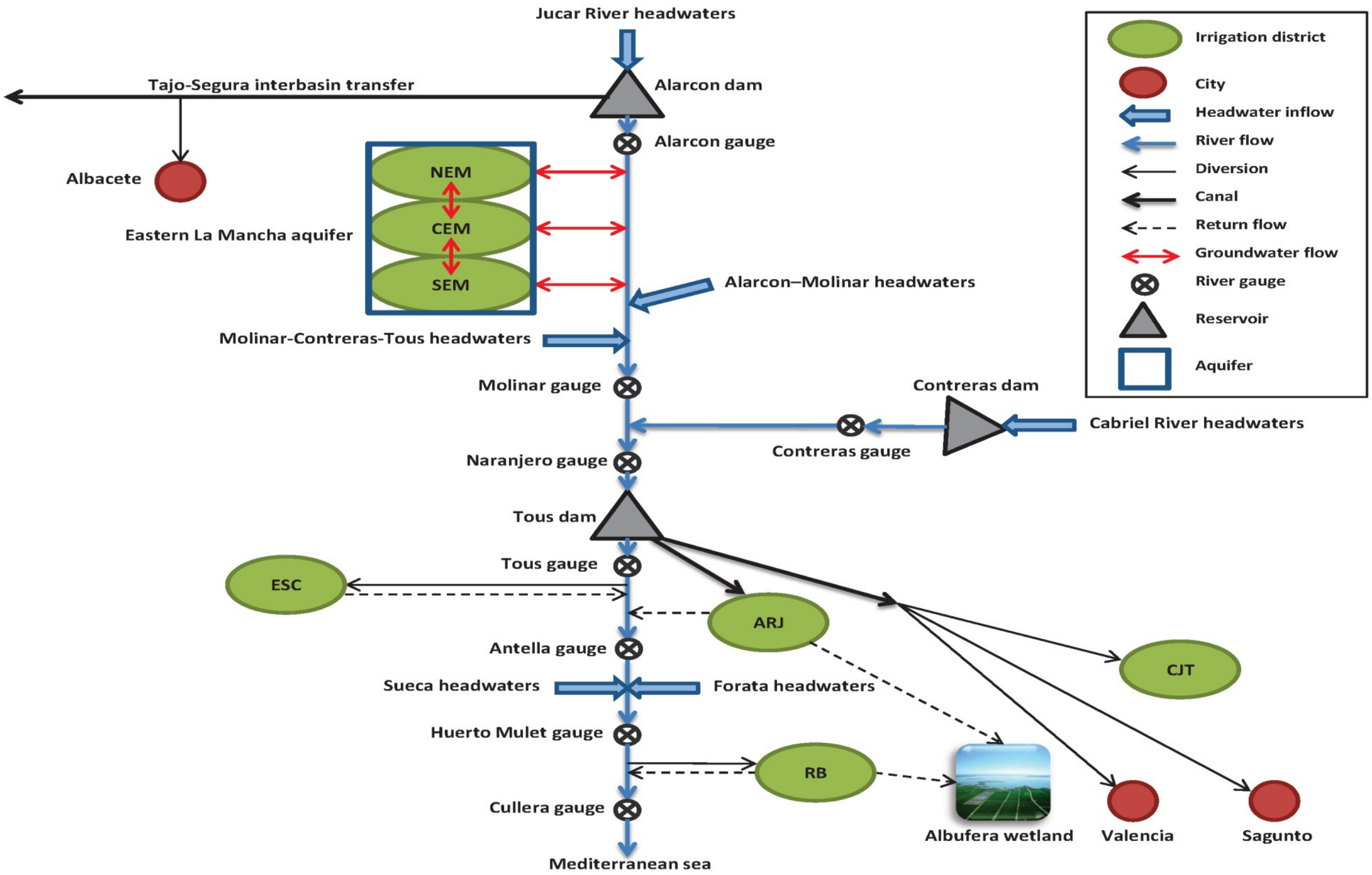
3.2 Data sources

Data on headwater inflows to the basin, gauged water flows, and reservoir inflows, releases and evaporation has 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 has 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 collected from field surveys, expert consultation, statistical reports, and published documentation (INE, 2009; GV, 2009; GCLM, 2009; MARM 2010). Irrigation water extractions by source of water in each district have been calculated using crop areas, water requirements, and location of irrigation technologies and their efficiencies. 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 a quadratic benefit function similar to the one specified in equation (25). Parameter estimation requires three data items: the observed water price and quantity for a specific time period, and the price elasticity of water demand (Young 2005). Information on urban water supply by source of water, 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 Martinez-Espiñeira (2002) and Arbues and Barberan (2004).

Figure 1. Network of the Jucar basin.



The environmental benefits and damage costs for the most important aquatic ecosystems in the Jucar are estimated. For the Albufera wetland, an environmental benefit function of the wetland from Kahil et al. (2015) is used. For the Jucar River, 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, CSIRO 2012, Banerjee et al. 2013). 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).

Return flows to the Jucar River and to aquifers have been calculated as the fraction the applied water not used in crop evapotranspiration or in urban consumption. The information about the contribution of return flows to streamflow and aquifer recharge is taken from the reports of the Jucar basin authority (CHJ 2014).

3.3 Model calibration

Integrated hydro-economic models typically require a careful calibration procedure before they can be used to assess sustainable water management policies. In this paper, both the hydrologic and the agricultural economic components of the Jucar model are calibrated. The 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. 2009). The agricultural economic component is calibrated using the Positive Mathematical Programming (PMP) 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, which is a normal flow year.

The hydrological component is calibrated so that its predicted gauged flows match the 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 properly measured.

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.

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 such as rivers and channels, and percolation. Additionally, the calibration procedure involves an adjustment of aquifer parameters such as 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 have 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. Then any changes brought about by new policy intervention 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. 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 in the appendix.

3.4 Climate change and policy scenarios

The modeling framework is used to analyze climate change impacts and adaptation possibilities under various climate and policy scenarios in the Jucar basin. Two climate change scenarios are considered: mild and severe. These scenarios cover climate change impacts on potential evapotransipration, surface runoff, and groundwater recharge as shown in table 1. 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.

The model is used to assess the outcomes of two policy alternatives under the climate change scenarios defined 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 for environmental damages caused by water resources depletion. The cost that groundwater users confront when pumping aquifers unsustainably is the increased pumping costs incurred by lowering the aquifer heads. Under unsustainable management, competing users ignore the common pool nature of groundwater creating the water extraction externality, where extractions by one user reduce the water stock available for others. Because every user believes that competitors will not conserve water for future use, there is no incentive to protect the water stock. Pumping by users takes place as long as the economic value of the marginal product of pumped water exceeds the marginal pumping cost. Beyond these marginal costs, there are no incentives to conserve water for the future or account for other environmental externalities related to groundwater depletion (Esteban and Albiac 2012).

In recent decades, aquifer systems have been suffering substantial pressures in arid and semi-arid regions, with extraction rates well above recharge (Richey et al. 2015). Significant negative impacts are already occurring in many basins worldwide, because the degradation of water bodies limits economic activities and endangers ecosystems (UNEP 2003; WWAP 2006). In addition, individual agents are unable to capture the future value of stock resources. Therefore, both surface water stored in reservoirs and groundwater resources in the absence of adequate regulation are misallocated and used more intensively than what is socially desirable (Esteban and Albiac 2012).

Sustainable management policy: This policy promotes the protection of water resources, accounting for long-term and environmental benefits. The sustainable management of water resources requires a reform of the water institutions and policies used at present that have failed to align private short-term goals with societal long-term goals (Guerry et al. 2015). For the purpose of this paper, sustainable water management is defined as the water extractions that do not exceed the natural replenishment rate and maintain minimum environmental flow thresholds. This policy is implemented 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 than 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 management policy choices.

3.5 Solving the model

The model is formulated as a dynamic nonlinear problem that maximizes the Jucar basin's net present value for a 20 years' time period. The GAMS package has been used for model development and scenario simulation (Brooke et al. 1988). The dimensions of the model are 391,317 equations, 421,764 variables and 1,039,011 nonzero elements. The model is solved using the CONOPT algorithm within GAMS, which is designed to solve large-scale nonlinear optimization models. See the GAMS code of the Jucar model in the appendix.

4. 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.

4.1 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 per year, divided between 690 Mm^3 for agricultural demand (86%) and 110 Mm^3 for urban demand (14%).[1] 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 affect reservoir storage, which increases by 10 Mm^3 per year. Groundwater extractions

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[1] About 260 Mm^3/year of water extractions by numerous small demand nodes are not included in the model.

Table 2. Hydrologic, land use and economic outcomes of the 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 (Mm^3/year)														
Headwater inflows														1355.5
Aquifer recharge														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													-39.3	-39.3
Aquifer-river discharge (river gains if >0)														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 (€/m^3)	0.10	0.11	0.09		0.08	0.03	0.03	0.01			0.06			
Urban water price (€/m^3)				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.

are 317 Mm^3 and they are the major water sources for the irrigation districts located in the region of Castilla La Mancha in the upper Jucar (NEM, CEM and SEM).

Results show that under the current policy setting and climate conditions, groundwater pumping results in aquifer depletion of about 39 Mm^3 per year. The consequence is that aquifer discharge to the river is no more than 46 Mm^3 per year, which is very low compared to the historical discharges of 250 Mm^3 before the largest pumping extractions took place in the 1999's (Sanz et al. 2011). The annual water outflow to the Mediterranean Sea is 417 Mm^3, well above the annual environmental flow threshold required to achieve a good ecological status of the Jucar River (63 Mm^3 or 2 m^3/s). The Albufera wetland receives about 89 Mm^3 per year from irrigation return flows, which meets the wetland water requirements in order to achieve a good ecological status (CHJ 2014).

The land use outcomes show that the irrigated area amounts to 123,000 ha per year, of which 53,500 ha are cereals, 16,000 ha are vegetables, and 53,500 ha are 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.

The 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 benefits. Environmental uses generate 29% of net benefits. The major share of net benefits accrues to urban uses, about 56% of the total. This large share of benefits calculated for urban uses occurs because of the low price elasticity of demand for urban uses and its associated high consumer surplus. The economic outcomes reflect the intense competition for water between agriculture, urban and environmental uses.

The last two rows in table 2 show the economic value of an additional cubic meter of water (or shadow price) for farmers and households from water reallocation or supply increases. These shadow prices provide important information to policymakers on the willingness to pay for water by users, they could guide allocation decision, and they could indicate whether investments in developing alternative sources of water such as desalination and water conservation are required or not. Results show that the shadow price of water is very high for urban use compared to agricultural use. These results justify the fact that agriculture usually faces the main adjustment to water scarcity. The marginal values of irrigation water are higher in the upper Jucar, where groundwater resources are intensively used, compared to those in the lower Jucar based mostly on surface water.

4.2 Mild climate change scenario

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

The economic outcomes of this scenario indicate that the mild climate change scenario reduces net benefits between 85 and 91 million € per year (up to 13%) compared to the baseline scenario. 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%) in the sustainable policy. Urban net benefits for both policies remain almost unchanged under this climate change scenario compared to the baseline because of the very small reduction in urban water supply. Urban water prices rise slightly by 1 and 2% under the unsustainable and sustainable policies, respectively.

The major impact of climate change falls on agriculture and the environment, which sustain the costs of adaptation. The reason is the large cutbacks in agriculture allocations coupled 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 mild climate change and the unsustainable policy, reservoir depletion is 10 Mm^3 per year, and aquifer depletion is 65 Mm^3 per year.

The sustainable policy, which avoids water stocks depletion and assures minimum river flows achieves higher environmental net benefits (about 8%) compared to the unsustainable policy. The aquifer discharge to the river increases under the sustainable policy compared to the unsustainable policy and the baseline scenario. This increase in aquifer discharges to the river enhances river flows available for water users

Table 3. Hydrologic, land use and economic outcomes of the mild climate change scenario and unsustainable management 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														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													-64.7	-64.7
Aquifer-river discharge (river gains if >0)														44.9
Outflow to Mediterranean Sea													98.1	98.1
Inflows to Albufera wetland													83.6	83.6
Land use outcomes														
Irrigated area (1000 ha/year)	6.2	36.3	14.3		16.7	2.9	11.8	14.8			103.0			103.0
Cereals	2.5	19.2	8.8		0.2	0.0	1.3	8.2			40.1			40.1
Vegetables	0.5	9.4	3.1		0.6	0.0	0.5	0.2			14.4			14.4
Fruit trees	3.3	7.7	2.4		15.8	2.9	10.0	6.4			48.5			48.5
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														
Gross benefits (million €/year)	10.5	87.1	29.7	75.1	86.6	15.1	58.9	48.5	430.6	30.6	336.3	536.3	122.7	995.3
Production costs (million €/year)	6.9	53.8	18.6	19.8	64.5	11.8	44.4	37.7	113.1	8.0	237.6	141.0	2.1	380.7
Net benefits (million €/year)	3.7	33.3	11.1	55.3	22.1	3.3	14.5	10.8	317.5	22.5	98.7	395.3	120.6	614.6
Marginal value of irrigation water (€/m^3)	0.11	0.11	0.09		0.09	0.03	0.04	0.01			0.07			
Urban water price (€/m^3)				1.29					1.31	1.31		1.30		

Note: see note to table 2.

Table 4. Hydrologic, land use and economic outcomes of the mild climate change scenario and sustainable management 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														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													0.0	0.0
Aquifer-river discharge (river gains if >0)														51.2
Outflow to Mediterranean Sea													148.9	148.9
Inflows to Albufera wetland													76.3	76.3
Land use outcomes														
Irrigated area (1000 ha/year)	3.0	24.4	8.6		15.5	2.6	9.9	15.0			79.0			79.0
Cereals	0.3	9.1	4.2		0.1	0.0	0.3	8.3			22.3			22.3
Vegetables	0.3	8.1	2.5		0.6	0.0	0.5	0.2			12.2			12.2
Fruit trees	2.4	7.2	1.9		14.8	2.6	9.1	6.4			44.5			44.5
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														
Gross benefits (million €/year)	6.9	73.1	23.2	75.1	82.2	13.9	53.1	48.7	430.4	30.6	301.0	536.1	130.3	967.4
Production costs (million €/year)	3.9	40.7	12.7	19.7	60.4	10.7	39.5	37.9	113.0	8.0	205.7	140.8	0.0	346.5
Net benefits (million €/year)	3.0	32.4	10.5	55.3	21.8	3.2	13.6	10.8	317.5	22.5	95.3	395.3	130.3	620.9
Marginal value of irrigation water (€/m^3)	0.14	0.12	0.10		0.09	0.03	0.05	0.01			0.08			
Urban water price (€/m^3)				1.30					1.31	1.31		1.31		

Note: see note to table 2.

downstream, and therefore puts less pressure on the water stocks in reservoirs that can be maintained.

Compared to the baseline scenario, the water flowing to the Mediterranean Sea decreases considerably under climate change for the two policies (up to 76%), but this water flow is higher under the sustainable than under unsustainable policies. Nevertheless, outflows to sea under both policies comply with the small minimum environmental flow threshold. The inflows to the Albufera wetland decrease under the mild climate change compared to the baseline scenario. The wetland receives larger inflows under the unsustainable 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.

4.3 Severe climate change scenario

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

The severe climate change scenario reduces basin net benefits between 133 and 147 million € per year (up to 21%) compared to the baseline scenario. 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 for 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 and sustainable policies, respectively.

The impacts of severe climate change on agriculture are considerable with benefits dropping between 15 and 40%, compared to the baseline. The cost of achieving sustainability under severe climate change is supported by agriculture with benefits falling 30% in comparison to the unsustainable policy. Without sustainability requirements, the depletion levels in reservoirs and aquifers are 10 and 92 Mm^3 per 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.

Table 5. Hydrologic, land use and economic outcomes of the severe climate change scenario and unsustainable management 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														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													-92.4	-92.4
Aquifer-river discharge (river gains if >0)														44.2
Outflow to Mediterranean Sea													31.5	31.5
Inflows to Albufera wetland													63.5	63.5
Land use outcomes														
Irrigated area (1000 ha/year)	5.8	29.7	12.3		12.6	1.9	7.4	12.7			82.3			82.3
Cereals	2.1	13.5	7.2		0.0	0.0	0.0	6.4			29.2			29.2
Vegetables	0.4	8.6	2.9		0.5	0.0	0.4	0.2			13.0			13.0
Fruit trees	3.3	7.5	2.2		12.0	1.9	7.0	6.1			40.0			40.0
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														
Gross benefits (million €/year)	10.1	79.4	27.4	75.1	73.8	11.9	45.6	44.6	430.1	30.5	292.7	535.7	89.7	918.1
Production costs (million €/year)	6.6	48.4	17.2	19.7	53.5	9.0	33.2	34.3	112.6	8.0	202.1	140.3	3.0	345.4
Net benefits (million €/year)	3.4	31.0	10.2	55.3	20.3	2.9	12.3	10.3	317.5	22.5	90.6	395.3	86.7	572.6
Marginal value of irrigation water (€/m^3)	0.11	0.12	0.10		0.10	0.04	0.06	0.01			0.08			
Urban water price (€/m^3)				1.30					1.34	1.34		1.33		

Note: see note to table 2.

Table 6. Hydrologic, land use and economic outcomes of the severe climate change scenario and sustainable management 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														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													36.2	36.2
Aquifer-river discharge (river gains if >0)														58.0
Outflow to Mediterranean Sea													73.9	73.9
Inflows to Albufera wetland													61.3	61.3
Land use outcomes														
Irrigated area (1000 ha/year)	0.0	2.5	4.4		10.9	1.4	5.8	13.1			38.1			38.1
Cereals	0.0	0.0	1.3		0.0	0.0	0.0	6.7			8.1			8.1
Vegetables	0.0	2.5	2.0		0.5	0.0	0.3	0.2			5.5			5.5
Fruit trees	0.0	0.0	1.0		10.4	1.4	5.6	6.2			24.6			24.6
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														
Gross benefits (million €/year)	0.5	20.8	18.1	75.0	66.2	9.7	38.5	45.3	429.8	30.5	199.3	535.3	99.6	834.2
Production costs (million €/year)	0.4	9.9	9.3	19.7	46.9	7.2	27.4	34.9	112.3	8.0	135.8	140.0	0.0	275.8
Net benefits (million €/year)	0.2	11.0	8.9	55.3	19.3	2.6	11.2	10.4	317.4	22.5	63.5	395.3	99.6	558.4
Marginal value of irrigation water (€/m^3)	0.24	0.17	0.11		0.11	0.04	0.06	0.01			0.11			
Urban water price (€/m^3)				1.32					1.36	1.36		1.35		

Note: see note to table 2.

Policymakers in arid and semiarid regions worldwide are constantly searching for policies leading to the sustainable use of water resources, mostly linked to reductions in overall basin extractions. The cost of such policies are given in terms of benefits losses (or gains) sustained by the groups of stakeholders. For policy success, the costs of these policies should be acceptable to stakeholders, eventually through compensation of losers. Otherwise, stakeholders will oppose any sustainable measure, leading to policy failure.

Table 6 shows how to meet sustainable outcomes under severe climate change in the Jucar basin. The objective is finding water allocations which have reasonable policy costs, measured by reduction in the present value of the stream of benefits along the planning horizon. Results indicate that the best way to achieve that is by substantially reducing groundwater pumping in the upper Jucar, and increasing the 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 cannot get water by depleting 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 slightly reduced under the sustainable policy compared to the unsustainable policy. Water flowing to the sea decreases substantially under severe climate change, between 82 and 92% compared to the baseline scenario. 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 the baseline scenario. Inflows to the wetland are lower under the sustainable policy compared to the unsustainable policy, because the smaller water extractions reduce also the return flow feeding the wetland.

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
Base	Normal	5101.1	1389.6	2653.6	6490.7	9144.3
Unsustainable 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.

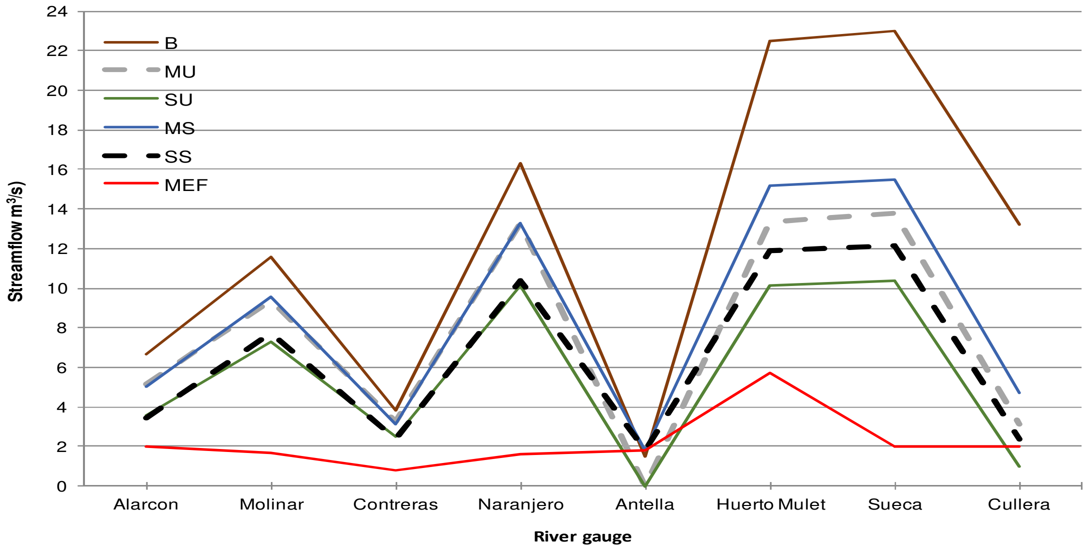
4.4 Tradeoffs among policies

The comparison between climate and policy scenarios shows the environmental and economic tradeoffs among policy choices. This information could be useful for the design of sustainable climate change adaptation policies at basin scale. Table 7 displays the present value of benefits for the climate and policy scenarios. Results indicate that climate change will have negative effects on the basin social benefits for the considered climate and policy scenarios. Benefits decline between 12 and 21% under climate change. However, the losses of private benefits are less than 10%. The impacts vary by group of users, with urban uses not very affected, and agricultural and environmental users bearing quite large damages.

Results show that the impacts of climate change depend on policy choices. The adaptation of stakeholders can be economically efficient, 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 to better engage the impacts of climate change. But this involves serious damages to water-dependent ecosystems and also threatens future human activities. Conversely, the inclusion of sustainability objectives within the adaptation policies reduces the climate change impacts on the environment, but leads to very costly impacts on current economic activities.

For agriculture, there is a substantial gap between the benefits obtained under severe climate change and sustainable policy, and all the other scenarios. This negative impact of combining severe climate change with sustainable policy is too detrimental to farmers, and the costs of the policy become prohibitive. Therefore, additional policy instruments are needed to compensate farmers for their large benefit losses such as providing them with payments for the water released to support ecosystem services.

Figure 2. Streamflow in different river gauges under the climate and policy scenarios.

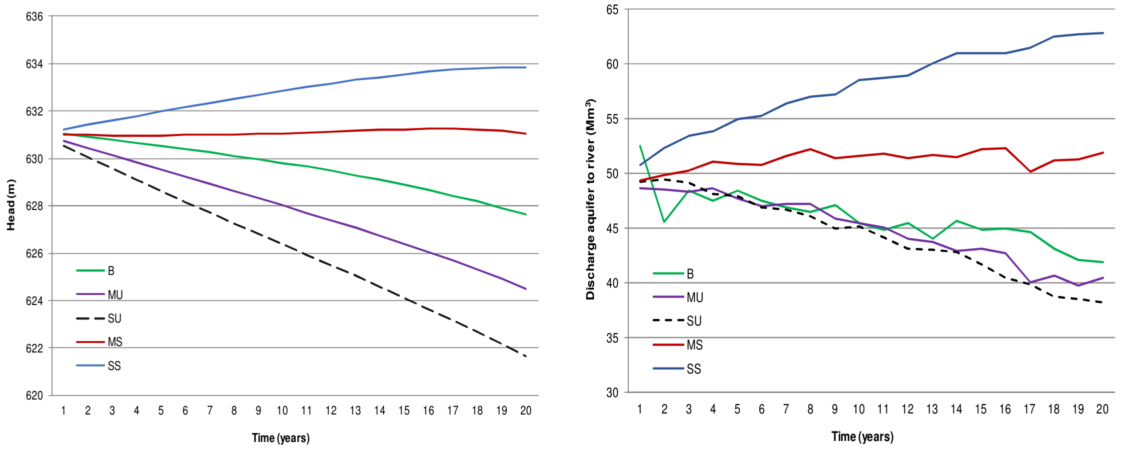


Note: B=Baseline scenario; MU=Mild climate change and unsustainable policy; SU=Severe climate change and unsustainable policy; MS=Mild climate change and sustainable policy; SS=Severe climate change and sustainable policy; MEF=Minimum environmental flows.

For environmental uses, the sustainable management policy reduces the negative impacts of climate change by increasing river flows and avoiding the depletion of aquifers and reservoirs. However, the Albufera wetland does not benefit from the sustainable policy because the Albufera depends on the irrigation return flows which diminish under the sustainable policy. A possible solution to recover water for the Albufera wetland could be the direct allocation of some river flow gains to the wetland.

Figure 2 shows the average river flow over the 20 year planning horizon in different river gauges under alternative climate and policy scenarios. River flows, which are the main drivers to maintain the river’s good ecological status, decline under all climate change and policy scenarios compared to the baseline. The decline is especially remarkable in the downstream gauges (from Antella to Cullera) where the basin’s major surface water users are located. However, river flow is higher in all gauges under the sustainable policy compared to the unsustainable policy. Non-compliance with the small environmental flow requirements occurs only in the Antella and Cullera gauges. Non-compliance in Antella occurs under mild or severe climate change for the the unsustainable policy. Non-compliance in Cullera occurs only under severe climate change for the unsustainable policy.

Figure 3. Aquifer head and discharge to the river under the climate and policy scenarios.



Note: See note to figure 1. Aquifer head and discharge in each year are average values for the three sub-aquifers.

Figure 3 shows the paths of the aquifer head and discharge from the aquifer to the river along the 20 years planning horizon for the climate and policy scenarios. Results from tables 2, 3 and 5 indicate that without sustainability requirements, groundwater pumping in the upper Jucar is very high compared to aquifer recharge. Pumping extractions amounts to 98% of recharge for the baseline scenario, 109% of recharge for the mild climate change, and 131% of recharge for the severe climate change. The consequence of the unsustainable policy is a steady drop in both the water table level and the aquifer discharges to the river. Under the sustainable policy, the water table recovers and discharges from the aquifer to the river increase, because farmers reduce pumping down to 74 and 25% of recharge for the mild and severe climate change, respectively.

5. Conclusions

River basins in arid and semiarid regions worldwide face important water scarcity challenges, which will be aggravated by climate change in the coming decades. Policymakers in these basins have to make difficult decisions on water management and policies that involve complex environmental and economic tradeoffs. Solving these challenges requires better analytical tools to advance more sustainable management and policy options. A key task is the integration of the complex interrelationships between hydrological, economic, institutional and environmental components in basins.

Hydro-economic modeling is an emerging tool for implementing comprehensive basin scale analysis that could inform the design of sustainable water management policies. However, hydro-economic models have to be capable to adequately reproduce the physical behavior of the basin, with a realistic representation of the different water sources and uses, including the interaction between surface water and groundwater, as well as the value of the 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 Jucar basin of Spain. The contribution of this paper to previous hydro-economic modeling efforts stems from the improvement of the river basin dynamics. A groundwater flow framework similar to the MODFLOW groundwater model is added to the standard hydro-economic formulation of basins. This improved methodological approach is capable of simulating the spatial and temporal heterogeneity of real-world aquifers, and most important the linkages between aquifer systems and river flows.

Results of applying the modeling framework to the Jucar basin demonstrate the model capabilities to assess the 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 hydrology, land use and economic values. Results illustrate how adaptation to climate change could be strategically undertaken at 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 crucial to assist policymakers in arid and semiarid basins in the design and implementation of sustainable water management policies.

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Appendix

Table A1. Intercept of the yield function (maximum yield) by irrigation district, crop and technology (Ton/ha).

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(Ton/ha)/Δha).

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

Mathematical appendix

The groundwater flow is calculated with a finite-difference groundwater flow equation based on the principles of water mass balance and Darcy's law. The formulation (equation 14) is similar to that used in the MODFLOW groundwater model (McDonald and Harbaugh 1984). Equation (14) is derived in the following way:

For simplicity and without loss of generality, we assume that n aquifer cells or sub-aquifers are represented by 1 row and n columns, where the set aqf consists of n elements: 1,2,…, n. These aquifer cells are connected serially to each other and to n river reaches, The set $river$ also consists of 1,2,…, n elements, where every cell is connected only to one river reach. Think of the river as a multi-colored ribbon, with a separate color for each reach, flowing on top of a series of blocks below (aquifer cells) in which both the river and aquifer are divided into n contiguous cells. The water mass balance for each aquifer cell is defined by:

$$\Delta Z_{aqf,t} = R_{aqf,t} - Q_{aqf,t} + X_{aqf,t} + X_{river,aqf,t} \qquad \text{(A1)}$$

where equation (A1) 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, $\Delta Z_{aqf,t}$, where $R_{aqf,t}$ 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:

$$\Delta Z_{aqf,t} = S_{aqf} \cdot A_{aqf} \cdot \left(H_{aqf,t} - H_{aqf,t-1}\right)/\Delta t \qquad \text{(A2)}$$

where parameters S_{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 (A3), and the water flow between sub-aquifers and the corresponding river reaches $X_{river,aqf,t}$ is defined by equation (A4). Equations (A3) and (A4) are formulated using the Darcy's law as follows:

$$X_{aqf,t} = C_{aqf,aqf-1} \cdot \left(H_{aqf-1,t} - H_{aqf,t}\right) + C_{aqf,aqf+1} \cdot \left(H_{aqf+1,t} - H_{aqf,t}\right) \tag{A3}$$

$$X_{river,aqf,t} = C_{river,aqf} \cdot \left(H_{river,aqf,t} - H_{aqf,t}\right) \tag{A4}$$

where equation (A3) states that the water flows between the sub-aquifers, aqf, and adjacent sub-aquifers, $aqf - 1$ and $aqf + 1$, depends 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 (A4) 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 (A1) can be written using equations (A2), (A3) and (A4) as follows:

$$S_{aqf} \cdot A_{aqf} \cdot \left(H_{aqf,t} - H_{aqf,t-1}\right)/\Delta t = R_{aqf,t} - Q_{aqf,t} + C_{aqf,aqf-1} \cdot \left(H_{aqf-1,t} - H_{aqf,t}\right) + C_{aqf,aqf+1} \cdot \left(H_{aqf+1,t} - H_{aqf,t}\right) + C_{river,aqf} \cdot \left(H_{river,aqf,t} - H_{aqf,t}\right) \tag{A5}$$

Solving for $H_{aqf,t}$ yields the groundwater flow equation (equation 14 in the text):

$$H_{aqf,t} = \left[1/\left\{\left(S_{aqf} \cdot A_{aqf}/\Delta t\right) + C_{aqf,aqf-1} + C_{aqf,aqf+1} + C_{river,aqf}\right\}\right] \cdot \left[R_{aqf,t} - Q_{aqf,t} + \left(S_{aqf} \cdot A_{aqf} \cdot H_{aqf,t-1}/\Delta t\right) + C_{aqf-1} \cdot H_{aqf-1,t} + C_{aqf+1} \cdot H_{aqf+1,t} + C_{river,aqf} \cdot H_{river,aqf}\right] \tag{A6}$$

GAMS Code

```
$ EOLCOM //
$ TITLE JUCAR BASIN OF SPAIN
$ OFFSYMXREF OFFSYMLIST OFFLISTING OFFUPPER

OPTION LIMROW= 100,  LIMCOL = 0, reslim = 1000000000, ITERLIM = 100000000;
********************************************************************************
* Integrated SW-GW basin scale optimization model
*Output control commands above vary the output's appearance
*EOLCOM > tells GAMS to ignore anything in the line's text after the symbol >
*OFFLISTING deletes all program lines and just includes GAMS listing
*Setting LIMROW = 0 eliminates equations' all equations in the GAMS listing
*It saves space, but is usually a bad idea till the model is known bullet proof
*Colors:  We suggest going to 'file' then to 'options,'
*then choose as many colors as possible for varying kinds of GAMS syntax
*It greatly simplifies error trapping.

* ------------------------------------------------------------------------------
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* June 6 2015
**************************************************************************************
$ONTEXT
Output control commands above vary the output's appearance
EOLCOM // tells GAMS to ignore anything in the line's text after the symbol //
OFFLISTING deletes all program lines and just includes GAMS listing
Set LIMROW = 0 to eliminate all equations in the GAMS listing
Set LIMROW = 100 or more to show all equations in listing. Helps trap errors

* ---------------------------------------------------------------------------------------
```

```
Model has these FLOW nodes:
8  headwater inflow nodes
21 river gauge nodes
11 diversion nodes
11 net diversion nodes
11 pumping nodes
11 application nodes
11 consumptive use nodes
11 water return flow at canal level nodes
11 water return flow at plot level nodes
3  aquifer to river discharge nodes
1  environmental flow node
5  unmeasured use flow nodes
3  reservoir release node
3  reservoir evaporation nodes

and these STOCK nodes:
3 reservoir nodes
3 aquifer nodes

* ---------------------------------------------------------------------------------------
FLOWS:  Spatial unit for FLOWS is set (index) i.  It lists all flows by node and function.
Each element in the set i is also assigned to one water use function subset (category)
Subset categories include:

   1. Inflow nodes to the system,                                inflow(i);

   2. Nodes on a river or tributary                              river(i);

   3. Diversion nodes                                            divert(i);

   4. Net diversion                                              ndivert(i);

   5. Pumping nodes                                              pump(i)

   6. Application nodes                                          apply(i)

   7. Consumptive uses                                           use(i);

   8. Return flow at canal level nodes directly to the river     returnc(i);
```

```
   9. Return flow at plot level nodes directly to the river      returnp(i);

  10. aquifer to river discharge nodes                           discharge(i)

  11. environmental flow node                                    envflow(i)

  12. Umeasured use flow nodes                                   unmeasure(i)

  13. NET reservoir releases from storage, outflow - inflow      rel(i);

  14. reservoir evaporation nodes, based on surf area            evp(i);

STOCKS: Spatial unit for STOCKS is the set index u.
Each element of the set u is assigned to one water use subset (category).
Subset categories are:

   1. Reservoir nodes,                                           res(u).
   2. Aquifer nodes                                              aqf(u).
* ----------------------------------------------------------------------------------------
TABLE OF CONTENTS

   Section 1. Sets
   Section 2. Data
   Section 3. Variables
   Section 4. Equations
   Section 5. Models
   Section 6. Solves
   Section 7. Displays
* ----------------------------------------------------------------------------------------
**************** Section 1 ***************************************************************
*  The following sets are specified as indices                                           *
*  for parameters (data), variables, and equations                                       *
******************************************************************************************
$OFFTEXT

SETS

******************************************************************************************
i     Flows -- location of important nodes in Jucar Basin of Spain
******************************************************************************************
```

```
/     Jucar_h_f         Headwater flow nodes                        inflow(i)
      Picazo_h_f
      AlarMoli_h_f
      MCT_h_f
      Cabriel_h_f
      Tousup_h_f
      Forata_h_f
      ScBels_h_f

      Jucar_v_f         River gauge measurement nodes                river(i)
      Alarcon_v_f
      Picazo_v_f
      Frailes_v_f
      MO_ND_v_f
      MO_CD_v_f
      MO_SD_v_f
      Alcala_v_f
      Alcala1_v_f
      MCT_v_f
      ContJucar_v_f
      Cabriel_v_f
      Contreras_v_f
      Tousup_v_f
      Tousdn_v_f
      CJT_v_f
      ESC_v_f
      ARJ_v_f
      HMullet_v_f
      RB_v_f
      Cullera_v_f

      MO_ND_d_f           Diversion nodes                             divert(i)
      MO_CD_d_f
      MO_SD_d_f
      Albacete_d_f
      NCC_d_f
      CJT_d_f
      Valencia_d_f
      Sagunto_d_f
      ESC_d_f
      ARJ_d_f
```

```
RB_d_f

MO_ND_nd_f          Net diversion nodes                        ndivert(i)
MO_CD_nd_f
MO_SD_nd_f
Albacete_nd_f
NCC_nd_f
CJT_nd_f
Valencia_nd_f
Sagunto_nd_f
ESC_nd_f
ARJ_nd_f
RB_nd_f

MO_ND_p_f           Pumping nodes                                pump(i)
MO_CD_p_f
MO_SD_p_f
Albacete_p_f
NCC_p_f
CJT_p_f
Valencia_p_f
Sagunto_p_f
ESC_p_f
ARJ_p_f
RB_p_f

MO_ND_a_f           Application nodes                            apply(i)
MO_CD_a_f
MO_SD_a_f
Albacete_a_f
NCC_a_f
CJT_a_f
Valencia_a_f
Sagunto_a_f
ESC_a_f
ARJ_a_f
RB_a_f

MO_ND_u_f            Consumptive use flow nodes                  use(i)
MO_CD_u_f
MO_SD_u_f
```

Albacete_u_f		
NCC_u_f		
CJT_u_f		
Valencia_u_f		
Sagunto_u_f		
ESC_u_f		
ARJ_u_f		
RB_u_f		
MO_ND_rc_f	Water return flow at canal level nodes	returnc(i)
MO_CD_rc_f		
MO_SD_rc_f		
Albacete_rc_f		
NCC_rc_f		
CJT_rc_f		
Valencia_rc_f		
Sagunto_rc_f		
ESC_rc_f		
ARJ_rc_f		
RB_rc_f		
MO_ND_rp_f	Water return flow at plot level nodes	returnp(i)
MO_CD_rp_f		
MO_SD_rp_f		
Albacete_rp_f		
NCC_rp_f		
CJT_rp_f		
Valencia_rp_f		
Sagunto_rp_f		
ESC_rp_f		
ARJ_rp_f		
RB_rp_f		
MO_ND_dis_f	Aquifer discharge to river	discharge(i)
MO_CD_dis_f		
MO_SD_dis_f		
Albufera_e_f	Environmental flows to Albufera wetland	envflow(i)
Picazo_m_f	Unmeasured use flow nodes	unmeasure(i)
Frailes_m_f		

```
      Alcala_m_f
      Alcala1_m_f
      HMullet_m_f

      Alarcon_rel_f        Reservoir-to-river release flow nodes       rel(i)
      Contreras_rel_f
      Tous_rel_f

      Alarcon_evp_f        Reservoir evaporation flow nodes            evp(i)
      Contreras_evp_f
      Tous_evp_f
/

*****************************************************************************************
*     Subsets of all Flow nodes above by class of node (function)
*****************************************************************************************

inflow(i)            Headwater flow nodes                        inflow(i)
/     Jucar_h_f      Jucar River headwater
      Picazo_h_f     Picazo gauge headwater (unmeasured)
      AlarMoli_h_f   Alarcon-Molinar headwater
      MCT_h_f        Molinar-Contreras-Tous headwater
      Cabriel_h_f    Cabriel River headwater
      Tousup_h_f     Inflows upstream Tous reservoir (unmeasured)
      Forata_h_f     Forata inflows
      ScBels_h_f     Sueca-Bellus inflows
/

river(i)             River gage measurement nodes                river(i)
/     Jucar_v_f      Jucar River gauge above Alarcon reservoir (with measurement data)
      Alarcon_v_f    Alarcon gauge below Alarcon reservoir (with measurement data)
      Picazo_v_f     El Picazo gauge between Alarcon and Molinar reservoirs (with measurement data)
      Frailes_v_f    Los Frailes gauge between Alarcon and Molinar reservoirs (with measurement data)
      MO_ND_v_f      Mancha Oriental Northern Domain gauge
      MO_CD_v_f      Mancha Oriental Central Domain gauge
      MO_SD_v_f      Mancha Oriental Southern Domain gauge
      Alcala_v_f     Alcala del Jucar gauge (with measurement data)
      Alcala1_v_f    Alcala del Jucar 1 gauge
      MCT_v_f        Molinar-Contreras-Tous gauge
      ContJucar_v_f  Contreras_Jucar gauge
      Cabriel_v_f    Cabriel River gauge above Contreras reservoir
```

```
      Contreras_v_f  Contreras gauge below Contreras reservoir
      Tousup_v_f     Tous gauge above Tous dam (with measurement data)
      Tousdn_v_f     Tous gauge below Tous dam (with measurement data)
      CJT_v_f        CJT gauge
      ESC_v_f        ESC gauge
      ARJ_v_f        ARJ gauge
      HMullet_v_f    Huerto Mullet gauge (with measurement data)
      RB_v_f         RB gauge
      Cullera_v_f    Cullera gauge (outflow to the sea gauge with limited measurement data)
/

divert(i)            Diversion nodes                             divert(i)
/     MO_ND_d_f      Mancha Oriental Northern Domain irrigation district
      MO_CD_d_f      Mancha Oriental Central Domain irrigation district
      MO_SD_d_f      Mancha Oriental Southern Domain irrigation district
      Albacete_d_f   City of Albacete
      NCC_d_f        Nuclear Central of Cofrentes
      CJT_d_f        Canal Jucar-Turia irrigation district
      Valencia_d_f   City of Valencia
      Sagunto_d_f    City of Sagunto
      ESC_d_f        Escalona-Carcagente irrigation district
      ARJ_d_f        Acequia Real Irrigation district
      RB_d_f         Ribera Baja irrigation district
/

ndivert(i)           Net diversion nodes                             ndivert(i)
/     MO_ND_nd_f     same nodes as divert(i)
      MO_CD_nd_f
      MO_SD_nd_f
      Albacete_nd_f
      NCC_nd_f
      CJT_nd_f
      Valencia_nd_f
      Sagunto_nd_f
      ESC_nd_f
      ARJ_nd_f
      RB_nd_f
/

adivert(ndivert)      ag divert nodes                           adivert(ndivert)
```

```
/     MO_ND_nd_f      ag diversions
      MO_CD_nd_f
      MO_SD_nd_f
      CJT_nd_f
      ESC_nd_f
      ARJ_nd_f
      RB_nd_f
/

mdivert(ndivert)      m divert nodes                          mdivert(ndivert)

/     Albacete_nd_f   m diversions
      Valencia_nd_f
      Sagunto_nd_f
/

idivert(ndivert)      Industrial divert nodes                  idivert(ndivert)

/    NCC_nd_f         i diversions
/

pump(i)              Pumping nodes                             pump(i)

/    MO_ND_p_f       same nodes as divert(i)
     MO_CD_p_f
     MO_SD_p_f
     Albacete_p_f
     NCC_p_f
     CJT_p_f
     Valencia_p_f
     Sagunto_p_f
     ESC_p_f
     ARJ_p_f
     RB_p_f
/

apply(i)              Application nodes                        apply(i)

/    MO_ND_a_f           same nodes as divert(i)
     MO_CD_a_f
     MO_SD_a_f
```

```
     Albacete_a_f
     NCC_a_f
     CJT_a_f
     Valencia_a_f
     Sagunto_a_f
     ESC_a_f
     ARJ_a_f
     RB_a_f
/

aapply(apply)         Application nodes per agricultural use     aapply(i)


/     MO_ND_a_f       same nodes as divert(i)
      MO_CD_a_f
      MO_SD_a_f
      CJT_a_f
      ESC_a_f
      ARJ_a_f
      RB_a_f
/

mapply (apply)        Application nodes per municipal use        mapply(i)

/     Albacete_a_f    same nodes as divert(i)
      Valencia_a_f
      Sagunto_a_f
/

iapply (apply)        Application nodes per industrial use        iapply(i)

/     NCC_a_f          same nodes as divert(i)
/

use(i)               Consumptive use flow nodes = div nodes      use(i)
/     MO_ND_u_f          same nodes as divert(i)
      MO_CD_u_f
      MO_SD_u_f
      Albacete_u_f
      NCC_u_f
      CJT_u_f
```

```
      Valencia_u_f
      Sagunto_u_f
      ESC_u_f
      ARJ_u_f
      RB_u_f
/

ause(use)
/     MO_ND_u_f        ag use
      MO_CD_u_f
      MO_SD_u_f
      CJT_u_f
      ESC_u_f
      ARJ_u_f
      RB_u_f
/


muse(use)
/     Albacete_u_f    m use
      Valencia_u_f
      Sagunto_u_f
/

iuse(use)
/     NCC_u_f         i use
/

returnc(i)        Surface water return flow at canal level nodes
/
  MO_ND_rc_f         surface returns occur at same places as divert (i)
  MO_CD_rc_f
  MO_SD_rc_f
  Albacete_rc_f
  NCC_rc_f
  CJT_rc_f
  Valencia_rc_f
  Sagunto_rc_f
  ESC_rc_f
  ARJ_rc_f
  RB_rc_f
```

```
/

returnp(i)       Surface water return flow at plot level nodes
/
  MO_ND_rp_f         surface returns occur at same places as divert (i)
  MO_CD_rp_f
  MO_SD_rp_f
  Albacete_rp_f
  NCC_rp_f
  CJT_rp_f
  Valencia_rp_f
  Sagunto_rp_f
  ESC_rp_f
  ARJ_rp_f
  RB_rp_f
/

areturnp(returnp)
/     MO_ND_rp_f     ag return
      MO_CD_rp_f
      MO_SD_rp_f
      CJT_rp_f
      ESC_rp_f
      ARJ_rp_f
      RB_rp_f
/

mreturnp(returnp)
/     Albacete_rp_f      m return
      Valencia_rp_f
      Sagunto_rp_f
/

ireturnp(returnp)
/     NCC_rp_f
/

discharge(i)
/
      MO_ND_dis_f          Aquifer discharge to river
      MO_CD_dis_f
```

```
      MO_SD_dis_f
/

envflow(i)             Environmental flows to Albufera wetland      envflow(i)
/ Albufera_e_f
/
unmeasure(i)           Unmeasured use flow nodes                   unmeasure(i)
/ Picazo_m_f           Unmeasured use flow at Picazo gauge
  Frailes_m_f          Unmeasured use flow at Frailes gauge
  Alcala_m_f           Unmeasured use flow at Alcala gauge
  Alcala1_m_f          Unmeasured use flow at Alcala 1 gauge
  HMullet_m_f          Unmeasured use flow at Huerto Mullet gauge
/


rel(i)                 Reservoir to river release flow nodes       rel(i)
/     Alarcon_rel_f    Alarcon reservoir releases to Jucar River
      Contreras_rel_f  Contreras reservoir releases to Cabriel River
      Tous_rel_f       Tous reservoir release to Ribera Alta and Baja
/

evap(i)                Reservoir evaporation                       evap(i)

/     Alarcon_evp_f    Alarcon reservoir evaporation = fn of annual ave exposed surface area
      Contreras_evp_f  Contreras reservoir evaporation = fn of annual ave exposed surface area
      Tous_evp_f       Tous reservoir evaporation = fn of annual ave exposed surface area
/

*****************************************************************************************
u     Stocks -- location of important stock nodes -- reservoirs only for now
*****************************************************************************************


/      Alarcon_res_s        reservoir stock node                       res(u)
       Contreras_res_s
       Tous_res_s

       MO_ND_aqf_s          Aquifer stock nodes                        aqf(u)
       MO_CD_aqf_s
       MO_SD_aqf_s
/
```

```
******************************************************************************************
*    Stock subsets lets us classify stocks by function (e.g. reservoir, aquifer...)
******************************************************************************************

res(u)                 Reservoir stock nodes                            res(u)

/     Alarcon_res_s    Alarcon reservoir storage vol
      Contreras_res_s  Contreras reservoir storage vol
      Tous_res_s       Tous reservoir storage vol
/

aqf(u)                 Aquifer stock nodes                              aqf(u)

/     MO_ND_aqf_s      Mancha Oriental Northern Domain aquifer
      MO_CD_aqf_s      Mancha Oriental Central Domain aquifer
      MO_SD_aqf_s      Mancha Oriental Southern Domain aquifer
/
******************************************************************************************
j     Major crops
******************************************************************************************
/ rice      Rice
  cer       Cereals including corn (Ribera) and alfalfa (MO)
  veg       Vegetables
  cit       Citrus
  frt       Other fruit trees including peach (Ribera) and olives and almonds (MO)
  wht       Wheat
  bar       Barley
  corn      Corn
  garl      Garlic
  Onn       Onion
  grap      grapes
/

per(j) Perennial crops
/ cit
  frt
  grap
/
******************************************************************************************
k     Irrigation technology
```

```
*****************************************************************************************
/ fld       Flood irrigation system
  spk       Sprinkler irrigation system
  drp       Drip irrigation system
/
*****************************************************************************************
p   policy set allows the conduct of several policy experiments
*****************************************************************************************
/  base       simulation
   opt_unsus  optimization_without sustainability requirements
   opt_sus    optimization_with sustainability requirements
/
*****************************************************************************************
s   climate scenario allows testing impacts of climate change
*****************************************************************************************
* Climate change scenarios for the Jucar basin are from CEDEX (2010)

/ normal      current climate conditions
  mildcc      mild climate change scenario
  severecc    severe climate change scenario
/

clm(s) climate change scenarios
/mildcc
 severecc
/
*****************************************************************************************
Rvr     River reaches linked to the different subaquifers
*****************************************************************************************
/rv1, rv2, rv3
/
*****************************************************************************************
t     time
*****************************************************************************************
/     1*20            Two time periods - expandable
/

tfirst(t)            initial period
tlast(t)             terminal period among all periods above
;
```

```
tfirst(t)= yes $(ord(t) eq 1      );   // picks 1st period
tlast(t) = yes $(ord(t) eq card(t));  // GAMS language -- picks last pd
;

Parameters

ID_ua   (ause,  aapply)   identity matrix connects apply nodes to use nodes
ID_ur   (ause,areturnp)   identity matrix connects return nodes to use nodes
ID_u_d  (muse,mdivert)    identity matrix connects use nodes to divert nodes

;
ID_ua   (ause,  aapply  )   $ (ord(ause) eq ord(aapply  )) = 1;
ID_ur   (ause,  areturnp)   $ (ord(ause) eq ord(areturnp)) = 1;
ID_u_d  (muse,mdivert)      $ (ord(muse) eq ord(mdivert))  = 1;

Display ID_ua, ID_ur, ID_u_d;

* renames sets that have multiple function
ALIAS (i,ip);
ALIAS (river, riverp);
ALIAS (divert, divertp);

**************** Section 2
*********************************************************************************************************************************
**********************
*  This section defines data in 3 formats                                               *
*  1.  Tables     (data in rows + columns)                                              *
*  2.  Parameters (columns of data)                                                     *
*  3.  Scalars    (single numbers)                                                      *
*********************************************************************************************************************************
*************************************************

*  Several 'maps' below summarize the basin's geometry by relative location:
*  water sources, mainstems, tributaries, outflow nodes, gauges, use nodes,
*  return flow nodes, reservoirs. Other additions could be cities, wetlands...
*  Basin geometry is summarized through judicious use of numbers 1, -1, and 0 (blank)

*********************************************************************************************************************************
*************************************************

*  Map #1:
```

```
*  Each column in map below is a streamgage.  Each row is a source or use of water.
*  Flow at ea gage (column) is directly influenced by at least 1 upstream row.
*  SOURCE adds to column flow              (+1)
*  USE deplete from column flow            (-1)
*  BLANK has no effect on column flow      (  )
*  So map accounts for all upstream sources (supplies) and uses (demands) in basin

*  Map is used to produce coefficients in equations below to define:
*  X(river) = Bhv * X(inflow) + Bvv * X(river)   + Bdv * X(divert)
*           + Brv * X(return) + Bgv * X(gwflows) + BLv * X(rel)
*
*  These B coefficient matrices are stacked below into a single matrix, named Bv
*  to allow for easy extraction

Table Bv_p(i,river)    Hydrologic Balance Map

**************************************************  Column Heads are River Gauges   ************************************************************
                  Jucar_v_f  Alarcon_v_f  Picazo_v_f  MO_ND_v_f  Frailes_v_f  Alcala_v_f  Alcala1_v_f  MO_CD_v_f  MO_SD_v_f  MCT_v_f  ContJucar_v_f  Cabriel_v_f  Contreras_v_f  Tousup_v_f  Tousdn_v_f  CJT_v_f  ESC_v_f  ARJ_v_f  HMullet_v_f  RB_v_f  Cullera_v_f

* ---------------------------------------------------------------------------- ---------------------------headwater inflow node (+) ------------------------------------------------------------------------------------------------
Jucar_h_f                 1
Picazo_h_f                                        1
AlarMoli_h_f                                                                           1
MCT_h_f                                                                                                                            1
Cabriel_h_f                                                                                                                                                   1
Tousup_h_f                                                                                                                                                                           1
Forata_h_f                                                                                                                                                                                                                                    1
ScBels_h_f                                                                                                                                                                                                                                    1
* ------------------------------------------------------------------------------------------------------------------------------------ river gage node rows (+) ----------------------------------------------------------------------------------------------------------
Jucar_v_f                              1
Alarcon_v_f                                       1
Picazo_v_f                                                   1
MO_ND_v_f                                                               0.67
Frailes_v_f                                                                            1
Alcala_v_f                                                                                 0.28
Alcala1_v_f                                                                                                   1
MO_CD_v_f                                                                                                                1
MO_SD_v_f                                                                                                                          1
MCT_v_f                                                                                                                                           1
ContJucar_v_f                                                                                                                                                                        1
Cabriel_v_f                                                                                                                                                                1
Contreras_v_f                                                                                                                                     1
Tousup_v_f                                                                                                                                                                                       1
Tousdn_v_f                                                                                                                                                                                                1
CJT_v_f                                                                                                                                                                                                           1
ESC_v_f                                                                                                                                                                                                                    1
ARJ_v_f                                                                                                                                                                                                                                 1
HMullet_v_f                                                                                                                                                                                                                                     1
RB_v_f                                                                                                                                                                                                                                                        1
Cullera_v_f
* ----------------------------------------------------------------------------------------------------------------------------------------- diversion nodes   (-)   ----------------------------------------------------------------------------------------------------------------------------------
MO_ND_d_f
MO_CD_d_f
MO_SD_d_f
Albacete_d_f                                     -1
NCC_d_f                                                                                                                                                                                  -1
CJT_d_f                                                                                                                                                                                                        -1
Valencia_d_f                                                                                                                                                                                                   -1
Sagunto_d_f                                                                                                                                                                                                    -1
ESC_d_f                                                                                                                                                                                                                 -1
ARJ_d_f                                                                                                                                                                                                                          -1
RB_d_f                                                                                                                                                                                                                                                              -1
* ---------------------------------------------------------------------------------------------------------------------- return flow node at canal level rows (+) ---------------------------------------------------------------------------------------------------------------------------
MO_ND_rc_f
MO_CD_rc_f
MO_SD_rc_f
Albacete_rc_f
NCC_rc_f
CJT_rc_f
Valencia_rc_f
Sagunto_rc_f
ESC_rc_f                                                                                                                                                                                                                                   0.19
ARJ_rc_f                                                                                                                                                                                                                                   0.08
```

```
RB_rc_f                                                                                                                  0.12
* -------------------------------------------------- return flow at plot level node rows (+) ---------------------------------------------
MO_ND_rp_f
MO_CD_rp_f
MO_SD_rp_f
Albacete_rp_f
NCC_rp_f
CJT_rp_f
Valencia_rp_f
Sagunto_rp_f
ESC_rp_f                                                                                                           0.19
ARJ_rp_f                                                                                                           0.08
RB_rp_f                                                                                                                  0.12
* ------------------------------------------------------ Aquifer discharge to river (-) ---------------------------------------------------
MO_ND_dis_f               -1
MO_CD_dis_f                                        -1
MO_SD_dis_f                                             -1
* ------------------------------------------------------ reservoir release node rows (+) -------------------------------------------------
Alarcon_rel_f 1
Contreras_rel_f                                                                1
Tous_rel_f                                                                                  1
* ------------------------------------------------------ Unmeasured use node rows (-) ----------------------------------------------------
Picazo_m_f           -1
Frailes_m_f                     -1
Alcala_m_f                             -1
Alcala1_m_f                                 -1
HMullet_m_f                                                                                                  -1
;
* Coefficient less than 1 are used to enable unmeasured sources or uses to match observed gauged flow
* Coefficients for return flows at canal and plot levels indicate the proportion of total flows that returns to the river
*************************************************************************************************************************************
*************************************************************************************************************************************

* Map #2:

* Enforces nonnegative flows at each use node (wet river)
* water sources or uses are rows.  Diversion nodes are columns.
* For any column, diversion < summed supplies from upstream sources (rows)
* e.g. SLV (Colorado) ag use < flows from RG and Conejos headwater sources

* X(divert) < Bhd * X(inflow) + Brd * X(river)  + Bdd * X(divert) +
*             Brd * X(return) + Bgd * X(gwflow) + BLd * X(rel)

* These B coefficient matrices are stacked below as the matrix, Bd

Table Bd_p(i, divert)  Wet river table

* -------------------------------------------  Col Heads are Diversion nodes ------------------------------------------------
                      MO_ND_d_f          MO_CD_d_f         MO_SD_d_f       Albacete_d_f       NCC_d_f       CJT_d_f         Valencia_d_f       Sagunto_d_f        ESC_d_f      ARJ_d_f   RB_d_f
* ------------------------------------------------------------------------------ headwater inflow nodes (+)-------------------------------------------------------------------------------
Jucar_h_f
Picazo_h_f
AlarMoli_h_f
MCT_h_f
Cabriel_h_f
Tousup_h_f
Forata_h_f
ScBels_h_f
* ---------------------------------------------------------------------------------- river gage nodes -----------------------------------------------------------------------------------
```

```
Jucar_v_f
Alarcon_v_f                                                                     1
Picazo_v_f
MO_ND_v_f
Frailes_v_f
Alcala_v_f
Alcala1_v_f
MO_CD_v_f
MO_SD_v_f
MCT_v_f
ContJucar_v_f                                                                                     1
Cabriel_v_f
Contreras_v_f
Tousup_v_f
Tousdn_v_f                                                                                                      1                 1                  1
CJT_v_f                                                                                                                                                                 1
ESC_v_f                                                                                                                                                                              1
RB_v_f                                                                                                                                                                                        1
Cullera_v_f
* -------------------------------------------------------------------------------- diversion nodes  (-)  ------------------------------------------------------------------------------------------
MO_ND_d_f
MO_CD_d_f
MO_SD_d_f
Albacete_d_f
NCC_d_f
CJT_d_f
Valencia_d_f                                                                                                   -1                                   -1
Sagunto_d_f                                                                                                    -1
ESC_d_f
ARJ_d_f
RB_d_f
* ------------------------------------------------------------------------ return flow at canal level nodes (+) -----------------------------------------------------------------------------------
MO_ND_rc_f
MO_CD_rc_f
MO_SD_rc_f
Albacete_rc_f
NCC_rc_f
CJT_rc_f
Valencia_rc_f
Sagunto_rc_f
ESC_rc_f
ARJ_rc_f
RB_rc_f
* ------------------------------------------------------------------------- return flow at plot level nodes (+) -----------------------------------------------------------------------------------
MO_ND_rp_f
MO_CD_rp_f
MO_SD_rp_f
Albacete_rp_f
NCC_rp_f
CJT_rp_f
Valencia_rp_f
Sagunto_rp_f
ESC_rp_f
ARJ_rp_f
RB_rp_f
* ------------------------------------------------------------------------- Aquifer discharge to river (-) ----------------------------------------------------------------------------------------
0.12
MO_ND_dis_f
MO_CD_dis_f
MO_SD_dis_f
```

```
* -------------------------------------------------------------------  reservoir release stock-to-flow node row (+)---------------------------------------------------------------------------
Alarcon_rel_f
Contreras_rel_f
Tous_rel_f
* --------------------------------------------------------------------------- Unmeasured use node rows (-) ---------------------------------------------------------------------------------------
Picazo_m_f
Frailes_m_f
Alcala_m_f
Alcala1_m_f
HMullet_m_f
*-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
;

***************************************************************************************************************************************************************************
***************************************************************************************************************************************************************************

* Map #3:
* Defines water diversion as net diversion (because of canal losses) and return flow at canal level
* X(diversion) = Bnd * X(ndivert) + Bnd * X(return)

Table Bnd_p(i,divert)  Table defines water diverted from a river as net diversion and return flow at canal level
* ----------------------------------------------- Apply nodes -------------------------------------------------------------
                 MO_ND_d_f    MO_CD_d_f    MO_SD_d_f   Albacete_d_f      NCC_d_f       CJT_d_f      Valencia_d_f    Sagunto_d_f    ESC_d_f    ARJ_d_f    RB_d_f
* ------------------------ divert nodes (+) ----------------------------------------------------------------------------------------------------------------------
MO_ND_nd_f
MO_CD_nd_f
MO_SD_nd_f
Albacete_nd_f                                              1
NCC_nd_f                                                                    1
CJT_nd_f                                                                                 0.6
Valencia_nd_f                                                                                             1
Sagunto_nd_f                                                                                                               1
ESC_nd_f                                                                                                                              0.45
ARJ_nd_f                                                                                                                                        0.47
RB_nd_f                                                                                                                                                    0.58
* ---------------------------------------------------- return flow nodes at canal level (+) -----------------------------------------------------------------------
MO_ND_rc_f
MO_CD_rc_f
MO_SD_rc_f
Albacete_rc_f                                              0
NCC_rc_f                                                                    0
CJT_rc_f                                                                                 0.4
Valencia_rc_f                                                                                             0
Sagunto_rc_f                                                                                                               0
ESC_rc_f                                                                                                                              0.55
ARJ_rc_f                                                                                                                                        0.53
RB_rc_f                                                                                                                                                    0.42
*-------------------------------------------------------------------------------------------------------------------------------------------------------------
;
* The sum of net diversion and return flows should be equal to 1
* Return flows are equal to return flows to river, aquifers and wetlands
```

```
*********************************************************************************************************************************
*********************************************************************************************************************************

* Map #4:

* Defines water applied as diversion plus pumping

* X(apply) = Bda * X(ndivert) + Bpa * X(pump)

* These two B coefficient vectors are stacked below as the matrix, Ba

Table Ba_p(i, apply)  Table defines water applied

* ------------------------------------------------- Apply nodes -----------------------------------------------------------------
                 MO_ND_a_f      MO_CD_a_f      MO_SD_a_f      Albacete_a_f       NCC_a_f       CJT_a_f       Valencia_a_f    Sagunto_a_f    ESC_a_f   ARJ_a_f    RB_a_f
* ------------------------ divert nodes (+) ---------------------------------------------------------------------------------------------------------------------------
--
MO_ND_nd_f
MO_CD_nd_f
MO_SD_nd_f
Albacete_nd_f                                                     1
NCC_nd_f                                                                            1
CJT_nd_f                                                                                          1
Valencia_nd_f                                                                                                     1
Sagunto_nd_f                                                                                                                    1
ESC_nd_f                                                                                                                                       1
ARJ_nd_f                                                                                                                                                1
RB_nd_f                                                                                                                                                            1
* --------------------------------------------------------------  pumping nodes (+) --------------------------------------------------------------------------------
MO_ND_p_f           1
MO_CD_p_f                          1
MO_SD_p_f                                         1
Albacete_p_f
NCC_p_f
CJT_p_f                                                                                           1
Valencia_p_f
Sagunto_p_f
ESC_p_f
ARJ_p_f
RB_p_f
*---------------------------------------------------------------------------------------------------------------------------------------------------------------------
-
;
*********************************************************************************************************************************
*********************************************************************************************************************************
* Map #5:
```

```
Table Bmu_p(mapply, muse)   Table defines consumptive use for urban nodes

* -----------------------  Use nodes ------------------------------------
                 Albacete_u_f     Valencia_u_f      Sagunto_u_f
* --------------------- apply nodes (+) --------------------------------
Albacete_a_f         1
Valencia_a_f                          1
Sagunto_a_f                                              1
*-----------------------------------------------------------------------
;

Table Biu_p(iapply, iuse)   Table defines consumptive use for industrial nodes

* -----------------------  Use nodes ------------------------------------
                 NCC_u_f
* --------------------- apply nodes (+) --------------------------------
NCC_a_f            1
*-----------------------------------------------------------------------
;

Table Brm_p(mapply, mreturnp)   Defines surface return flow at plot level as a percent of application for urban nodes

* -----------------------  Return flow nodes -----------------------------------
                     Albacete_rp_f    Valencia_rp_f      Sagunto_rp_f
* --------------------- apply nodes (+) ---------------------------------------
Albacete_a_f              0
Valencia_a_f                              0
Sagunto_a_f                                                 0
*------------------------------------------------------------------------------
;

Table Bri_p(iapply, ireturnp)   Defines surface return flow at plot level as a percent of application for industries

* -----------------------  Return flow nodes -----------------------------------
                     NCC_rp_f
* --------------------- apply nodes (+) ---------------------------------------
NCC_a_f                0
*------------------------------------------------------------------------------
;

Table Benr_p(i,envflow)   Defines environmental flows to Albufera wetland as percentaje of return flows

* This parameter is defined for the case of the Albufera wetland and for the Jucar basin
* The Albufera wetland receives part of return flows of ARJ and RB irrigation districts following CHJ
```

```
* ---------------  Environmental flows in the Albufera wetland node --------------------
                                 Albufera_e_f
* --------------------return flow at canal level nodes (+) -----------------------------
MO_ND_rc_f
MO_CD_rc_f
MO_SD_rc_f
Albacete_rc_f
NCC_rc_f
CJT_rc_f
Valencia_rc_f
Sagunto_rc_f
ESC_rc_f
ARJ_rc_f                           0.28
RB_rc_f                            0.23
* ----------------- return flow at plot level nodes (+) --------------------------------
MO_ND_rp_f
MO_CD_rp_f
MO_SD_rp_f
Albacete_rp_f
NCC_rp_f
CJT_rp_f
Valencia_rp_f
Sagunto_rp_f
ESC_rp_f
ARJ_rp_f                           0.28
RB_rp_f                            0.23
*---------------------------------------------------------------------------------------
;

**************************************************************************************************************************************************
**************************************************************************************************************************************************
* Hydrogeology details
* Map #6

Parameters

C12_p(aqf)          Conductance between subaquifer ND and CD  (Mm2 per year )        /MO_ND_aqf_s 255, MO_CD_aqf_s 0, MO_SD_aqf_s 0/
C21_p(aqf)          Conductance between subaquifer CD and ND  (Mm2 per year )        /MO_ND_aqf_s 0, MO_CD_aqf_s 255, MO_SD_aqf_s 0/
C23_p(aqf)          Conductance between subaquifer CD and SD  (Mm2 per year )        /MO_ND_aqf_s 0, MO_CD_aqf_s 78.5, MO_SD_aqf_s 0/
C32_p(aqf)          Conductance between subaquifer SD and CD  (Mm2 per year )        /MO_ND_aqf_s 0, MO_CD_aqf_s 0, MO_SD_aqf_s 78.5/
SL_p(aqf)           Surface irrigation land height            (Mm           )        /MO_ND_aqf_s 6.8, MO_CD_aqf_s 6.6, MO_SD_aqf_s 6.7/
Surfarea_p(aqf)     Surface area of each subaquifer           (Mm2          )        /MO_ND_aqf_s 187400, MO_CD_aqf_s 329400, MO_SD_aqf_s 217900/

S_p(aqf)            Specific yield of each subaquifer         (dimensionless)        /MO_ND_aqf_s 0.032, MO_CD_aqf_s 0.035, MO_SD_aqf_s 0.017/
Cr_p(Rvr)           River reaches conductance                 (Mm2  per year)        /rv1 7.6, rv2 172, rv3 0.81/
dt                  Time step                                 (Year         )        /1/
```

```
H0_p(aqf)           Initial subaquifer heads                  (Mm          )        /MO_ND_aqf_s 6.4, MO_CD_aqf_s 6.2, MO_SD_aqf_s 6.4/
intercept_r_p(Rvr)  River head Intercept                                             /rv1 6.91, rv2 5.88, rv3 4.28/
slope_r_p(Rvr)      River head slope                                                 /rv1 0.0001, rv2 0.0005, rv3 0.0001/
Qre_p(aqf)          Recharge in each subaquifer               (Mm3 per year )        /MO_ND_aqf_s 65, MO_CD_aqf_s 100, MO_SD_aqf_s 55/
Qr_p(aqf,t,p,s)     Recharge in each subaquifer               (Mm3 per year )
;

Qr_p(aqf,t,p,'normal') $ (ord(t) eq 1)   =  1.00 * Qre_p(aqf);
Qr_p(aqf,t,p,'normal') $ (ord(t) gt 1)   =  normal(1.00 * Qre_p(aqf), 0.00 * Qre_p(aqf));

* Climate change impact estimates are from CEDEX(2010)
* Scenarios B2 ECHAM4 (FIC) and A2 HadCM3 (SDSM)

Qr_p(aqf,t,p,'mildcc'  ) $ (ord(t) eq 1)   =  0.78 * Qre_p(aqf);
Qr_p(aqf,t,p,'mildcc'  ) $ (ord(t) gt 1)   =  normal(1.00 * Qr_p(aqf,'1',p,'mildcc'  ), 0.00 * Qr_p(aqf,'1',p,'mildcc'  ));

Qr_p(aqf,t,p,'severecc') $ (ord(t) eq 1)   =  0.55 * Qre_p(aqf);
Qr_p(aqf,t,p,'severecc') $ (ord(t) gt 1)   =  normal(1.00 * Qr_p(aqf,'1',p,'severecc'), 0.00 * Qr_p(aqf,'1',p,'severecc'));

Display Qr_p;

Parameter  weight_r_aq(aqf,Rvr)  Defines relationship between river reaches and subaquifers
;
weight_r_aq(aqf,Rvr) $ (ord(aqf) eq ord(Rvr)) = 1 ;

Display  weight_r_aq ;

Table Bp_p(pump,aqf)  Defines relationship between pumping nodes and aquifer nodes

                      MO_ND_aqf_s        MO_CD_aqf_s          MO_SD_aqf_s

         MO_ND_p_f       1
         MO_CD_p_f                           1
         MO_SD_p_f                                                 1
;

Table Brr_p(river,Rvr)  Defines relationship between river gauges and river reaches

                           rv1     rv2     rv3
          Picazo_v_f        1
          Alcala1_v_f               1
          MO_CD_v_f                         1
;
Table Bda_p(discharge,aqf) Defines relationship between discharge nodes and aquifer nodes

                           MO_ND_aqf_s        MO_CD_aqf_s          MO_SD_aqf_s
```

```
            MO_ND_dis_f       1
            MO_CD_dis_f                        1
            MO_SD_dis_f                                             1
;

Table Buaq_p(ause,aqf)  Defines relationship between use nodes and aquifer nodes

                        MO_ND_aqf_s        MO_CD_aqf_s          MO_SD_aqf_s

           MO_ND_u_f       1
           MO_CD_u_f                         1
           MO_SD_u_f                                            1
;

Table Brp_p(areturnp,aqf) Defines relationship between return nodes and aquifer nodes

                          MO_ND_aqf_s        MO_CD_aqf_s          MO_SD_aqf_s

           MO_ND_rp_f         1
           MO_CD_rp_f                          1
           MO_SD_rp_f                                               1
;

Parameters gw_u_p(ause) Defines GW users /MO_ND_u_f  1, MO_CD_u_f  1, MO_SD_u_f  1, CJT_u_f  0, ESC_u_f  0, ARJ_u_f  0, RB_u_f  0/
;

*********************************************************************************************************************************
*********************************************************************************************************************************

* ag details
* Map #7
* Table defines hydrologic outcomes after applying water to crops
* Water apply = water use + water return flow at plot level.
* The whole matrix is defined as BBa_p


Table    BBa_p(i, j, k)            Per ha crop water applied for various use indicators (Mm3 per 1000 ha)

*******************************************  Column Heads are Crops  **************************************************************************
                    rice.fld         cer.fld          veg.fld          cit.fld          frt.fld
*------------------------------------------ apply node rows (+) ------------------------------------------------------------------------------
CJT_a_f              12.00            8.00            12.00             7.00             7.00
ESC_a_f                                                                 6.50             5.50
ARJ_a_f              12.00            8.10            14.00             6.30             5.60
RB_a_f               18.00            7.70            15.80             7.20             7.20
MO_ND_a_f                                              4.46
MO_CD_a_f                                              5.10
```

```
MO_SD_a_f                                               4.99
*----------------------------------------- use node rows (+) -------------------------------------------------------------------------------
CJT_u_f               7.20            4.80              8.40            4.90             4.90
ESC_u_f                                                                 4.55             3.85
ARJ_u_f               7.20            4.86              9.80            4.41             3.92
RB_u_f               10.80            4.62             11.06            5.04             5.04
MO_ND_u_f                                               2.90
MO_CD_u_f                                               3.32
MO_SD_u_f                                               3.25
*-------------------------------------- return flow at plot level node rows(+) -------------------------------------------------------------
CJT_rp_f             4.80             3.20             3.60             2.10             2.10
ESC_rp_f                                                                1.95             1.65
ARJ_rp_f             4.80             3.24             4.20             1.89             1.68
RB_rp_f              7.20             3.08             4.74             2.16             2.16
MO_ND_rp_f                                             1.56
MO_CD_rp_f                                             1.79
MO_SD_rp_f                                             1.75
*---------------------------------------------------------------------------------------------------------------------------------------------------------------------------


+                                    cer.spk          veg.drp         cit.drp          frt.drp       wht.spk    bar.spk     corn.spk     garl.drp    onn.drp     grap.drp
*--------------------------------------------------------- apply node rows (+) ----------------------------------------------------------------------------------------------
CJT_a_f                               5.50             7.00            5.40              4.50
ESC_a_f                                                                5.00              3.65
ARJ_a_f                               6.90            10.00            4.90              4.00
RB_a_f                                6.70            10.00            5.20              5.00
MO_ND_a_f                             4.57             2.65                              1.81         2.30       2.00         7.00        2.50       5.00         1.30
MO_CD_a_f                             5.71             3.07                              2.65         3.20       2.70         8.50        3.00       6.10         1.40
MO_SD_a_f                             4.62             2.62                              2.06         2.30       2.00         7.00        2.50       5.00         1.30
*--------------------------------------------------------- use node rows (+) ------------------------------------------------------------------------------------------------
CJT_u_f                               4.40             6.30            4.86              4.05
ESC_u_f                                                                4.50              3.29
ARJ_u_f                               5.52             9.00            4.41              3.60
RB_u_f                                5.36             9.00            4.68              4.50
MO_ND_u_f                             3.66             2.38                              1.63         1.84       1.60         5.60        2.25       4.50         1.17
MO_CD_u_f                             4.57             2.76                              2.38         2.56       2.16         6.80        2.70       5.49         1.26
MO_SD_u_f                             3.70             2.36                              1.86         1.84       1.60         5.60        2.25       4.50         1.17
*------------------------------------------------- return flow at plot level node rows(+) -----------------------------------------------------------------------------------
CJT_rp_f                              1.10             0.70            0.54              0.45
ESC_rp_f                                                               0.50              0.37
ARJ_rp_f                              1.38             1.00            0.49              0.40
RB_rp_f                               1.34             1.00            0.52              0.50
MO_ND_rp_f                            0.91             0.26                              0.18         0.46       0.40         1.40        0.25       0.50         0.13
MO_CD_rp_f                            1.14             0.31                              0.26         0.64       0.54         1.70        0.30       0.61         0.14
MO_SD_rp_f                            0.92             0.26                              0.21         0.46       0.40         1.40        0.25       0.50         0.13
*---------------------------------------------------------------------------------------------------------------------------------------------------------------------------
```

```
* The sum of use and retrun flows should be equal to applied water
* Return flows are equal to the sum of return flows to river, aquifers and wetland

Parameters   BBas_p(i, j, k, s)   Per ha crop water applied for various use indicators by climate scenario (Mm3 per 1000 ha)
;

BBas_p(i, j, k,  'normal') = 1.00 * BBa_p(i, j, k) ;
BBas_p(i, j, k,  'mildcc') = 1.13 * BBa_p(i, j, k) ;
BBas_p(i, j, k,'severecc') = 1.22 * BBa_p(i, j, k) ;
Display BBas_p;
```

```
*******************************************************************************************************************
*******************************************************************************************************************
* Map #8:

* Table relates reservoir stocks in a period to its prev periods' stocks minus
* releases.
* For any reservoir stock node at the column head
*   (+1) :added water at flow node -- thru releases -- takes from column's res
*         stock (-)
*   (-1) :added water at flow node adds to column's reservoir stock
*   (  ) :added water at flow node has no effect on column's reservoir stock

* Z(res(t)) = Z(res(t-1)) + BLv * X(rel(t))

Table BLv_p(rel, u)      Links reservoir stocks to downstream release flows

********* Column Heads are Reservoir Stocks -- rows are release flows  ******************
********* Table = diagonal matrix for > 1 reservoir--only 1 for now    ******************

                         Alarcon_res_s        Contreras_res_s       Tous_res_s
      Alarcon_rel_f           -1
      Contreras_rel_f                              -1
      Tous_rel_f                                                        -1
;

*****************************************************************************************
* Map #9:

* Table relates reservoir stocks to evaporation
* (-1): added evap subtracts a reservoir's volume
* (  ): added evap has no effect on a reservoir's vol

Table Ber_p(evap, res)  Links reservoir evaporation to volume loss

********** Column Heads are reservoir stocks -- rows are evaporation loss flows ********
********** Table = diagonal matrix for > 1 reservoir -- only 1 for now *****************

                        Alarcon_res_s        Contreras_res_s        Tous_res_s
      Alarcon_evp_f         -1
      Contreras_evp_f                              -1
```

```
      Tous_evp_f                                                      -1
;

Table Be_p(evap, res)     Reservoir evaporation (Mm3) as a fraction of its area (ha)

                  Alarcon_res_s         Contreras_res_s          Tous_res_s
Alarcon_evp_f         0.0104
Contreras_evp_f                             0.0069
Tous_evp_f                                                         0.0281
;

Parameters Bes_p(evap,res,s)  Reservoir evaporation (Mm3) as a fraction of its area (ha) in each policy and climate scenario
;

Bes_p(evap,res,  'normal') = 1.00 * Be_p(evap, res);

Bes_p(evap,res,  'mildcc') = 1.13 * Be_p(evap, res);

Bes_p(evap,res,'severecc') = 1.22 * Be_p(evap, res);

Display Bes_p;

*********************************************************************************************************************************
*  END OF BASIN GEOMETRY MAPS THAT CONNECT NODES                                                                          *
*********************************************************************************************************************************

**************** Section 2 **************************************************************
*
*  DATA                                                                                  *
*
*****************************************************************************************
* Data characterize a basin's unique observed quantities relevant for policy analysis
*****************************************************************************************

*Data on water inflows to the basin in 2009

Table sources_p(inflow,t)  Annual 'headwater' inflows (Mm3)

*****Data are for 2009 from Jucar Basin hydrological Plan (Mm3)*******************
* Inflows to Picazo and AlarMoli are equal to contribution of Alarcon Molinar subbasin in data set
* Inflows upstream Tous reservoir is unmeasured flows requiered for calibaration
```

```
                    1
Jucar_h_f          213.72
Picazo_h_f           7.00
AlarMoli_h_f        16.00
MCT_h_f            289.00
Cabriel_h_f        138.32
Tousup_h_f          45.09
Forata_h_f           9.00
ScBels_h_f         608.00
;

Parameter  source_p(inflow,t,s)     Source inflows
;

source_p(inflow,t,   'normal') $ (ord(t) eq 1) =        1.00 * sources_p(inflow,'1');
source_p(inflow,t,   'normal') $ (ord(t) gt 1) = normal(1.00 * sources_p(inflow,'1'), 0.20 * sources_p(inflow,'1'));

source_p(inflow,t,   'mildcc') $ (ord(t) eq 1) =        0.73 * sources_p(inflow,'1');
source_p(inflow,t,   'mildcc') $ (ord(t) gt 1) = normal(1.00 * source_p(inflow,'1','mildcc'), 0.20 *
source_p(inflow,'1','mildcc'));

source_p(inflow,t,'severecc' ) $ (ord(t) eq 1) =        0.54 * sources_p(inflow,'1');
source_p(inflow,t,'severecc' ) $ (ord(t) gt 1) = normal(1.00 * source_p(inflow,'1','severecc' ), 0.20 *
source_p(inflow,'1','severecc' ));

Display source_p;

*Reservoir data

Parameters
z0_p(res)                   Initial reservoir levels at stock nodes (Mm3)
zmax_p(res)                 Maximum capacity by reservoir           (Mm3)
;

z0_p('Alarcon_res_s')     =   98.42;   // Alarcon reservoir starting volume
zmax_p('Alarcon_res_s')   = 1118.00;   // Alarcon reservoir max capacity

z0_p('Contreras_res_s')   =  112.51;   // Contreras reservoir starting volume
zmax_p('Contreras_res_s') =  440.00;   // Contreras reservoir max capacity
```

```
z0_p('Tous_res_s')        =   55.00;   // Tous reservoir starting volume
zmax_p('Tous_res_s')      =  378.60;   // Tous reservoir max capacity


Parameters
B0ar_p(res)  Area (ha)-Capacity (Mm3) Function intercept: Intcpt for reservoir area as linear fn of volume = 0
B1ar_p(res)  Area (ha)-Capacity (Mm3) Function slope:     (1st order) Slope for res area = linear fn of vol = d(area)\d(vol)
;

B0ar_p('Alarcon_res_s')   = 0.00;
B1ar_p('Alarcon_res_s')   = 6.12;

B0ar_p('Contreras_res_s') = 0.00;
B1ar_p('Contreras_res_s') = 6.19;

B0ar_p('Tous_res_s')      = 0.00;
B1ar_p('Tous_res_s')      = 2.80;

*******************************************************************************************************************
*******************************************************************************************************************

* Agricultural details follow

Table   Yield_p(ause,j,k)         Crop Yield (1000 Ton per 1000 ha)

*********************************************************************************************************************************
rice.fld         cer.fld          veg.fld          cit.fld          frt.fld
*use node rows (+)
*-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
CJT_u_f            6.19            10.06            39.03            22.21            10.00
ESC_u_f                                                              22.21            10.00
ARJ_u_f            6.19            10.06            39.03            22.21            10.00
RB_u_f             6.19            10.06            39.03            22.21            10.00
MO_ND_u_f                                            3.75
MO_CD_u_f                                            4.06
MO_SD_u_f                                            3.48
*-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------

+                                 cer.spk          veg.drp          cit.drp          frt.drp     wht.spk    bar.spk     corn.spk     garl.drp    onn.drp     grap.drp
*use node rows (+)
*-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
CJT_u_f                            10.06            39.03            22.21            10.00
ESC_u_f                                                              22.21            10.00
ARJ_u_f                            10.06            39.03            22.21            10.00
RB_u_f                             10.06            39.03            22.21            10.00
MO_ND_u_f                          15.22             3.75                              1.99       4.16       4.55        10.06        5.80        61.73        7.57
MO_CD_u_f                          16.10             4.06                              1.99       4.16       4.55        10.06        5.80        61.73        7.57
MO_SD_u_f                          15.22             3.48                              1.99       4.16       4.55        10.06        5.80        61.73        7.57
*-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
```

```
;
**********************************************************************************************************************************

Table   Price_p(ause,j)           Crop Prices (Million euro per 1000 ton)

*******************************************************************************************************************************
                 rice          cer          veg          cit           Frt      wht    bar    corn    garl    onn     grap
*use node rows (+)
*------------------------------------------------------------------------------------------------------------------------------
CJT_u_f          0.303         0.206        0.157        0.221         0.519
ESC_u_f                                                  0.221         0.519
ARJ_u_f          0.303         0.206        0.157        0.221         0.519
RB_u_f           0.303         0.206        0.157        0.221         0.519
MO_ND_u_f                      0.100        0.260                      0.460    0.200  0.170  0.210   1.100   0.110   0.210
MO_CD_u_f                      0.100        0.260                      0.460    0.200  0.170  0.210   1.100   0.110   0.210
MO_SD_u_f                      0.100        0.260                      0.460    0.200  0.170  0.210   1.100   0.110   0.210
*------------------------------------------------------------------------------------------------------------------------------
;
*******************************************************************************************************************************

Parameter     Price1_p(ause,j,k)           Crop price over technologies (Million euro per 1000 ton)
;
Price1_p(ause,j,k) = Price_p(ause,j);
DISPLAY Price1_p;

**********************************************************************************************************************************

Table         Prod_cost_p(ause,j,k)  Crop non-water production costs (Million euro per 1000 ha)

*******************************************************************************************************************************************************************
                 rice.fld         cer.fld          veg.fld           cit.fld          frt.fld
*use node rows (+)
*------------------------------------------------------------------------------------------------------------------------------------------------------------------
CJT_u_f           0.409            1.139             3.202            3.429            2.754
ESC_u_f                                                               3.827            3.177
ARJ_u_f           1.009            1.536             3.742            3.800            3.146
RB_u_f            1.189            1.702             4.004            3.917            3.242
MO_ND_u_f                                            0.000
MO_CD_u_f                                            0.040
MO_SD_u_f                                            0.002
*------------------------------------------------------------------------------------------------------------------------------------------------------------------

+                                 cer.spk          veg.drp           cit.drp          frt.drp    wht.spk    bar.spk     corn.spk      garl.drp    onn.drp     grap.drp
*use node rows (+)
*------------------------------------------------------------------------------------------------------------------------------------------------------------------
CJT_u_f                            1.139             3.202            3.429            2.754
ESC_u_f                                                               3.827            3.177
ARJ_u_f                            1.536             3.742            3.800            3.146
RB_u_f                             1.702             4.004            3.917            3.242
MO_ND_u_f                          0.060             0.000                             0.200      0.124      0.114       0.780        2.625       2.550       0.553
MO_CD_u_f                          0.050             0.040                             0.120      0.050      0.050       0.640        2.590       2.470       0.560
MO_SD_u_f                          0.170             0.002                             0.222      0.182      0.164       0.955        2.689       2.680       0.585
```

```
*--------------------------------------------------------------------------------------------------------------


;
*********************************************************************************************************************************

Parameter   nprod_cost_p(ause,j,k,p)
;
nprod_cost_p(ause,j,k,p) = Prod_cost_p(ause,j,k);
DISPLAY nprod_cost_p;

********************************************************************************

Parameter     pwater(ause)             Price of water (Million euro per Mm3)
/
 MO_ND_u_f  0.00
 MO_CD_u_f  0.00
 MO_SD_u_f  0.00
 CJT_u_f    0.08
 ESC_u_f    0.025
 ARJ_u_f    0.03
 RB_u_f     0.01
/
;

Parameter

pump_cost_p       Pumping costs           (MEuro per Mm per Mm3)                                 /0.25/

pump_Fxcost_p     Fixed pumping costs     (MEuro per 1000 ha)                                    /0.34/

;

Parameter   npwater(ause,p)
;
npwater(ause,p) = pwater(ause);
DISPLAY npwater;

********************************************************************************
*Land use data

Table       Land_tot_p(ause,j)         Observed area in production by crop and agricultural node (1000 ha)
```

```
**********************************************************************************************************************************
                        rice          cer          veg          cit          Frt     wht    bar    corn    garl    onn     grap
*use node rows (+)
*---------------------------------------------------------------------------------------------------------------------------------
CJT_u_f                 0.37          0.10         0.68         14.79        3.22
ESC_u_f                                                          3.26        0.15
ARJ_u_f                 2.91          0.19         0.60          9.88        1.69
RB_u_f                  8.50          0.11         0.23          6.14        0.29
MO_ND_u_f                             0.93         0.20                      0.11    0.93   0.91   0.30    0.13    0.19    3.34
MO_CD_u_f                             9.46         5.00                      0.90   10.04  11.37   6.57    2.86    3.92    7.63
MO_SD_u_f                             3.81         1.90                      1.46    3.61   4.14   2.54    0.88    1.20    1.40
*---------------------------------------------------------------------------------------------------------------------------------
;

Table           pct_crops(ause,j,k)          Proportion of total area by crop and technology

                              fld            spk          drp
*--------------------------------------------------------------------------------
CJT_u_f.rice                  1.0
CJT_u_f.cer                   0.8            0.2
CJT_u_f.veg                   0.3                         0.7
CJT_u_f.cit                   0.2                         0.8
CJT_u_f.Frt                   0.3                         0.7

ESC_u_f.rice
ESC_u_f.cer
ESC_u_f.veg
ESC_u_f.cit                   0.4                         0.6
ESC_u_f.Frt                   0.1                         0.9

ARJ_u_f.rice                  1.0
ARJ_u_f.cer                   0.6            0.4
ARJ_u_f.veg                   0.2                         0.8
ARJ_u_f.cit                   0.45                        0.55
ARJ_u_f.Frt                   0.1                         0.9

RB_u_f.rice                   1.0
RB_u_f.cer                    0.9            0.1
RB_u_f.veg                    0.2                         0.8
RB_u_f.cit                    0.3                         0.7
RB_u_f.Frt                    0.2                         0.8

MO_ND_u_f.wht                                1.0
MO_ND_u_f.bar                                1.0
MO_ND_u_f.corn                               1.0
MO_ND_u_f.cer                                1.0
MO_ND_u_f.garl                                            1.0
MO_ND_u_f.onn                                             1.0
MO_ND_u_f.veg                 0.65                        0.35
MO_ND_u_f.grap                                            1.0
MO_ND_u_f.Frt                                             1.0

MO_CD_u_f.wht                                1.0
MO_CD_u_f.bar                                1.0
MO_CD_u_f.corn                               1.0
MO_CD_u_f.cer                                1.0
MO_CD_u_f.garl                                            1.0
MO_CD_u_f.onn                                             1.0
MO_CD_u_f.veg                 0.55                        0.45
```

```
MO_CD_u_f.grap                                            1.0
MO_CD_u_f.Frt                                             1.0

MO_SD_u_f.wht                                1.0
MO_SD_u_f.bar                                1.0
MO_SD_u_f.corn                               1.0
MO_SD_u_f.cer                                1.0
MO_SD_u_f.garl                                            1.0
MO_SD_u_f.onn                                             1.0
MO_SD_u_f.veg                 0.57                        0.43
MO_SD_u_f.grap                                            1.0
MO_SD_u_f.Frt                                             1.0

*-------------------------------------------------------------------------------
;

Parameter       Land_p(ause,j,k)             Total observed Land in production by crop and technology for base year (1000 ha);
Land_p(ause,j,k) = Land_tot_p(ause,j) * pct_crops(ause,j,k)
Display Land_p;

Parameter       tot_Land(ause);
tot_Land(ause) = sum((j,k), Land_p(ause,j,k));
Display tot_Land;

Table           Landuse_p(ause,j,k)         Links irrigation districts to crops and technologies

* A value of 0 means that irrigation district does not include that crop

*********************************************************************************************************************************
*
                        rice.fld         cer.fld          veg.fld          cit.fld          frt.fld
*use node rows (+)
*-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------
CJT_u_f                    1                1                1                1                1
ESC_u_f                                                                       1                1
ARJ_u_f                    1                1                1                1                1
RB_u_f                     1                1                1                1                1
MO_ND_u_f                                                    1
MO_CD_u_f                                                    1
MO_SD_u_f                                                    1
*-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------

+                                        cer.spk          veg.drp          cit.drp          frt.drp    wht.spk    bar.spk     corn.spk     garl.drp    onn.drp     grap.drp
*use node rows (+)
*-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------
CJT_u_f                                     1                1                1                1
ESC_u_f                                                                       1                1
ARJ_u_f                                     1                1                1                1
RB_u_f                                      1                1                1                1
MO_ND_u_f                                   1                1                                 1         1           1           1            1          1            1
MO_CD_u_f                                   1                1                                 1         1           1           1            1          1            1
MO_SD_u_f                                   1                1                                 1         1           1           1            1          1            1
*-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------
```

```
;

Parameter  Landuses_p(ause,j,k,t,p,s);
Landuses_p(ause,j,k,t,p,s) = Landuse_p(ause,j,k);
Display Landuses_p;

*********************************************************************************************

Parameter       Cost_has_p  (ause,j,k,p,s)   cost per ha exclusive of pumpung costs (MEuro per 1000 ha)
                Cost_pmp_p  (ause,j,k,p,s)   pumping costs (MEuro per 1000 ha)
                Cost_ha_p   (ause,j,k,p,s)   Total crop production costs (MEuro per 1000 ha)
                Netrev_ha_p (ause,j,k,p,s)   Net revenue (MEuro per 1000 ha)
;

Cost_has_p (ause,j,k,p,s)  $ (Landuse_p(ause,j,k) eq 1)   = [npwater(ause,p) * (sum(aapply, BBas_p(aapply,j,k,s) * ID_ua
(ause,aapply)))] + nprod_cost_p(ause,j,k,p);


Cost_pmp_p  (ause,j,k,p,s) $ (Landuse_p(ause,j,k) eq 1)   = ([{pump_cost_p * (sum(aqf, Buaq_p(ause,aqf) * (SL_p(aqf) -
H0_p(Aqf)))) * (sum(aapply, BBas_p(aapply,j,k,s) * ID_ua  (ause,aapply)))}
                                                         +   pump_Fxcost_p] * gw_u_p(ause)) ;

Cost_ha_p   (ause,j,k,p,s) $ (Landuse_p(ause,j,k) eq 1)   =  Cost_has_p (ause,j,k,p,s) + Cost_pmp_p (ause,j,k,p,s) ;

Netrev_ha_p (ause,j,k,p,s) $ (Landuse_p(ause,j,k) eq 1)   =  Price1_p(ause,j,k) * Yield_p(ause,j,k) - Cost_ha_p(ause,j,k,p,s) ;

Display Cost_has_p, Cost_pmp_p, Cost_ha_p, Netrev_ha_p;

Parameter

* Positive mathematical programming (pmp) parameters derived below.
* It has 2 parameters that force (calibrate) optimized acreage and yields to match historical baseline
* This calibration sets the foundation for a quadratic programming model
* in which all constraints are removed to the crop mix.
* model is driven only by these requirements
*
*  1.   price of land/water equals declining value of marginal product under assumed profit max
*  2.   base land and water constraints are respected
*  3.   Historical data on average profitability, land in production, crop mix, and yield are reproduced
*
* PMP ensures smooth adjustments to future water supply or policy changes
```

```
B0_p(ause,j,k)     intercept term in crop-water prodn fn forces vmp of water = water price
B1_p(ause,j,k)     linear term does the same.  Should be negative.  Greater land in production reduces average yield (Ricardian
Rent)
;

B1_p(ause,j,k) $ (Landuse_p(ause,j,k) eq 1) =  -Netrev_ha_p(ause,j,k,'base','normal') / [price1_p(ause,j,k) * Land_p(ause,j,k)];
// Under profit max, higher observed net rev per acre says increased acreage reduces yields by more
B0_p(ause,j,k) $ (Landuse_p(ause,j,k) eq 1) =   Yield_p(ause,j,k) - B1_p(ause,j,k) * Land_p(ause,j,k);

Display B0_p, B1_p;

* Check

Parameter Obsyield_p(ause,j,k) Observed yield
;

Obsyield_p(ause,j,k) = B0_p(ause,j,k) + B1_p(ause,j,k) * Land_p(ause,j,k) ;

Display Obsyield_p ;

**************** End of Agricultural data *******************************************************************************
*****************************************************************************************************************************
* urban details follow

Parameter scal (muse)             Number of households by urban node (1000 persons)
/Albacete_u_f     180.196
 Valencia_u_f    1605.348
 Sagunto_u_f       66.070
/
;

Parameter grow (muse)             Population growth rate (%)
/Albacete_u_f     0.0014
 Valencia_u_f     0.01
 Sagunto_u_f      0.01
/
;
Parameter scale(muse,t)            Acccounts for growing city population
;
scale(muse,t) = scal(muse) * (1 + grow (muse)) ** (ord(t)-1);
```

```
Display scale;

Parameter p_elasticity_p(muse)     Urban use node estiamted price elasticity of demand

/Albacete_u_f      -0.15
 Valencia_u_f      -0.15
 Sagunto_u_f       -0.15
/
;

Parameter mu_use_p(muse)           Observed water supplied  (Mm3 per 1000 persons)

* We are considering the water supply to Valencia from the Jucar river (76%)
* and not from the Turia River (24%)

/Albacete_u_f  0.086
 Valencia_u_f  0.051
 Sagunto_u_f   0.088
/
;

* Data on water prices and costs are from CHJ (2014)
* Anejo 9, recuperacion de costes de los servicios del agua

Parameter mu_price_p(muse)         Observed price charged (Million Euro per Mm3)

/Albacete_u_f    1.11
 Valencia_u_f    1.11
 Sagunto_u_f     1.11
/
;

Parameter mu_cost_p(muse)          Observed average costs (Million Euro per Mm3)

/Albacete_u_f    1.29
 Valencia_u_f    1.29
 Sagunto_u_f     1.29
/
;
```

```
Parameter Ben_u_p(muse,*)           Per household benefit
;

Ben_u_p(muse, 'intercept') =   0.0;
Ben_u_p(muse, 'linear')    =         mu_price_p(muse) * (p_elasticity_p(muse) - 1) / p_elasticity_p(muse);   // intcpt of price
dep MI dem fn = choke price
Ben_u_p(muse, 'quadratic') =   0.5 * mu_price_p(muse) / (p_elasticity_p(muse) *            mu_use_p(muse));  // 0.5 * slope of
price dep MI dem fn = dp/dq


Display ben_u_p;

**************************** End of urban data *********************************************************************************
*********************************************************************************************************************************

Scalar rho   Discount rate
/0.05/
;

Parameter

DF(t)        Discount factor
;

DF(t) = 1/((1+rho)**(ord(t)-1));

Display DF;

*************** Section 3 ***********************************************************
*  These endogenous (unknown) variables are defined                                 *
*  Their numerical values are not known til GAMS solves the model                   *
*************************************************************************************

Variables

* water
X_v          (i,        t,p,s)      Water flows -- diversion-use-return - etc. (Mm3)
X_jk_v       (i,j,k,    t,p,s)      Flows: - diversion-use-return - etc by node crop and irrigation technology (Mm3)
Q_v          (aqf,      t,p,s)      Groundwater net pumping by subaquifer node (Mm3)
Flow_aq_v    (aqf,      t,p,s)      Flow between subaquifers (Mm3)
Flow_r_aq_v  (aqf,      t,p,s)      Flow between river reaches and subaquifers (Mm3)
Storge_aq_v  (aqf,      t,p,s)      Storage change in each subaquifer (Mm3)
```

```
Balance_aq_v (aqf,       t,p,s)     Water balance in each subaquifer (Mm3)

* economics

*Agricultural use
Netrev_v     (ause,j,  k,t,p,s)     Net revenue by crop and technology (Million € per 1000 ha)
Income_jk_v  (ause,j,  k,t,p,s)     Income by crop and technology (Million €)
INCOME_v     (ause,      t,p,s)     Total agricultural income by use-time-policy-climate (Million €)
MNB_ag_v     (aapply,j,k,t,p,s)     Marginal net benefit of water (Euro per m3)

*Urban use
Mi_Ben_u_v   (muse,      t,p,s)     Benefits over all urban households (Consumer and producer surplus) (Million €)
Mi_Cost_u_v  (muse,      t,p,s)     MI cost (Million €)
Mi_NB_u_v    (muse,      t,p,s)     MI net benefits (Million €)
Mi_Mben_u_v  (muse,      t,p,s)     Marginal benefits of urban use (€ per m3)
Mi_Mc_u_v    (muse,      t,p,s)     Marginal cost of urban use (€ per m3)
Mi_MNB_u_v   (muse,      t,p,s)     Marginal net benefit of urban use (€ per m3)

*Environmental benefits
Env_Ben_Alb_v(envflow,   t,p,s)     Environmental benefits of the Albufera wetland (Million €)
Env_Ben_out_v(           t,p,s)     Other environmental benefits linked to water flows in the river (Million €)

*Basin level
Tot_mben_base_normal_v              Urban benefits under base policy and normal climate                                  (Million €)
Tot_agben_base_normal_v             Agricultural benefits under base policy and normal climate                           (Million €)
Tot_envben_base_normal_v            Environmental benefits under base policy and normal climate                          (Million €)
Tot_ben_base_normal_v               Total basin benefits under base policy and normal climate                            (Million €)

Tot_mben_opt_unsus_normal_v         Urban benefits under unsustainable management policy and normal climate              (Million €)
Tot_agben_opt_unsus_normal_v        Agricultural benefits under unsustainable management policy and normal climate       (Million €)
Tot_envben_opt_unsus_normal_v       Environmental benefits under unsustainable management policy and normal climate      (Million €)
Tot_ben_opt_unsus_normal_v          Total basin benefits under unsustainable management policy and normal climate        (Million €)

Tot_mben_opt_unsus_mildcc_v         Urban benefits under unsustainable management policy and mild cc                     (Million €)
Tot_agben_opt_unsus_mildcc_v        Agricultural benefits under unsustainable management policy and mild cc              (Million €)
Tot_envben_opt_unsus_mildcc_v       Environmental benefits under unsustainable management policy and mild cc             (Million €)
Tot_ben_opt_unsus_mildcc_v          Total basin benefits under unsustainable management policy and mild cc               (Million €)

Tot_mben_opt_unsus_severecc_v       Urban benefits under unsustainable management policy and severe cc                   (Million €)
Tot_agben_opt_unsus_severecc_v      Agricultural benefits under unsustainable management policy and severe cc            (Million €)
Tot_envben_opt_unsus_severecc_v     Environmental benefits under unsustainable management policy and severe cc           (Million €)
Tot_ben_opt_unsus_severecc_v        Total basin benefits under unsustainable management policy and severe cc             (Million €)

Tot_mben_opt_sus_mildcc_v           Urban benefits under sustainable management policy and mild cc                       (Million €)
```

```
Tot_agben_opt_sus_mildcc_v           Agricultural benefits under sustainable management policy and mild cc                 (Million €)
Tot_envben_opt_sus_mildcc_v          Environmental benefits under sustainable management policy and mild cc                (Million €)
Tot_ben_opt_sus_mildcc_v             Total basin benefits under sustainable management policy and mild cc                  (Million €)

Tot_mben_opt_sus_severecc_v          Urban benefits under sustainable management policy and severe cc                      (Million €)
Tot_agben_opt_sus_severecc_v         Agricultural benefits under sustainable management policy and severe cc               (Million €)
Tot_envben_opt_sus_severecc_v        Environmental benefits under sustainable management policy and severe cc              (Million €)
Tot_ben_opt_sus_severecc_v           Total basin benefits under sustainable management policy and severe cc                (Million €)

;

Positive variables

Land_v       (use,j,k,  t,p,s)       Total land production in ag areas - crop - time (1000 ha)

* water
Z_v          (res,      t,p,s)       Water stocks -- reservoirs (Mm3)
Za_v         (res,      t,p,s)       Water stocks-- area by reservoir (ha)

Inflows_r_v  (Rvr,      t,p,s)       Inflow to river reaches linked to subaquifers (Mm3)
Ht_aq_v      (aqf,      t,p,s)       Head in each subaquifer (Mm)
Hr_v         (Rvr,      t,p,s)       Head in each river reach (Mm)
Hrr_v        (Aqf,      t,p,s)       Head in each river reach linked to subaquifer (Mm)

Depths_v     (Aqf,      t,p,s)       Pumping depth in each subaquifer (Mm)
Depth_v      (ause,     t,p,s)       Pumping depth in each use node (Mm)
Pumpcost_m_v (ause,     t,p,s)       Pumping costs (Million € per Mm3)
Pumpcost_ha_v(ause,j,k, t,p,s)       Pumping costs (Million € per ha)
Yield_v      (ause,j,k, t,p,s)       Crop yield by technology (1000 Ton per 1000 ha)
Grossrev_v   (ause,j,k, t,p,s)       Gross revenue by crop and technology (Million € per 1000 ha)
Grossrevs_v  (ause,     t,p,s)       Total gross revenues (Million €)
Prod_costs_v (ause,     t,p,s)       Total production costs (Million €)

;

**************** Section 4 *****************************************************************
*  The following equations state relationships among a basin's
*  hydrology, institutions, and economics
********************************************************************************************

Equations

********************************************************************************************
* Equations named
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*****************************************************************************************
*Land Block

Land_e                   (ause,        t,p,s)       Agricultural land constraint
Land_per_e               (ause,per,  k,t,p,s)       Perennial land constraint

*Hydrology Block

Inflows_e                (inflow,      t,p,s)       Flows: set source nodes
Rivers_e                 (river,       t,p,s)       Flows: hydrologic mass balance for each flow node: sources = uses
Divs_e                   (divert,      t,p,s)       Flows: wet river
Ndivert_e                (ndivert,     t,p,s)       Flows: Net diverion
Return_e                 (returnc,     t,p,s)       Flows: Return flows at canal level
Applies_e                (apply,       t,p,s)       Flows: water applied (sources) can come from diversions or pumping
Evaps_e                  (evap,        t,p,s)       Flows: set reservoir evaporation losses by flow node
Area_e                   (res,         t,p,s)       Reservoir area
Reservoirs_e             (res,         t,p,s)       Stock: reservoir mass balance accounting

Ht_aq0_normal_e          (aqf,         t,p,s)       Initial subaquifer head in normal climate
Ht_aq_normal_e           (aqf,         t,p,s)       Head in each subaquifer in normal climate
Ht_aq_clm_e              (aqf,         t,p,clm)     Head in each subaquifer in climate change scenarios
Q_e                      (aqf,         t,p,s)       Net pumping in each subaquifer
Inflows_r_e              (Rvr,         t,p,s)       Inflows in river reaches linked to subaquifers
Hr_e                     (Rvr,         t,p,s)       Head in river reaches
Flow_aq_e                (aqf,         t,p,s)       Flow between subaquifers
Hrr_e                    (Aqf,         t,p,s)       Head in each subaquifer linked to river reach
Flow_r_aq_e              (aqf,         t,p,s)       Flow between river reach and subaquifer
Discharge_r_aq_e         (discharge,   t,p,s)       Flow between river reach and subaquifer
Storge_aq_e              (aqf,         t,p,s)       Storage change in each subaquifer
Balance_aq_e             (aqf,         t,p,s)       Balance in each subaquifer


Ag_apply_jk_e            (aapply,  j,k,t,p,s)       Flows: water applied (uses) for crop prodxn by acreage crop and technology
Ag_use_jk_e              (ause,    j,k,t,p,s)       Flows: water used for crop prodxn by acreage crop and technology
Ag_ret_jk_e              (areturnp,j,k,t,p,s)       Flows: return flow at plot level from crop prodxn by acreage by crop and technology
Ag_apply_e               (aapply,      t,p,s)       Flows: water applied  (uses) for crop prodxn summed over acreage and technology
Ag_use_e                 (ause,        t,p,s)       Flows: water used     for crop prodxn summed over acreage and technology
Ag_ret_e                 (areturnp,    t,p,s)       Flows: water returned at plot level in crop prodxn summed over acreage and technology

MI_Uses_e                (muse,        t,p,s)       Flows: set use levels by flow node: use = proportion of application
MI_Returns_e             (mreturnp,    t,p,s)       Flows: set return flow levels by flow node: rf = prop of application

Envflow_e                (envflow,     t,p,s)       Flows: Environmental flows to Albufera wetland
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*Economics block

Depths_e                 (Aqf,         t,p,s)       Pumping depth in each subaquifer
Depth_e                  (ause,        t,p,s)       Pumping depth in each use node
Pumpcost_m_e             (ause,        t,p,s)       Pumping costs per Mm3
Pumpcost_ha_e            (ause,    j,k,t,p,s)       Pumping costs per ha
Yield_e                  (ause,    j,k,t,p,s)       Yield by crop technology
Grossrev_e               (ause,    j,k,t,p,s)       Gross revenue by crop technology

Grossrevs_e              (ause,        t,p,s)       Total gross revenues
Prod_costs_e             (ause,        t,p,s)       Total production costs

Netrev_e                 (ause,    j,k,t,p,s)       Net revenue by crop technology
Income_jk_e              (ause,    j,k,t,p,s)       Farm income by crop technology
Income_e                 (ause,        t,p,s)       Total farm income by policy and climate scenario
MNB_ag_e                 (aapply,  j,k,t,p,s)       Marginal net benefits of water

Mi_Ben_u_e               (muse,        t,p,s)       Gross urban benefits
Mi_Cost_u_e              (muse,        t,p,s)       Urban water costs
Mi_NB_u_e                (muse,        t,p,s)       Net urban benefits
Mi_MB_u_e                (muse,        t,p,s)       Marginal benefits
Mi_Mc_u_e                (muse,        t,p,s)       Marginal Costs
Mi_MNB_u_e               (muse,        t,p,s)       Marginal net Benefit

Env_Ben_Alb_e            (envflow,     t,p,s)       Environmental benefits of the Albufera wetland
Env_Ben_out_e            (             t,p,s)       Other environmental benefits linked to water flows in the river


Tot_mben_base_normal_e                              Total urban benefits under base policy and normal climate
Tot_agben_base_normal_e                             Total agricultural benefits under base policy and normal climate
Tot_envben_base_normal_e                            Total environmental benefits under base policy and normal climate
Tot_ben_base_normal_e                               Total basin benefits under base policy and normal climate

Tot_mben_opt_unsus_normal_e                         Total urban benefits under unsustainable management policy and normal climate
Tot_agben_opt_unsus_normal_e                        Total agricultural benefits under unsustainable management policy and normal climate
Tot_envben_opt_unsus_normal_e                       Total environmental benefits under unsustainable management policy and normal climate
Tot_ben_opt_unsus_normal_e                          Total basin benefits under unsustainable management policy and normal climate

Tot_mben_opt_unsus_mildcc_e                         Total urban benefits under unsustainable management policy and mild cc
Tot_agben_opt_unsus_mildcc_e                        Total agricultural benefits under unsustainable management policy and mild cc
Tot_envben_opt_unsus_mildcc_e                       Total environmental benefits under unsustainable management policy and mild cc
Tot_ben_opt_unsus_mildcc_e                          Total basin benefits under base unsustainable management policy and mild cc

Tot_mben_opt_unsus_severecc_e                       Total urban benefits under unsustainable management policy and severe cc
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Tot_agben_opt_unsus_severecc_e                      Total agricultural benefits under unsustainable management policy and severe cc
Tot_envben_opt_unsus_severecc_e                     Total environmental benefits under unsustainable management policy and severe cc
Tot_ben_opt_unsus_severecc_e                        Total basin benefits under unsustainable management policy and severe cc

Tot_mben_opt_sus_mildcc_e                           Total urban benefits under sustainable management policy and mild cc
Tot_agben_opt_sus_mildcc_e                          Total agricultural benefits under sustainable management policy and mild cc
Tot_envben_opt_sus_mildcc_e                         Total environmental benefits under sustainable management policy and mild cc
Tot_ben_opt_sus_mildcc_e                            Total basin benefits under sustainable management policy and mild cc

Tot_mben_opt_sus_severecc_e                         Total urban benefits under sustainable management policy and severe cc
Tot_agben_opt_sus_severecc_e                        Total agricultural benefits under sustainable management policy and severe cc
Tot_envben_opt_sus_severecc_e                       Total environmental benefits under sustainable management policy and severe cc
Tot_ben_opt_sus_severecc_e                          Total basin benefits under sustainable management policy and severe cc

;
*****************************************************************************************************************************************
Equations DEFINED algebraiclly using DECLARED equation names
*****************************************************************************************************************************************
*  Land  Block

Land_e       (ause,    t,p,s)..                         sum((j,k), Land_v(ause,j,k,t,p,s) * Landuses_p(ause,j,k,t,p,s)) =L=
tot_Land(ause);

Land_per_e   (ause,per,k,t,p,s) $ (ord(t) gt 1)..       Land_v(ause,per,k,t,p,s) =l= Land_v(ause,per,k,t-1,p,s);

* Hydrology  Block

Inflows_e    (inflow,  t,p,s)..   X_v(inflow,t,p,s) =E= source_p(inflow,t,s);

Rivers_e     (river,   t,p,s)..   X_v(river,t,p,s)  =E= sum(inflow,      Bv_p(inflow,    river)  * X_v(inflow,     t,p,s)) +
                                                        sum(riverp,      Bv_p(riverp,    river)  * X_v(riverp,     t,p,s)) +
                                                        sum(divert,      Bv_p(divert,    river)  * X_v(divert,     t,p,s)) +
                                                        sum(returnc,     Bv_p(returnc,   river)  * X_v(returnc,    t,p,s)) +
                                                        sum(returnp,     Bv_p(returnp,   river)  * X_v(returnp,    t,p,s)) +
                                                        sum(discharge,   Bv_p(discharge, river)  * X_v(discharge,  t,p,s)) +
                                                        sum(rel,         Bv_p(rel,       river)  * X_v(rel,        t,p,s)) +
                                                        sum(unmeasure,   Bv_p(unmeasure, river)  * X_v(unmeasure,  t,p,s)) ;

Divs_e       (divert,  t,p,s)..   X_v(divert,t,p,s) =L= sum(inflow,      Bd_p(inflow,   divert)  * X_v(inflow,     t,p,s)) +
                                                        sum(river,       Bd_p(river,    divert)  * X_v(river,      t,p,s)) +
                                                        sum(divertp,     Bd_p(divertp,  divert)  * X_v(divertp,    t,p,s)) +
                                                        sum(returnc,     Bd_p(returnc,   divert) * X_v(returnc,    t,p,s)) +
                                                        sum(returnp,     Bd_p(returnp,  divert)  * X_v(returnp,    t,p,s)) +
                                                        sum(discharge,   Bd_p(discharge, divert) * X_v(discharge,  t,p,s)) +
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```
                                                        sum(rel,         Bd_p(rel,      divert)  * X_v(rel,        t,p,s)) +
                                                        sum(unmeasure,   Bd_p(unmeasure,divert)  * X_v(unmeasure,  t,p,s)) ;


Ndivert_e    (ndivert, t,p,s).. X_v(ndivert, t,p,s) =E= sum(divert,      Bnd_p(ndivert,divert)   * X_v(divert,     t,p,s)) ;

Return_e     (returnc, t,p,s).. X_v(returnc, t,p,s) =E= sum(divert,      Bnd_p(returnc,divert)   * X_v(divert,     t,p,s)) ;

Applies_e    (apply,   t,p,s).. X_v(apply,   t,p,s) =E= sum(ndivert,     Ba_p(ndivert,  apply)   * X_v(ndivert,    t,p,s)) +
                                                        sum(pump,        Ba_p(pump,     apply)   * X_v(pump,       t,p,s)) ;

* Reservoirs mass balance

Evaps_e      (evap,    t,p,s).. X_v(evap,    t,p,s) =E= sum(res, Bes_p(evap,res,s) * Za_v(res,t,p,s)) ;

Area_e       (res,     t,p,s).. Za_v(res,    t,p,s) =E= B0ar_p(res) + B1ar_p(res) * Z_v(res,t,p,s) ;

Reservoirs_e (res,     t,p,s).. Z_v (res,    t,p,s) =E= z0_p(res)$(ord(t) eq 1) + Z_v(res,t-1,p,s)
                                                     +  sum(rel,  BLv_p(rel, res) * X_v(rel, t,p,s))
                                                     +  sum(evap, Ber_p(evap,res) * X_v(evap,t,p,s));

* Aquifer hydrogeology

* The following 5 equations requiered to calculate aquifer head

Ht_aq0_normal_e      (aqf,t,p,'normal') $ (ord(t) eq 1)..   Ht_aq_v (aqf,t,p,'normal') =E= H0_p(aqf) ;

Ht_aq_normal_e       (aqf,t,p,'normal') $ (ord(t) gt 1)..   Ht_aq_v (aqf,t,p,'normal') =E= {1 / [(Surfarea_p(aqf) * S_p(aqf) / dt) +
C12_p(aqf) + C21_p(aqf) + C23_p(aqf) + C32_p(aqf) + (sum(Rvr, Cr_p(Rvr) * weight_r_aq(aqf,Rvr)))]}
                                                                    * [(Surfarea_p(aqf) * S_p(aqf) *  Ht_aq_v(aqf,t-1,p,'normal')/dt)
                                                                    +  (C12_p(aqf) * Ht_aq_v(aqf+1,t,p,'normal')) + (C21_p(aqf) *
Ht_aq_v(aqf-1,t,p,'normal'))+ (C23_p(aqf) * Ht_aq_v(aqf+1,t,p,'normal'))+ (C32_p(aqf) * Ht_aq_v(aqf-1,t,p,'normal'))
                                                                    +  (sum(Rvr, Cr_p(Rvr) * Hr_v(Rvr,t,p,'normal') *
weight_r_aq(aqf,Rvr))) + Qr_p(aqf,t,p,'normal') - Q_v(aqf,t,p,'normal')]  ;

Ht_aq_clm_e       (aqf,t,p,clm) ..  Ht_aq_v     (aqf,t,p,clm)   =E= {1 / [(Surfarea_p(aqf) * S_p(aqf) / dt) + C12_p(aqf) + C21_p(aqf) +
C23_p(aqf) + C32_p(aqf) + (sum(Rvr, Cr_p(Rvr) * weight_r_aq(aqf,Rvr)))]}
                                                                    * [(Surfarea_p(aqf) * S_p(aqf) * (H0_p(aqf) $ (ord(t) eq 1) +
Ht_aq_v(aqf,t-1,p,clm))/dt)
                                                                    +  (C12_p(aqf) * Ht_aq_v(aqf+1,t,p,clm)) + (C21_p(aqf) * Ht_aq_v(aqf-
1,t,p,clm))+ (C23_p(aqf) * Ht_aq_v(aqf+1,t,p,clm))+ (C32_p(aqf) * Ht_aq_v(aqf-1,t,p,clm))
                                                                    +  (sum(Rvr, Cr_p(Rvr) * Hr_v(Rvr,t,p,clm) * weight_r_aq(aqf,Rvr))) +
Qr_p(aqf,t,p,clm) - Q_v(aqf,t,p,clm)]  ;
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```
Q_e           (aqf,t,p,s)..   Q_v         (aqf,t,p,s)   =E= sum(pump, Bp_p (pump, aqf) * X_v(pump, t,p,s)) - sum(areturnp,
Brp_p(areturnp,aqf) * X_v(areturnp,t,p,s)) ;

Inflows_r_e   (Rvr,t,p,s)..   Inflows_r_v (Rvr,t,p,s)   =E= sum(river,Brr_p(river,Rvr) * X_v(river,t,p,s)) ;

Hr_e          (Rvr,t,p,s)..   Hr_v        (Rvr,t,p,s)   =E= slope_r_p(Rvr) * Inflows_r_v (Rvr,t,p,s) + intercept_r_p(Rvr) ;  // river
flows map into river heads

Flow_aq_e     (aqf,t,p,s)..   Flow_aq_v   (aqf,t,p,s)   =E=(C12_p(aqf) * (Ht_aq_v (aqf+1,t,p,s) - Ht_aq_v (aqf,t,p,s))) +
                                                           (C21_p(aqf) * (Ht_aq_v (aqf-1,t,p,s) - Ht_aq_v (aqf,t,p,s))) + (C23_p(aqf) *
(Ht_aq_v (aqf+1,t,p,s) - Ht_aq_v (aqf,t,p,s))) +
                                                           (C32_p(aqf) * (Ht_aq_v (aqf-1,t,p,s) - Ht_aq_v (aqf,t,p,s)));

* The following 3 equations are requiered to calculate the flow between aquifer and river

Hrr_e            (Aqf,      t,p,s).. Hrr_v       (Aqf,t,p,s) =E=  sum(Rvr, Hr_v(Rvr,t,p,s) * weight_r_aq(Aqf,Rvr)) ;

Flow_r_aq_e      (aqf,      t,p,s).. Flow_r_aq_v (aqf,t,p,s) =E= (sum(Rvr, Cr_p(Rvr) * weight_r_aq(aqf,Rvr))) * (Hrr_v (aqf,t,p,s) -
Ht_aq_v (aqf,t,p,s)) ;

Discharge_r_aq_e (discharge,t,p,s).. X_v   (discharge,t,p,s) =E=  sum(aqf, Bda_p(discharge,aqf) * Flow_r_aq_v (aqf,t,p,s));

* The following two equations are used to calculated storage and balance in aquifers

Storge_aq_e   (aqf,t,p,s)..   Storge_aq_v (aqf,t,p,s)   =E= Surfarea_p(aqf) * S_p(aqf) * (Ht_aq_v (aqf,t,p,s) - (H0_p(aqf) $ (ord(t) eq
1) + Ht_aq_v(aqf,t-1,p,s)));

Balance_aq_e  (aqf,t,p,s)..   Balance_aq_v(aqf,t,p,s)   =E= Qr_p(aqf,t,p,s) - Q_v (aqf,t,p,s) + Flow_aq_v(aqf,t,p,s) + Flow_r_aq_v
(aqf,t,p,s) - Storge_aq_v(aqf,t,p,s);


* Ag hydrology

Ag_apply_jk_e(aapply, j,k,t,p,s) ..  X_jk_v  (aapply, j,k,t,p,s)   =E= sum(ause, BBas_p(aapply,  j,k,s)
                                    * Land_v (ause,   j,k,t,p,s) * ID_ua  (ause,        aapply    ));   // ag water applied based on
acreage by irrig tech

Ag_use_jk_e  (ause,   j,k,t,p,s) ..  X_jk_v  (ause,   j,k,t,p,s)   =E=           BBas_p(ause,    j,k,s)
                                    * Land_v (ause,   j,k,t,p,s)                                   ;

Ag_ret_jk_e  (areturnp,j,k,t,p,s)..  X_jk_v  (areturnp,j,k,t,p,s)  =E= sum(ause, BBas_p(areturnp,j,k,s)
                                    * Land_v (ause,   j,k,t,p,s) * ID_ur  (ause,       areturnp   ));

Ag_apply_e   (aapply,     t,p,s).. X_v  (aapply,        t,p,s)   =E= sum((j,k), X_jk_v(aapply,  j,k,t,p,s));
```

```
Ag_use_e     (ause,       t,p,s)..  X_v  (ause,          t,p,s)   =E= sum((j,k), X_jk_v(ause,    j,k,t,p,s));

Ag_ret_e     (areturnp,   t,p,s)..  X_v  (areturnp,      t,p,s)   =E= sum((j,k), X_jk_v(areturnp,j,k,t,p,s));

* Urban hydrology

MI_Uses_e    (muse,       t,p,s)..  X_v  (muse,          t,p,s)   =E= sum(mapply,   Bmu_p(mapply, muse    ) * X_v(mapply,    t,p,s)) ;

MI_Returns_e (mreturnp,   t,p,s)..  X_v  (mreturnp,      t,p,s)   =E= sum(mapply,   Brm_p(mapply, mreturnp) * X_v(mapply,    t,p,s)) ;


* Environmental flows to Albufera wetland

Envflow_e    (envflow,    t,p,s)..  X_v  (envflow,       t,p,s)   =E= sum(returnc,  Benr_p(returnc,envflow) * X_v(returnc,   t,p,s)) +
                                                                      sum(returnp,  Benr_p(returnp,envflow) * X_v(returnp,   t,p,s)) ;

* Economics Block

**********************  Agricultural benefits ***************************************************************************

Depths_e     (Aqf,        t,p,s)..  Depths_v    (Aqf,       t,p,s)  =E= SL_p(aqf) - ht_aq_v(Aqf,t,p,s);                 // depth
increases with falling head

Depth_e      (ause,       t,p,s)..  Depth_v     (ause,      t,p,s)  =E= sum(aqf, Buaq_p(ause,aqf) * Depths_v(Aqf,t,p,s)) ;

Pumpcost_m_e (ause,       t,p,s)..  Pumpcost_m_v(ause,      t,p,s)  =E= pump_cost_p * Depth_v(ause,t,p,s) ;

Pumpcost_ha_e(ause,j,k,   t,p,s)..  Pumpcost_ha_v(ause,j,k, t,p,s)  =E= [{Pumpcost_m_v(ause,t,p,s) * (sum(aapply, BBas_p(aapply, j, k,s)
* ID_ua  (ause,aapply)))} + pump_Fxcost_p] * gw_u_p(ause) ;

Yield_e      (ause,j,k,   t,p,s)..  Yield_v     (ause,  j,k,t,p,s)  =E= B0_p(ause,j,k) + B1_p(ause,j,k) * Land_v(ause,j,k,t,p,s) ;

Grossrev_e   (ause,j,k,   t,p,s)..  Grossrev_v  (ause,  j,k,t,p,s)  =E= price1_p(ause,j,k) * Yield_v(ause,j,k,t,p,s)             ;

Netrev_e     (ause,j,k,   t,p,s)..  Netrev_v    (ause,  j,k,t,p,s)  =E= Grossrev_v(ause,j,k,t,p,s) - Cost_has_p(ause,j,k,p,s) -
Pumpcost_ha_v(ause,j,k, t,p,s) ;

Grossrevs_e  (ause,       t,p,s)..  Grossrevs_v (ause,      t,p,s)  =E= sum((j,k), Grossrev_v  (ause,  j,k,t,p,s) *
Land_v(ause,j,k,t,p,s)) ;

Prod_costs_e (ause,       t,p,s)..  Prod_costs_v(ause,      t,p,s)  =E= sum((j,k), (Cost_has_p(ause,j,k,p,s) + Pumpcost_ha_v(ause,j,k,
t,p,s)) * Land_v(ause,j,k,t,p,s)) ;
```

```
Income_jk_e  (ause,j,k,   t,p,s)..  Income_jk_v (ause,  j,k,t,p,s)  =E= Land_v(ause,j,k,t,p,s) * Netrev_v(ause,j,k,t,p,s)        ;

Income_e     (ause,       t,p,s)..  INCOME_v    (ause,      t,p,s)  =E= sum((j,k),Income_jk_v (ause,j,k,t,p,s))                 ;

MNB_ag_e     (aapply,j,k, t,p,s) $ ((sum(ause, Landuse_p(ause,j,k)* ID_ua  (ause,aapply))) eq 1) ..
                                    MNB_ag_v    (aapply,j,k,t,p,s)  =E= {{[2 * (sum(ause, price1_p(ause,j,k) *  B1_p(ause,j,k) * ID_ua
(ause,aapply))) * X_jk_v  (aapply, j,k,t,p,s)]
                                                                        + [BBas_p   (aapply,j,k,s) * (sum(ause, B0_p(ause,j,k) *
price1_p(ause, j,k  ) * ID_ua   (ause,aapply    )))]
                                                                        - [BBas_p   (aapply,j,k,s) * (sum(ause, nprod_cost_p(ause,j,k,p)
* ID_ua  (ause,aapply)))]}/[(BBas_p(aapply,j,k,s)**2)]}
                                                                                                   - (sum(ause, {npwater(ause,p) +
[{Pumpcost_ha_v(ause,j,k, t,p,s)/(BBas_p(aapply, j, k,s))} * gw_u_p(ause)]} * ID_ua  (ause,aapply)));

***********************  Urban benefits *********************************************************************************************

Mi_Ben_u_e   (muse,t,p,s)..     Mi_Ben_u_v (muse,t,p,s) =E= scale(muse,t) * Ben_u_p(muse, 'intercept')+
                                                            Ben_u_p(muse, 'linear') * X_v(muse,t,p,s)+
                                                            (1/scale(muse,t)) * Ben_u_p(muse, 'quadratic') * X_v(muse,t,p,s) *
X_v(muse,t,p,s) ;

Mi_Cost_u_e  (muse,t,p,s)..     Mi_Cost_u_v(muse,t,p,s) =E= mu_cost_p(muse)  * X_v(muse,t,p,s);

Mi_NB_u_e    (muse,t,p,s)..     Mi_NB_u_v  (muse,t,p,s) =E= Mi_ben_u_v(muse,t,p,s) - Mi_Cost_u_v(muse,t,p,s);


Mi_MB_u_e    (muse,t,p,s)..     Mi_Mben_u_v(muse,t,p,s) =E= Ben_u_p(muse, 'linear') +
                                                            2 * (1/scale(muse,t))   * Ben_u_p(muse, 'quadratic') * X_v(muse,t,p,s);
Mi_Mc_u_e    (muse,t,p,s)..     Mi_Mc_u_v  (muse,t,p,s) =E= mu_cost_p(muse);  // marginal cost

Mi_MNB_u_e   (muse,t,p,s)..     Mi_MNB_u_v (muse,t,p,s) =E= Mi_Mben_u_v(muse,t,p,s) - Mi_Mc_u_v(muse,t,p,s);  // marg net benefit

***********************  Environmental benefits ***************************************************************************************

* Environmental benefits of the Albufera wetland are estimated from Kahil et al.(2015)

Env_Ben_Alb_e(envflow,t,p,s)..  Env_Ben_Alb_v(envflow,t,p,s) =E= -0.0061 * X_v(envflow,t,p,s)**2 + 1.685 * X_v(envflow,t,p,s) ;

* Other environmental benefits from water flowing in the river including dilution of wastewater, pesticides and fertilizers, reducing
salt intrusion,
* climate regulation, erosion control, habitat for fish and wildlife, recreation and amenity values, etc
* These benefits are estimated based on water outflows to the sea (Cullera gauge) and valuation studies from the literature (0.5 €/m3)

Env_Ben_out_e(       t,p,s)..  Env_Ben_out_v(       t,p,s) =E= 0.25 * X_v('Cullera_v_f',t,p,s) ;
```

```
***********************  Total basin benefits *****************************************************************************************
* For simulation and normal

Tot_mben_base_normal_e   .. Tot_mben_base_normal_v  =E= sum((muse,   t), DF(t) * Mi_NB_u_v(muse,t,'base','normal')) ;  //scalar benefits
for base policy normal inflows

Tot_agben_base_normal_e  .. Tot_agben_base_normal_v =E= sum((ause,   t), DF(t) * INCOME_v (ause,t,'base','normal')) ;

Tot_envben_base_normal_e .. Tot_envben_base_normal_v=E= sum{t, DF(t) * [(sum(envflow,  Env_Ben_Alb_v(envflow,t,'base','normal'))) +
Env_Ben_out_v(t,'base','normal')]} ;

Tot_ben_base_normal_e    .. Tot_ben_base_normal_v   =E= Tot_mben_base_normal_v + Tot_agben_base_normal_v ;

* For optimization, unsustainable management and normal

Tot_mben_opt_unsus_normal_e   .. Tot_mben_opt_unsus_normal_v  =E= sum((muse,   t), DF(t) * Mi_NB_u_v(muse,t,'opt_unsus','normal')) ;
//scalar benefits for base policy normal inflows

Tot_agben_opt_unsus_normal_e  .. Tot_agben_opt_unsus_normal_v =E= sum((ause,   t), DF(t) * INCOME_v (ause,t,'opt_unsus','normal')) ;

Tot_envben_opt_unsus_normal_e .. Tot_envben_opt_unsus_normal_v=E= sum{t, DF(t) * [(sum(envflow,
Env_Ben_Alb_v(envflow,t,'opt_unsus','normal'))) + Env_Ben_out_v(t,'opt_unsus','normal')]} ;

Tot_ben_opt_unsus_normal_e    .. Tot_ben_opt_unsus_normal_v   =E= Tot_mben_opt_unsus_normal_v + Tot_agben_opt_unsus_normal_v ;

* For optimization, unsustainable management and mild cc

Tot_mben_opt_unsus_mildcc_e   .. Tot_mben_opt_unsus_mildcc_v  =E= sum((muse,   t), DF(t) * Mi_NB_u_v(muse,t,'opt_unsus','mildcc')) ;
//scalar benefits for base policy normal inflows

Tot_agben_opt_unsus_mildcc_e  .. Tot_agben_opt_unsus_mildcc_v =E= sum((ause,   t), DF(t) * INCOME_v (ause,t,'opt_unsus','mildcc')) ;

Tot_envben_opt_unsus_mildcc_e .. Tot_envben_opt_unsus_mildcc_v=E= sum{t, DF(t) * [(sum(envflow,
Env_Ben_Alb_v(envflow,t,'opt_unsus','mildcc'))) + Env_Ben_out_v(t,'opt_unsus','mildcc')]} ;

Tot_ben_opt_unsus_mildcc_e    .. Tot_ben_opt_unsus_mildcc_v   =E= Tot_mben_opt_unsus_mildcc_v + Tot_agben_opt_unsus_mildcc_v ;

* For optimization and unsustainable management severe cc

Tot_mben_opt_unsus_severecc_e  .. Tot_mben_opt_unsus_severecc_v  =E= sum((muse,   t), DF(t) * Mi_NB_u_v(muse,t,'opt_unsus','severecc')) ;
//scalar benefits for base policy normal inflows

Tot_agben_opt_unsus_severecc_e .. Tot_agben_opt_unsus_severecc_v =E= sum((ause,   t), DF(t) * INCOME_v (ause,t,'opt_unsus','severecc')) ;
```

```
Tot_envben_opt_unsus_severecc_e.. Tot_envben_opt_unsus_severecc_v=E= sum{t, DF(t) * [(sum(envflow,
Env_Ben_Alb_v(envflow,t,'opt_unsus','severecc'))) + Env_Ben_out_v(t,'opt_unsus','severecc')]} ;

Tot_ben_opt_unsus_severecc_e   .. Tot_ben_opt_unsus_severecc_v   =E= Tot_mben_opt_unsus_severecc_v + Tot_agben_opt_unsus_severecc_v ;

* For optimization, sustainable management and mild cc

Tot_mben_opt_sus_mildcc_e   .. Tot_mben_opt_sus_mildcc_v  =E= sum((muse,   t), DF(t) * Mi_NB_u_v(muse,t,'opt_sus','mildcc')) ;  //scalar
benefits for base policy normal inflows

Tot_agben_opt_sus_mildcc_e  .. Tot_agben_opt_sus_mildcc_v =E= sum((ause,   t), DF(t) * INCOME_v (ause,t,'opt_sus','mildcc')) ;

Tot_envben_opt_sus_mildcc_e .. Tot_envben_opt_sus_mildcc_v=E= sum{t, DF(t) * [(sum(envflow,
Env_Ben_Alb_v(envflow,t,'opt_sus','mildcc'))) + Env_Ben_out_v(t,'opt_sus','mildcc')]} ;

Tot_ben_opt_sus_mildcc_e    .. Tot_ben_opt_sus_mildcc_v   =E= Tot_mben_opt_sus_mildcc_v + Tot_agben_opt_sus_mildcc_v ;

* For optimization and sustainable management severe cc

Tot_mben_opt_sus_severecc_e  .. Tot_mben_opt_sus_severecc_v  =E= sum((muse,   t), DF(t) * Mi_NB_u_v(muse,t,'opt_sus','severecc')) ;
//scalar benefits for base policy normal inflows

Tot_agben_opt_sus_severecc_e .. Tot_agben_opt_sus_severecc_v =E= sum((ause,   t), DF(t) * INCOME_v (ause,t,'opt_sus','severecc')) ;

Tot_envben_opt_sus_severecc_e.. Tot_envben_opt_sus_severecc_v=E= sum{t, DF(t) * [(sum(envflow,
Env_Ben_Alb_v(envflow,t,'opt_sus','severecc'))) + Env_Ben_out_v(t,'opt_sus','severecc')]} ;

Tot_ben_opt_sus_severecc_e   .. Tot_ben_opt_sus_severecc_v   =E= Tot_mben_opt_sus_severecc_v + Tot_agben_opt_sus_severecc_v ;

*************************** End of equations ***************************************************************************************

**************** Section 5 *****************************************************
*  The following section defines models.
*  Each model is defined by a set of equations used
*  for which one single variable is optimized (min or max)
********************************************************************************

Model Jucarmodel /ALL/;

**************** Section 6 *****************************************************
*  The following section defines all solves requested,
*  Each solve states a single model for which an optimum is requested.
*
```

```
*  Upper, lower and fixed bounds on certain variables can also be included here
*  Bounding variables here gives that variable a non-zero shadow price where the
*  optimal solution appears at that boundary.  If the bound doesn't constrain the model
*  the variable's shadow price is zero (complementary slackness)
********************************************************************************

* Non-negative flows at nodes below

X_v.lo(inflow, t,p,s) = 0;
X_v.lo(river,  t,p,s) = 0;
X_v.lo(divert, t,p,s) = 0;
X_v.lo(use,    t,p,s) = 0;
X_v.lo(returnc,t,p,s) = 0;
X_v.lo(returnp,t,p,s) = 0;

* Fixed flows to enable unmeasured sources or uses to match observed gauged flow (only for base policy)
X_v.lo('Alarcon_v_f',  tfirst,'base','normal')     = 104.09 - 1;
X_v.up('Alarcon_v_f',  tfirst,'base','normal')     = 104.09 + 1;
X_v.lo('Contreras_v_f',tfirst,'base','normal')     =  66.39 - 1;
X_v.up('Contreras_v_f',tfirst,'base','normal')     =  66.39 + 1;
X_v.lo('Picazo_v_f',   tfirst,'base','normal')     =  96.7  - 1;
X_v.up('Picazo_v_f',   tfirst,'base','normal')     =  96.7  + 1;
X_v.lo('Frailes_v_f',  tfirst,'base','normal')     =  61.72 - 1;
X_v.up('Frailes_v_f',  tfirst,'base','normal')     =  61.72 + 1;
X_v.lo('Alcala_v_f',   tfirst,'base','normal')     =  76.88 - 1;
X_v.up('Alcala_v_f',   tfirst,'base','normal')     =  76.88 + 1;
X_v.lo('Tousup_v_f',   tfirst,'base','normal')     = 464.36 - 1;
X_v.up('Tousup_v_f',   tfirst,'base','normal')     = 464.36 + 1;
X_v.lo('Tousdn_v_f',   tfirst,'base','normal')     = 462.02 - 1;
X_v.up('Tousdn_v_f',   tfirst,'base','normal')     = 462.02 + 1;
X_v.lo('HMullet_v_f',  tfirst,'base','normal')     = 632.16 - 1;
X_v.up('HMullet_v_f',  tfirst,'base','normal')     = 632.16 + 1;

* Fixed diversion to urban demand nodes (only for base policy)
X_v.fx('Albacete_d_f',tfirst,'base','normal') =  15.50;
X_v.fx('Valencia_d_f',tfirst,'base','normal') =  82.00;
X_v.fx('Sagunto_d_f', tfirst,'base','normal') =   5.80;

X_v.fx('Albacete_d_f',t,'base','normal') $ (ord(t) gt 1) =  [15.50/scal ('Albacete_u_f')] * scale('Albacete_u_f',t);   // Includes
population growth
X_v.fx('Valencia_d_f',t,'base','normal') $ (ord(t) gt 1) =  [82.00/scal ('Valencia_u_f')] * scale('Valencia_u_f',t);
X_v.fx('Sagunto_d_f', t,'base','normal') $ (ord(t) gt 1) =  [ 5.80/scal  ('Sagunto_u_f')] * scale('Sagunto_u_f', t);

* Minimum human water needs (for unsustainable and sustainable management policy)
```

```
X_v.lo('Albacete_d_f',tfirst,'opt_unsus',s) =  13.00;
X_v.lo('Valencia_d_f',tfirst,'opt_unsus',s) =  52.00;
X_v.lo('Sagunto_d_f', tfirst,'opt_unsus',s) =   1.00;

X_v.lo('Albacete_d_f',t,'opt_unsus',s) $ (ord(t) gt 1) =  [13.00/scal ('Albacete_u_f')] * scale('Albacete_u_f',t); // Includes population
growth
X_v.lo('Valencia_d_f',t,'opt_unsus',s) $ (ord(t) gt 1) =  [52.00/scal ('Valencia_u_f')] * scale('Valencia_u_f',t);
X_v.lo('Sagunto_d_f', t,'opt_unsus',s) $ (ord(t) gt 1) =  [ 1.00/scal  ('Sagunto_u_f')] * scale('Sagunto_u_f', t);

X_v.lo('Albacete_d_f',tfirst,'opt_sus',s) =  13.00;
X_v.lo('Valencia_d_f',tfirst,'opt_sus',s) =  52.00;
X_v.lo('Sagunto_d_f', tfirst,'opt_sus',s) =   1.00;

X_v.lo('Albacete_d_f',t,'opt_sus',s) $ (ord(t) gt 1) =  [13.00/scal ('Albacete_u_f')] * scale('Albacete_u_f',t); // Includes population
growth
X_v.lo('Valencia_d_f',t,'opt_sus',s) $ (ord(t) gt 1) =  [52.00/scal ('Valencia_u_f')] * scale('Valencia_u_f',t);
X_v.lo('Sagunto_d_f', t,'opt_sus',s) $ (ord(t) gt 1) =  [ 1.00/scal  ('Sagunto_u_f')] * scale('Sagunto_u_f', t);

* Fixed diversion to NCC under all scenarios
X_v.fx('NCC_d_f',     t,p,s) =  14.00;

* Fixed GW pumping in CJT irrigation district under all scenarios
X_v.fx('CJT_p_f',     t,p,'normal'  ) =  1.00 * 56.00;
X_v.fx('CJT_p_f',     t,p,'mildcc'  ) =  0.78 * 56.00;
X_v.fx('CJT_p_f',     t,p,'severecc') =  0.55 * 56.00;

* Fixed unmeasured flows (for all scenarios)
* Negative number indicates unmeasured inflows and positive ones indicate unmeasured use or evaporation
X_v.fx('Picazo_m_f', t,p,s)   =  0.890;
X_v.fx('Frailes_m_f',t,p,s)   =  0.753;
X_v.fx('Alcala_m_f', t,p,s)   =  0.840;
X_v.fx('Alcala1_m_f',t,p,s)   =  0.317;
X_v.fx('HMullet_m_f',t,p,s)   =  0.718;

* Minimum environmental flows are from CHJ (for sustainable management policy)
x_v.lo ('Alarcon_v_f'  ,t,'opt_sus',s) =  63.07;              //minimum environmental flows below Alarcon reservoir 2 m3/s
x_v.lo ('MCT_v_f'      ,t,'opt_sus',s) =  53.61;              //minimum environmental flows below Molinar reservoir 1.7 m3/s
x_v.lo ('Contreras_v_f',t,'opt_sus',s) =  25.23;              //minimum environmental flows below Contreras reservoir 0.8 m3/s
x_v.lo ('Tousup_v_f'   ,t,'opt_sus',s) =  50.46;              //minimum environmental flows above Tous reservoir 1.6 m3/s
x_v.lo ('ARJ_v_f'      ,t,'opt_sus',s) =  56.77;              //minimum environmental flows at Azud de Antella 1.8 m3/s
x_v.lo ('HMullet_v_f'  ,t,'opt_sus',s) = 179.76;              //minimum environmental flows at Huerto Mullet 5.7 m3/s
x_v.lo ('RB_v_f'       ,t,'opt_sus',s) =  63.07;              //minimum environmental flows at Azud de Sueca 2 m3/s
x_v.lo ('Cullera_v_f'  ,t,'opt_sus',s) =  63.07;              //minimum environmental flows at Azud de Cullera 2 m3/s
```

```
* Lower and upper bounds on reservoir stock for technical reasons (for all scenarios)
* For simulation and optimization
Z_v.lo('Alarcon_res_s',  t,  p,s) = 30.00;
Z_v.lo('Contreras_res_s',t,  p,s) = 16.00;
Z_v.lo('Tous_res_s',     t,  p,s) = 18.00;
Z_v.up(res,              t,  p,s) = zmax_p      (res);  // reservoir maximum physical capacity

* Sustainability terminal condition: each water stock (reservoir and aquifer) ends with terminal volume > starting volume
* It avoids depleting stocks in last period
* For sustainable management policy
Z_v.lo    (res,tlast,'opt_sus',s) = 1.00 * z0_p(res);  // reservoir terminal storage volume > 1.0 times starting value
Ht_aq_v.lo(aqf,tlast,'opt_sus',s) = 1.00 * H0_p(aqf);  // Aquifer terminal head > 1.0 times starting value

* first solve starts here
Solve Jucarmodel using nlp maximizing Tot_ben_base_normal_v;
* second solve starts here
Solve Jucarmodel using nlp maximizing Tot_ben_opt_unsus_normal_v;
* third solve starts here
Solve Jucarmodel using nlp maximizing Tot_ben_opt_unsus_mildcc_v;
* fourth solve starts here
Solve Jucarmodel using nlp maximizing Tot_ben_opt_unsus_severecc_v;
* fifth solve starts here
Solve Jucarmodel using nlp maximizing Tot_ben_opt_sus_mildcc_v;
* sixth solve starts here
Solve Jucarmodel using nlp maximizing Tot_ben_opt_sus_severecc_v;

*****   end of solves ********
```