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A Multiregional Input–Output Hydro-Economic Modeling Framework: An Application to the Ebro River Basin

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Sustainable water management is challenging because of the wide range of agents who need water and the different kinds of use, in a context of limited water availability. The availability of water for use, at a given point in time and space, depends on numerous physical and climatic variables, as well as upstream uses and downstream commitments. Therefore, any analysis of water use and management must inevitably be made in the context of such variability. This paper develops an integrated, multiregional, hydro-economic modeling framework to analyze the spatial and temporal dependencies between economic agents in the different regions and areas of a river basin. We combine hydro-economic modeling (partial economic equilibrium) and a multiregional input–output model (general equilibrium) to take advantage of both methodologies. Spatial variability is considered in the input–output models, but variability in both time and space is also considered by the hydro-economic model. Hydro-economic models are used to quantify direct impacts, but not indirect impacts in some specific sectors of the economy, while the input–output model reveals the relationships between all sectors and regions, and facilitates the assessment of total impacts (direct plus indirect) of a range of scenarios. While the methodology described in this paper is applicable to any river basin, the case study considered is the Ebro River Basin, in Spain. To show the potential of the modeling

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framework, two scenarios are simulated to assess the impacts on water use, value added, and jobs across scales. The results of these scenarios show that decreases in water availability have negative impacts on socio-economic variables (value added and employment). The trade-off between water availability and socio-economic variables depends on the temporal and spatial variability of the resource, and affects each location in the basin in a different way, demonstrating the importance of the methodology developed.

Keywords: Hydro-economic model; multiregional input–output; water management; Ebro River Basin; socio-economic impacts.

1. Introduction

Freshwater quality and availability are affected by several variables, some of a geographical and climatic nature, and others of an economic, productive, or social nature. Climate change implies changes in rainfall and temperatures, with diverse consequences worldwide (Hoegh-Guldberg *et al.* 2018) at a time that population growth and changing living standards have adversely affected water quality and availability (United Nations 2015), implying rising demands on water for different economic uses (Duarte *et al.* 2019). Unavoidably, water management will clearly play a key role in any climate change adaptation strategy (Tan and Foo 2018).

Water management is a challenging issue for all societies, given the wide and heterogeneous range of agents who need water and the different kinds of use. The most obvious, consumptive uses (drinking water, irrigation, and so on) compete not only with each other but sometimes also with non-consumptive uses (e.g., hydropower production and cooling for thermoelectric power plants that require water availability at specific locations and times, thereby conditioning other uses). In addition, recreational use, such as fishing, and environmental uses require minimum levels of water quantity and quality at specific points or reaches along a river, again conditioning other consumptive and non-consumptive uses. So, in a context of irregular and limited water supply, the consideration of temporal and spatial variability in the design of modeling tools for water use and management becomes essential. In this sense, hydro-economic models are powerful tools that capture the effects of interactions between hydrological and economic systems, helping to ensure that economic outcomes must involve a consideration of the spatial distribution of water resources (Harou *et al.* 2009).

A number of published hydro-economic models are designed to evaluate water-allocation policies (George *et al.* 2011), while others analyze inter-sectoral strategies, water markets and pricing, and climate change impacts. For example, Pulido-Velázquez *et al.* (2008) developed a monthly basis hydro-economic model to assess the trade-offs between water use and environmental requirements, and López-Díaz (2018) constructed a water–energy–food nexus model to throw light on the conflict between economic and environmental concerns arising from biofuel production in Mexico. Akter *et al.* (2014) proposed a hydro-ecological-economic model to evaluate water policies, taking the Murray–Darling River Basin in Australia as the case study for their analysis. Kahil *et al.* (2015, 2016a) discussed measures to mitigate climate change in arid and semi-arid regions, using an annual-basis model, and Crespo *et al.* (2019) proposed a hydro-economic model to evaluate the trade-off between environmental flows and water consumption. The hydro-economic part of our model is based on that developed in Kahil *et al.* (2015, 2016c), with two significant changes: groundwater is not considered and the time scale is monthly.

Economic relationships in production chains are increasingly complex, implying that changes in production and demand in one geographical area, as well as primary resource constraints, may involve production bottlenecks and adaptations over the whole supply chain, with associated impacts on income and employment. Environmentally extended multiregional input–output (E-MRIO) models are powerful tools to capture the intersectoral economic links and their indirect effects on the socio-economic and environmental variables, and water in particular [see, for instance, Almazán-Gómez *et al.* (2019), Cazcarro *et al.* (2015, 2013), Lenzen and Foran (2001), and Wiedmann (2009)]. However, water variability in time and space is not usually considered in input–output models, a feature that is central to hydro-economic models. Water resources are the focus of many intervention policies that target a specific water-use sector (e.g., irrigated agriculture), causing indirect effects in other sectors (Dinar 2014). Thus, the coupling of socio-economic and water systems has received major attention in recent years, following the rise of socio-hydrology (Sivapalan *et al.* 2014, 2012), and several models have been developed to couple human behavior and water systems, including economic and hydrologic approaches. These include coupled micro-economic and hydrologic models (Essenfelder *et al.* 2018; Pérez-Blanco *et al.* 2021) and coupled macro-economic and water demand analysis (Parrado *et al.* 2020, 2019), including use of the input–output model (Pérez-Blanco *et al.* 2018). However, most of these prior works do not include hydrological modules that comprehensively describe water flows, to represent physical and environmental constraints. It is important to note that hydro-economic models are usually used to quantify direct (but not indirect) impacts, while input–output models reveal the relationships between sectors and regions and facilitate assessment of the total impacts (direct plus indirect impacts) of different scenarios. This paper aims to develop an integrated, multiregional, input–output hydro-economic modeling framework to analyze the spatial and temporal dependencies between economic agents in the different regions of a river basin. While the methodology is applicable to any river basin elsewhere, the case study considered is the Ebro River Basin (ERB) in Spain, one of the most representative of the semi-arid Mediterranean basins (Milano *et al.* 2013). The study provides a framework to distinguish and determine key parameters and productive relationships. The ERB is also strongly representative of environmental pressures at the European level, as it suffers from highly unequal distribution of water resources, ever-increasing demand, and a whole range of serious threats (e.g., the Ebro Delta is one of the most ecologically vulnerable areas in Europe). The ERB supports highly productive agriculture, in which water management experiences have, in general, been very successful.

Figure 1 depicts the main hydrological features of the ERB and irrigated land, which accounts for the lion's share of water demand, as well as reflecting the multiregional nature of the basin. As shown in Figure 1, the Ebro River crosses seven Autonomous Communities of Spain — the regional level at which most water policy decisions are made. These are Cantabria (the river's headwaters), Castile–Leon, the Basque Country, La Rioja, Navarre, Aragon, and Catalonia (where it runs into the Mediterranean). The ERB covers an area of 85,569 km^2, making it the largest river basin in Spain and one of the most important semi-arid

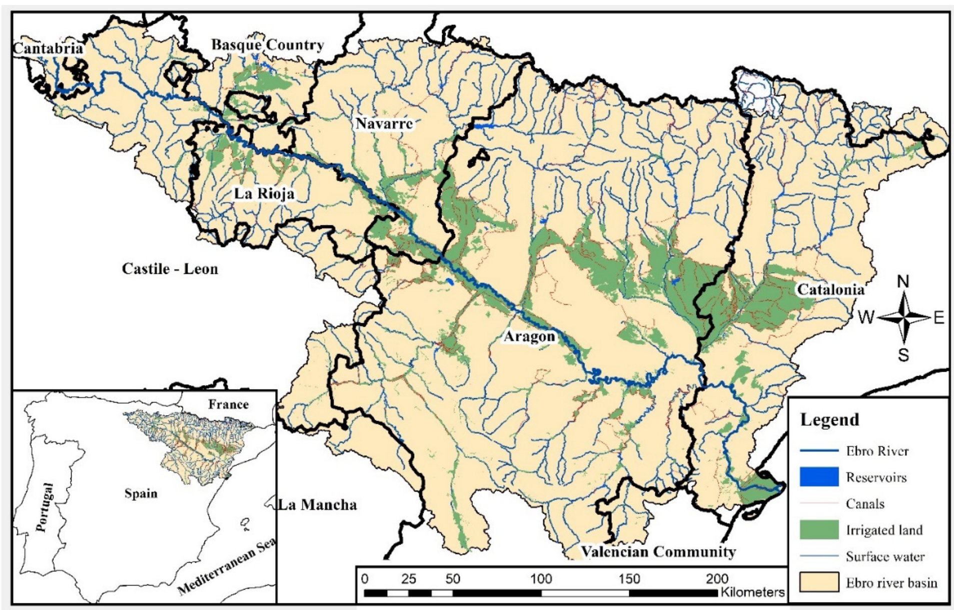

Figure 1. The Ebro River Basin, Northeastern Spain

Source: Made by the authors.
Note: The thick black lines depict regional boundaries. The Basque Country, Navarre, La Rioja, Aragon, and Catalonia are the key regions.

basins in the whole of the Mediterranean region (Milano *et al.* 2013). The river's mean annual discharge into the sea is 9,281 Mm^3, and the ERB's mean annual runoff is 14,500 Mm^3. There are 125 reservoirs in the ERB, with a total storage capacity of 7,833 Mm^3, or 54% of mean annual runoff, along with an extensive network of irrigation canals. The ERB serves some 5,744 km^2 of irrigated farmland, requiring more than 4,500 Mm^3/year of water, compared to a consumption of around 500 Mm^3/year for municipal and industrial uses.

This paper approaches the economic and environmental analysis of the ERB within a multiregional framework, and from a local standpoint, considering the successive and enchained water uses in the river basin. Different economic activities and water flows are considered, allowing for the design of measures to mitigate environmental impacts and foster sustainable regional growth. This enables consideration of various geographic and sector-related factors that have traditionally been studied separately, including the environmental impact of economic activities, sectoral and multiregional dependencies, the role of technological change in production techniques and consumption patterns, and opportunities for local and regional cooperation between different users of water.

Specifically, the modeling framework developed in this paper integrates a broad range of socio-economic data including urban, industrial, and crop water requirements, measured in terms of domestic consumption, industrial output, and monthly consumption per hectare for each crop grown, along with land yields, production costs of each sector, and the like. These socio-economic data are obtained from the multiregional input–output table (MRIOT) developed in Almazán-Gómez *et al.* (2019), and from a municipal-level database created for the ERB (available upon request). This database allows obtaining downscaled results at the municipal level using a methodology similar to those developed in the pioneering works of Cazcarro *et al.* (2016a, 2016b).

By linking hydro-economic and input–output methodologies, we may establish a set of water availability constraints in a multiregional model, based on characteristic monthly flows in the ERB, prior use, and environmental needs. This multisectoral and multiregional hydro-economic modeling framework allows a joint and integrated analysis of both the structure of the economy and that of the actual water flows, considering interconnected uses of the resource. Using this integrated framework, we can then propose measures to maximize concurrently the direct and indirect benefits obtained from the associated water-use activities.

The framework developed here is versatile, allowing the simulation of varying scenarios involving different water availabilities in each area, as well as accounting for changes in environmental requirements, water demand conditions, gains in the efficiency of irrigation, and so on. In this line, to show the potential of the framework to provide geographical and sectorial economic and environmental impacts, two hydrological scenarios that involve reductions in water availability are simulated to observe the changes in water use and the impact on value added and employment at both the regional (Autonomous Community) and municipal levels.

Although the scenarios proposed mainly aim to show the capacity of the framework to address challenging research questions, examining the sustainability of water supply and the impacts of water management, the scenarios represent two potential threats to the ERB related to water availability and water-use constraints. Severe droughts, although relatively unusual in the ERB, have increased in frequency in recent decades and are expected to be more frequent and intense in Mediterranean countries in the near future. To illustrate this issue, the model simulates water inflows during the most recent severe drought affecting the ERB (in the period of 2004–2005). The negative trend of water availability in recent decades in the ERB is shown in Sánchez-Chóliz and Sarasa (2015). Regarding potential restrictions on water uses, some stakeholders have claimed that greater environmental flows have sparked recurrent political and social debates, with implications for constraining the water available for consumption (Almazán-Gómez *et al.* 2018; Almazán-Gómez and Sánchez-Chóliz 2016). This is explored in the second scenario.

The rest of the paper is organized as follows: Section 2 describes the hydro-economic model and its link to the input–output framework. Section 3 contains the results of two scenarios developed to demonstrate the potential of the model. Section 4 discusses the results and presents conclusions.

2. Materials and Methods

2.1. *Building a hydro-economic model for the ERB*

The hydrological schema used (Figure 2) is a node–link network associated with the water flows, in which nodes represent geographical points[1] where the flows join and/or diverge, and links represent the water stream relationships between the nodes. The model is constrained by physical and environmental restrictions, such as the water availability in each head flow, the monthly environmental flow requirements along the river's course, and the reservoir capacity.

To capture the whole basin flows, the schema splits its five Autonomous Communities into 17 areas, which the model identifies as different regions, in order

[1] A detailed explanation of the components used in the water flow scheme and the identification of the model components with reality can be seen in Appendix A.1. Since groundwater is relatively little used in the ERB (CHE 2016), the model considers only surface hydrological components.

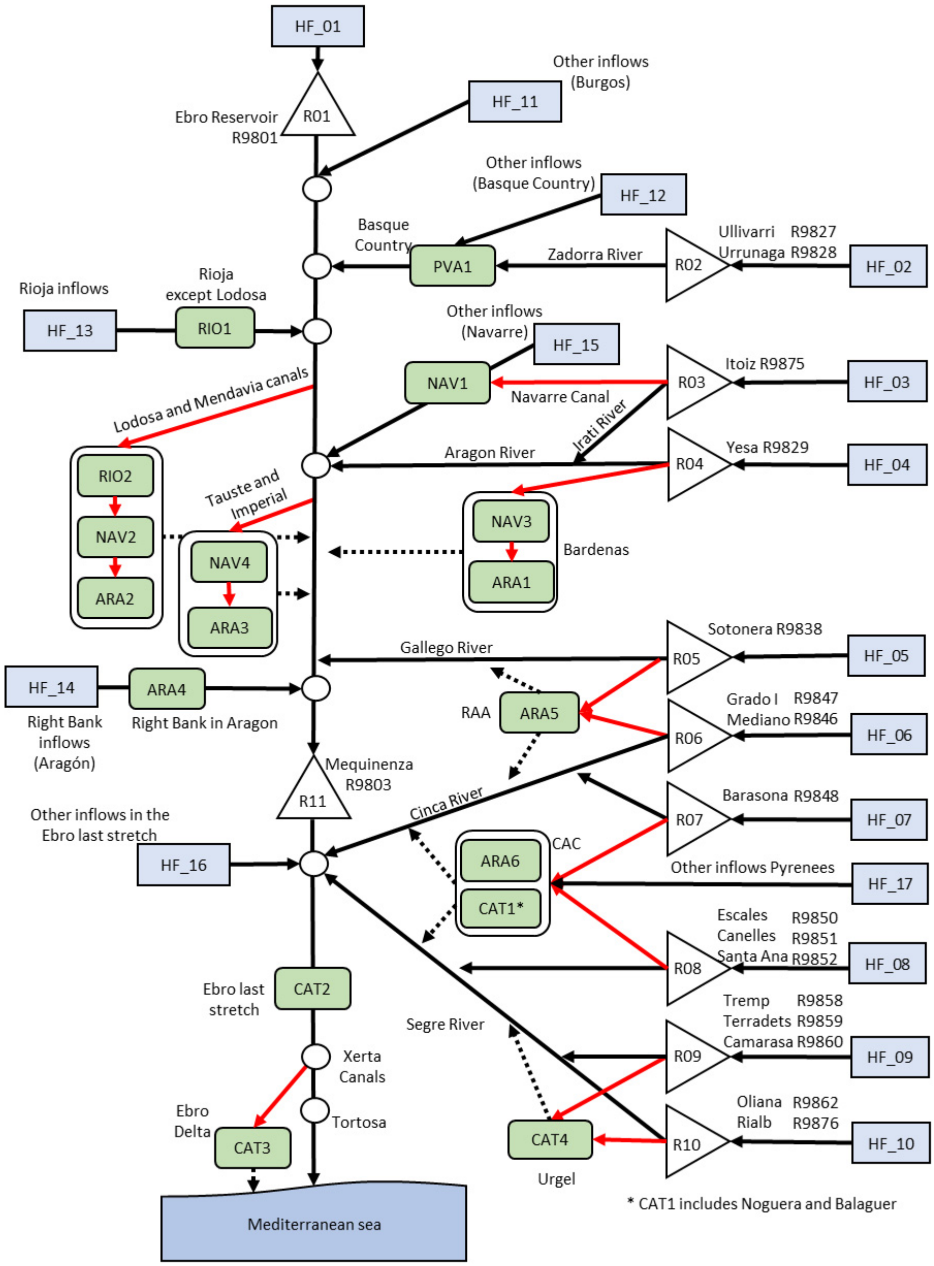

Figure 2. General Outline of the Surface Water Network of the Ebro River Basin (color online)

Notes: The triangles represent reservoirs, while the green rectangles represent areas of water use and the circles are river gauges. The black arrows represent the river's natural course and the red arrows stand for water diversions/canals, while the dotted arrows identify water return flows. These components are discussed in detail in Appendix A.1.

to better capture all flows throughout the whole of the river basin. This is an improvement on a prior work developed for the ERB, which only considered the five administrative Autonomous Regions as economic and water units (Almazán-Gómez *et al.* 2021). The new scheme considers 17 areas sharing common water sources (e.g., tributaries, runoff) and several points of water use. Under this schema, the water flows are more realistic, representing a distinct improvement. The new hydro-economic model allows more and better hypotheses to be made. Also, the results of the partial equilibrium from the hydro-economic model are more concise geographically. Figure 2 depicts the ERB water flows considered in the model schematically, based on the current surface flows.

The model developed to represent water flows and withdrawals is based on monthly flows, in line with Pulido-Velázquez *et al.* (2008), who argue that monthly rather than annual intervals usually provide a better explanation of hydrological variations, as well as reflecting the seasonal behavior of water demand more accurately. Moreover, the environmental requirements are modeled by applying monthly minimum flow restrictions throughout the schema, in line with the monthly minimum flows established for specific sections and points in the ERB, see Annex 5 of CHE (2015a). Thus, water shortages in the ERB are not determined by overall annual availability (Almazán-Gómez *et al.* 2018; Almazán-Gómez and Sánchez-Chóliz 2016), but by the distribution of the available water over the year, and by the capacity of storage infrastructures.

2.1.1. *Water flow equations and environmental and physical constraints*

The schematic hydrological model of the ERB is based on the principles of water mass balance and continuity of river flow (Kahil *et al.* 2016c, 2015), which determine the volume of water available in the different reaches of the river and water stocks held in reservoirs [Eqs. (1)–(4)]. The available water can be used for socio-economic activities, subject to the environmental restrictions established [Eq. (4)].

Specifically, Eq. (1) represents surface flow continuity. Streamflow at each river gauge d in month m is equal to the sum of flows over any upstream node j whose activities impact that streamflow. These nodes include headwater inflow, river gauge, diversion, surface return flow, and reservoir release. The streamflow at each river gauge is required to be non-negative.

Equation (2) represents the available water after use. Water supply to basin's users[2] is met by diversions from a stream. The water-leaving node is equal to the

[2]The users of water in the model are grouped into three categories: urban, industrial, and irrigation. "Urban use" refers to drinking water and sanitation, and "industrial use" encompasses all productive sectors, with the exception of irrigation.

input water when the node has no diversions, or all diversions in that month are zero. However, the water diverted for any use is subtracted at the node where it is used, so that the outgoing water volume represents the difference between inflows and water diverted. Surface water diversion constraints are required to avoid diversion exceeding the available streamflow at each diversion node. In addition, diversions are required to be non-negative.

Equation (3) is the mass balance equation for reservoirs, meaning that the water stock in the reservoirs each month is equal to the previous month's stock plus inflows, less the outflows. Finally, Eq. (4) refers to environmental flows and environmental minimum stocks in reservoirs (see Appendix A.2). These four equations determine the available water for use at the different nodes, given the physical rules and environmental restrictions mentioned in the following:

$$0 \leq w_{\text{in}_{d,m}} = \sum_{j} \beta_{j,d} w_{\text{out}_{j,m}} + \text{HF}_{d,m}, \tag{1}$$

$$w_{\text{out}_{d,m}} = w_{\text{in}_{d,m}} - w_{\text{div}_{d,m}}, \tag{2}$$

$$S_{r,m} = S_{r,m-1} + \sum_{j} \beta_{j,r} w_{\text{out}_{j,m}} - w_{\text{out}_{r,m}}, \tag{3}$$

$$w_{\text{out}_{d,m}} \geq E_{d,m}^{\min} \geq 0, \quad S_{r,m} > E_{r,m}^{\min} \geq 0, \tag{4}$$

where $w_{\text{in}_{d,m}}$ is the water inflow at node d in month m; $w_{\text{out}_{j,m}}$ is the water outflow from node j in month m; $\beta_{j,d}$ is the portion of water from node j reaching node d; and $\text{HF}_{d,m}$ is the runoff entering node d directly in month m (head flows). $w_{\text{div}_{d,m}}$ is the water diverted to supply uses. $S_{r,m}$ is the water stored at reservoir node r in month m. Finally, $E_{d,m}^{\min}$ is the minimum EF established for node d in the month m and $E_{r,m}^{\min}$ is the minimum stock established for reservoir r in the month m.

Water-use and return flow equations

The equations forming the next block [Eqs. (5)–(12)] address the points where water is used, linking water consumption to the socio-economic activities discussed in the next subsection. Equation (5) identifies the amount of water diverted in each river reach, that is the sum of water diverted to supply the different agents considered. Equations (6)–(8) apply to the water diverted strictly for consumption use that each activity needs ($\text{USE}_{d,m}^{xxx}$ nodes) plus the losses in canalization ($\text{LOS}_{d,m}^{xxx}$ nodes), plus the return flows ($\text{RET}_{d,m}^{xxx}$ nodes). Note that the nodes that identify losses and consumption uses imply subtractions of water available in the model, while return flows imply greater diversions and water outcropping in another river reach.

Equation (9) identifies the net irrigation water requirements (evapotranspiration) in each water-use zone, $\text{USE}_{d,m}^{\text{IRR}}$, calculated as the sum of net requirements for each crop $(\text{USE}_{d,m}^{\text{IRR},c})$. These net irrigation water requirements therefore depend on water needs per hectare of each crop c in each water-use zone ($\text{Wr}_{d,m}^{c}$), and the area under each crop in each zone (h_d^c). All of the crops and industries in each zone or area are represented by their own nodes, which individually measure the water used and the return flows. This allows different ratios to be set for each crop between applied water, evapotranspiration, and water return flows, so as to capture different efficiencies in water use by crop.

Equation (10) represents the water used by the various industrial sectors of polygon d in month m ($\text{USE}_{d,m}^{\text{IND}}$), which is the sum of the water used by other industries f in zone d ($\text{USE}_{d,m}^{\text{IND},f}$). This consumption depends on the water needed to produce one unit of output in the industry concerned (Wr_d^f), multiplied by the industry's total output, Q_d^f. Production is assumed to be constant throughout the year, so that the monthly requirement is one-twelfth of the annual requirement. The irrigation water requirements for each crop and their monthly distribution $(\text{Wr}_{d,m}^{c})$ are estimated based on the data provided by Martínez-Cob (2004). The water requirements of other industries (Wr_d^f) are obtained from the WIOD database (Genty *et al.* 2012).

Equation (11) estimates the domestic water consumption. Drinking and sanitation water in each water-use zone is calculated based on a fixed coefficient per capita ($\text{Wr}^{\text{percapita}}$) and the population $(\text{Pop}_{d,m}^{\text{URB}})$. According to the ERB data (CHE 2015b), the per-capita domestic water requirement is set at 319 LPD. Furthermore, 100% efficiency is assumed for main transportation of both domestic and industrial water, together with returns of 80% on applied water (CHE 2015a). Equations (12) and (13) establish return flows on irrigation in each region $(\text{RET}_{d,m}^{\text{IRR}})$ as the sum of return flows on each irrigated crop $(\text{RET}_{d,m}^{\text{IRR},c})$ and return flows from industry $(\text{RET}_{d,m}^{\text{IND}})$ as the sum of return flows from each individual industry $(\text{RET}_{d,m}^{\text{IND},f})$,

$$w_{\text{div}_{d,m}} = \text{DIV}_{d,m}^{\text{IRR}} + \text{DIV}_{d,m}^{\text{IND}} + \text{DIV}_{d,m}^{\text{URB}}, \tag{5}$$

$$\text{DIV}_{d,m}^{\text{IRR}} = \text{LOS}_{d,m}^{\text{IRR}} + \text{USE}_{d,m}^{\text{IRR}} + \text{RET}_{d,m}^{\text{IRR}}, \tag{6}$$

$$\text{DIV}_{d,m}^{\text{IND}} = \text{LOS}_{d,m}^{\text{IND}} + \text{USE}_{d,m}^{\text{IND}} + \text{RET}_{d,m}^{\text{IND}}, \tag{7}$$

$$\text{DIV}_{d,m}^{\text{URB}} = \text{LOS}_{d,m}^{\text{URB}} + \text{USE}_{d,m}^{\text{URB}} + \text{RET}_{d,m}^{\text{URB}}, \tag{8}$$

$$\text{USE}_{d,m}^{\text{IRR}} = \sum_c \text{USE}_{d,m}^{\text{IRR},c} = \sum_c \text{Wr}_{d,m}^{c} * h_d^c, \tag{9}$$

$$\mathrm{USE}_{d,m}^{\mathrm{IND}} = \sum_f \mathrm{USE}_{d,m}^{\mathrm{IND},f}, \quad \mathrm{USE}_{d,m}^{\mathrm{IND},f} = \frac{\mathrm{Wr}_d^f * Q_d^f}{12}, \tag{10}$$

$$\mathrm{USE}_{d,m}^{\mathrm{URB}} = \mathrm{Wr}_{d,m}^{\mathrm{percapita}} * \mathrm{Pop}_{d,m}^{\mathrm{URB}}, \tag{11}$$

$$\mathrm{RET}_{d,m}^{\mathrm{IRR}} = \sum_c \mathrm{RET}_{d,m}^{\mathrm{IRR},c}, \tag{12}$$

$$\mathrm{RET}_{d,m}^{\mathrm{IND}} = \sum_f \mathrm{RET}_{d,m}^{\mathrm{IND},f}. \tag{13}$$

2.1.2. *Behavioral functions for economic activities and objective function*

As explained above, consumption water demand by region is subdivided into three categories in the model, comprising irrigation, other industrial use, and domestic use. For the irrigation cost function, it is assumed that all input requirements per hectare of zone d under each crop c, from each industry i and region $r(\phi_{i,c}^{r,d})$, are constant and can be obtained from the MRIOT of the ERB. Hence, the non-labor cost per hectare (ϕ_c^d) is also constant, as shown in the following equation:

$$\phi_{i,c}^{r,d} = \frac{z_{i,c}^{r,d}}{h_c^d}, \quad \phi_c^d = \frac{\sum_r \sum_i z_{i,c}^{r,d}}{h_c^d}, \tag{14}$$

where $z_{i,c}^{r,d}$ is the annual demand from farmers growing crop c in zone d for the products of industry i located in region r, and h_c^d is the number of hectares planted with crop c in zone d. ϕ_c^d is the annual cost per hectare of crop c in zone d. This information is obtained directly from the MRIOT.

A decreasing irrigation production function is proposed, in line with the usual approach taken in the literature (Crespo *et al.* 2019; Kahil *et al.* 2016c, 2016b), so that average land productivity for each crop and region will decrease when land use for a given crop increases in a given region, while costs per hectare are constant. Linear functions are used for the sake of simplicity [see Eq. (15)], where ψ_c^d is the average productivity per hectare in d and $\beta_1^{c,d}$ (always negative) is the slope capturing decreasing productivity. The profit obtained on each crop grown in each region (π_c^d) can thus be expressed as shown in Eq. (16).

Data from the 2009–2010 hydrological year was used to obtain $\beta_0^{c,d}$ and $\beta_1^{c,d}$ in the calibration of the model, on the assumption that there were no restrictions on the desired water use in that year and that the hectares planted optimized yields,

$$\psi_c^d = \beta_0^{c,d} + \beta_1^{c,d} h_c^d, \tag{15}$$

$$\pi_c^d = (\psi_c^d - \phi_c^d) h_c^d. \tag{16}$$

The objective function of the model is to maximize farm profits on all irrigated crops in the river basin $(\max \sum_d \sum_c \pi_c^d)$, subject to the relationships and constraints mentioned above [Eqs. (1)–(13)]. Note that labor cost is not included in the cost function, so the farm profit calculated is a proxy of value added.

Equation (17) represents the profit of other industries (i.e., all activities except irrigated farming). The profit of each industry (π_f^d) is defined as output minus intermediate inputs, and the relevant data was also obtained from the MRIOT of the ERB,

$$\pi_f^d = Q_f^d - \sum_r \sum_i z_{i,f}^{r,d}, \tag{17}$$

where Q_f^d is the output (in million euros) of industry f in zone d, and $z_{i,f}^{r,d}$ is the annual demand in industry f in zone d for crops or other goods produced by activity i located in region r.

Water withdrawals for domestic use will depend on the population of each region [Eq. (11)], and the population will in turn depend on jobs [Eq. (18)]. A fixed ratio is assumed between employment and population in each water-use zone,[3]

$$\text{Pop}_{d,m} = \alpha_d E_d = \alpha_d \sum_f E_f^d + \alpha_d \sum_c E_c^d. \tag{18}$$

The coefficient α_d is the population/jobs ratio, which is greater than one and differs for each zone d. E_f^d represents the jobs associated with activity f in zone d, while E_c^d represents the jobs associated with crop c. The required level of employment in any industry (except irrigated farming) is proportional to the level of output, in line with the standard assumption for input–output models. In the case of irrigation, it is assumed that the number of jobs will be proportional to the number of hectares under each crop in each region. Hence, both agricultural employment and industrial employment condition the population settled in each region and district.

Due to the characteristics of the equations in this model, the results can be interpreted as an equilibrium only in the irrigated crop production sectors. To know the consequences of this partial equilibrium over the whole economic system, we use the input–output model.

[3]This is a long-run adaptation assumption. Although a certain flexibility can be assumed in the long run, even worse impacts can be expected in the medium term, given the rigidities in water consumption and industrial water demands.

2.2. Input–output model and socio-economic impacts

2.2.1. *Adaptation of the multiregional model to the zone structure*

The MRIO model is adapted to the geographical structure of the river and computes the indirect effects across the economies of the productive changes derived from the hydro-economic model, linking both models through the production variables. Our starting point is an MRIOT that consists of five main regions (Almazán-Gómez *et al.* 2019). However, the information it contains does not fit the water-use zones defined in the hydro-economic model. Therefore, before running the integrated model, it will be necessary to move from a matrix comprising the five key regions of the ERB to one including all 17 water-use zones (or regions) included in the hydro-economic model.

We have constructed an auxiliary matrix that contains the sectoral weightings of the 428 industries included in the MRIOT, for each of the 1,480 municipalities of the Ebro Basin. As the hydro-economic model is split into 17 water-use zones, the municipal weightings are aggregated based on the definition of the zones, in order to obtain 17 vectors, one for each zone, representing the associated sectoral weightings, which we call $\mathbf{s}^r$ (1×428), where the super-index r denotes the zone in question. Three additional vectors were then added to this vector set to represent the rest of Spain, the European Union, and the rest of the world. The water-use zones are described in Appendix A.1.

The matrices $\mathbf{Z}^{rs}$ (428×428), which represent the inter-sectoral trade between zones r and s, were obtained from Eq. (19). These submatrices make up the matrix of intermediate inputs $(\mathbf{Z}^{rs})$ (8560×8560) of the new MRIOT. In Eq. (19), $\mathbf{Z}$ (428×428) is the matrix of intermediate inputs in the Ebro Basin, $\hat{s}^r$ is the diagonal vector of weightings for region r, and $\hat{s}^s$ is the diagonal vector of weightings for region s. A similar method applying the relevant percentages is applied to allocate the needed vectors (output, value added, taxes, employment, etc.) and to obtain the final demand matrix,

$$\hat{s}^r \mathbf{Z} \hat{s}^s = \mathbf{Z}^{rs}, \quad \hat{s}^r \mathbf{Y} = \mathbf{Y}^r. \tag{19}$$

The application of this equation (or distribution method) to the rows and columns of MRIOT for the ERB provides an initial approximation, which assumes that each sector of each zone sells and buys according to its own weighting and to the equivalent ratios for the region as a whole (Basque Country, La Rioja, Navarre, Aragon, and Catalonia).

2.2.2. *Obtaining results at the municipal level*

Water-use zones are utilized in the model to represent groups of municipalities that withdraw water from the same reach of the river. However, the socio-economic impacts simulated can be associated with more specific areas by extending the input–output analysis with municipal data and employing GIS representation techniques.

The SABI database (Bureau Van Dijk 2017) is used here because it contains information on output and other relevant variables at the municipal level for all industries, except in the primary sector, revealing the proportion of output in each region and industry represented by the output of each industry in each municipality. The relevant percentages are estimated for the primary sector using own data, which distinguish between irrigated and rainfed crops and consider the area given over to each crop at the municipal level, as well as yields by region. Data on crop production and livestock are calculated based on the 2009 census data (INE 2011), yields according to MAGRAMA (2011), and prices published by IAEST (2013).

These shares were used to obtain the matrix $\mathbf{M}$ (1480 × 8560), which contains, by columns, the percentage of gross output for each industry in the water-use zone concerned, represented by the output of each industry in the 1,480 municipalities of the ERB. Having obtained the matrix $\mathbf{M}$, Eq. (20) can be used to determine the gross output per industry at the municipal level, $\mathbf{X}_m$ (1480×8560). Meanwhile, Eq. (21) allocates socio-economic or environmental variables at the municipal level,

$$\mathbf{Z}_m = \mathbf{M}(\mathbf{I} - \mathbf{A})^{-1}\hat{\mathbf{y}} = \mathbf{ML}\hat{\mathbf{y}}, \tag{20}$$

$$\mathbf{e}_m = \mathbf{M}\hat{\mathbf{e}}\hat{\mathbf{x}}^{-1}\mathbf{L}\mathbf{y}, \tag{21}$$

where $\hat{\mathbf{y}}$ is the final demand vector (the hat denotes that the vector is diagonalized); $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse; $\mathbf{M}(1480 \times 8560)$ is the municipal allocation matrix; $\mathbf{Z}_m(1480 \times 8560)$ is the matrix that contains the output associated with each industry at the municipal level (subscript m denotes the municipal level); $\mathbf{x}$ is the output vector; $\mathbf{e}$, commonly called the satellite account, is a generic vector containing the socio-economic or environmental data examined (value added, jobs, blue water, etc.); and $\mathbf{e}_m$ is the column vector (1480×1) reflecting the value of the variable at the municipal level.

2.2.3. *Integrated multiregional input–output hydro-economic modeling framework*

Having rendered the multiregional model compatible with the hydro-economic model, it is possible to estimate the impacts of water availability shocks using the integrated model.

The benchmark is an economic general equilibrium depicted by a 2010 MRIOT obtained for the ERB and denoted by $\mathbf{T}_0$, and the hydrological scenario calibrated to the 2009–2010 hydrological year, denoted by HEM_0. $\mathbf{T}_0$ is defined by a matrix of technical coefficients $\mathbf{A}_0$, an output vector $\mathbf{x}_0$, a value-added coefficient vector $\mathbf{v}_0$, and one vector of final demand $\mathbf{y}_0$ that is the final demand matrix aggregated. These variables verify the fundamental relationships of any MRIOT [Eq. (22)] and are compatible with the results of the optimization collected by HEM_0,

$$\begin{gathered}\mathbf{x}_0 = \mathbf{A}_0\mathbf{x}_0 + \mathbf{y}_0 \leftrightarrow \mathbf{x}_0 = (\mathbf{I} - \mathbf{A}_0)^{-1}\mathbf{y}_0, \\ (1, 1, \ldots, 1)\mathbf{v}_0\hat{\mathbf{x}}_0 = \mathbf{y}_0(1, 1, \ldots, 1)'.\end{gathered} \tag{22}$$

Any change in water availability is evaluated in the hydro-economic model, providing new values of water consumption, output, value added, and intermediate inputs used for irrigation; this new economic partial equilibrium is HEM_1. Then, using the following equations, it is possible to obtain the new economic general equilibrium associated with a new MRIOT_1. See Figure 3 for a brief scheme of this process.

Thus, after a simulated shock, the new matrix of technical coefficients $\mathbf{A}_1$ is obtained using Eqs. (23) and (24). The irrigation requirements in terms of intermediate input are assumed to be constant per hectare, and will therefore vary depending on changes in the number of hectares under each crop in each water-use zone [Eq. (23)]. In the case of other industries [Eq. (24)], we assume that the technical coefficients do not change and nor does the (Leontief) production function,

$$a_{i,j,1}^{r,s} = a_{i,j,0}^{r,s} \frac{x_{j,0}^s}{x_{j,1}^s} \frac{h_{j,1}^s}{h_{j,0}^s}, \quad \forall j \in \{\text{irrigation crops}\}, \tag{23}$$

$$a_{i,j,1}^{r,s} = a_{i,j,0}^{r,s}, \quad \forall j \notin \{\text{irrigation crops}\}. \tag{24}$$

Once $\mathbf{A}_1$ is known, we also know the new vector $\mathbf{v}_1$, which changes only in the field of irrigation, so a new balance can be obtained defined by the already known

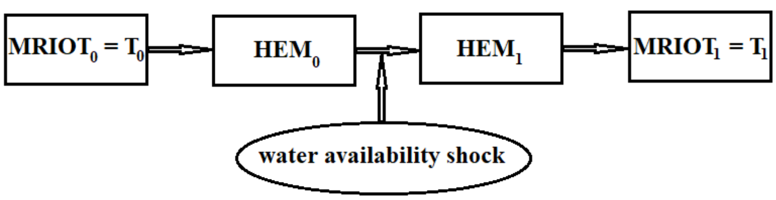

Figure 3. Scheme of the Process

$\mathbf{A}_1$ and $\mathbf{v}_1$ values, and by the other required vectors $\mathbf{x}_1$ and $\mathbf{y}_1$[4] Taken together, these vectors will define the equilibrium of a new multiregional model $\mathbf{T}_1$, which must verify the following basic relationships:

$$\begin{gathered}\mathbf{x}_1 = \mathbf{A}_1\mathbf{x}_1 + \mathbf{y}_1 \leftrightarrow \mathbf{x}_1 = (\mathbf{I} - \mathbf{A}_1)^{-1}\mathbf{y}_1, \\ (1, 1, \ldots, 1)\mathbf{v}_1\hat{\mathbf{x}}_1 = \mathbf{y}_1(1, 1, \ldots, 1)'.\end{gathered} \tag{25}$$

To obtain the values of the final equilibrium [Eq. (25)], we represent the economy in the form of two blocks — irrigation and other sectors — [Eqs. (26) and (27)], where the irrigation block is denoted by subscript c (crops) and other industries by subscript n,

$$\mathbf{x}_c = \mathbf{A}_{c,c}\mathbf{x}_c + \mathbf{A}_{c,n}\mathbf{x}_n + \mathbf{y}_c, \tag{26}$$

$$\mathbf{x}_n = \mathbf{A}_{n,c}\mathbf{x}_n + \mathbf{A}_{n,n}\mathbf{x}_n + \mathbf{y}_n \leftrightarrow \mathbf{x}_n = (\mathbf{I} - \mathbf{A}_{n,n})^{-1}(\mathbf{A}_{n,c}\mathbf{x}_c + \mathbf{y}_n). \tag{27}$$

For simplicity, let us now assume that the changes in the irrigators' final demand are proportional to the pre-shock final demand observed (though more complex options are possible).[5] Therefore, $\mathbf{y}_n$ is the final demand vector adjusted by the changes in the irrigators' income. Moreover, as in any simulation, the hydro-economic part of the model provides the output of the irrigation sector $\mathbf{x}_c$. Equation (27) can be applied to calculate the output of this scenario for all non-irrigated activities ($\mathbf{x}_n$) and consequently the impacts on value added, employment, and water consumption. Then, the equilibrium defined by Eqs. (26) and (27), that is the final equilibrium defined by Eq. (25), is fully determined.

Note that the shocks to water availability have two main drivers that affect not only the irrigation sector, but also the rest of the economy. They are the changes in final demand due to the changes in the irrigators' income and the change in the intermediate inputs required by the irrigators, that, in turn, have two components, changes in the production function that imply changes in the technical coefficients (matrix $\mathbf{A}$), and changes in the irrigators' output. This can be better seen in Eqs. (28) and (29), where $\Delta\mathbf{x}$ has two components, $(\mathbf{I} - \mathbf{A}_0)^{-1}\Delta\mathbf{y}$, which

[4] In this work, the HEM is calibrated using socio-economic data from the IO model. Then, the HEM determines the components of MRIO. So, in this paper, the coupling is unidirectional. However, the framework developed reveals mutual influences between both parts of the integrated framework, i.e., if any exogenous change appears in the irrigated crop production sectors in the IO model, this affects the calibration of the HEM.

[5] We assume this hypothesis about the change in final demand for the sake of simplicity, although it is the key to linking the input–output model and the hydro-economic model. Other alternatives are possible, e.g., estimating the changes in final demands through the income elasticities of farmers, but (26) and (27) are the right equations in any case.

captures the impact via final demand, and $(\mathbf{I}-\mathbf{A}_0)^{-1}\Delta\mathbf{A}\mathbf{x}_1$, which measures the impact due to the change in intermediate inputs,

$$\mathbf{x}_1 = \mathbf{A}_0\mathbf{x}_1 + \Delta\mathbf{A}\mathbf{x}_1 + \mathbf{y}_1 \leftrightarrow \mathbf{x}_1 = (\mathbf{I}-\mathbf{A}_0)^{-1}(\Delta\mathbf{A}\mathbf{x}_1 + \mathbf{y}_1), \tag{28}$$

$$\begin{aligned}\Delta\mathbf{x} = \mathbf{x}_1 - \mathbf{x}_0 &= (\mathbf{I}-\mathbf{A}_0)^{-1}(\Delta\mathbf{A}\mathbf{x}_1 + \mathbf{y}_1) - (\mathbf{I}-\mathbf{A}_0)^{-1}\mathbf{y}_0 \\ &= (\mathbf{I}-\mathbf{A}_0)^{-1}(\Delta\mathbf{A}\mathbf{x}_1 + \Delta\mathbf{y}). \end{aligned}\tag{29}$$

3. Results

Three scenarios have been simulated to show the potential of the developed modeling framework combining hydro-economic and input–output models. In the first scenario (S1), the benchmark, the inflows of water into the basin are set at a level equal to the median monthly inflows for each head flow, based on the monthly observations from October 1980 to September 2013. This median hydrological year results in an annual inflow of 11,495 Mm^3. The monthly inflows are presented in Table 1. Meanwhile, the environmental flows for the whole basin are set at 25% of the sum of median upstream inflows, which almost equal the actual Ebro Delta's environmental flows, set by the ERB Authority, of 3,016 Mm^3. Environmental flows for most river reaches in the ERB are not set (CHE 2014) (or they cannot be perfectly identified in our scheme), so, in terms of environmental flows, the model sets 25% of upstream inflows in every river reach, treating all reaches the same as the delta. This scenario is considered representative of the observed conditions in recent years.

In S1, maximizing the value added of irrigated agriculture through the hydro-economic model leads to exactly the levels of production, value added, and employment reflected in the input–output table, because the theoretical distribution and availability of water over the hydrological year and the environmental flows required under this scenario are compatible with the observed uses, which are the same as in S1, shown in Table 2.

In the second scenario (S2), we examine the effects of an increase in environmental flows at all points to 50% of the natural flow in a median hydrological year.[6] Since the median annual inflow is 11,495 Mm^3 (Table 1), the volume required at the Ebro Delta in this scenario is 5,747 Mm^3, leaving another 5,747 Mm^3 available for consumption, which is 1,517 Mm^3 higher than the 4,230 Mm^3 of consumption found in the base scenario (see Table 2).

[6]Here, 50% is arbitrarily chosen, but is in line with a proposal of some ERB stakeholders demanding greater environmental flows. In CSTE (2015), three different proposals for the Ebro Delta's environmental flow are presented that claim between 5,877 Mm^3 and 9,920 Mm^3.

Table 1. Water Inflows in S1 (Mm^3)

Inflow Node	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
HF_01	5.1	8.1	20.9	36.7	40.2	28.4	33.4	35.6	49.3	48.4	14	8.4	328.4
HF_02	20.5	23.2	44.7	41.4	30.3	29.3	35.6	36.8	19.4	12.8	7.7	7.3	309
HF_03	1.2	18.9	48.6	62.8	51	74.2	95.1	47.8	35.4	50.3	17.6	5.3	508.2
HF_04	36.3	66.8	109.4	112.1	90.8	111	134.5	157.3	131	81.3	22.7	15.5	1,068.8
HF_05	5.7	15.3	28.9	25.4	20.5	31.1	42.2	32.3	50.4	33.1	14.5	12.7	312
HF_06	66.7	110.5	97	67.4	55.9	70	92.2	168.1	184.5	161	71.1	42.4	1,186.8
HF_07	35.9	51.6	39.3	30.9	23.5	55	53.3	80.5	99.5	65.3	30.9	16.9	582.6
HF_08	22	30.8	41	32.8	25.6	43.6	45.2	64.1	99.4	90.8	40.5	13.8	549.5
HF_09	22.1	54.3	84.5	55.9	47.1	49.4	87.3	130.2	214.6	124.1	42.4	36.8	948.5
HF_10	56.9	35	40	63.6	47.7	52.7	35.2	95.4	91.6	22.4	44.5	44.8	629.7
HF_11	7.6	54.9	70.3	184.8	120.2	55.3	27.1	53.6	69.2	−18.6	−10.8	−3.7	609.9
HF_12	1.5	31.8	20.4	106.5	79.2	−14	6.7	32.5	40.2	8.9	4.9	1.7	320.3
HF_13	14.8	41.3	90.7	279.6	87.1	67.3	46.4	30.4	101.2	78.3	54	38.9	930.1
HF_14	27.5	27.2	35.4	54.9	56.1	82.4	83.3	94.8	78.3	80.8	68.2	46.8	735.6
HF_15	2.5	140.1	135	227.8	163.5	45.1	47.1	136.9	60.7	22.3	−13.4	−20.1	947.7
HF_16	39.9	40.1	74.7	67.1	42.5	79.7	93.2	142.9	182.7	85.5	36.4	31.6	916.3
HF_17	90.5	75.7	74.9	66.3	79.2	113	44.3	32.8	−13	1.1	13.2	33.5	611.3
Total	456.9	825.5	1,055.7	1,515.9	1,060.4	973.4	1,001.9	1,372	1,494.5	947.6	458.3	332.6	11,494.8

Table 2. Consumed Water in S1 (Mm^3)

Demand Node	Domestic	Industrial	Irrigation	Total
ARA1	0.7	22.5	314	337.3
ARA2	0.1	3.3	13.3	16.6
ARA3	21	138.3	158.7	318
ARA4	3.6	71.6	236.6	311.8
ARA5	4.3	61.5	646.4	712.1
ARA6	1.4	39.4	360.5	401.3
CAT1	7.1	76	287.3	370.4
CAT2	0.5	9.2	79.9	89.5
CAT3	2.7	40.4	380.3	423.4
CAT4	4.9	119	344.8	468.7
NAV1	12.2	82.9	60.9	156
NAV2	1.4	11.6	111.5	124.4
NAV3	0.5	9.3	87.5	97.4
NAV4	0.3	4.7	35	39.9
PVA1	7.2	101.5	27.1	135.8
RIO1	5.8	55.1	82.2	143.1
RIO2	1.7	13.8	67.5	83.1
Total	75.2	860.3	3,293.5	4,229

The third scenario (S3) refers to the 2004–2005 hydrological year, a drought year in which farms suffered severely. The water inflows in this scenario are those observed in the 2004–2005 hydrological year. The monthly distribution of the head flows used in S3 results in a total annual inflow of 8,981 Mm^3, 21.9% less than the annual median hydrological year. In this scenario, we maintain the environmental flow requirement established in S1. The concrete head flow distribution by months can be seen in Appendix A.

Table 3 shows the results of scenario 2 compared with the baseline scenario (S1) at the regional level. As can be seen, consumption falls by 341 Mm^3 to 3,888 Mm^3 in this scenario (S2). Table 3 also shows that the increase in environmental flows imposes a restriction on consumption, which would imply the loss of more than 6,600 jobs and of value added worth almost €250 million in the global economy. Looking only at the ERB, the impact is over €190 million in terms of value added and involves the loss of more than 4,500 jobs. These losses are concentrated in Aragon and Catalonia. In percentage terms, Aragon suffers the greatest impact, losing slightly under 0.5% of value added and over 0.5% of jobs, compared to other regions such as the Basque Country and Navarra, which still lose, but significantly less in relative terms. This is mainly due to the exposure of each region to irrigation (irrigated farming in relation to the total economy) and to

Table 3. Changes Compared to S1 in Value Added (VA) and Employment (EMP) in S2 at Regional Level

	All Sectors				Irrigated Farming					
	VA ($\times 10^3$ EUR)	EMP (Jobs)	VA (%)	EMP (%)	VA ($\times 10^3$ EUR)	EMP (Jobs)	VA (%)	EMP (%)	Water Use (Mm^3)	Water Use (%)
Aragon	−140, 399	−3, 179	−0.438	−0.549	−78, 960	−2, 015	−12.85	−12.85	−297	−14.16
Catalonia	−33, 685	−1, 136	−0.225	−0.355	−15, 462	−746	−2.57	−2.57	−27	−2
Navarre	−2, 409	−43	−0.015	−0.016	−465	−11	−0.18	−0.18	−1	−0.30
Basque Country	−1, 117	−21	−0.012	−0.012	0	0	0	0	0	0
La Rioja	−13, 879	−252	−0.185	−0.183	−6, 816	−130	−3.20	−3.20	−16	−6.88
Total ERB	−191, 489	−4, 631	−0.238	−0.311	−101, 703	−2, 901	−5.95	−5.22	−341	−8.06
RSP	−21, 150	−410	−0.002	−0.002						
REU	−15, 684	−324	0	0						
ROW	−14, 552	−1, 277	0	0						
TOTAL	−242, 875	−6, 642	0	0						

Note: Data in thousands of euros, jobs, and percentage. RSP: Rest of Spain, REU: Rest of European Union, and ROW: Rest of the World.

Table 4. Changes in Value Added (VA) and Employment (EMP) in S3 at Regional Level

	All Sectors				Irrigation					
	VA ($\times 10^3$ EUR)	EMP (Jobs)	VA (%)	EMP (%)	VA ($\times 10^3$ EUR)	EMP (Jobs)	VA (%)	EMP (%)	Water use (Mm^3)	Water use (%)
Aragon	−326,846	−7,419	−1.019	−1.282	−186,544	−4,760	−30.36	−30.36	−688	−32.80%
Catalonia	−144,408	−5,049	−0.966	−1.576	−73,082	−3,525	−12.15	−12.15	−121	−8.96
Navarre	−7,301	−136	−0.044	−0.049	−2,313	−52	−0.91	−0.91	−6	−1.45
Basque Country	−2,422	−46	−0.026	−0.026	0	0	0	0	0	0
La Rioja	−18,538	−334	−0.247	−0.243	−8,573	−163	−4.03	−4.03	−20	−8.65
Total ERB	−499,515	−12,983	−0.621	−0.873	−270,513	−8,501	−15.81	−15.29	−835	−19.74%
RSP	−52,141	−1,006	−0.006	−0.006						
REU	−42,556	−886	0	0						
ROW	−41,182	−3,707	0	0						
TOTAL	−635,394	−18,583								

the continual increases in minimum flows required at each control point along the river.

The impact on irrigated farming is shown on the right-hand side of Table 3. As can be seen, this effect is much larger in percentage terms, and Aragon stands out, losing value added worth almost €80 million and more than 2,000 jobs. The result is an overall contraction of more than 10% in this sector. The second most-affected region in absolute terms is Catalonia, which loses more than €15 million in value added and almost 750 jobs, representing a 2.5% contraction in its irrigated farming sector. Meanwhile, La Rioja loses farm value added of almost €7 million and 130 jobs, a loss that is worse than Catalonia's in percentage terms. Finally, irrigated farming in Navarre suffers relatively little and the Basque Country comes off entirely unscathed because it has no irrigated farm sector. So, the central areas of the basin, with a greater agrarian weight (although to a large extent with low value added), endure the greatest impacts.

The last two columns of Table 3 show the impact on water consumption in each region in this scenario. Once again, Aragon suffers by far the largest impact with a reduction of nearly 300 Mm^3 in the water used in irrigation, which represents almost 15% of the region's total water use, while irrigation water use in Catalonia drops by only 27 Mm^3 or 2% of its total water use. Finally, irrigation water use in La Rioja shrinks by almost 7%, although this is only 16 Mm^3 in absolute terms.

These results at the regional level, although illustrative of the general dependencies, may understate the specific local impacts of scenarios and policy interventions. To prevent this, in Section 2.2.2 a strategy was developed to estimate effects at the municipal level. Given the significant geographic component of such local effects, they are shown graphically to better reflect the areas impacted.

Figure 4 shows the percentage value added lost at the municipal level in this scenario compared to the benchmark (S1), in which value added and employment are based on actual observations for 2010. As can be observed, the reduction in available water caused by the increase in environmental flows would significantly affect the economy in all of the municipalities belonging to the Riegos del Alto Aragón (RAA), Canal de Aragón y Catalunya, and Jalón-Jiloca irrigation schemes in Aragon, and those of the Najerilla scheme in La Rioja, all areas where the primary sector and specifically irrigated farming are the primary drivers of the local economy. Compared with the 0.44% drop in value added found in Aragon as a whole, Figure 4 shows that local losses are almost 30% in those rural municipalities with a largely agrarian economy. Job losses in S2, compared to the baseline scenario, can be seen in Appendix A. The municipalities with the largest job losses overlap those suffering the sharpest falls in value added, and even by the percentages.

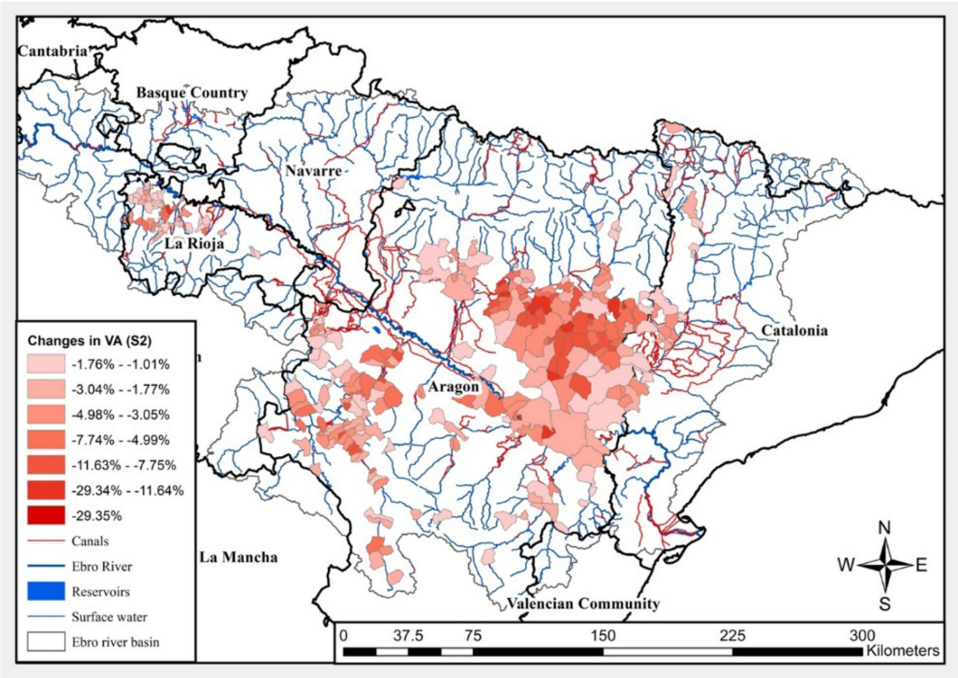

Figure 4. Changes in Value Added in S2 (All Sectors)

Note: Values of less than 1% are omitted.

Having established the overall economic impact at the municipal level (considering all sectors), we now consider how this scenario would impact the irrigation in each municipality. Figure 5 shows the percentage fall in value added from irrigated farming that would occur in a median flow year if 50% of upstream flows were earmarked as environmental (S2). This scenario would slash the value added generated by irrigation by up to 60%. The worst-affected areas would be the irrigation schemes mentioned above.

For simplicity, this discussion will focus on the aggregate value added and employment losses in irrigated farming. However, the model offers results for each municipality and activity, which could be used to calculate the distribution of individual impacts on each crop or activity.

Aside from socio-economic impacts, Figure 5 shows the areas where the pressure on water resources is greatest and water management options would not be sufficient to meet the demand in the baseline water-use scenario constructed using observations for 2009–2010. Figure 5 thus reveals which areas would be forced to cut their production of irrigated crops, and by how much. As can be seen, pressure on water resources is higher than in the rest of the Ebro Basin in the whole

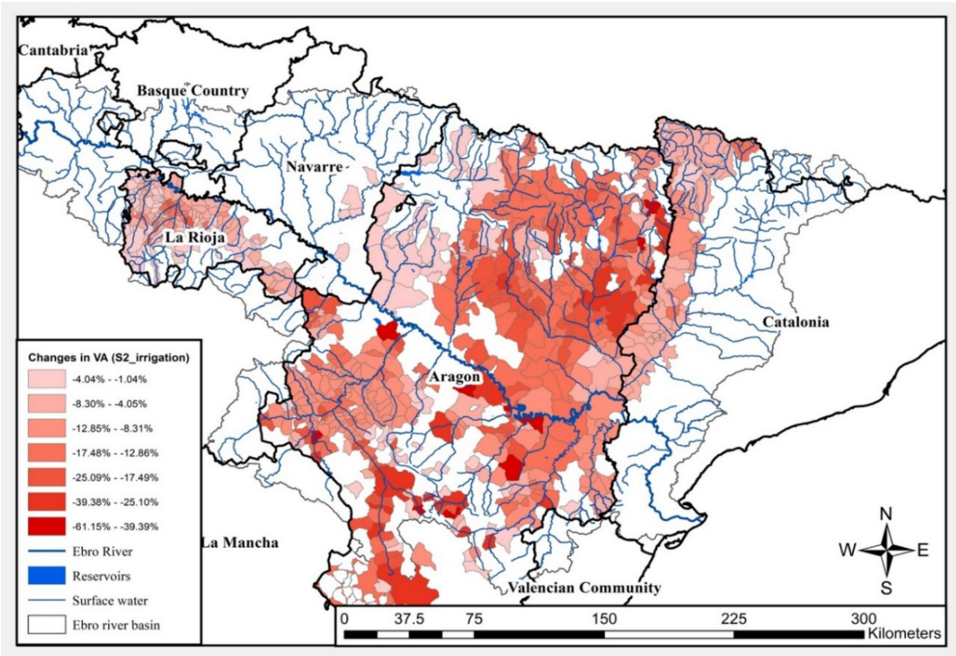

Figure 5. Changes in Value Added from Irrigated Farming in S2

Note: Values of less than 1% are omitted.

of Aragon, with the exception of the Bardenas District. Likewise, the Catalan municipalities associated with the Canal de Aragón y Catalunya and the municipalities of La Rioja supplied with water from canals associated with the Najerilla River would also suffer sharp falls in the value added by irrigation as a consequence of shrinking production in response to resource pressure. Meanwhile, the Basque Country, Navarre, and Easternmost Catalonia could continue with the consumption observed in 2010 under the conditions set forth in this scenario, and it is safe to say that resource pressure is less in these areas. Consumption at the level of water-use zones and the differences with the scenario S1 can be seen in Appendix A. This reveals that the water-use zones that would suffer the most from the imposition of an ERB-wide 50% environmental flow requirement, as simulated in this scenario, would be ARA4, ARA5, ARA6, CAT1, and RIO1.

The results of scenario 3, aggregated by Autonomous Community, are shown in Table 4. The first four columns of this table reflect the impact on the total economy of each region. The conditions set for this scenario would cause a fall of almost €500 million in added value and the loss of 13,000 jobs in the Ebro Basin. This impact would be concentrated in Aragon and Catalonia. Once again, however, impacts at the general level are not representative of the hits taken by the different sectors of the economy on an individual basis. Columns 5–8 show the fall in value added produced by irrigated farming, revealing much larger impacts in relative terms in Aragon (30%) and Catalonia (12%). The overall reduction in water use totals 835 Mm^3, mainly concentrated in Aragon.

The consumption of water in each of the water-use zones and differences between the uses in S3 and the observed uses in 2010 included in the benchmark scenario (S1) can be seen in Appendix A. This reveals the areas most affected, in the first instance, by the conditions of scenario 3. Water use is lower than in S1 in ARA1 and NAV3 (Bardenas), ARA4 (right bank), ARA5 (Riegos del Alto Aragón), ARA6 and CAT1 (Canal de Aragón y Catalunya), and RIO1 (La Rioja), clearly due to reduced availability. The results of this scenario show a steep fall in water use in percentage terms in the Aragonese right bank (ARA4) and in the water-use zone identified with the Riegos del Alto Aragón irrigation scheme and the Canal de Aragón y Catalunya (CAT1). In these areas, the pressure on the available water is greater than in the rest of the basin.

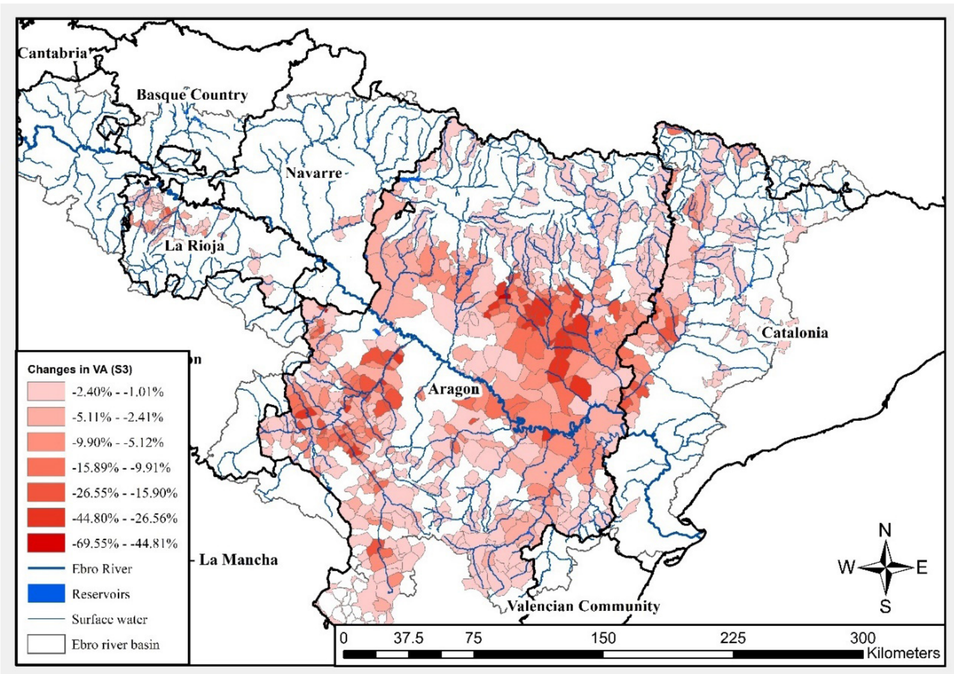

Figure 6. Changes in Value Added in S3 (All Sectors)

Note: Values of less than 1% are omitted.

We now focus on the spatial distribution of the losses in value added represented in Figure 6, which outlines the impact of scenario S3 on the overall economy in each municipality. By assuming the levels of water availability for 2005, this scenario reveals the variations in value added and employment affecting the Aragonese municipalities situated on the right bank of the Ebro River, along the banks of the Jalón-Jiloca and Guadalope Rivers, and in the Riegos del Alto Aragón irrigation scheme. The economies of these municipalities are markedly agrarian, and the drought conditions assumed in scenario 3 could entail losses of up to 50% in value added and/or employment (in Appendix A). We also see sharp falls in value added and jobs in some municipalities in the northeast of Aragón and Catalonia (served by the Canal de Aragón y Catalunya). Meanwhile, value added and jobs are also affected in some municipalities in the northwest of La Rioja, although less severely. However, these conditions have little or no effect on municipal economies in Navarre and the Basque Country.

4. Discussion and Conclusions

The objective of this paper has been to integrate the temporal and spatial characteristics of water flows throughout an entire river basin as a water-planning unit, combining water-flow modeling with a multiregional input–output framework to obtain a multiregional and multisectoral hydro-economic model. The tool developed in this paper allows an assessment of the impact of different water availabilities and policy intervention scenarios, based on socio-economic variables, across various geographical levels.

The hydrological scheme used for the empirical analysis is a simplification of the surface water flows in the Ebro Basin. It offers a significant level of detail, although it is, of course, conditioned by the available data. This hydrological part of the general model is based on the principles of water mass balance and continuity of river flow, which determine the volumes of available water at each river reach. The hydro-economic model described stands out from others of its kind in that it combines and integrates monthly hydrological data with the socio-economic data obtained from the multiregional and multisectoral input–output framework, as well as the available municipal-level information.

The hydrological part of the model considers monthly flows and monthly water demands. The economic aspect of the model is based on annual equations, while the partial equilibrium is obtained by maximizing the annual farm profits on all irrigated crops in the river basin. So, in this regard, the model should be classified as static.

This work reveals how different water availability scenarios impact value added and employment, allowing analysis not only at the regional but also at the municipal level. The paper demonstrates the potential of the developed model by simulating two water availability scenarios and calculating the impact on water use, value added, and employment at the municipal level and by industry. These findings are presented graphically using GIS techniques. The results of these two scenarios demonstrate the existence of a quantifiable trade-off between the availability of water for consumption and added value/jobs, in line with Almazán-Gómez *et al.* (2019). However, this trade-off depends on the temporal and spatial variability of the resource, and affects each of the municipalities in the basin in a different way.

Our results can be benchmarked against estimates from previous studies of the socio-economic impact of the 2005 drought in the ERB, as shown in Table 5. However, it is important to note that the methodological approaches used in these studies are different, and therefore, direct comparison of results is not straightforward. Note that our model assumes direct impacts only in the irrigation systems. Note also that Pérez y Pérez and Barreiro-Hurlé (2009) include the whole Autonomous Community of Catalonia in their approach of the ERB, meanwhile we consider only the municipalities included in the ERB. This fact could explain the higher estimates of value added. In terms of employment, they report smaller losses in indirect impacts, that could be attributable to the methodology; note that we use a multiregional input–output framework that captures spillover effects within and between regions, and they use an aggregated input–output table. Despite the differences between our study and those in Table 5, our estimates are broadly consistent with previous estimates. For instance, according to Hernández-Mora *et al.* (2013), the most affected areas are the provinces of Huesca and Lleida; this coincides with the most affected areas in scenario S3 of our study.

The results also show that irrigation in the Basque Country and Navarra does not exert significant pressure on water availability in these regions, based on the observed data for 2010. However, the opposite is the case in some irrigation schemes in Aragon, in the same scenario.

The model is versatile, allowing the simulation of various water availability scenarios and imposing a range of restrictions to simulate different policies (e.g., setting lower bounds for certain crop outputs for food security reasons, or upper bounds to prevent overproduction). The methodological approach presented can be extended to other river basins in the world, particularly transboundary basins spanning multiple countries that compete for scarce water resources, opening the door to a more complex integrated analysis.

Our work can be understood as a first step in this direction. Nevertheless, our model is affected by different sources of uncertainty. First, the model does not take into account groundwater flows and/or uses, or the smaller reservoirs in the basin.

Table 5. Socio-Economic Impacts of the 2005 Drought Evaluated in Other Works

		Pérez y Pérez and Barreiro-Hurlé (2009)	Hernández-Mora *et al.* (2013)	Scenario (S3) in this Study
Value added	Total impact attributable to agricultural sector	716.54 ($\times 10^6$ EUR)		499.52 ($\times 10^6$ EUR)
	Direct impact on the agricultural sector	405 ($\times 10^6$ EUR)	337.01 ($\times 10^6$ EUR)	270.51 ($\times 10^6$ EUR) — irrigation
	Indirect impact attributable to agricultural sector	311.54 ($\times 10^6$ EUR)	262.90 ($\times 10^6$ EUR)	229.01 ($\times 10^6$ EUR)
Jobs	Total impact attributable to agricultural sector	10,532 (jobs)	—	12,983 (jobs)
	Direct impact on the agricultural sector	8,052 (jobs)	—	8,501 (jobs) — irrigation
	Indirect impact attributable to agricultural sector	2,480 (jobs)	—	4,482 (jobs)

(This is a weakness that will be addressed in the future.) Second, we assume that production technologies (shares of the physical inputs used) of each product are the same in $\mathbf{T}_0$ and $\mathbf{T}_1$, i.e., under the different water regimes. However, water scarcity or water constraints drive changes in cultivation techniques and input substitution, increasing productivity at the same time. This has not been considered in this paper. A better consideration of technological change and its global impact in a context of water limitation is a clear, further extension of this analysis. Third, although both the HEM and the IO model influence each other, the coupling is unidirectional. The results obtained from the hydro-economic part of the model determine a partial equilibrium and set the basis for the changes in the global economy measured in the input–output part of the model. However, in this work, the results from the input–output part of the model do not influence the hydro-economic part. This is a future research line that can be addressed using the frameworks depicted in Parrado *et al.* (2020, 2019), where micro–macro-economic two-way feedback models are presented. However, these works do not include hydrological modules to accurately represent physical constraints. Lastly, there is a limited representation in the model of the heterogenous behaviors of water users, beyond the optimized behavior, which could be improved in future work (Kahil *et al.* 2019).

In our analysis, we focus on the observable impacts within the Ebro Basin, which are relatively large. Nevertheless, the multiregional nature of the general model would allow for the estimation of changes in value added and employment in the rest of Spain, the EU, and the world. In the simulated scenarios, it is assumed, for the sake of simplicity, that foregone agricultural outputs (determined by the hydro-economic part of the model) are not replaced by imports from other regions or by other agricultural commodities. However, this assumption can be relaxed, which would enhance the general relevance of the model, although it would be necessary to include adjustments to model the substitutability of different goods. As a way forward, a computable general equilibrium model could be built that would always take water availability into account at each point throughout the ERB (or any other river basin elsewhere).

Acknowledgments

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Appendix A

A.1. *Geographical structure and water flows scheme*

This appendix contains a detailed explanation of the components used in the water flow scheme and identifies the model components with the reality.

A.1.1. *Head flows*

The simplified hydrological scheme we use consists of 17 head flows. The first head flow (HF_01) is identified with the source of the Ebro River and its tributaries as they flow into the Ebro Reservoir. Because this reservoir is fed directly by this headwater, it is associated with the inflows observed, and approach that is also applied with other head flows. The second head flow (HF_02) is identified with the contributions made by the Basque Mountains to the Ebro Basin, which are regulated downstream by the Ullivarri and Urrunaga Reservoirs. The third head flow (HF_03) identifies the incoming water received by Itoiz Reservoir, which supplies the Navarra Canal, and the fourth (HF_04) represents water from the River Aragón flowing into Yesa Reservoir.

Meanwhile, the headwaters HF_05–HF_10 identify incoming water received by the reservoirs of the Ebro Basin located in the Central and Eastern Pyrenees. More specifically, HF_05 represents the waters of the Sotón and Gállego Rivers flowing into La Sotonera Reservoir, while the incoming water from the Río Segre (HF_06) is stored and managed by the Grado-Mediano system of reservoirs, which together with La Sotonera supplies the Riegos del Alto Aragón Canals as well as downstream requirements on the Gállego and Cinca Rivers.

HF_07 identifies the Pyrenean contributions that fill Barasona Reservoir via the Ésera River, while HF_08 recharges the Noguera Ribagorzana reservoir system (Escalés, Canelles, and Santa Ana). These reservoirs, together with Barasona, supply the Canal de Aragón y Cataluña. The water inflows reaching the basin from the Noguera Pallaresa River, which are stored in the Tremp–Terradets–Camarasa reservoir system, are identified as HF_09. This system feeds the Urgel Canal. HF_10 is the Segre River, which feeds the Urgel Canal and is used in the management of Oliana and Rialb Reservoirs.

Accordingly, flows HF_01–HF_10 are headwaters that directly feed some reservoirs and are therefore easily quantifiable because we know the monthly inflows at all of them. However, not all of the headwaters in the basin, identified as HF_11–HF_17, are associated with a specific reservoir. These serve as adjustment head flows, so they can sometimes take negative values. Finally, the percolation and evaporation occurring between the different river sections present a somewhat complex picture, and they are therefore accounted for via these adjustment headwaters for the sake of simplicity.

HF_11 represents the contributions of the Ebro Tributaries between the Ebro Reservoir and the municipality of Miranda de Ebro, which may be treated as net contributions to the ERB from the province of Burgos. Meanwhile, the head flow identified as HF_12 is made up of unmeasured contributions rising in the Basque Country with runoff toward the Ebro. We assume that these contributions flowing into the Ebro are usable, together with the waters flowing out of the Ullivarri and Urrunaga Reservoirs, in the water-use zone labeled PVA1, which comprises the entire area of the Basque Country belonging to the Ebro Basin.[7] The water not consumed in this zone flows into the Ebro.

The available water from La Rioja is identified as HF_13. There are no reservoirs with significant capacity in La Rioja or, in general, anywhere on the right bank of the Ebro. For this reason, all contributions from La Rioja to the Ebro Basin (Najerilla, Iregua, Cidacos, and other smaller rivers and streams) are included in this head flow, which supplies the water-use zone RIO1, comprising all municipalities in La Rioja except those supplied by the Lodosa Canal.

Similarly, the head flow HF_14 identifies right bank contributions in Aragon (Rivers Jalón, Huerva, Guadalope, and other streams), while the water-use zone ARA4 groups all of the Aragonese municipalities lying on the right bank of the Ebro, except for those supplied by the Lodosa Canal or the Imperial Canal.

Head flow HF_15 comprises Navarrese contributions that are not regulated by the Itoiz Reservoir and runoff toward the Ebro. These contributions are treated as usable in the NAV1 zone in Navarre.

According to the gauging station data for the last stretch of the Ebro (MAPAMA 2016b), the volume of water in the Ebro downstream from Ribarroja Reservoir is, as a general rule, greater than the volume of outflows from the reservoir even though there are no relevant tributaries along this stretch. These outcrops are identified by the header HF_16.

Finally, head flow HF_17 accounts for all other left bank outcrops in the lower stretch, comprising contributions from tributaries of the Rivers Cinca and Segre that are not impounded in the reservoirs included in the ERB schema.

Monthly data for head flows HF_01–HF_10 (i.e., head waters flowing directly into a reservoir) were obtained from the gauging yearbook (MAPAMA 2016b), while the figures for the adjustment head flows included in the model comprise monthly water consumption/requirement estimates based on the irrigation land declared in the last available agricultural census (INE 2011) and the estimated

[7]Water-use zones are described in Section A.1.3.

water requirements per hectare of the different crops grown Martínez-Cob (2004). The total 2010 output of other sectors of the ERB's economy was also taken into consideration, together with the estimated water consumption per unit of production of the industries concerned (Genty *et al.* 2012), and the municipal census also for 2010 (INE 2011).

A.1.2. *Canals and reservoirs*

The Ebro River Basin has 125 reservoirs larger than 1 Mm^3, which represent a total storage capacity of 7,833 hm^3 or just over 50% of the average annual contribution. The schema represents only the higher-capacity reservoirs. Also, given that the greatest consumptive uses are made by irrigation, we have defined water-use regions based on the main irrigation zones, given that irrigation makes the greatest consumptive use of water. For the sake of simplicity, we have therefore discarded low-capacity reservoirs and have grouped certain others.

Reservoirs are labeled using codes along similar lines to head flows. For example, Ebro Reservoir in Cantabria (assigned a code 9801 in the gauging yearbook) collects water from the HF_01 head flow and it is therefore labeled R01 in the schema for the sake of consistency.

Based on geographical proximity and the fact that the contributions to both come from the Zadorra River, the Ullivarri (9827) and Urrunaga (9828) Reservoirs are treated as a single combined facility. The resulting reservoir (R02) therefore accounts for the water by both reservoirs (HF_02) and is also assigned the impoundment capacity of both.

Itoiz Reservoir, coded R03, receives water from the HF_03 head flows. This reservoir, located at the confluence of the Irati River and its tributary the Urrobi, is the starting point of the Navarra Canal. In our modeling, we assume that this channel supplies all the populations included in the NAV1 water-use zone. The next reservoir, R04, is Yesa, which collects the waters described as head flow HF_04. The Bardenas Canal draws its water from R04 to supply users in zones NAV3 and ARA1.

In the simplified hydrological scheme used (Figure 2), we identify only six reservoirs for the province of Huesca and the Catalan Pyrenees (R05–R10), each of which is associated with one of the main rivers in this eastern end of the Pyrenees, resulting in the simplified schema described in the following and represented in Figures A.1 and A.2.

La Peña and Ardisa Reservoirs are both small (capacities of 15 hm^3 and 3 hm^3, respectively) and they have therefore not been included in the model. However, the data for these reservoirs serves as a gauging station allowing calculation of the incoming water reaching R05, which consists of HF_05. Based on the schema

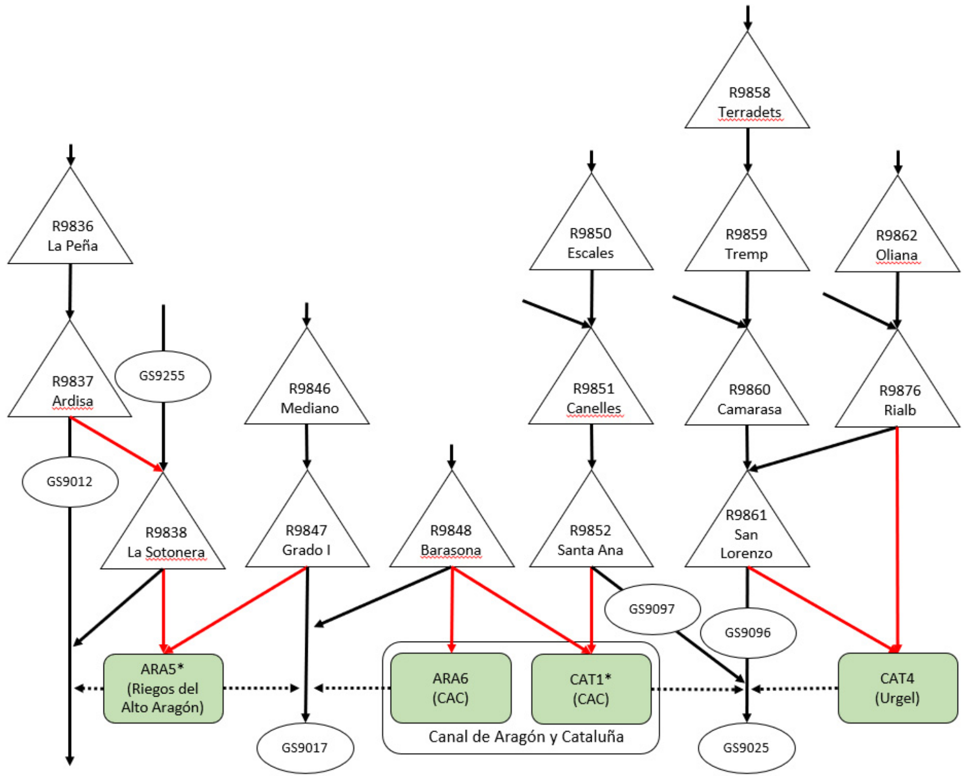

Figure A.1. Schema of Reservoirs in Huesca Province and Catalonia (Gállego, Cinca, and Segre)

presented in Figure A.2, water enters the reservoir R05 and leaves the Ardisa Dam which does not pass the Gauging Station GS9012 plus fringe water at the Gauging Station GS9255. The capacity of R05 is that of La Sotonera Reservoir (186 hm^3), which is part of the RAA system. Accordingly, the model includes an associated channel from this reservoir to supply the ARA5 zone. This channel represents the canals and channels that carry water from La Sotonera (R05) to the municipalities of Upper Aragón.

Reservoir R06 identifies the Grado I and Mediano System. The capacity of R06 is the sum of both of its component reservoirs and collects its waters from the head flow identified as HF_06 (Río Cinca). It supplies zone ARA5 via a channel in our model, which represents the canals and irrigation channels carrying water from the reservoir to the municipalities that we have included in the ARA5 water-use zone. Most of the water demand in this area is associated with the Riegos del Alto Aragón irrigation community.

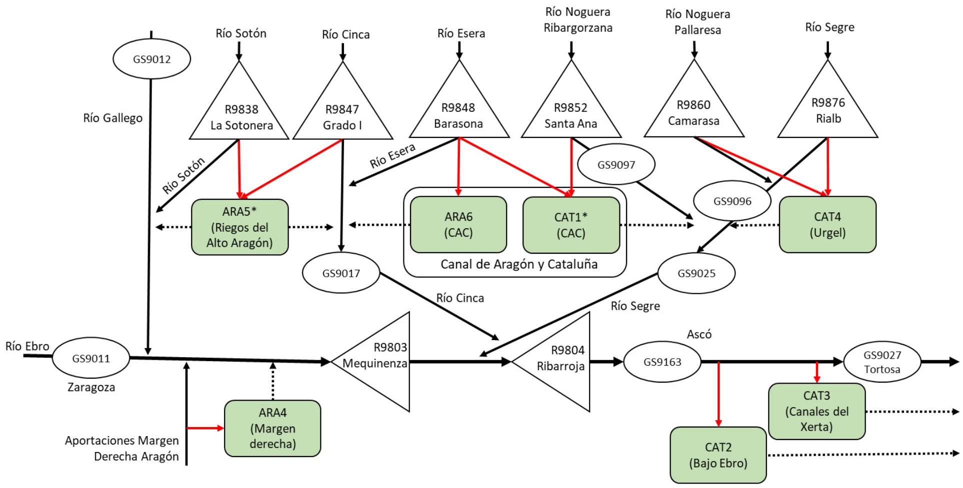

Figure A.2. Schema of Middle and Lower Ebro

The reservoir labeled R07 in the schema is Barasona Reservoir. Together with the Noguera Ribagorzana reservoir system (Escalés, Canelles, and Santa Ana Reservoirs) identified as R08, Barasona supplies the water used in zones ARA6 and CAT1, comprising mainly the irrigation in Canal de Aragón y Cataluña.

Water-use zone CAT4 is supplied by the Noguera Pallaresa and Segre Rivers. San Lorenzo Reservoir is omitted from the schema here because of its small capacity of only 10 hm^3; Reservoir R09 identifies the Noguera Pallaresa reservoir system (Tremp, Terradets, and Camarasa), while R10 represents the Segre reservoir system comprising Oliana and Rialb.

The reservoir identified as R11 in Figure 2 represents the Mequinenza–Ribarroja system, which does not collect any water from the Rivers Cinca and Segre, whose waters meet further downstream.

The capacity of the reservoirs in our model is the sum of the impoundment capacities they represent in reality. However, upper and lower monthly storage thresholds of 90% and 30% of capacity are also established in the model for operational (maximum level) and environmental (minimum level) reasons. Moreover, minimum outflows are also set for the reservoirs in line with those established by the ERB Authority, if any.

A.1.3. *Water-use zones*

In terms of physical geography, the Ebro River Basin actually includes parts of nine Autonomous Communities and 1,724 municipalities. As modeled here, however, the ERB consists only of the five most representative regions in terms of area, population, and economy, namely the Basque Country, La Rioja, Navarre, Aragon, and Catalonia from the river's source to its delta, comprising a total of 1,480 municipalities. In order to combine the hydro-economic model with the input–output framework, meanwhile, the water zones modeled had to represent each of these five regions as a whole, and because of this it was decided to group municipalities in view of water flows and the concentration of uses, so that the sum of the resulting water-use zones would match the complete regions of the input–output table.

The most water-intensive sector of the ERB economy is irrigated farming, and the water-use zones defined therefore overlap irrigation schemes as far as possible. However, the uses considered go beyond irrigation alone so as to take account of the water needs of all the municipalities that make up each water-use zone. This appendix lists all of the municipalities modeled, and the water-use zones with which each is associated. Meanwhile, the zones resulting from the aggregation procedure are represented in Figure A.3 and the key water-use data for each grouping is shown in Table A.1.

Each water-use zone supports (1) domestic demand consisting of the drinking and sanitation water used by the population, which depends on the number of

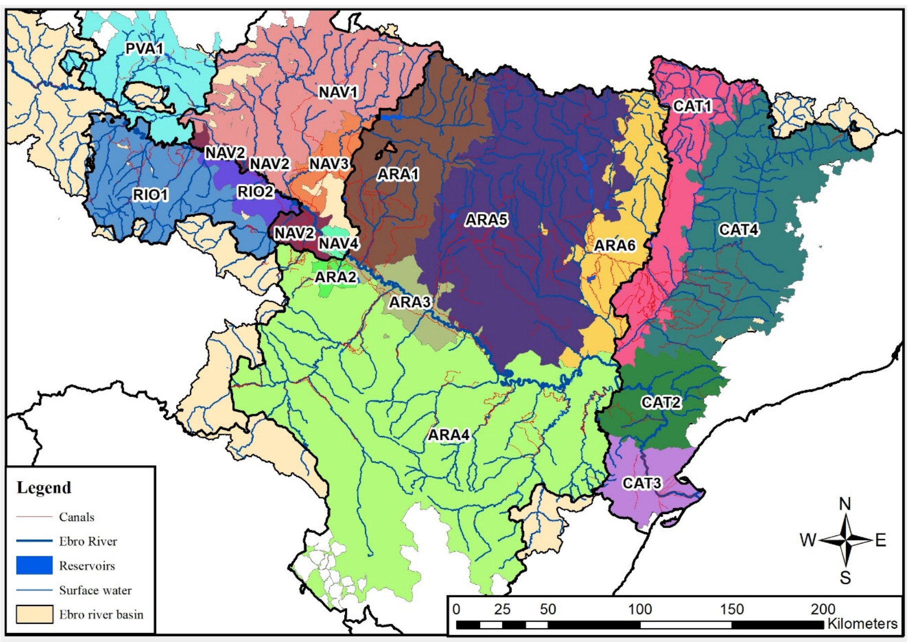

Figure A.3. Water-Use Zones in the Ebro River Basin

Table A.1. Consumptive Water Uses by Zone

Water-Use Zone	Total Blue Water Used (hm^3)	Blue Water Used by Farms (hm^3)	Blue Water Used by Industry (hm^3)	Urban Blue Water Used (hm^3)
ARA1	178	155	23	1.2
ARA2	10	6	3	0.3
ARA3	242	104	138	17.2
ARA4	600	529	72	6.7
ARA5	443	382	61	3.9
ARA6	750	711	39	1.7
CAT1	778	702	76	5.6
CAT2	126	116	9	1.3
CAT3	237	197	40	3.4
CAT4	617	498	119	4.9
NAV1	179	96	83	11.3
NAV2	124	113	12	2
NAV3	113	103	9	0.8
NAV4	51	47	5	0.3
PVA1	168	67	102	7.2
RIO1	285	230	55	5.8
RIO2	158	144	14	1.7
Total	5,135	4,200	860	75.2

Source: Made by the authors.

people living in each zone; (2) industrial demand, which depends on the water needs of each local industry and the level of output in each zone; and (3) irrigation, which depends on the number of hectares under each crop, water requirements per hectare, and the distribution of water needs over the year.

Environmental requirements are also applied in addition to the demand in some zones. These represent the volume of downstream flows remaining after abstractions for the domestic, industrial, and farm use, and they are set in line with the ecological flows established by the ERB Authority (CHE 2014) to the extent that these are identifiable in the schema. No minimum environmental flows apply to the zones that receive water from artificial water courses (canals), in line with our understanding of ERB policy.

Aragon is divided into six water-use zones, Catalonia and Navarre into four zones each, and La Rioja into two, while the Basque Country forms a single zone. Let us begin with a brief description of the resulting groupings.

ARA1 represents the Aragonese municipalities served by the Bardenas Canal. ARA2 comprises all of the Aragonese municipalities that are supplied by the Lodosa Canal and ARA3 comprising those supplied by the Canal Imperial. ARA4 includes all of the Aragonese municipalities on the right bank of the Ebro River that are not already included in the previous zones. ARA5 consists mainly of the municipalities making up the Riegos del Alto Aragón irrigation scheme and certain other municipalities further to the north. Finally, ARA6 represents the Aragonese municipalities served by the Canal de Aragón y Catalunya and several municipalities to the north.

CAT1 comprises mainly the Catalan municipalities supplied by the Canal de Aragón y Catalunya and some others located further the north. CAT2 represents the Catalan municipalities downstream of the Ribarroja Reservoir. CAT3 consists of the municipalities of the Ebro Delta, which are mainly supplied by the Xerta Channels. CAT4 comprises the municipalities supplied by the waters of the River Segre.

NAV1 represents the regions served by the Canal de Navarra, which is in turn supplied by Itoiz Reservoir and other sources such as the Ega, Arga, and Cidacos Rivers. NAV2 comprises the municipalities served by the Lodosa and Mendavía Channels, while NAV3 is supplied by the Bardenas Canal. NAV4 comprises the Navarrese municipalities supplied by the Tauste and Imperial Canals.

As mentioned above, the part of the Basque Country forming a part of the ERB was not split into different water-use zones and the label PVA1 applies to the whole region. Likewise, zone RIO1 includes all the municipalities of La Rioja except those supplied by the Lodosa Canal, which are labeled RIO2.

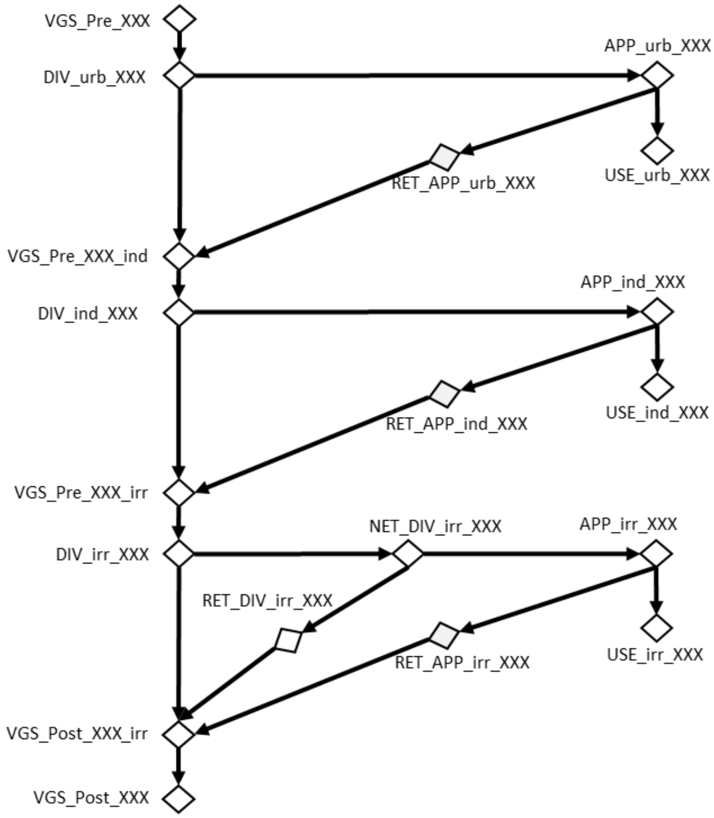

Figure A.4. Schematic Pattern of Flows in Water-Use Zones

Let us now consider the movement of water within the zones defined in the model. This is reflected schematically in Figure A.4, in which the arrows identify the relationships between. As may be observed, the diagram consists of three loops representing the cycle of drinking and sanitation water (domestic uses) in the first place, followed by industrial, and finally the agricultural uses and revealing the pattern of flows. Based on the uses described, the next step was to define minimum outflows in line with the environmental flows established by the ERB Authority, which are measured at the last node of each zone, labeled VGS_Post_XXX.

The water available for use in each water-use zone is the sum of all water flows received from upstream (i.e., net upstream flows of water used). Figure A.4 shows a schematized zone in which the initial node is labeled VGS_Pre_XXX, where *XXX* denotes the water-use zone, and the last node is labeled VGS_Post_XXX, allowing us to account for all water flows entering the zone and then leaving it unconsumed.

Potential water losses associated with use which do not return to the course of the river are treated as water requirements attributable to the activities concerned.

A part of the available water flowing into the zone at VGS_Pre_XXX is diverted at the node DIV_urb_XXX for urban use (APP_urb_XXX), while the rest flows on to the node VGS_Pre_XXX_ind. Channel efficiency of 100% is assumed for urban water mains and service pipes, so that the water diverted is equal to domestic water use and the transport loss is zero (or otherwise accounted for as urban consumption). Meanwhile, the water used in this subschema is split at the node APP_urb_XXX between actual consumption (USE_urb_XXX) and water returned to the river basin (RET_APP_urb_XXX) at the VGS_Pre_XXX_ind node. We assume a return of 80% on used urban and industrial water (CHE 2015a) in all water-use zones. As explained below, the amount of water used to meet urban/domestic demand is proportional to the population of each water-use zone.

The distribution process for industrial uses is the same as for domestic uses, beginning at VGS_Pre_XXX_ind, where the available water is split between the diversion made for industrial uses (APP_ind_XXX) and the rest, which flows on to VGS_Pre_XXX_irr. Once again, the water intended for use is divided between actual industrial consumption (USE_ind_XXX) and the water returned to the river (RET_APP_ind_XXX) at the node VGS_Pre_XXX_Irr. We again assume a return of 80% (CHE 2015a).

Finally, the irrigation water use and consumption schema is similar to the domestic and industrial patterns, with the difference that channel efficiency is assumed to be less than 100%. This means that there is an additional node, NET_DIV_irr_XXX, in the irrigation water loop, where the flow is split between water going on for actual use (APP_irr_XXX) and the water losses at the channel level (RET_DIV_irr_XXX), which is assumed to return to the main flow at VGS_Post_XXX_irr. Meanwhile, the water actually used in irrigation is again divided at the node APP_irr_XXX between actual consumption/evapotranspiration (USE_irr_XXX) and returns from plots/application nodes, RET_APP_irr_XXX, which flow back to the river at VGS_Post_XXX_Irr. The available water measured at this node (VGS_Post_XXX_irr) is equal to the outgoing water at node VGS_Post_XXX, where environmental requirements must be met, so that the outflows from the water-use zones comply with the minimum levels set. Accordingly, these requirements constitute a restriction on upstream water uses.

A.2. *Environmental and physical constraints*

The equations are subject to a number of constraints. To begin with, outgoing water from any node is defined as a positive variable and it must therefore be greater than or equal to zero for all nodes. Second, maximum and minimum stock levels (upper and lower bounds) are established for each reservoir, equal to 90% and 30% of total capacity. These limits are set for operational and environmental reasons.

It is further assumed that environmental flows and consumption uses for a given year must be met with the water available in that year. Therefore, the water stock available in each reservoir must be kept constant from one year to the next in the model. The resulting sustainability constraint requires that the volume of water stored in each reservoir at the end of the water year (September) must be equal to the volume stored at the beginning of the year (October).

Equation (4) applies only to nodes subject to environmental flow requirements. In this regard, minimum environmental flows are established for the schematic nodes that can be identified with points or areas for which the ERB Authority sets environmental flows in reality (CHE 2015b). Additional environmental flows equal to 25% of the sum of the median upstream head flows are also established at some points in our schema for which there are no corresponding ERB environmental flows. The median flow data for each month was calculated based on the 1980–2013 data from the gauging stations yearbook. The minimum flows established for the hydrologic components of the model are shown in Table A.2.

The first set of constraints in Table A.2 identifies the minimum outflow of each reservoir, which is fixed based on the minimum outflow required by the ERB Authority (CHE 2015a). However, no official minimum outflows exist for reservoirs R05, R09, and R11, or for the nearby downstream river reaches. In these cases, the environmental flow is set at 25% of the median upstream inflows.

The second set of constraints in Table A.2 refers to the canals. The "Post_Lodosa" constraint establishes a minimum flow in the Ebro below the Lodosa Diversion equal to the minimum environmental flow officially set by the ERB Authority. Environmental flows are also fixed downstream of the other canals depicted in our schema, except for CanalalR09, for which a flow equal to 25% of the median upstream inflow has been set.

The schema also identifies other points or gauging stations for which the ERB Authority sets the environmental flows. These are situated in the water-use zones (third set of constraints) and along the river itself (fourth set of constraints, represented as circles in Figure 2). The ERB Authority estimates the environmental flows for the Ebro Delta and the Tortosa Gauging Station, which are included in the model based on the environmental flows in the "Xerta to Mediterranean" stretch of the river.

Table A.2. Minimum Flow Constraints (hm^3)

Variable	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Description
R01_outflow	1	2	2	2	2	2	2	2	2	2	1	1	Fixed by ERB Authority
R02_outflow	2	2	2	3	2	3	3	2	2	2	2	2	Fixed by ERB Authority
R03_outflow	2	5	6	8	7	7	7	8	3	2	2	2	Fixed by ERB Authority
R04_outflow	6	6	6	6	5	5	6	6	5	5	4	5	Fixed by ERB Authority
R05_outflow	1	4	7	6	5	8	11	8	13	8	4	3	25% Median upstream inflow
R06_outflow	3	3	3	3	2	2	3	3	3	2	2	2	Fixed by ERB Authority
R07_outflow	2	2	2	2	1	2	2	2	2	2	2	2	Fixed by ERB Authority
R08_outflow	4	4	4	4	3	3	4	4	5	4	4	4	Fixed by ERB Authority
R09_outflow	6	14	21	14	12	12	22	33	54	31	11	9	25% Median upstream inflow
R10_outflow	10	10	10	10	8	9	10	12	11	9	9	9	Fixed by ERB Authority
R11_outflow	31	107	151	283	185	128	138	165	159	99	45	28	25% Median upstream inflow
Post_Lodosa	23	26	29	30	27	28	30	28	24	20	18	17	Fixed by ERB Authority
Pst_Imperial	54	52	94	94	85	42	44	41	35	30	36	35	Fixed by ERB Authority
Pst_C_Navarra	4	4	5	5	5	5	5	4	4	3	2	3	Fixed by ERB Authority
Pst_Bardenas	7	8	12	12	10	13	14	15	13	12	11	10	Fixed by ERB Authority
Pst_CanalR05	1	4	7	6	5	8	11	8	13	8	4	3	Fixed by ERB Authority
Pst_CanalR06	17	28	24	17	14	18	23	42	46	40	18	11	Fixed by ERB Authority
Pst_CanalR07	9	13	10	8	6	14	13	20	25	16	8	4	Fixed by ERB Authority
Pst_CanalR08	5	8	10	8	6	11	11	16	25	23	10	3	Fixed by ERB Authority
Pst_CanalR09	6	14	21	14	12	12	22	33	54	31	11	9	25% Median upstream inflow
Pst_CanalR10	14	9	10	16	12	13	9	24	23	6	11	11	Fixed by ERB Authority
VGS_Pst_PVA1	4	5	7	8	7	7	7	6	4	3	1	3	Fixed by ERB Authority
VGS_Pst_RIO1	6	6	7	7	6	6	7	7	5	4	4	4	Fixed by ERB Authority
VGS_Pst_NAV1	5	6	7	7	7	7	7	6	5	4	3	4	Fixed by ERB Authority

Table A.2. (*Continued*)

Variable	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Description
VGS_Pst_ARA4	3	3	3	3	3	3	3	3	3	3	3	3	Fixed by ERB Authority
VGS_01	10	11	13	14	13	14	15	13	11	10	9	8	Fixed by ERB Authority
VGS_02	15	17	20	23	21	21	21	19	16	13	10	11	Fixed by ERB Authority
VGS_03	23	26	29	30	27	28	30	28	24	20	18	17	Fixed by ERB Authority
VGS_04	39	43	48	49	43	46	48	45	38	33	29	30	Fixed by ERB Authority
VGS_05	54	52	94	94	85	42	44	41	35	30	36	35	Fixed by ERB Authority
VGS_06	86	81	123	123	109	71	76	81	75	61	66	65	Fixed by ERB Authority
VGS_08	214	207	244	254	363	402	236	244	210	214	214	207	Fixed by ERB Authority
Xerta_to_Mediterranean	0	52	24	67	0	13	23	24	49	54	54	0	Estimated data

Table A.3. Water Inflows in Scenario 3 for the 2004–2005 Water-Year (hm^3)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
HF_01	1	0	50	50	41	60	106	60	74	32	0	0	474
HF_02	4	19	22	12	22	36	16	7	3	3	2	3	149
HF_03	0	15	32	63	55	64	95	32	18	53	14	0	441
HF_04	5	40	49	59	55	66	50	162	109	42	0	0	636
HF_05	15	15	6	5	2	39	18	11	52	29	25	21	238
HF_06	0	148	28	18	5	43	22	134	91	28	0	37	556
HF_07	39	0	52	41	31	53	64	68	144	118	21	3	633
HF_08	0	61	11	6	11	31	11	29	44	55	24	27	311
HF_09	0	3	33	35	9	42	57	144	188	65	49	29	653
HF_10	22	32	26	12	14	48	32	56	167	55	33	1	499
HF_11	47	158	182	186	242	311	155	53	6	−8	−2	−5	1,327
HF_12	1	23	15	76	57	−10	5	23	29	6	3	1	229
HF_13	16	29	65	195	62	48	33	22	72	56	39	28	664
HF_14	15	15	19	29	30	44	45	51	42	43	36	25	393
HF_15	2	100	96	163	117	32	34	98	43	16	−10	−14	677
HF_16	28	29	53	48	30	57	67	102	131	61	26	23	655
HF_17	65	54	53	47	57	81	32	23	−9	1	9	24	437
Total	259	741	793	1,045	839	1,045	840	1,077	1,204	656	270	203	8,971

A.3. *Scenarios' data*

The third scenario (S3) refers to 2004–2005 water-year, a drought year in which farms suffered severely. The water inflows in this scenario are the ones observed in the 2004–2005 water-year. The monthly distribution of the head flows used in S3 results in a total annual inflow of 8,981 Mm^3 as shown in Table A.2, significantly less than the annual median water-year inflow of 11,495 Mm^3. In this scenario, we keep the environmental flow requirement established in S1.

A.4. *Direct and Indirect Impacts on Socio-Economic Variables*

The starting point is an economy defined by a matrix of technical coefficients $\mathbf{A}_0$, an output $\mathbf{x}_0$, and one vector of final demand $\mathbf{y}_0$. The value-added coefficients for each sector $\mathbf{v}_0$ can now be calculated based on the data found in the MRIOT denoted by $\mathbf{T}_0$, which represents an I–O-type general equilibrium. These variables verify the fundamental relationships of the following model:

$$\begin{gathered} \mathbf{x}_0 = \mathbf{A}_0\mathbf{x}_0 + \mathbf{y}_0 \leftrightarrow \mathbf{x}_0 = (\mathbf{I} - \mathbf{A}_0)^{-1}\mathbf{y}_0, \\ (1, 1, \ldots, 1)\mathbf{v}_0\hat{\mathbf{x}}_0 = \mathbf{y}_0(1, 1, \ldots, 1)^T. \end{gathered} \tag{A.1}$$

Any changes in water availability arising in the hydro-economic model calibrated for the same year as the input–output table will result in optimization via the objective function, providing the new values of output for irrigation, which will in turn lead to associated changes in value added, in the area with each crop, and, ultimately, in the productive technologies used in irrigation.

The new multiregional balance can now be obtained because the irrigation requirements in terms of intermediate input are known (they are constant per hectare), and it will therefore vary depending on changes in the number of hectares under each crop in each water-use zone [Eq. (A.2)]. Hence, the technical coefficients of the irrigated crops will vary in line with changes in water availability. In the case of other industries, meanwhile, the technical coefficients do not change and neither does the (Leontief) production function, even though intermediate inputs differ depending on the output [Eq. (A.3)], so that the new matrix of technical coefficients $\mathbf{A}_1$ can be obtained,

$$a_{i,j,1}^{r,s} = a_{i,j,0}^{r,s} \frac{x_{j,0}^s}{x_{j,1}^s} \frac{h_{j,1}^s}{h_{j,0}^s}, \quad \forall j \in c, \tag{A.2}$$

$$a_{i,j,1}^{r,s} = a_{i,j,0}^{r,s}, \quad \forall j \notin c. \tag{A.3}$$

Once $\mathbf{A}_1$ is known, we also know the new vector $\mathbf{v}_1$, which changes only in the field of irrigation, so a new balance can be obtained, defined by the already known $\mathbf{A}_1$ and $\mathbf{v}_1$ values, and by the other vectors $\mathbf{x}_1$ and $\mathbf{y}_1$ required. Taken together, these vectors will define the equilibrium of a new multiregional model $\mathbf{T}_1$, which must verify the following basic relationships [Eq. (A.4)]. We also define Eq. (A.5),

$$\begin{gathered}\mathbf{x}_1 = \mathbf{A}_1\mathbf{x}_1 + \mathbf{y}_1 \leftrightarrow \mathbf{x}_1 = (\mathbf{I} - \mathbf{A}_1)^{-1}\mathbf{y}_1, \\ (1, 1, \ldots, 1)\mathbf{v}_1\hat{\mathbf{x}}_1 = \mathbf{y}_1(1, 1, \ldots, 1)^T,\end{gathered} \tag{A.4}$$

$$\Delta\mathbf{x} = \mathbf{x}_1 - \mathbf{x}_0, \Delta\mathbf{A} = \mathbf{A}_1 - \mathbf{A}_0, \Delta\mathbf{y} = \mathbf{y}_1 - \mathbf{y}_0, \Delta\mathbf{v} = \mathbf{v}_1 - \mathbf{v}_0. \tag{A.5}$$

This would allow calculation of the impacts on the integrated model, which clearly have a dual origin, to with changes in intermediate inputs in the irrigation sector and the shift in income from irrigation. This means that we can analyze the outcome as a double impact, one associated with changes in the intermediate inputs required for irrigation and the other caused by a demand shock. Equations (A.1), (A.4), and (A.5) support this and allow writing the following equations:

$$\mathbf{x}_1 = \mathbf{A}_0\mathbf{x}_1 + \Delta\mathbf{A}\mathbf{x}_1 + \mathbf{y}_1 \leftrightarrow \mathbf{x}_1 = (\mathbf{I} - \mathbf{A}_0)^{-1}(\Delta\mathbf{A}\mathbf{x}_1 + \mathbf{y}_1), \tag{A.6}$$

$$\begin{aligned}\Delta\mathbf{x} = \mathbf{x}_1 - \mathbf{x}_0 &= (\mathbf{I} - \mathbf{A}_0)^{-1}(\Delta\mathbf{A}\mathbf{x}_1 + \mathbf{y}_1) - (\mathbf{I} - \mathbf{A}_0)^{-1}\mathbf{y}_0 \\ &= (\mathbf{I} - \mathbf{A}_0)^{-1}(\Delta\mathbf{A}\mathbf{x}_1 + \Delta\mathbf{y}).\end{aligned} \tag{A.7}$$

As may be observed, $\Delta\mathbf{x}$ has two components, $(\mathbf{I} - \mathbf{A}_0)^{-1}\Delta\mathbf{y}$, which captures the impact via final demand, and $(\mathbf{I} - \mathbf{A}_0)^{-1}\Delta\mathbf{A}\mathbf{x}_1$, which measures the impact due to the change in intermediate inputs. Given the relations defining the new balanced $\mathbf{T}_1$, we may now obtain the vectors $\mathbf{x}_1$ and $\mathbf{y}_1$. Based on Eq. (A.7), we can obtain

$$\Delta\mathbf{x} = [\mathbf{I} - (\mathbf{I} - \mathbf{A}_0)^{-1}\Delta\mathbf{A}]^{-1}(\mathbf{I} - \mathbf{A}_0)^{-1}[\Delta\mathbf{A}\mathbf{x}_0 + \Delta\mathbf{y}]. \tag{A.8}$$

This shows that increases in output for each new scenario simulated will also depend on the final demand, which is not a one-size-fits-all solution. We know that a reduction in available water entails falls in value added by the different irrigated crops. However, it is the way in which these reductions are transmitted to the final demand that is important. Here, knowledge of the elasticities of goods and farm incomes would allow this gap to be bridged. This process depends on the social and institutional framework, and it should not be ignored or played down.

Let us now assume a very simple dependency and, returning to Eq. (A.4), represent the economy in the form of two blocks, irrigation and other sectors. This representation is shown in Figure A.5 and represented by the following equations,

$\mathbf{A}_{11}\hat{\mathbf{z}}_1$	$\mathbf{A}_{12}\hat{\mathbf{z}}_2$	$\mathbf{Y}_1$
$\mathbf{A}_{21}\hat{\mathbf{z}}_1$	$\mathbf{A}_{22}\hat{\mathbf{z}}_2$	$\mathbf{Y}_2$
$\mathbf{v}_1'\hat{\mathbf{z}}_1$	$\mathbf{v}_2'\hat{\mathbf{z}}_2$	

Figure A.5. Reorganized Structure of Input–Output Table

which describe the new equilibrium after the water shock simulation, where irrigation is denoted by subscript 1 and other industries by subscript 2:

$$\mathbf{z}_1 = \mathbf{A}_{11}\mathbf{z}_1 + \mathbf{A}_{12}\mathbf{z}_2 + \mathbf{y}_1, \tag{A.9}$$

$$\mathbf{z}_2 = \mathbf{A}_{21}\mathbf{z}_2 + \mathbf{A}_{22}\mathbf{z}_2 + \mathbf{y}_2 \leftrightarrow \mathbf{z}_2 = (\mathbf{I} - \mathbf{A}_{22})^{-1}(\mathbf{A}_{21}\mathbf{z}_1 + \mathbf{y}_2). \tag{A.10}$$

In any given simulation, the hydro-economic part of the model provides the output of the irrigation sector $\mathbf{z}_1$. Let us further assume that the institutional framework leads to a final demand $\mathbf{y}_2$ proportional to the pre-shock final demand in other industries (non-irrigation sectors).

For the sake of simplicity, let us further assume that the changes in the irrigators' final demand are proportional to the pre-shock final demand observed. Therefore, $\mathbf{y}_2$ is the final demand vector adjusted by the changes in the irrigators' income. In the light of this, Eq. (A.10) can be applied to calculate the output of this scenario for all non-irrigated activities ($\mathbf{z}_2$) and consequently the impacts on value added, jobs, and water consumption. Therefore, Eq. (A.10) can be applied to calculate the output of this scenario for all non-irrigated activities $\mathbf{z}_2$. Then, the equilibrium is completely determined. In this equilibrium, meanwhile, the value added by irrigation will always be $\mathbf{v}'_1\mathbf{z}_1$, irrespective of the institutional criterion being chosen to determine $\mathbf{y}_2$.

A.5. *Tables and figures of section 3*

This subsection includes the results presented in Tables A.4 and A.5 and Figures A.6–A.8 for the different scenarios.

Table A.4. Water Consumed in Scenario 2 (hm^3)

Zone	Urban	Industrial	Irrigation	Total	S2–S1	S2–S1 (%)
ARA1	0.7	22.5	301.6	324.8	−12.5	−3.70%
ARA2	0.1	3.3	13.3	16.6	0	0%
ARA3	21	138.3	158.7	318	0	0%
ARA4	3.5	71.6	185.4	260.6	−51.2	−16.43%
ARA5	4.2	61.5	519.2	584.9	−127.2	−17.86%
ARA6	1.4	39.4	254.5	295.3	−106.1	−26.43%
CAT1	7.1	76	260.2	343.3	−27.1	−7.31%
CAT2	0.5	9.2	79.9	89.5	0	0%
CAT3	2.7	40.4	380.3	423.4	0	0%
CAT4	4.9	119	344.8	468.7	0	0%
NAV1	12.2	82.9	60.9	156	0	0%
NAV2	1.4	11.6	111.5	124.4	0	0%
NAV3	0.5	9.3	86.2	96.1	−1.2	−1.28%
NAV4	0.3	4.7	35	39.9	0	0%
PVA1	7.2	101.5	27.1	135.8	0	0%
RIO1	5.8	55.1	66.7	127.6	−15.6	−10.87%
RIO2	1.7	13.8	67.5	83.1	0	0%
Total	75.1	860.3	2,952.8	3,888.1	−340.9	−8.06%

Table A.5. Water Consumed in S3 (Mm^3)

Zone	Domestic	Industrial	Irrigation	Total	S3–S1	S3–S1 (%)
ARA1	0.7	22.5	250.4	273.6	−51.2	−15.77%
ARA2	0.1	3.3	13.3	16.6	0	0%
ARA3	21	138.3	158.7	318	0	0%
ARA4	3.5	71.6	95.8	170.9	−89.7	−34.41%
ARA5	4.2	61.5	280.5	346.1	−238.8	−40.82%
ARA6	1.4	39.4	243.3	284	−11.3	−3.81%
CAT1	7	76	166.4	249.3	−94	−27.38%
CAT2	0.5	9.2	79.9	89.5	0	0%
CAT3	2.7	40.4	380.3	423.4	0	0%
CAT4	4.9	119	344.8	468.7	0	0%
NAV1	12.2	82.9	60.9	156	0	0%
NAV2	1.4	11.6	111.5	124.4	0	0%
NAV3	0.5	9.3	81.4	91.3	−4.8	−5.01%
NAV4	0.3	4.7	35	39.9	0	0%
PVA1	7.2	101.5	27.1	135.8	0	0%
RIO1	5.8	55.1	62.7	123.6	−4	−3.14%
RIO2	1.7	13.8	67.5	83.1	0	0%
Total	74.8	860.3	2,459.3	3,394.4	−493.7	−12.70%

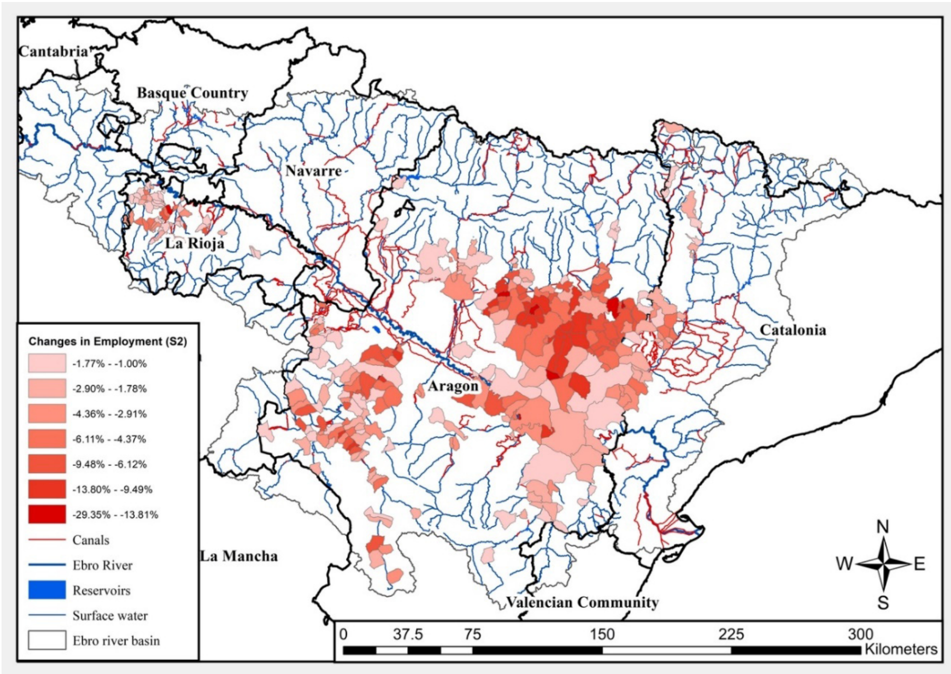

Figure A.6. Changes in Employment in Scenario 2 (All Sectors)

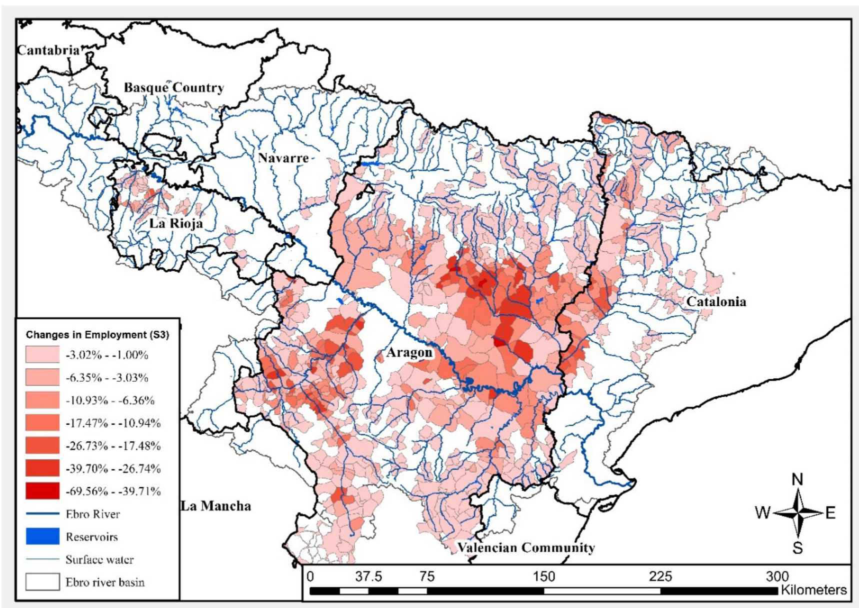

Figure A.7. Changes in Jobs in Scenario 3 (All Sectors)

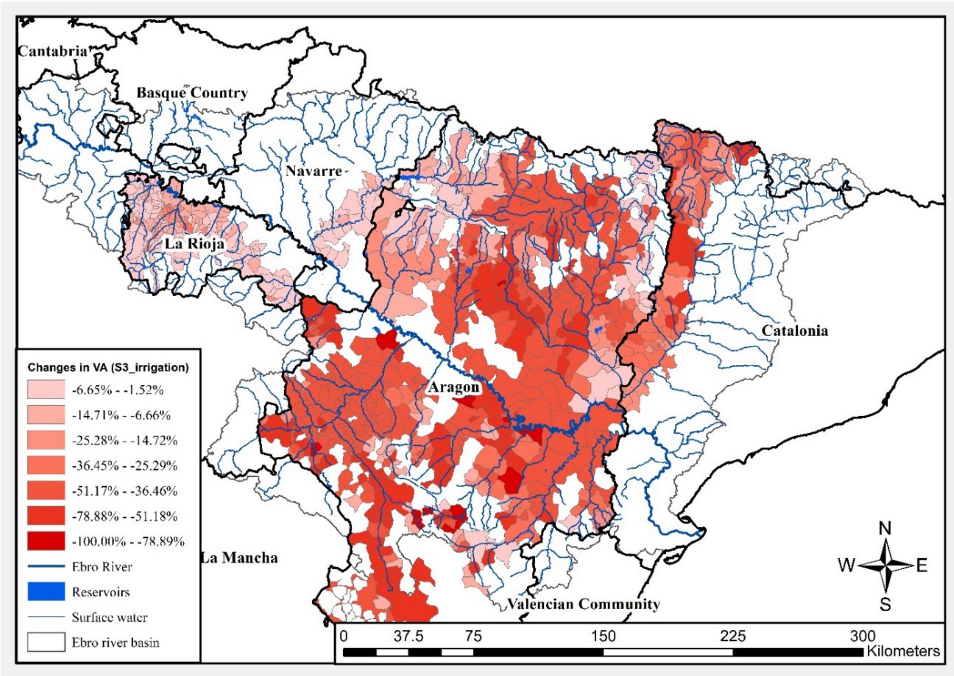

Figure A.8. Changes in Value Added in Irrigated Farming for Scenario 3

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