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Tesis Doctoral

WATER GOVERNANCE IN THE EBRO RIVER BASIN: CONSTRUCTION OF A MULTIREGIONAL AND MULTISECTORAL HIDRO-ECONOMIC MODEL

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Water governance in the Ebro River Basin: Construction of a multiregional and multisectoral hydro-economic model

Doctor of Philosophy in Economics

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"Fresh water is a fundamental requirement for the survival, well-being and socio-economic development of all humanity. Yet, we continue to act as if fresh water were a perpetually abundant resource. It is not. Fresh water is precious: we cannot live without it. It is irreplaceable: there are no substitutes for it. And it is sensitive: human activity has a profound impact on the quantity and quality of fresh water available. It depends on us how much is used in a particular region, and what kind of uses it is put to." (Kofi Annan, Secretary-General of the UN, message for the occasion of World Day for Water, 1999).

A todos aquellos que confiaron en mí.
Sin vosotros, nunca hubiera sido posible.

Agradecimientos

El presente texto recoge parte de las investigaciones realizadas durante mi etapa como estudiante de Doctorado, cuatro largos años que se me hacen cortos gracias al apoyo recibido por algunas instituciones y las personas que las componen. Mi formación como investigador y en consecuencia las investigaciones y resultados logrados no hubieran sido posibles en otro caso, por lo que en las siguientes líneas textualizo lo que espero que ellos ya sepan, mi agradecimiento más sincero.

La realización de una Tesis Doctoral es un reto arduo y largo en el tiempo, por lo que requiere constancia y paciencia, además de conocimiento. Por ello, quiero dedicar estas primeras líneas, y no puede ser de otra manera, a los directores de la presente Tesis: Julio y Rosa. Gracias por la confianza que, años atrás, depositasteis en mí, Gracias por vuestras indicaciones, Gracias por vuestra disposición, Gracias por vuestra tenacidad y vuestra paciencia. Gracias por vuestras indicaciones que me han guiado en esta etapa. Vosotros habéis hecho posible este texto. GRACIAS.

Durante mis estudios de Máster tuve la oportunidad de colaborar en un proyecto de investigación financiado por la Confederación Hidrográfica del Ebro (CHE), y cuyo investigador principal fue Luis Antonio Sáez. Debo agradecerle a él, y al resto de investigadores del proyecto, Julio, Rosa y Ana Serrano, que quisieran contar conmigo para sacar dicho proyecto adelante. De aquí parte mi interés sobre la gestión del agua, y aquí considero que comienza mi carrera investigadora.

Mi etapa como estudiante de Doctorado no hubiera sido igual sin el apoyo económico que me supuso la beca (FPU) que me concedió el, entonces denominado, Ministerio de Educación, Cultura y Deporte, a quien además de agradecerle la financiación le quiero agradecer el formato de la misma, pues me ha permitido ser personal de la Universidad de Zaragoza, y miembro del departamento de Análisis Económico. En este seno me formé académicamente, y en este seno me he formado además de como investigador, como docente. Aquí, rodeado de los que considero prácticamente mi familia, he crecido como persona y por eso quiero agradecer la disponibilidad, la flexibilidad, y la ayuda recibida en lo que respecta no sólo a la investigación y la docencia, sino también a la burocracia.

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Dar las gracias al grupo CREDENAT, es darle las gracias a cada uno de sus integrantes, que no enumero pues son muchos. Compañeros y amigos, como valido de vuestros esfuerzos os digo que de vuestra mano he recorrido los primeros pasos de este camino y en vuestra compañía quiero seguir andándolo. De este gran grupo, además, quiero agradecer el apoyo intelectual y moral que me han brindado Raquel y Sofía, quienes, mostrando una gran disponibilidad y paciencia, a pesar de estar inmersas en la última etapa de su Tesis, siempre encontraron hueco para ayudarme a resolver cuestiones tanto laborales como personales.

La presente Tesis opta a la mención internacional, y uno de los requisitos para tal fin es la realización de una estancia de investigación en el extranjero. Este requisito, en mi caso fue una oportunidad gracias a la amabilidad y disposición de Taher Kahil. Gracias Taher por abrirme las puertas del *International Institute for Applied Systems Analysis* (IIASA), por presentarme como uno más de tu equipo de trabajo, por tu gran dedicación y preocupación, por tu generosidad y apoyo, por enseñarme todo lo que sabes sobre modelos hidroeconómicos. Una parte de esta Tesis nace de aquella semilla. Gracias.

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Decía unas pocas líneas arriba “cuatro largos años que se me hacen cortos”. Y es que, en estos cuatro años, me he encontrado con una fuente inagotable de energía, de ánimos, y de fuerza. Gracias Sala de Becarios 1. Gracias por todo el apoyo y disponibilidad que me habéis dado, Gracias por levantarme con una sonrisa. Gracias por alegrarme las mañanas, las tardes y alguna noche. Compañeros y amigos, por ser como sois, GRACIAS.

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This text brings together the results of my four long years of research as a PhD student, which nonetheless seem to me soon over thanks to the institutional support and personal encouragement I received. Neither my training nor, indeed, my research would have been possible without the help of so many people to whom I owe my most sincere thanks, as I hope they already know.

To write a Doctoral Thesis is a long and arduous challenge, which requires knowledge and understanding, of course, but also perseverance and patience. For this reason, I want to begin by thanking my Thesis supervisors, Julio Sánchez and Rosa Duarte. Thank you for the trust you placed in me at the outset, thank you for your recommendations, thank you for your willingness to help and for your tenacity and patience. Thank you, in short, for your guidance from beginning to end of my Thesis, which I could not have completed without you. THANKS.

While I was still an MA student, I was offered the opportunity to participate in a research project funded by the Ebro River Basin Authority (CHE in its Spanish acronym), which was led by Luis Antonio Sáez. I can only thank him, and the other researchers, Julio, Rosa and Ana Serrano, for their readiness to include me in this project, which kindled my interest in water management and, I believe, launched my research career begins.

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Within this great family, I cannot but mention the warmth and shelter that belonging to the CREDENAT research group on growth, demand and natural resources have meant for me, easing my entry into academic life. Aside from such intangibles, my membership of this group has opened the way for me to participate in, in turn allowing me to attend conferences and courses that have undoubtedly helped me develop as a researcher. I refer here not only to the knowledge I was able to acquire in this way but also, returning to the intangible, to the network of contacts have been able to make. *The most important thing in life is not knowing everything, but having the phone number of the person who does.* – Les Luthiers.

To thank the CREDENAT group is to thank each of its members, whom I cannot individually name here because there are so many of them. My dear colleagues and friends, I have walked the first steps of this path with you, and it is my hope and desire to go on in your company for many years to come. Finally, I wish to thank Raquel and Sofia especially for their intellectual and moral support, and for their patience and willingness to help me resolve both work and personal issues, despite being engrossed in completing their own theses.

This thesis is eligible for international mention, and one of the requirements for which is to complete a research stay abroad. In my case, this was an invaluable opportunity thanks to the kindness and enthusiasm of Taher Kahil, who opened the doors of the *International Institute for Applied Systems Analysis* (IIASA) to me. Thank you, Taher, for treating me as one of your team, for your dedication and concern, for your generosity and support, and for teaching me everything you know about hydro-economic models. This thesis is in no small part the fruit of the seed you planted.

As part of my training, I also stayed at the European Commission's research centres in Seville, where I was able to advance my research with the Economics of Agriculture group - (JRC.D.4). Thanks to all the group for your welcome and to those of you who shared that summer with me. I am especially grateful to Emanuele and Alfredo, who made my stay in Seville possible. Thank you for sharing your time and knowledge with me.

Let me again thank the Department of Economic Analysis at the University of Zaragoza, which has found room for me not only as a researcher but also now as a member of the teaching staff. I am particularly grateful for the flexibility shown me and the trust placed in me by those with whom I have shared teaching. Thanks Paco. Thanks Mara. Thanks Gemma.

If the “four long years” of my research as a “seem to me soon over” as I said at the beginning of these Acknowledgements, it is because I found an inexhaustible source of energy, encouragement, and strength in Thank you Fellows Room 1. Thank you all for your support and the kindness you have shown me. Thank you for greeting me with a smile. Thank you for cheerfulness morning, noon and not a few nights. Comrades and friends, thank you for just being as you are. THANK YOU.

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Introducción general

El cambio climático y la seguridad alimentaria representan retos inminentes para el desarrollo humano y económico a muy distintas escalas. A nivel mundial, se estima que el impacto del cambio climático sobre la disponibilidad y calidad de los recursos hídricos, la producción agraria, la productividad de la tierra y los distintos ecosistemas puede llevar a reducciones de entre el 5% y el 20% del Producto interior bruto (Stern, 2008). En la misma línea, el panel intergubernamental sobre el cambio climático (IPCC, 2014) advierte del incremento de la temperatura media mundial, hecho asociado al incremento del nivel del mar, inundaciones y reducciones de la producción alimenticia. Por otra parte, la globalización y dependencia internacional de las economías, y particularmente, la creciente internacionalización de la cadena de producción agroalimentaria hace que el logro de la seguridad alimentaria se sitúe como uno de los principales retos locales, nacionales y mundiales, logro que depende en buena medida de los recursos hídricos de que disponga cada país o región, así como de la gestión que haga de ellos. La relevancia de todos estos temas queda patente con su inclusión como objetivos del milenio por parte de las Naciones Unidas (United Nations, 2015), el logro de la seguridad alimentaria (objetivo 2), la reducción del cambio climático y su impacto (objetivo 13) y el logro de patrones de consumo y producción sostenibles (objetivo 12).

En esta misma línea, si pensamos en la cantidad y calidad del agua, vemos que está viendo afectada por numerosas variables. Por ejemplo el incremento en los usos y el cambio climático están conduciendo a una disminución de la disponibilidad de agua dulce (Alcamo et al., 2007; Gerten et al., 2008), pero también lo hacen los procesos de la revegetación en cabecera (Bielsa and Cazcarro, 2014); y a la vez que esto ocurre, los usos actuales y la gestión que se realiza del agua llevan a la generación de diversos tipos de contaminación, lo que también supone una reducción de su disponibilidad. La Directiva Marco del Agua (DMA) de la Unión Europea fue, en buena medida, promulgada por estos motivos (European Communities, 2000). En concreto, la DMA requiere que los Estados miembros de la Unión Europea alcancen un buen estado ecológico en todas sus masas de agua y establezcan requerimientos hídricos medioambientales sobre ellas. En otras palabras, se deben establecer caudales medioambientales en todos los ríos europeos que fijen volúmenes y la distribución de estos en el tiempo, así como estándares de calidad de las aguas (Acreman and Dunbar, 2004; Acreman and Ferguson, 2010). Y es que, se está considerando, por parte de la Unión Europea (UE), que la gobernanza del agua es un factor clave para hacer frente a las consecuencias del cambio climático y trazar las sendas que nos conduzcan a la consecución de los objetivos del milenio.

Sin embargo, la gobernanza del agua resulta un reto arduo para todas las sociedades, dado los diferentes tipos de bienes y servicios que hacen uso del agua y de los diferentes tipos de usos. Los más evidentes, los usos consuntivos (agua de boca, regadío, …) compiten no sólo entre ellos, sino también en ocasiones con los usos no consuntivos (producción hidroeléctrica, refrigeración de centrales, …), que exigen una disponibilidad del agua en momentos y espacios del tiempo determinados y que condicionan el resto de los usos; esto ocurre frecuentemente con la industria hidroeléctrica y los regadíos asociados a embalses. Por su parte, los usos recreativos (pesca, por ejemplo) y/o los medioambientales, requieren unos mínimos de cantidad y calidad en puntos o tramos específicos, condicionando también a otros usos consuntivos y no consuntivos.

El agua dulce es un recurso natural imprescindible para la vida y para el desarrollo de cualquier actividad y su valor depende del lugar y del tiempo (Hanemann, 2006). Por ello es conveniente estudiar todo lo relativo al agua y su gestión siempre en un contexto de variabilidad en tiempo y espacio. Es más, la adaptación al cambio climático y el crecimiento económico en esta época, en la que los sistemas productivos son claramente interdependientes a distintas escalas (intersectorialmente e interregionalmente) y que a su vez son influidos por las condiciones ambientales y por sus impactos, requieren también del estudio en profundidad de aspectos centrales tales como el papel del cambio tecnológico, la mejora de los sistemas de gobernanza, las responsabilidades del productor y del consumidor, en un contexto de cadena global de producción, y la vinculación de los aspectos locales y globales de la producción.

Finalmente, no debemos olvidar que el transporte del agua resulta caro en infraestructuras y mantenimiento, además de suponer grandes pérdidas del recurso. Según Gupta y van der Zaag (2008), asumir los costes por trasvases que supongan transporte del agua a grandes distancias sólo estaría justificado para asegurar necesidades vitales. Por todo ello es necesario y lógico asumir, como haremos en esta tesis, que las cuencas hidrográficas son las unidades básicas de planificación y de gestión hídrica, asumiendo para ésta los límites físicos de las cuencas como límites de planificación. Fronteras físicas que poco o nada tienen que ver frecuentemente con las fronteras administrativas. De hecho, existen ríos que conforman fronteras o ríos que atraviesan distintos países o regiones, obligando a gobiernos y agentes con distintos intereses, a participar unidos en la gobernanza; lo que puede derivar en la aparición de conflictos.

Dada esta realidad, es clave para la gestión del agua el desarrollo de modelos multisectoriales y multirregionales que permitan estudiar las dependencias espaciales y temporales entre los agentes económicos de las diferentes regiones de una cuenca. Si bien la metodología que desarrollamos es aplicable a cualquier cuenca hidrográfica, el área de estudio de la tesis será la cuenca del Ebro, una de las más representativas de las cuencas semiáridas mediterráneas (Milano et al., 2013a), obteniendo en este marco los parámetros y relaciones productivas principales. La cuenca del Ebro es un entorno altamente representativo a nivel europeo tanto de presión ambiental (la cuenca está caracterizada por una desigual distribución de los recursos hídricos; las demandas son crecientes; el delta del Ebro está considerada como una de las más importantes zonas vulnerables en Europa), como por su productividad agraria y agroalimentaria, y por las experiencias exitosas de gestión de los recursos hídricos. Más datos sobre la cuenca del Ebro y su caracterización socioeconómica pueden verse en el capítulo 1, que dedicamos exclusivamente al área de estudio.

Sobre los objetivos, las fuentes de datos y las metodologías:

De acuerdo con todo lo anterior, esta tesis avanza en el análisis económico y ambiental del valle del Ebro tanto desde un punto de vista global como local. Estudiaremos las consecuencias de la sucesión de usos del agua en el valle y algunos conflictos entre usuarios. Además, con el objeto de diseñar medidas de mitigación de impacto ambiental y de crecimiento regional sostenible, integraremos las actividades económicas y los flujos hídricos en un mismo modelo. Esto implica tener en cuenta, de forma integrada geográfica y sectorialmente, elementos que tradicionalmente se han estudiado de forma aislada y local (o regional), tales como el impacto ambiental de las actividades económicas, la especialización productiva, las dependencias sectoriales y multirregionales de la producción y de los usos del agua, el papel del cambio tecnológico (en las técnicas de producción y en los patrones de consumo), las posibilidades de cooperación (local y regional) entre agentes implicados en el uso del agua, y como marco general la gobernanza y gestión de los recursos hídricos asociados a la cuenca del Ebro.

La elaboración de la presente tesis ha exigido un esfuerzo considerable en lo que a la búsqueda y tratamiento de datos se refiere. Este esfuerzo nos ha llevado a tres resultados empíricos importantes; el primero es la construcción de una base de datos a nivel municipal de la cuenca del Ebro y cuyas características principales pueden consultarse en el Anexo del capítulo 1. El segundo, que es una contribución central de la presente tesis, es la construcción de la tabla multirregional de la cuenca del Ebro, que hasta dónde llega nuestro conocimiento es la primera tabla input-output multirregional elaborada para una cuenca hidrográfica. El tercero es la construcción de un modelo hidroeconómico para la cuenca del Ebro que integra flujos de agua y estructura input-output y que tampoco se ha hecho anteriormente.

Las metodologías principales que usaremos en esta tesis son: el marco input-output, la teoría de juegos, los modelos hidroeconómicos y los sistemas de información geográfica. Estas metodologías nos permitirán, desde el marco multirregional que caracteriza la cuenca, simular alternativas a la gestión y evaluar impactos socioeconómicos y medioambientales.

El marco input-output nos permite conocer la interrelación entre sectores y regiones a la vez que nos permite evaluar los impactos directos e indirectos frente a un posible shock, por estos motivos, ha sido ampliamente utilizado en Economía y es una herramienta muy útil en la economía del medioambiente. La teoría de juegos también ha sido ampliamente utilizada en economía, y en particular en la Economía del agua, al permitir analizar los conflictos entre los jugadores bajo muy diferentes enfoques. El enfoque del juego puede asociarse con las condiciones institucionales en que se desarrolla la actividad económica; en ese sentido, la necesidad de cooperar y de competir en los procesos de gestión del agua son muy adecuados para la teoría de juegos. Esta permite determinar óptimos de reparto atendiendo a distintos criterios y poderes de negociación, o determinar coaliciones óptimas y los repartos óptimos dentro de estas coaliciones. Los modelos hidroeconómicos tienen en cuenta el espacio y el tiempo, tanto para su parte hidrológica, como para su parte socioeconómica; por ello, se convierten en una herramienta muy útil para estudiar y/o evaluar las capacidades y alternativas o escenarios de gestión hídrica. Por su parte, los sistemas de información geográfica son fuentes de información que combinaremos con los datos y resultados que vayamos obteniendo; además, nos apoyaremos en los sistemas de información geográfica para realizar análisis espaciales de los distintos usos del agua y de los impactos de los diferentes escenarios que propongamos. Más adelante, en el segundo capítulo, aportamos un mayor detalle sobre las metodologías y herramientas usadas.

Sobre la estructura de la tesis:

Los objetivos antes señalados y los instrumentos metodológicos nos definen en buena medida los diferentes apartados de esta tesis. El siguiente capítulo (capítulo 1), lo dedicamos a la caracterización socioeconómica y medioambiental del área de estudio, la cuenca del Ebro, fijándonos especialmente en los flujos hídricos que discurren por esta cuenca. En el capítulo 2 revisaremos inicialmente otras aportaciones que se han hecho en economía y gestión del agua y que nos servirán de guía en nuestro trabajo. En este tercer capítulo veremos las principales características de cada una de nuestras metodologías base: los modelos input-output en la sección 2.1, la teoría de juegos en la 2.2, los modelos hidroeconómicos en la 2.3 y los sistemas de información geográfica en la 2.4.

Tras la revisión metodológica, el capítulo 3 analiza un caso concreto de gestión, el conflicto existente entre los usos del agua en el tramo bajo del Ebro y los requerimientos medioambientales del Delta. Este capítulo sirve de introducción y justificación en parte de los siguientes. El Ebro es el río más caudaloso de España y conduce al Delta sedimentos procedentes del Pirineo y del Sistema Ibérico entre otros. Estos aportes de sedimentos conforman y mantienen el Delta y permiten combatir la cuña salina actual, problema que se ha agravado con la regulación aguas arriba (especialmente en Mequinenza) y con el cambio climático que provoca incrementos en el nivel del mar.

La Confederación Hidrográfica del Ebro (CHE) es la encargada de elaborar los planes hidrológicos para la cuenca del Ebro (CHE, 2014). Tras la elaboración de dicho plan, los distintos agentes interesados pueden expresar su opinión y plantear cambios. En los últimos años en estas rondas de consultas los caudales mínimos medioambientales fijados para el Delta han sido tildados de insuficientes en varias ocasiones por algunos agentes; hecho que se ve reflejado en la memoria de dichos planes. Agentes representativos de estas demandas son la agencia catalana del agua (ACA) y la comisión de sostenibilidad de las tierras del Ebro (CSTE). Estos dos agentes han planteado sendas propuestas de caudales mínimos (ACA, 2007; CSTE, 2015). Por este motivo, el capítulo 3 lo dedicamos a analizar las posibilidades de incrementar los caudales ecológicos del Delta acorde a dichas propuestas y planteando diversas alternativas de gestión del tramo bajo del Ebro. En la actualidad, la gestión del cumplimiento de los caudales medioambientales del Delta recae en exclusiva sobre el embalse de Mequinenza, solución que ha llevado en ocasiones a este embalse a niveles de agua embalsada preocupantes medioambientalmente y a ojos de los regantes y usuarios que de él se abastecen. Las alternativas de gestión que proponemos tienen en cuenta el uso de otros embalses para este objetivo. Para nuestro análisis hemos construido un modelo de flujos hídricos simplificado en el que hemos simulado con datos mensuales reales de 50 años distintas alternativas de gestión. Los resultados del modelo los analizamos haciendo uso de la teoría de juegos.

El análisis interregional e intersectorial es clave para entender las dependencias socioeconómicas y también en términos medioambientales de la cuenca del Ebro, por este motivo en el capítulo 4 lo dedicamos a explicar la construcción de una tabla input-output que atienda a sus fronteras físicas, así como a analizar interregional e intersectorialmente sus flujos comerciales, lo que conlleva el estudio de los flujos virtuales de valor añadido, empleo y agua implícitos asociados con la cuenca. Describiremos, por tanto, las fuentes usadas y los pasos principales del proceso seguido para la construcción de la tabla multirregional de la cuenca del Ebro. En este sentido, debemos destacar que aproximaremos la cuenca del Ebro por las partes que recaen dentro de la cuenca de las 5 regiones más representativas que la componen, que son Aragón, Cataluña, País Vasco, La Rioja y Navarra; por lo que la tabla input-output multirregional de la cuenca del Ebro contempla estas regiones, así como el resto de España, el resto de la UE y el resto del Mundo.

Para la elaboración de la tabla multirregional input-output nuestras fuentes principales son las tablas proporcionadas por los institutos de estadística de las regiones consideradas, así como el Instituto Nacional de Estadística, y la base WIOD de datos de tablas input-output mundial (Timmer et al., 2015) y. De cara a extender el modelo medioambientalmente, nos apoyaremos en las cuentas satélite existentes en WIOD (Genty et al., 2012), en los datos de (Chapagain and Hoekstra, 2004) y en los datos de un modelo multirregional previo desarrollado para toda España (Cazcarro et al., 2014). Dado nuestro interés en la gobernanza del agua, la tabla tiene un elevado nivel de desagregación en lo que respecta al sector primario, principal usuario consuntivo de agua. Más concretamente, el sector primario, para las regiones de la cuenca del Ebro, lo dividimos en 3: producción vegetal, producción animal y resto del sector primario. Hecha esta primera división, dividimos la producción vegetal en 18 grupos de cultivos y estos cultivos a su vez los dividimos entre regadío y secano. La producción animal se divide también en 6 grupos.

Este nivel de desagregación, además de permitirnos caracterizar la cuenca con mayor detalle, nos da pie a utilizar esta tabla como base para la construcción de un modelo hidroeconómico de la cuenca del Ebro. Una vez construida la tabla, utilizamos ésta y los sistemas de información geográfica (GIS) para profundizar en la caracterización de la cuenca, analizando las interdependencias regionales y sectoriales asociadas a diversas variables.

Dando continuación a los capítulos 3 y 4, dónde usamos la modelización de flujos hídricos simplificada y construimos la tabla multirregional input-output de la cuenca del Ebro, el capítulo 5 lo dedicamos a vincular ambas metodologías, siendo esto una contribución científica importante porque, hasta donde conocemos, esta integración no se ha realizado previamente.

Vinculando estas metodologías dotamos a nuestro modelo multirregional (capítulo 4) de un conjunto de restricciones en la disponibilidad de agua sujeta a los flujos que caracterizan la cuenca mes a mes, los usos previos y las necesidades medioambientales. Los modelos hidroeconómicos tienen una de sus bases en la modelización de flujos hídricos respetando los principios del balance de masas de agua y la continuidad del caudal del río, que determinan el volumen de disponibilidad de agua en los diferentes tramos fluviales. Para ello, determinaremos nodos que contabilizan el agua disponible y formularemos ecuaciones que determinan la relación entre los distintos nodos (las direcciones que toma el agua). Es decir, su componente hidrológico identifica el agua disponible para su uso en cada zona, sus usos y también el destino del agua no usada.

La otra base de los modelos hidroeconómicos, son las ecuaciones de comportamiento de los agentes. El uso de agua que hagan los agentes estará asociado a un determinado nodo, quiere decir, las extracciones de agua que cada agente realice serán mermas asociadas a un nodo concreto, por lo que el agua disponible para cada agente está determinada por el uso de los agentes ubicados aguas arriba y por la hidrología. Aquí toma relevancia la tabla multirregional input-output de la cuenca del Ebro, pues las ecuaciones de comportamiento las basaremos en las relaciones intersectoriales e interregionales que subyacen en esta tabla y en las condiciones de equilibrio del marco input-output.

Este modelo hidroeconómico multisectorial y multirregional, permitirá analizar de una forma conjunta e integrada las actividades económicas de producción y consumo y la realidad fluyente de las aguas en el Valle y sus usos sucesivos. Este modelo nos permite plantear la maximización del beneficio de las actividades asociadas a los usos del agua, pero sin simplificar, como es usual, el componente económico. Restricciones de uso del recurso hídrico, cambio tecnológico, comercio regional, importaciones y exportaciones, cambios en las demandas, etc., son temas que pueden abordarse con este modelo y que haremos en cierta medida. Por otra parte, los impactos medioambientales (nos focalizaremos en la temática del agua) de las distintas producciones y consumos, pueden ser cuantificadas de forma detallada, viendo los pesos de cada actividad y de cada lugar o región. El uso de diferentes escenarios es de gran utilidad para ello, así como la utilización de sistemas de información geográfica. Por ello, tras la construcción del modelo hidroeconómico de la cuenca del Ebro nos disponemos a mostrar la potencialidad de éste proponiendo diversos escenarios y analizando los resultados. En este análisis de resultados, cobra protagonismo el uso de los sistemas de información geográfica, pues nos ayudarán a localizar las áreas afectadas e identificar las posibles vías de mejora.

Finaliza la tesis con un resumen final, en él se recogen los principales resultados obtenidos, se comentan algunas de las conclusiones prácticas y políticas que se han alcanzado y se describen las futuras direcciones de investigación surgidas de la tesis.

General introduction

Climate change and food safety are both imminent challenges for social and economic development, despite the differences in their order of magnitude. It is estimated that the global impact of climate change on the availability and quality of water resources, farm output, land productivity and ecosystems could cut world GDP by between 5% and 20% (Stern, 2008). Meanwhile, the intergovernmental panel on climate change (IPCC, 2014) has sounded the alarm over the increase in average global temperatures, a phenomenon associated with rising sea levels, flooding and falling food production. In this context, globalization and the growing interdependence of national economies, which is starkly evident in the internationalization of agri-food production chains, have made food security into a major issue not only locally or nationally but even at the global level. Success will depend to a great extent on the available water resources in each country or region, and on the management of those resources. The importance of these issues is reflected in the Sustainable Development Goals (SDGs) set by the UN in 2015 (United Nations, 2015), which include zero hunger (goal 2); responsible consumption and production (goal 12); and climate action (goal 13).

It becomes clear almost as soon as one begins to think seriously about water that multiple variables affect the quantity and quality of the resource. For example, increased consumption and climate change put pressure on the availability of fresh water (Alcamo et al., 2007; Gerten et al., 2008), but so do bedding and revegetation processes (Bielsa and Cazcarro, 2014), while different water uses and management options may cause contamination, again leading to a reduction in availability. The European Union Water Framework Directive (WFD) (European Communities, 2000) was adopted largely in view of these issues. Specifically, the WFD obliges the Member States of the European Union to take steps to assure the ecological condition of all water bodies and to set environmental flow water requirements. In other words, the volume and distribution of environmental flows over must be defined for all European rivers, together with minimum water quality standards (Acreman and Dunbar, 2004; Acreman and Ferguson, 2010). In general terms, then, the European Union (EU) considers that water governance is a key tool to repair the effects of climate change and to chart paths towards the achievement of the millennium goals.

Water governance is an arduous challenge for all societies, however, given the enormous range of goods and services that make use of water in some way and the sheer diversity of actual and possible uses. The most obvious consumptive uses (drinking water, irrigation and so on) compete not only with each other but sometimes also with non-consumptive uses (hydroelectric generating, power plant cooling, etc.) that require water availability at specific locations and times, thereby conditioning other uses. Such conflicts are common enough in relation to water stored in reservoirs associated with hydroelectric generating and irrigation. Meanwhile, recreational uses like fishing and environmental uses also require minimum water quantity and quality at specific points or reaches along a river, again conditioning other consumptive and non-consumptive uses.

Fresh water is an essential natural resource for life and for almost any kind of economic development, and its value depends on both place and time (Hanemann, 2006). Hence, any analysis of water use and management must inevitably be made in a context of variability in time and space. Furthermore, adaptation to climate change and economic growth in a world where production systems are clearly interdependent at different levels across economic sectors and regions, and are directly influenced by environmental conditions and their impacts, cannot be addressed without close consideration of key issues like the role of technological change, the improvement of governance systems, producer and consumer responsibility in the context of the global production chain, and the links between local and global aspects of production.

Let us not forget, meanwhile, that water is expensive to transport, requiring major capital expenditures to build and maintain infrastructure, not to mention the significant cost of losses along the way. In this light, Gupta and van der Zaag (2008) argue that the costs of long-distance water transportation can only be justified where such transfers are required to guarantee vital supplies.

This thesis treats hydrographic basins as the basic water planning and management units, as seems only logical for all of the above reasons, assuming their physical limits as planning constraints. Meanwhile, rivers often mark borders or run through different countries and regions, obliging governments and other riparian agents representing sometimes very diverse interests to cooperate in governance. Such situations can, on occasion, lead to conflict.

In this light, multisectoral, multiregional models like that developed here to analyse the spatial and temporal dependencies between economic agents in the different regions of a river basin are indispensable for water management. While the methodology described here is applicable to any hydrographic basin, the case study considered in this thesis will be the Ebro River Basin (ERB), perhaps the most representative of the semi-arid Mediterranean basins (Milano et al., 2013a), which will provide a framework to distinguish and determine key parameters and productive relationships. The ERB is a highly 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 (the Ebro Delta is one of the most ecologically vulnerable areas in Europe). On the plus side, however, it supports highly productive agriculture, while water management experiences have in general been highly successful. Chapter 1 is given over entirely to the case study area, providing more detailed geographical and socio-economic information about the ERB.

Objectives, data sources and methodologies

As explained above, this thesis approaches the economic and environmental analysis of the ERB both from a global and local standpoint, examining the consequences of the succession of water uses in the river basin and some of the conflicts between users. The model also integrates different economic activities and water flows, allowing the design of measures to mitigate environmental impacts and foster sustainable regional growth. This allows consideration of a series of geographic and sector-related factors that have traditionally been studied separately at the local (or regional) level, including the environmental impact of economic activities, specialization, sectoral and multi-regional dependencies measured in terms of output and water uses, the role of technological change on production techniques and consumption patterns, and opportunities for local and regional cooperation between different users of water, and the general framework for governance and management of the ERB's water resources .

The considerable research effort required in terms of data mining and data processing to prepare this thesis study produced important empirical results, allowing, in the first place the construction of a municipal-level database for the ERB, the main characteristics of which are outlined in in the Annex to Chapter 1; in the second, construction of a multiregional and multisector input-output table for the ERB, which is a central contribution to this thesis and, to the best of our knowledge, is the first such MRIO model to be made for any hydrographic basin; and in the third, construction of a hydro-economic model for the ERB which integrates water flows and an input-output structure, another first.

The main methodologies utilized in this thesis are the input-output framework, game theory, hydro-economic models and geographic information systems. These methodologies will allow us to simulate water management alternatives and evaluate socioeconomic and environmental impacts in the multiregional context of the ERB.

The input-output framework reveals the interrelationships between sectors and regions and facilitates assessment of the direct and indirect impacts of possible shocks. For these reasons it has been widely used in economics and has proved a very useful tool to address environmental questions. Game theory has also been taken up enthusiastically by economists, particularly those studying water issues, because it permits analysis of conflict between players from a variety of sometimes very different angles. Among other possibilities, the game theory approach, which is well suited to reflect cooperation and competition in water management processes, can be associated with the institutional conditions under which economic activity takes place allowing researchers to determine the optimal distribution of available water in different scenarios based on a range of criteria and varying assumptions with regard to negotiating power, and to identify both optimal coalitions and optimal distributions within them. Hydro-economic models also take space and time into account, in both hydrological and socioeconomic terms, offering a very handy tool to study and/or evaluate water management capabilities and alternatives.

Meanwhile, geographic information systems (GIS) provide a range of data which we will combine with our findings. We rely on geographic information systems to carry out spatial analysis of the different uses of water and the impacts of the different scenarios that we propose. More detail on the methodologies and tools used is provided in the second chapter.

Thesis structure:

The objectives and methodological instruments mentioned above largely define the different sections of this thesis. Chapter 1 offers a socioeconomic and environmental description of the Ebro River Basin, paying special attention to its water flows. In Chapter 2 we review other contributions made in the fields of economics and water management to outline the context of the case study, and we discuss the main characteristics of our base methodologies: (input-output models in section 2.1, game theory in 2.2, hydro-economic models in 2.3 and geographic information systems in 2.4).

Following this methodological review, Chapter 3 examines a specific water management case study involving the conflict between water use in the last stretch of the Ebro and the environmental requirements of the Delta. This chapter introduces and partly justifies what follows. The Ebro is the largest river in Spain, and the sediments it carries downstream from the highlands of the Pyrenees and the Iberian System help to make up and maintain the Delta, at the same time counteracting the growing salt wedge, a problem that has worsened due to upstream regulation (especially at Mequinenza) and climate change, which has raised sea levels in recent decades.

The ERB Authority (*Confederación Hidrográfica del Ebro* or CHE in the Spanish acronym) is responsible for hydrological planning in the River Basin (CHE, 2014). After initial drafting, these plans are submitted to the ERB’s stakeholders to obtain their opinions and allow them to propose changes. In recent years, certain players, in particular the the Catalan Water Agency (*Agència Catalana de l'Aigua* or ACA) and the Lower Ebro Sustainability Commission (*Comissió per a la sostenibilitat de les Terres de l'Ebre* or CSTE) , have branded the minimum environmental flows set for the Delta as insufficient in these rounds of consultations, as reflected in the planning reports, and both . agencies have put forward their own proposals for minimum environmental flows (ACA, 2007; CSTE, 2015). Chapter 3 analyses the options available to increase ecological flows in the Delta in line with these proposals, suggesting various management alternatives for the final stretch of the Ebro. The management of environmental flows into the Delta is currently handled solely from the Mequinenza dam, a solution that has sometimes drained water from the reservoir to environmentally concerning levels, drawing protests from irrigators and other users. The management alternatives that we propose take into account the possibility of using other reservoirs to help achieve the objective of increased environmental flows in the Ebro Delta. A simplified water flow model was built for the purpose of this analysis, simulating possible management alternatives using a real monthly data set spanning 50 years. We analyse the results of this model using game theory.

Interregional and inter-sectoral analysis is key to understanding socio-economic dependencies and environmental conditions in the Ebro Basin, and Chapter 4 is therefore given over to the construction of an input-output table that matches it geographically and to the analysis of interregional and inter-sector trade flows based on the associated implicit virtual flows of value added, jobs and water. This chapter, then, describes the sources used and the main steps in the process followed to construct the multi-regional IO table. In this regard, let us note that our model approach the ERB by the part of five of Spain's Autonomous Communities (the most representative political regions), namely Aragon, the Basque Country, Catalonia, La Rioja and Navarre; Therefore, the multi-regional input-output table for the ERB considers these regions, as well as the rest of Spain, the rest of the EU and the rest of the world.

Our main sources for the construction of the multi-regional input-output table are the tables provided by regional statistics offices, the Spanish National Statistics Institute, and the World Input-Output Database (WIOD) (Timmer et al., 2015). We rely on the existing satellite accounts at WIOD (Genty et al., 2012), the data reported by Chapagain and Hoekstra (2004) and data from a previous multi-regional model developed for the whole of Spain (Cazcarro et al., 2014) to extend the model environmentally. Given our interest in water governance, the table reflects a high level of primary sector disaggregation, which is the main consumptive user of water. More specifically, the primary sector in the ERB regions, is split between crop cultivation, livestock, and other primary sector activities. Farm output is then further subdivided into 18 groups of irrigated and rainfed crops, which are in turn segmented into, and six livestock groups.

This level of disaggregation not only adds detail to the description of the ERB but means that we can use the IO table as a basis for the construction of a hydro-economic model, which is then used together with GIS data flesh out our portrayal of the ERB by analysing the regional and sectoral interdependencies associated with a range of different variables.

Chapter 5 links the methodologies employed to build the simplified water flow model and multi-regional input-output table for the ERB in Chapters 3 and 4. This is itself a significant scientific contribution, because these approaches have never, to the best of our knowledge, been integrated in this way before.

By linking water flow modelling and IO methodologies, we may establish a set of water availability constraints in our multiregional model (Chapter 4) based on characteristic monthly flows in the ERB, previous uses and environmental needs. Water flow modelling of this kind, respecting the principles of water mass balance and the continuity of river flow, which determine the volume of water availability in the different river sections, is a key feature of hydro-economic models. To this end, we determine a series of nodes where water availability is calculated, formulating equations to describe the relationships between nodes (i.e. the direction of the different water flows). In other words, the hydrological component of the model identifies the water available in each area of the river basin every month, uses of the resource and the destination of unused water.

Agent behaviour equations form the other pillar of hydro-economic models. Water use by the agents in a river basin is associated with a given node, so that withdrawals by each agent are subtracted from a specific node. Hence, the water available for use by a given agent is determined by upstream use by other agents and by hydrological conditions. It is here that multiregional input-output table for the ERB comes in, because the behavioural equations used are based on the underlying inter-sectoral and interregional relationships and on the equilibrium conditions of the input-output framework.

This multi-sectoral and multi-regional hydro-economic model allows a joint, integrated analysis of both productive and consumptive economic activities and of actual water flows taking into consideration successive uses of the resource. Using this model we can, then, propose measures to maximize the benefits obtained from the activities associated with different water uses, but without oversimplifying the economic component, as is all too often the case. The issues that can be addressed with this model include constraints on the use of water resources, technological change, regional trade, imports and exports, changes in demand and so on, and we will look at some of these below. Meanwhile, the environmental impacts of different productive and consumptive water uses can also be quantified in detail by looking at the share accounted for by each activity at each node or for each region. Analysis of different scenarios using GIS data is ideal for these purposes. For this reason, we set out to show the potential of the hydro-economic model of the ERB constructed on the basis described, proposing various scenarios and analysing the results. GIS plays a key role in this analysis, helping locate the areas affected by the impacts observed and identify possible ways to improve outcomes.

This thesis ends with a summary and conclusions section, in which we describe and discuss key findings together with some practical and political conclusions from this research, as well as the future lines of enquiry that it suggests.

Chapter 1

Study Area

1.1. Description of the Ebro basin

The empirical research described in this thesis focuses on the Ebro River Basin (ERB) as a case study. The ERB covers an area of 85,569 km^2 (almost 17% of Spain's total land mass), and according to 2013 municipal registers and the ERB Authority (*Confederación Hidrográfica del Ebro* or CHE in its Spanish acronym), it supplies 3,226,921 people in a total of 1,724 towns and villages including the cities of Zaragoza, Vitoria, Pamplona, Logroño, Lleida and Huesca, where some45% of the basin's population live. The ERB is located in the northeast of Spain, between the highlands of the Iberian System on the Ebro's right bank and the ranges of the Basque Mountains and the Pyrenees on the left, where most of the river's water resources come from. In fact, the three main tributaries of the Ebro, the Gállego, the Cinca and the Segre, as well as the vast majority of minor streams, are located on this side of the Ebro.

According to the draft ERB Hydrological Plan for 2021-2027 (CHE, 2019), which is based on 2016 data, the basin generates some 8.1% of Spain's gross value added. Compared to Spain as a whole, the value added generated in the Ebro River Basin is biased towards agriculture and industry to the detriment of services, which respectively account for 4.13% and 27.73% of total (for 2.60% and 17.80% for Spain as a whole), underlining the importance of the primary and secondary sectors in the ERB. Meanwhile, the value added by construction in the ERB is very similar to the rest of Spain. However, the service sector represents 62.49% compared to 74% nationally.

The Ebro Basin includes parts of nine Autonomous Communities (political regions), displaying a marked multi-regional character like Spain as a whole. As shown in Table 1.1 and Figure 1.1, the area of each Autonomous Community that forms part of the ERB (shown in percentage terms in the fourth column) varies widely, as does the percentage area of the ERB represented by each community (fifth column).

Table 1.1. Autonomous Communities forming part of the Ebro Basin

Autonomous Community	Total area (km^2)	Area included in the ERB (km^2)	% area in the Ebro Basin	% of Ebro Basin	Population (thousands of inhabitants)	Population living in the ERB	Value Added in the ERB (millions of euros)*
Aragon	47,720	42,111	88.25%	49.21%	1,347	1,293	30,938
Catalonia	32,091	15,635	48.72%	18.27%	7,554	591	14,599
Navarre	10,390	9,229	88.83%	10.79%	644	616	15,872
Castile-León	94,227	8,148	8.65%	9.52%	2,520	93	3,140
La Rioja	5,045	5,023	99.56%	5.87%	322	322	7,259
Basque Country	7,230	2,678	37.04%	3.13%	2,192	287	9,045
Castile-La Mancha	79,462	1,119	1.41%	1.31%	2,101	2	186
Valencia	23,254	851	3.66%	0.99%	5,114	5	229
Cantabria	5,327	775	14.55%	0.91%	592	18	347

Source: Ebro River Basin Authority (CHE, 2015); *estimated figures for 2010

The predominant Autonomous Community in the Ebro Basin is Aragon, both by area and by population. As shown in Table 1.1, Aragón accounts for almost 50% of the total area of the ERB, 40% of its population and 36% of the value added it generates. Meanwhile Catalonia makes up 18% of the ERB by area, almost 20% by population and 18% by value added. The third largest Autonomous Community by area in the basin is Navarre, which represents more than 10%, and also the most value added *per capita*. Castile-León ranks fourth in terms of area, however, but the largely upland areas through which the Ebro flows in this region are sparsely populated and the region contributes less than 5% to the ERB's total population and to its value added. La Rioja is the fifth largest region in the ERB by area and more than 99% of the Autonomous Community belongs to the basin. La Rioja has a population of 322,415, accounting for around 10% of the ERB total, and it contributes some 9% of total value added. The Basque Country represents just over 3% of the ERB by area, but its higher population density means it accounts for some 9% of the total living in the basin and almost 12% of its value added. The other Autonomous Communities (Castile-La Mancha, the Autonomous Community of Valencia and Cantabria) are residual, together accounting for only 3% of the ERB's total area, and just 1% of its population and value added.

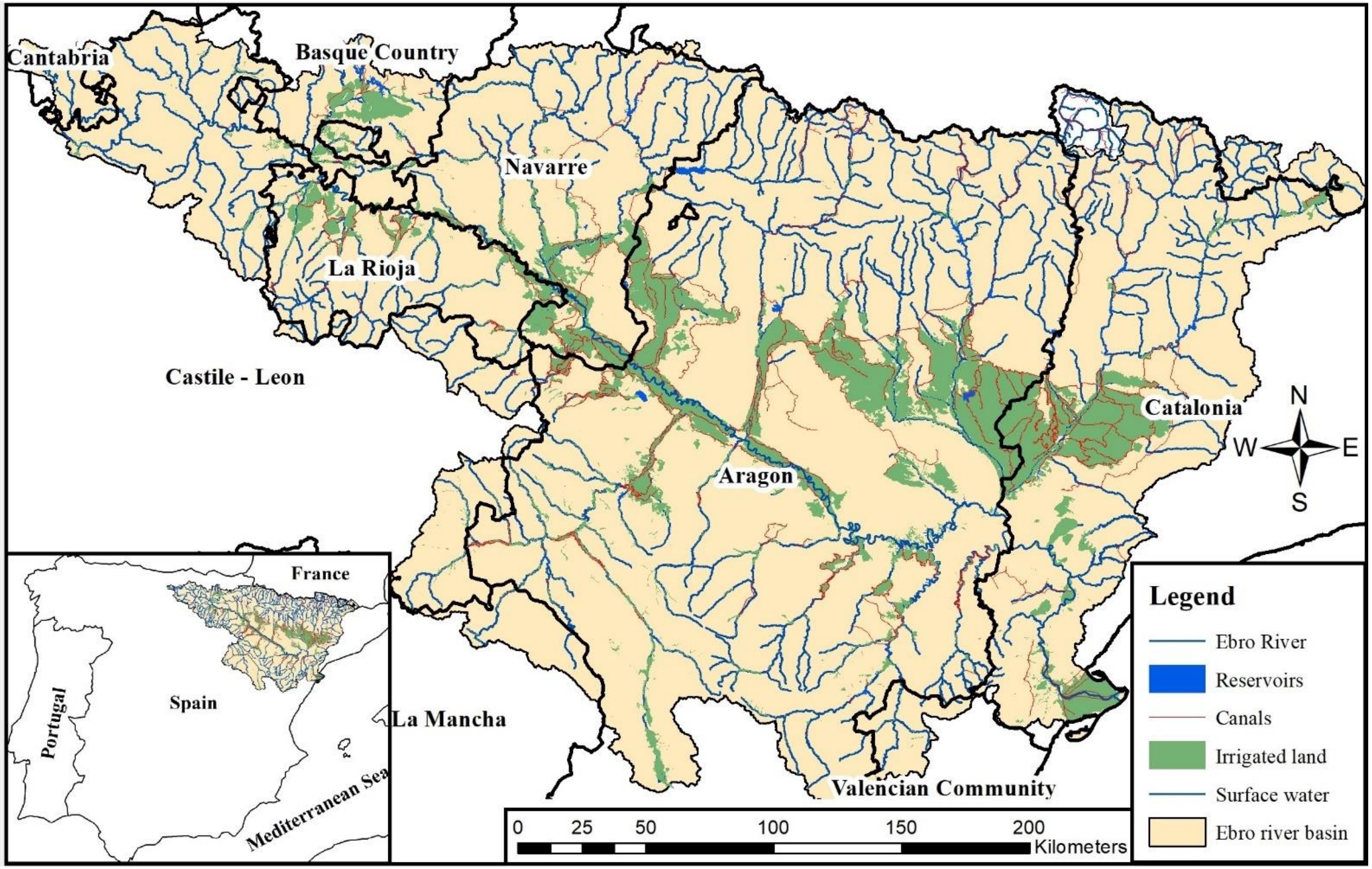
Given the very small area of the ERB they represent, we opted to discard Castile-La Mancha, the Autonomous Community of Valencia and Cantabria regions for modelling purposes. Castile-Leon was also excluded because the socioeconomic data for the region as a whole are not representative of the area falling within the Ebro Basin, which in any case accounts for less than 7% of the Autonomous Community's total value added and population. The multiregional analysis is therefore based on a model of the ERB including only the parts of Aragon, Catalonia, Navarre, La Rioja and the Basque Country that belonging to the river basin.

The regions making up the ERB (as modelled) display differentiated production structures, which in turn generate differences in water consumption. This can be seen in the distribution of value added (VA) between sectors. As shown in Table 1.2, the service sector is predominant in all five regions, with shares ranging from 53% in the Basque Country to 63% in Aragon. Construction accounts for a similar share of the total (around 10%) in all five regions analysed. The share represented by industry various considerably, however, representing 19% of total value added in Catalonia and 22% in Aragon 22%, rising to 34% in the Basque Country and 29% in Navarre, both regions with a markedly more industrial economy.

Meanwhile, the primary sector contributes almost 8% of total value added in Catalonia, almost 30% of which is obtained from livestock farming and 53% from irrigated crops, compared to 15% from rainfed crops. La Rioja ranks second out of the five Autonomous Communities in terms of the size of its primary sector. As in Catalonia, more than 50% of farm value added in La Rioja comes from irrigated crops. Though its primary sector is the largest in absolute terms, Aragon ranks only third in terms of the value added by farming, which accounts for 5% of the regional total. Some 40% of the value added contributed comes from irrigated crops, 30% from rainfed crops and 25% from animal husbandry.

The fifth column of Table 1.2 shows our estimates of the water consumed by each sector based on the municipal level data contained in our database (see Annex at the end of this Chapter), applying a fixed coefficient by obtained from the environmental satellite accounts of the World Input-Output Database (WIOD) (Genty et al., 2012). This column refers to blue water consumed directly in the production processes of each sector. The region that consumes the most water in the ERB is Aragón, where 44% of consumptive use occurs according to our calculations. The second region that consumes the most water is Catalonia ranks second in the ERB in terms of blue water consumption on 35%. Navarra and La Rioja consume around 9% each and the Basque Country uses only 3% of the ERB’s blue water.

Figure 1.1. The Ebro river basin



Source: Own work based on GIS data obtained from MAPAMA, (2016)

Table 1.2 Value added and consumed water by sector.

Region	Sector	VA (million €)	VA (%)	Water Consumed (hm^3)	AWP (€/m^3)
Aragon	Irrigated crops	633	2.05%	1,887	0.34
	Rainfed crops	469	1.52%	0	-
	Livestock	388	1.25%	131	2.96
	Other primary sector	58	0.19%	23	2.52
	Industry	6,997	22.62%	13	538.23
	Construction	2,920	9.44%	170	17.18
	Services	19,473	62.94%	0	-
	Total	30,938	100.00%	2224	561.23
Catalonia	Irrigated crops	605	4.14%	1,513	0.4
	Rainfed crops	168	1.15%	0	-
	Livestock	332	2.27%	119	2.79
	Other primary sector	35	0.24%	15	2.33
	Industry	2,753	18.86%	8	344.13
	Construction	1,619	11.09%	103	15.72
	Services	9,087	62.24%	0	-
	Total	14,599	100.00%	1758	365.37
Navarre	Irrigated crops	255	1.61%	359	0.71
	Rainfed crops	201	1.27%	0	-
	Livestock	65	0.41%	28	2.32
	Other primary sector	14	0.09%	5	2.8
	Industry	4,643	29.25%	10	464.3
	Construction	1,350	8.51%	66	20.45
	Services	9,344	58.87%	0	-
	Total	15,872	100.00%	468	490.58
Basque Country	Irrigated crops	28	0.31%	67	0.42
	Rainfed crops	68	0.75%	0	-
	Livestock	57	0.63%	14	4.07
	Other primary sector	3	0.03%	1	3
	Industry	3,055	33.78%	8	381.88
	Construction	962	10.64%	78	12.33
	Services	4,872	53.86%	0	-
	Total	9,045	100.00%	168	401.7
La Rioja	Irrigated crops	211	2.91%	374	0.56
	Rainfed crops	117	1.61%	0	-
	Livestock	54	0.74%	6	9
	Other primary sector	16	0.22%	7	2.29
	Industry	1,997	27.51%	7	285.29
	Construction	692	9.53%	49	14.12
	Services	4,172	57.47%	0	-
	Total	7,259	100.00%	443	311.26
Total		77,713	-	5,061	15.35

Source: Own Work - AWP: Apparent water productivity (€/m^3)

As may be observed, consumption associated with services and rainfed crops is practically zero, given the negligible use of water required in these sectors. Furthermore, water consumption is largely concentrated in the primary sector, in particular irrigated farming. Irrigation in Aragon uses 37% of all the water consumed in the ERB, while Catalonia uses a further 30%. Navarre and La Rioja use 7% of total water consumption each to irrigate crops, and the Basque country just 1%.

The last column of Table 1.2 shows apparent water productivity calculated on the basis of value added contributed by each sector in each region and on the water needed to generate it. This exercise shows industrial water uses to be the most productive, while the make-up of industry in each region largely determines differences in apparent water productivity between industries. Meanwhile, construction generates 12-20 euros of value added per cubic meter of used water but irrigation, which uses water as one of its main inputs, produces a meagre 0.34-0.71 euros of value added per cubic meter consumed (largely due to evapotranspiration).

Description of water resources

The Ebro Basin presents high levels of evapotranspiration (450 mm) but low, irregular rainfall (620 mm) according to Novau and Campo (1995). Based on data for the period 1940-2005, the average annual available water was 16,448 hm^3/year, although data for period 1980-2005 show average annual available water of 14,623 hm^3/year. Nevertheless, this data series displays high volatility with an observed maximum annual availability of 24,019 hm^3/year and a minimum of 8,402 hm^3/year. The observations on which these data series are based were obtained by the CHE's information and control systems. According to the ERB Authority, the Automatic Hydrological Information System (SAIH in its Spanish acronym) consists of 27 water quality control stations, as well as gauging stations on rivers (225), canals (285) and reservoirs (99). The system also has an extensive network of precipitation measurement stations (373) and temperature measurement stations (193), as well as poles in the Pyrenees (110) and Cantabrian Mountains (5) to observe accumulated snowfall. The CHE publishes the measurements taken by these facilities online in real time at www.saihebro.com, while the revised data are included in the capacity yearbook, which is currently edited and published by the government agency CEDEX (Centre for Civil Engineering Studies and Experimentation) (http://ceh-flumen64.cedex.es/anuarioaforos) (MAPAMA, 2016b).

Thanks to these information systems, we know that there has been a small fall in average annual precipitation over the last eight decades (Valencia et al., 2015). According to the ERB Hydrological Plan for 2015-2021 (CHE, 2015, p. 59) "*Most studies that have sought to transfer the results of general climate change models to the scale of the Ebro River Basin concur that rainfall will decrease and temperatures will rise accompanied by an increase in evapotranspiration, and that this will cause a reduction in natural water resources.*"

To make matters worse, the increase in consumptive uses and revegetation have driven a clear negative trend in water availability (Milano et al., 2013a). Moreover, the volume of water reaching the Mediterranean has also shrunk appreciably (Sánchez-Chóliz and Sarasa, 2015), in in line with the trend observable in the contributions to deltas and estuaries from river basins around the world (Gerten et al., 2008).

In order to guarantee resource renewability and the ecological health of all water bodies, as required by the EU Water Framework Directive (European Communities, 2000), it will be necessary to create controlled avenues, the implement water quality and contamination controls, and set minimum flows for individual stretches of rivers and minimum contributions to the sea (Acreman and Dunbar, 2004; Acreman and Ferguson, 2010). All these needs are addressed in recent ERB hydrological plans. However, the volume of water that needs to be dammed to create artificial avenues, minimum flow requirements in the different stretches of the Ebro, both to absorb diffuse pollution and to protect ecosystems, and environmental flows into the Delta (contributions to the Mediterranean) condition the water available for other uses in both time and space (Bonsch et al., 2015). Meanwhile, the amount of water available for use in the ERB is further limited by inter-basin transfers like the Zadorra-Arratia transfer for hydroelectric use and to supply the Greater Bilbao conurbation (maximum concession of 283 hm^3/year and average transfer volumes of 192 hm^3/year between 1980-2013) and the Ebro-Campo de Tarragona transfer (between 70-80 hm^3/year).

The ERB is criss-crossed by an extensive network of canals supplying both irrigation systems and the general population. These canals mainly run parallel to the Ebro (Lodosa, Tauste and Imperial Canals) on the river's left bank (Bardenas, Riegos del Alto Aragón, Canal de Aragón y Cataluña and Canal de Urgel), taking advantage of the fact that this is the area (Pyrenees) with the highest rainfall, and therefore the greatest water availability, in the Ebro Basin and in the Delta (Canales del Cherta).

Based on 2009 data, meanwhile, the quality of surface water bodies in the Ebro Basin, is acceptable though improvable with some 478 out of 644 surface water bodies meeting the "good condition" standard. In the case of groundwater, meanwhile, 83 out of 105 subterranean water bodies are in good qualitative condition. There is relatively little use of groundwater in the Ebro Basin and the quantitative status 104 of these underground bodies is therefore good.

Description of agricultural water demand

Agriculture accounts for the greatest consumptive use of water in the ERB, and for this reason it will focus our attention. The most recent national farm census published for Spain (INE, 2011) shows a total cultivated area of 2.3 million cultivated hectares in the Ebro Basin, 1.7 million hectares under rainfed and the remaining0.57) under irrigated crops. Demand for irrigation water implies withdrawals of more than 7,500 cubic hectometres, representing estimated consumptive use of more than 4,500 hm^3 given an average efficiency level of slightly above 60% (CHE, 2018). The consumptive use of water by livestock farmers is less than 57 Hm^3 in contrast (Crespo et al., 2018), while urban and industrial uses in the basin account for around 500 hm^3. These mainly agricultural water withdrawals are very significant in relative terms, given overall water availability and environmental requirements.

The case study described here includes 18 rainfed and irrigated crop types, analysed using data from the 2009 Spanish agricultural census, the most recent available when this research was undertaken (INE, 2011). Cultivation under rainfed conditions does not imply any additional demand for water from the hydrological network (blue water), although it does entail rainwater consumption and therefore a reduction in potential water availability. Table 1.3 shows the area in hectares given over to rainfed crops by Autonomous Community.

Table 1.3. Rainfed land considered in the model (Hectares)

	Aragon	Catalonia	Navarre	Basque Country	Rioja	Total
Wheat	214,773	37,254	62,044	17,111	18,008	349,190
Other winter crops	50,113	9,653	14,635	62	479	74,942
Corn	4,439	1,054	1,014	15,064	0	21,571
Barley	380,292	108,107	98,352	8,809	20,335	615,895
Other summer crops	210	0	0	77	0	287
Alfalfa	30,909	0	0	27	234	31,170
Other fodder crops	39,182	15,506	8,277	58	568	63,591
Other industrial crops	13,995	1,765	3,486	44	3,227	22,517
Citrus frits	0	0	1	197	0	198
Pome fruits	425	0	0	94	6	525
Stone fruits	5,653	0	0	252	192	6,097
Fleshy fruits	2	1,642	569	308	0	2,521
Dried fruits	59,714	32,921	1,655	1,497	9,407	105,194
Legumes	9,433	483	2,641	161	267	12,985
Horticulture	278	423	1,343	13	0	2,057
Olives	36,722	71,671	2,966	15	2,873	114,247
Vineyards	29,844	12,760	10,558	0	33,118	86,280
Rice	0	0	0	0	0	0
Total rainfed crops	875,986	293,239	207,540	44,090	88,714	1,509,569

Source: Own work using data from INE (2011)

As shown in Table 1.3, barley and wheat take pride of place in the cultivation of rainfed crops in the Ebro Basin. The olive occupies the third place, followed by maize, dried fruits and vineyards, which also account for significant hectarage. Looking at the totals by region, Aragon appears as the region with the most cultivated hectares under rainfed cultivation, representing more than half the of the total for the entire Ebro Basin. Figure 1.2 shows the distribution of rainfed barley throughout the ERB. As may be observed, barley is fairly widely grown throughout the ERB, though with a greater concentration in the Cinco Villas and Huesca districts. Meanwhile, Figure 1.3 shows the hectarage per municipality under rainfed wheat. In this case, we see that rainfed wheat cultivation is concentrated in the Aragonese municipalities along the banks of the Ebro and to a lesser extent along the first stretch of the river belonging to Castile-León and the Basque Country. Figure 1.4 represents the spatial distribution of olive groves in the Ebro Basin, which are mainly concentrated in the Province of Burgos (Castile-León), and in south-eastern Aragón (Alcañiz and Caspe) and southern Catalonia.

Figure 1.2 Barley - rainfed (hectares)

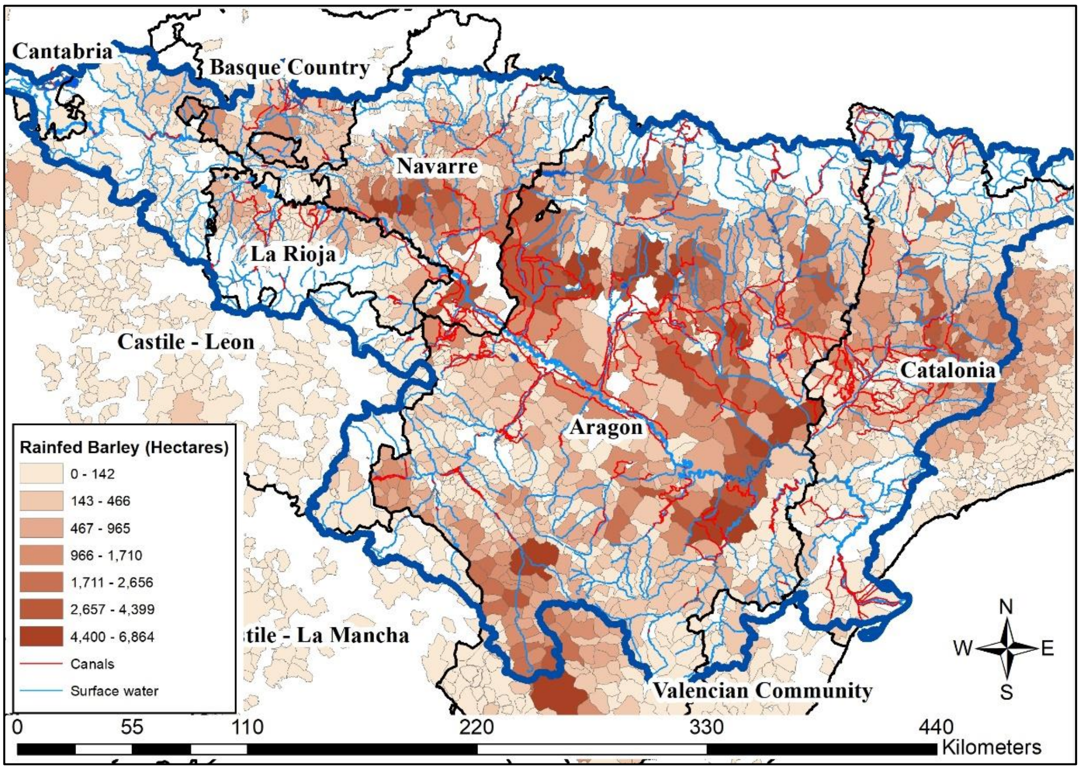


Figure 1.3. Wheat - rainfed (hectares)

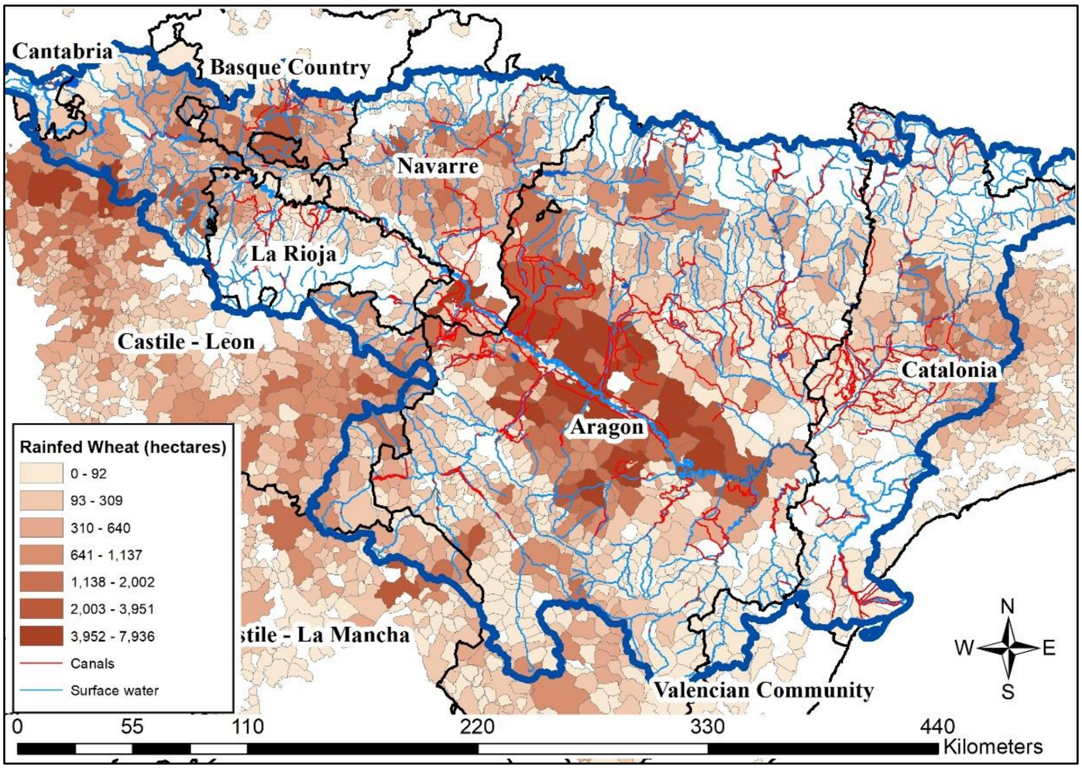


Figure 1.4. Olives - rainfed (hectares)

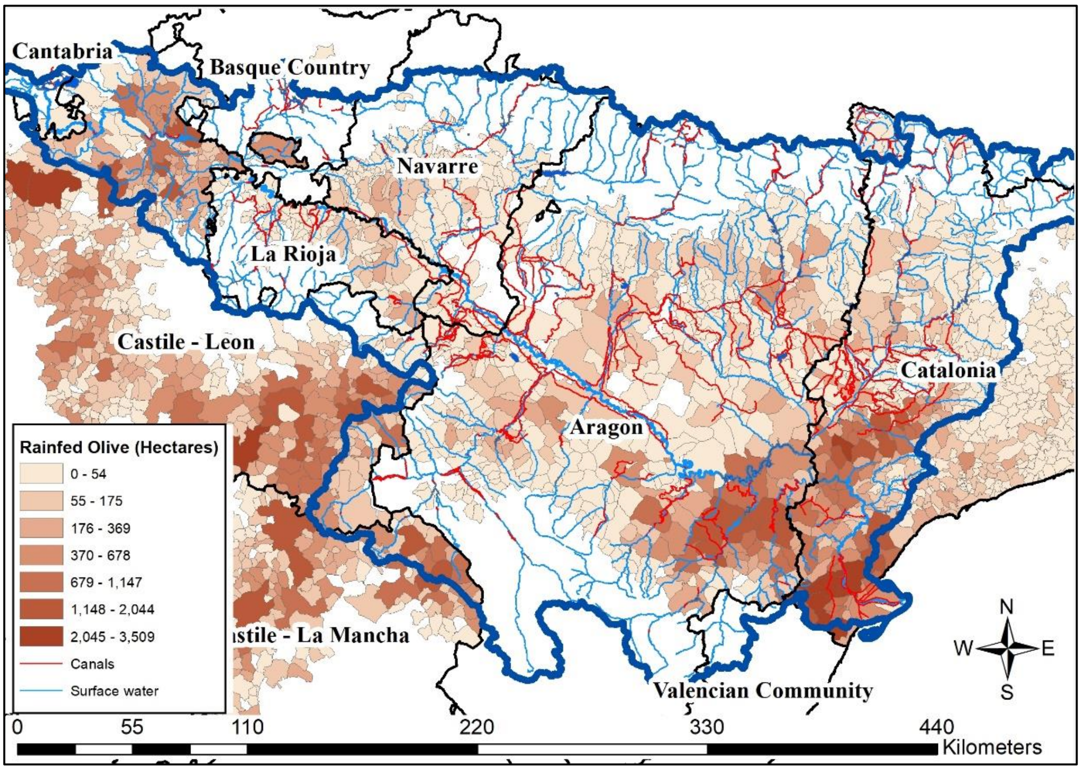


Table 1.4 shows the irrigated hectarage by crop type and region. Once again we find that Aragon is the predominant region in terms of crop production almost 50% of the total irrigated land in the Ebro Basin. As reflected in this table corn, wheat, barley, alfalfa, and other fodder crops are the most widespread irrigated crops in the Ebro basin.

Figure 1.5 shows the distribution of irrigated barley throughout the basin. As may be observed, the cultivation of this crop is concentrated in the Aragonese part of the Ebro Valley, extending almost uniformly along the banks of the Bardenas, Riegos del Alto Aragón, Aragón y Cataluña and Imperial Canals, not to mention other smaller irrigation waterways. Figure 1.6, meanwhile, reflects the distribution of irrigated wheat. As can be seen, the cultivation of this crop is more concentrated, particularly along the the Bardenas Canal, the area around the city of Zaragoza and along the Aragón y Cataluña Canal. Not all of the Autonomous Communities, in particular Catalonia, differentiated between alfalfa and other of fodder crops in the farm census, even though alfalfa predominates in them. Figure 1.7 shows the number of hectares given over to fodder crops (including), revealing that they are cultivated mainly in Aragon, especially along the Bardenas Imperial Canals and to a lesser extent along the Riegos del Alto Aragón and the Aragón y Catalonia Canals. Finally, Figure 1.8 shows the distribution of rice cultivation throughout the basin, which is much less widespread given the large amount of water it needs. In Aragon, the crop is confined largely to the Cinco Villas district and the Riegos del Alto Aragón area, and in Catalonia it is concentrated in the Ebro Delta, which benefits from excellent climate conditions for the cultivation of rice, from the sediments that the carries down to its end, and from the availability of water.

Table 1.4. Irrigated land included in the model (Hectares)

	Aragon	Catalonia	Navarre	Basque Country	Rioja	Total
Wheat	33,872	13,787	9,274	17	3,954	60,904
Other Winter crops	1,424	2,033	973	0	108	4,538
Corn	58,972	23,915	12,898	18	747	96,550
Barley	34,932	13,128	8,670	70	3,711	60,511
Other summer crops	770	0	0	0	0	770
Alfalfa	69,525	0	0	14	765	70,304
Other fodder crops	14,557	30,108	7,566	0	253	52,484
Other industrial crops	5,175	374	1,833	66	510	7,958
Citrus fruits	0	9,008	0	5	0	9,013
Pome fruits	7,965	0	0	5	2,832	10,802
Stone fruits	21,139	0	0	1,183	1,564	23,886
Fleshy fruits	43	39,055	2,727	2,043	21	43,889
Dried fruits	3,545	3,931	830	124	553	8,983
Legumes	3,604	119	1,050	21	163	4,957
Horticulture	3,312	2,160	7,968	2	7,367	20,809
Olive	6,675	12,748	2,706	0	2,481	24,610
Grapevine	4,312	4,325	10,480	0	11,473	30,590
Rice	12,892	21,548	2,080	0	0	36,520
Total irrigated crops	282,716	176,239	69,055	3,568	36,502	568,080

Source: Own work based on data from INE (2011)

Figure 1.5. Barley - irrigated (hectares)

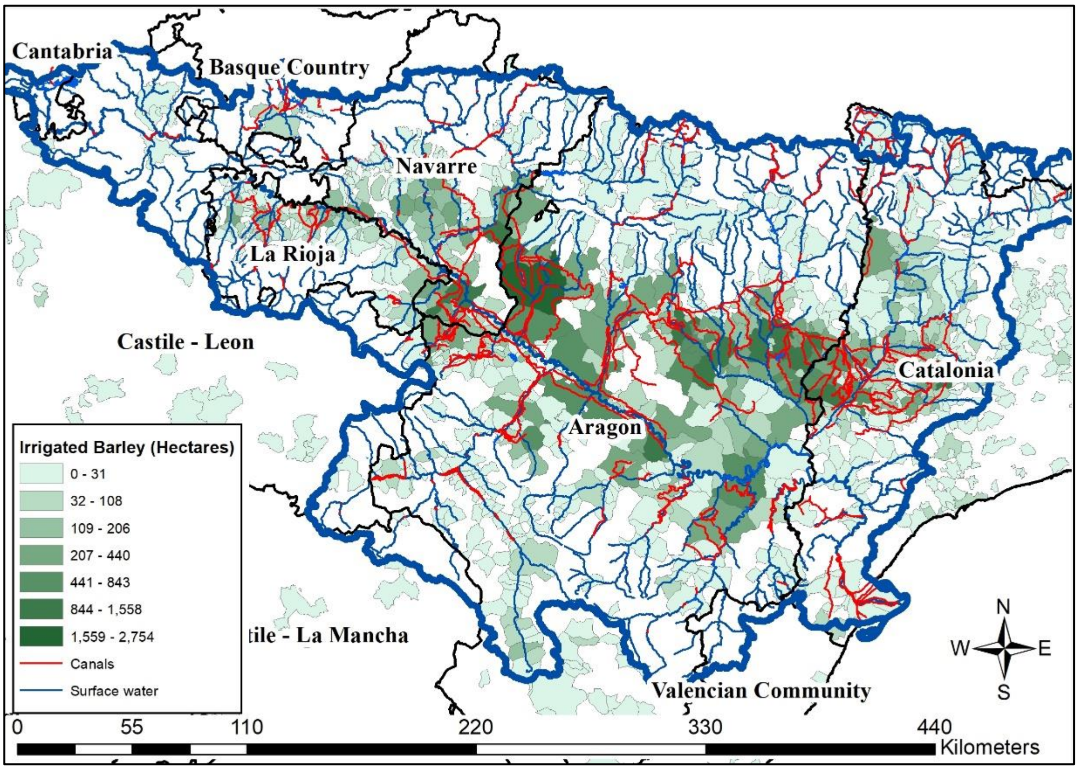


Figure 1.6. Wheat - irrigated (hectares)

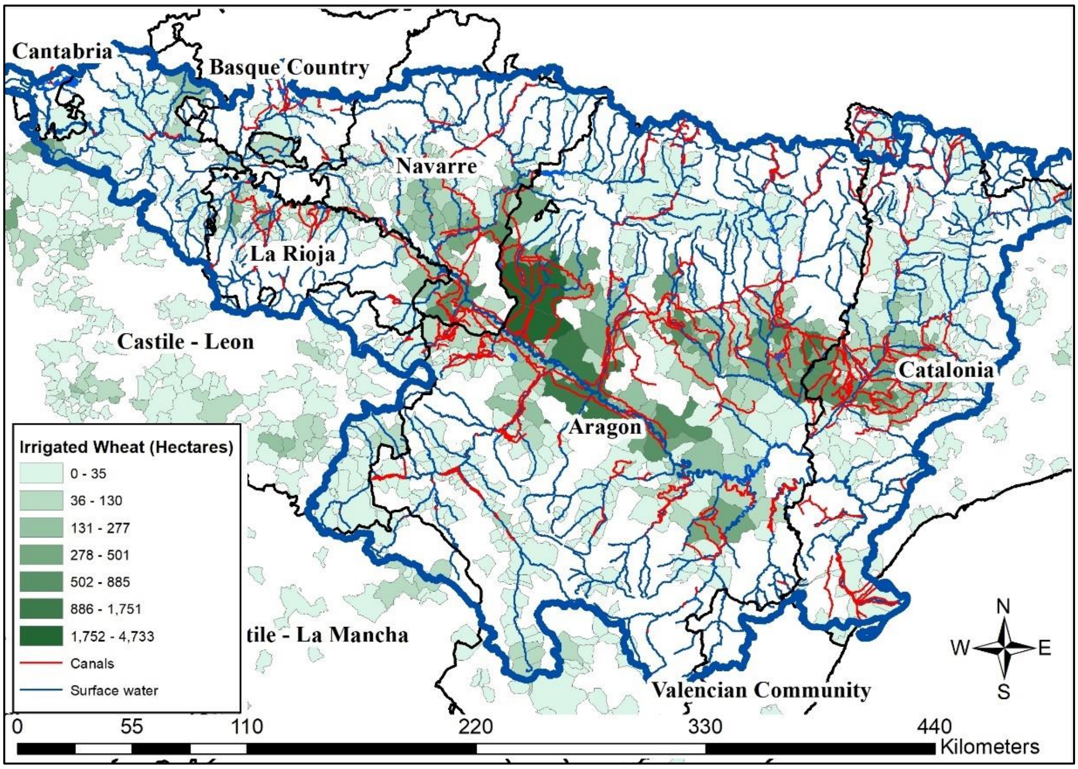


Figure 1.7. Fooder (Alfalfa included) - irrigated (hectares)

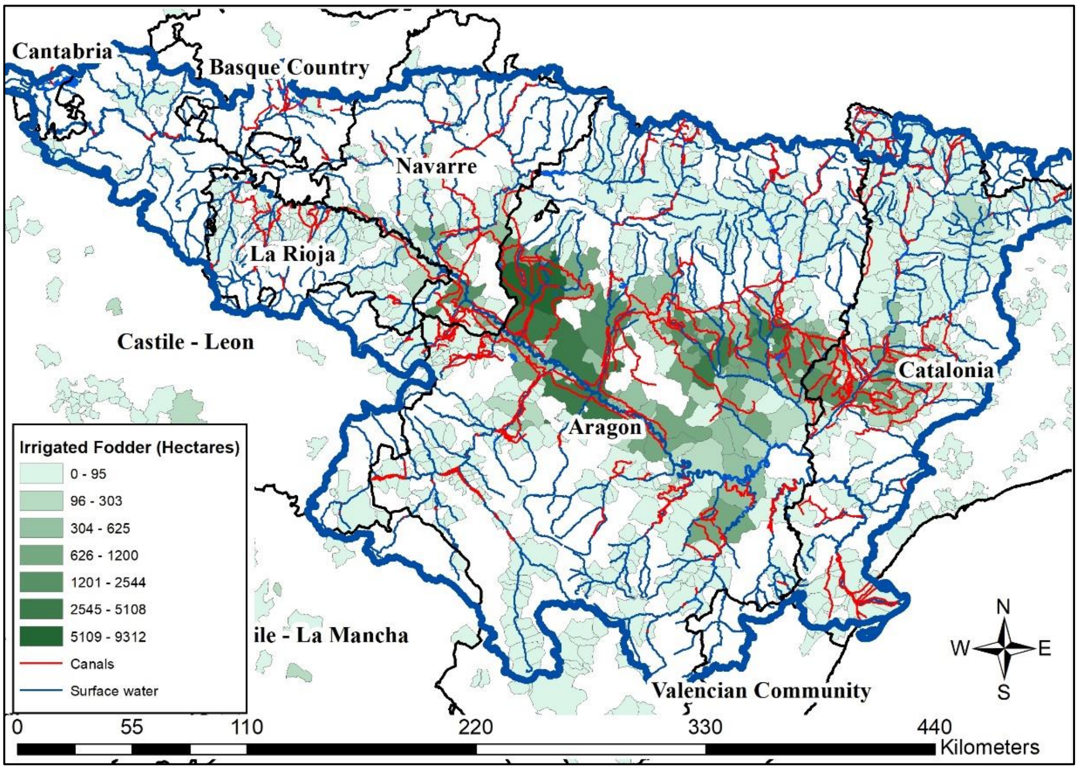
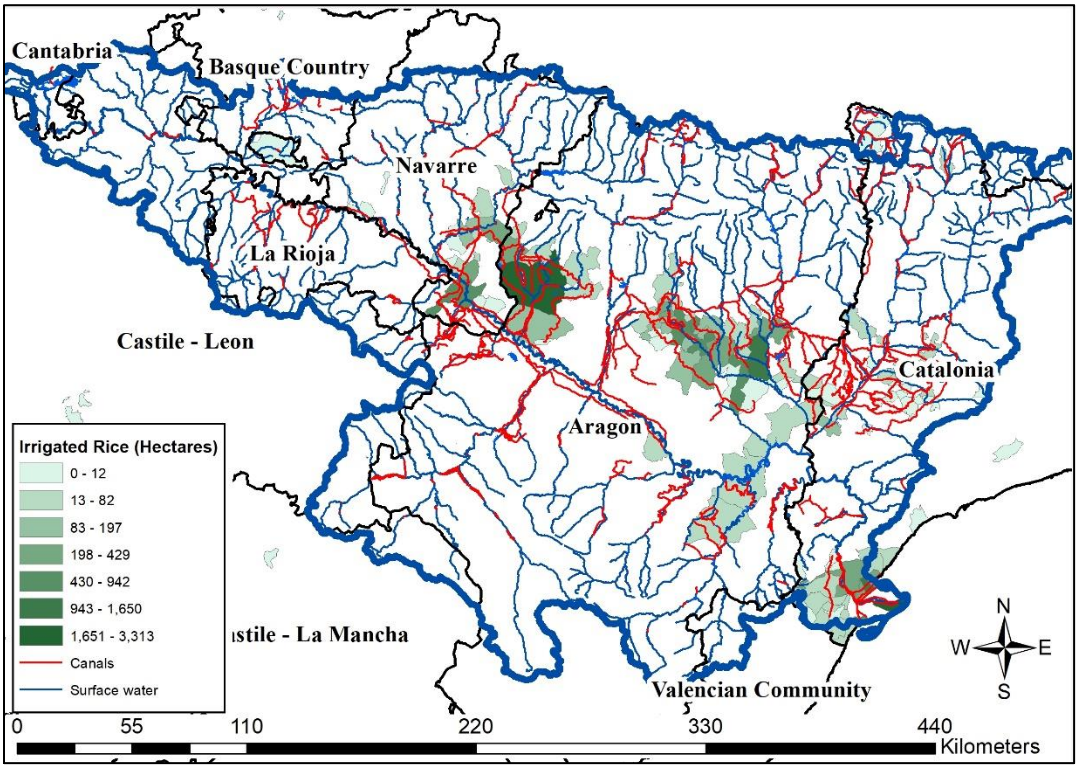


Figure 1.8. Rice - irrigated (hectares)



Electricity generating

The other major consumer of water in the ERB is the electricity industry. Generating requires large volumes of cooling water for thermal and nuclear power plants, and turbine water for in hydroelectric plants. Cooling of thermal and especially nuclear power plants involves semi-consumptive use, since a part of the water used evaporates. This use also raises the temperature of the river, which can have serious effects in nearby areas. The Ebro basin has two nuclear power plants, Santa María de Garoña, which has installed capacity of 466 Mw, and the two reactors at Ascó, which have installed capacity of 1,033 Mw and 1,027 Mw respectively. The Santa María de Garoña plant, situated in the province of Burgos, was closed down in 2013 and dismantling began in 2019. The Ascó facility, meanwhile, is situated in the lower stretch of the Ebro in the province of Tarragona. The combined output of both plants in 2011 was 18,203 Gwh/year (CHE, 2017) of which 3,742 Gwh/year were produced by the since mothballed Garoña plant. A historical series of cooling water demand for the nuclear reactors in the Ebro basin will be found in Sesma Martín and Rubio-Varas (2017). We may note here that demand for refrigeration water was estimated to be more than 3,500 hm^3/year when both nuclear plants were in operation, while the consumptive use (evaporation) was estimated at between 45 and 50 hm^3/year, according to public data provided by CHE (2017). Consumptive use is therefore low in relative terms, but the large volume of cooling water needed should be considered a restriction.

The ERB has 457 hydroelectric power plants with a total installed capacity of 3,894 MW which produced 5,110 Gwh/year in 2011. However, this output is very unevenly spread, with 15 hydroelectric plants accounting for more than 50% of the hydroelectric power generated. Although hydroelectric power plants do not make consumptive use of water, the water discharges required can sometimes go against the interests of other users.

Urban and other industrial water demand

The Ebro Basin supplies domestic water for 3,226,921 people living in 1,724 towns and villages. As shown in Table 1.5, the cities of Zaragoza, Vitoria, Pamplona, Logroño and Lleida are the largest settlements with more than 100,000 inhabitants each, accounting for almost 45% of the ERB's total population. Zaragoza is the Ebro's biggest city and Spain's fifth biggest, and its central geographical position roughly half way along the river's length makes it a focal point. The city also contributes Zaragoza almost 20% of the ERB's gross product. The water used to satisfy domestic and industrial water demand in Zaragoza comes mainly from the Yesa reservoir and the Imperial Canal, although the city also takes water directly from the Ebro.

Table 1.5. Ten largest towns in the Ebro river basin

Municipality	Province	Inhabitants	GDP (Million €)	GDP per capita (€)
Zaragoza	Zaragoza	675,121	16,732	24,784
Vitoria	Alava	238,247	7,885	33,097
Pamplona	Navarre	197,488	5,857	29,658
Logroño	La Rioja	152,650	3,925	25,715
Lleida	Lleida	137,387	4,147	30,188
Huesca	Huesca	52,347	1,333	25,459
Soria	Soria	39,838	845	21,219
Miranda de Ebro	Burgos	39,038	838	21,462
Tudela	Navarra	35,268	1,048	29,719
Teruel	Teruel	35,241	856	24,280

Source: Own work

Vitoria, the provincial capital of Alava, is the second most populous city in the Ebro Basin with more than 230,000 inhabitants and significant industry. The water used by the city's residents industries comes from the Zadorra reservoir system, which supplies practically all of the towns in Alava province and the Greater Bilbao area. Pamplona, the capital of Navarre, has around 200,000 inhabitants, which makes it the third biggest city in the ERB, and it also ranks third in terms of GDP. Pamplona water supply currently comes from three sources, namely the Manatial de Arteta, (a spring fed by the underground aquifer of the Sierra de Andina), the Eugi reservoir (20 hm^3) and the Itoiz reservoir (Canal de Navarra). Logroño is the ERB's fourth city by population and fifth in GDP terms. It is supplied from the Islallana dam on Iregua River with back-up from the 33 hm^3 of the Gonzalo Lacasa reservoir on the Arroyo de los Albercos, a tributary of the Iregua. Finally, Lleida is the fifth most populous city in the ERB and the fourth in terms of GDP. The city's water supply (and that of the surrounding district) comes from the Santa Ana reservoir via the Piñana Canal.

Water management institutions

Regulation and management of the ERB's resources are necessary in view of the sometimes-conflicting interests of stakeholders and, above all, because water is a prerequisite for life. Meanwhile, the very high levels of political devolution achieved by the Autonomous Communities in recent years makes has vastly the regional nature of Spain as a country. However, hydrographic basins that include parts of more than one

Autonomous Community are managed by public law entities formed on the basis of their physical geography rather than regional political structures. The hydrographic confederations are therefore attached to the recently renamed Ministry for Ecological Transition (former Environment Ministry), and their main functions are to manage water resources in the public hydraulic domain, grant rights to exploit water resources, the plan and build hydraulic infrastructure and oversee environmental conditions in the river basins concerned, paying special attention to the conservation of resources and water quality. Meanwhile, the work of the hydrographic confederations is based on the principle of user participation and they are required to seek consensus among stakeholders before taking any action above and beyond normal operating procedures (Omedas-Margelí, 2011). The study area forms part of the Ebro Hydrographic Confederation.

Given the high volumes of water demand in agriculture and the intensive consumptive use of the resource in the water-energy-food nexus, not to mention demand from other industries and the general population, and the needs of hydroelectric generating plants and environmental flow requirements, all factors that are linked in one way or another with the ERB's already high levels of socioeconomic development, it comes as no surprise that the countless competing water uses require permanent management to address both general and emerging or special issues throughout the river basin. This is our framework. Meanwhile, climate forecasts point to increasing supply-side problems and ever intensifying pressure on the resource, which will in turn require diligent, holistic management.

1.2. Surface water flows in the Ebro river Basin

This section will describe the principal surface water flows in the Ebro basin and identify the key points of use. The information obtained is key for this Thesis, because one of the principal methodologies applied involves hydrological modelling.

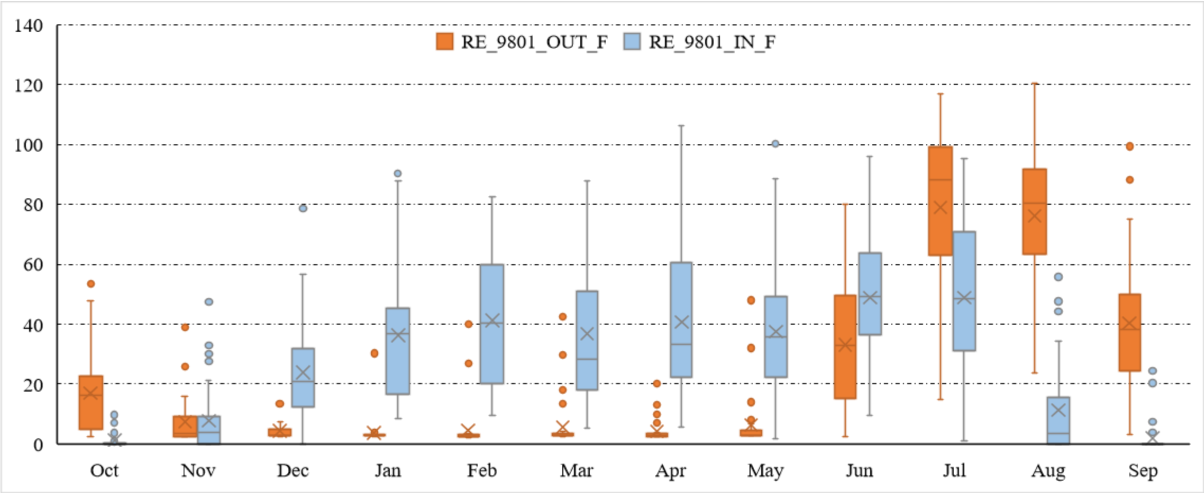
The Ebro rises at Fontibre in Cantabria, from where it enters the province of Burgos (Castile-León). From the Tovalina valley to Miranda de Ebro, the river forms the border between Burgos and the Basque Country. Most of the contributions from the Basque Country flow into the river along this border stretch, especially around Miranda de Ebro. There are three significant reservoirs in this initial reach. These are the Ebro reservoir in Cantabria, and the Ullivarri and Urrunaga reservoirs, both in the vicinity of Vitoria (Basque Country). The waters of the Ebro reservoir (code 9801, see MAPAMA (2016b) or http://ceh-flumen64.cedex.es/anuarioaforos) feed and mark the start of the river's main course, while the waters of the Ullivarri (9827) and Urrunaga (9828) reservoirs supply the Greater Bilbao area via the Zadorra-Arratia transfer (200 Hm^3 per year according to CHE), the city of Vitoria and the irrigated areas of practically the entire province of Álava (Zadorra Irrigation Scheme). The main contributions to the Ebro from the Basque Country therefore come from the Zadorra River, discounting the uses described, and other smaller tributaries.

The Ebro reservoir has a maximum capacity of 541 Hm^3 and is the main regulatory dam on the upper stretch of the Ebro. The average annual flow (1980-2013) through the dam is 286 Hm^3. Figure 1.9 shows the monthly distribution of inflows and outflows at the Ebro reservoir in the form of a boxplot. Inflows (in blue) are practically nil in the month of October and then rise month by month until February, remaining at an average level of around 40-45 Hm^3 until July and then dropping back around 10 Hm^3 in August and practically zero again in September. Outflows from the Ebro reservoir (shown in orange in Figure 1.9) reflect a pattern of water storage and retention during the winter and spring months, when practically no water is discharged, and water outflows concentrated in the period from June to October.

The Ebro reservoir holds an average water stock of 323 Hm^3. Figure 1.10 presents the monthly distribution of the stock in the reservoir, which increases in line with the relationship between inflows and outflows depicted in the previous boxplot between November and June, when the imbalance with inflows begins to increase to cover downstream water demands.

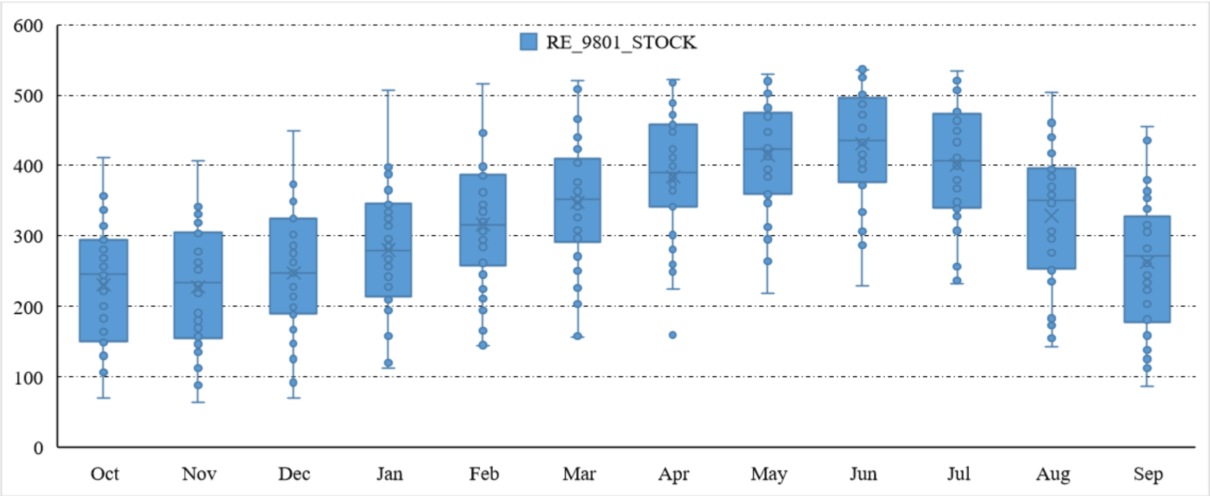
The Ullivarri (9827) and Urrunaga (9828) reservoirs, are situated very close to each other. The Ullivarri reservoir has an average annual flow of 150 Hm^3. The pattern of inflows (see Figure 1.11) is similar to that already described for the Ebro reservoir, while outflows follow a pattern of minimum monthly discharges of 10 Hm^3, which do not increase significantly in the summer months. Figure 1.12 shows the monthly distribution of the water stock in the Ullivarri reservoir, which holds an average of 101 Hm^3.

Figure 1.9. Ebro Reservoir (9801) – Distribution of inflows and outflows (Hm^3)



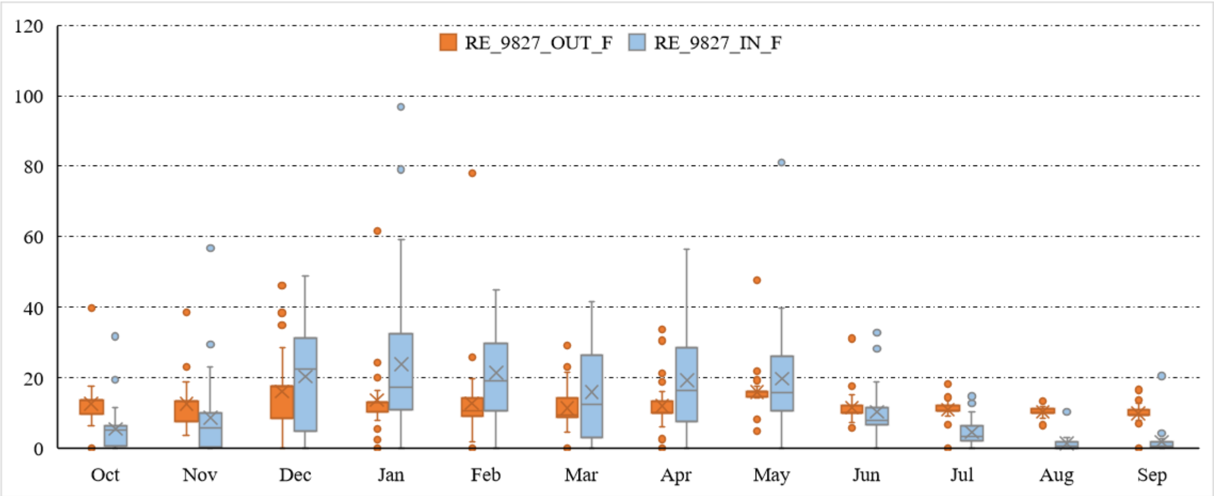
Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.10. Ebro Reservoir (9801) – water stock distribution (Hm^3)



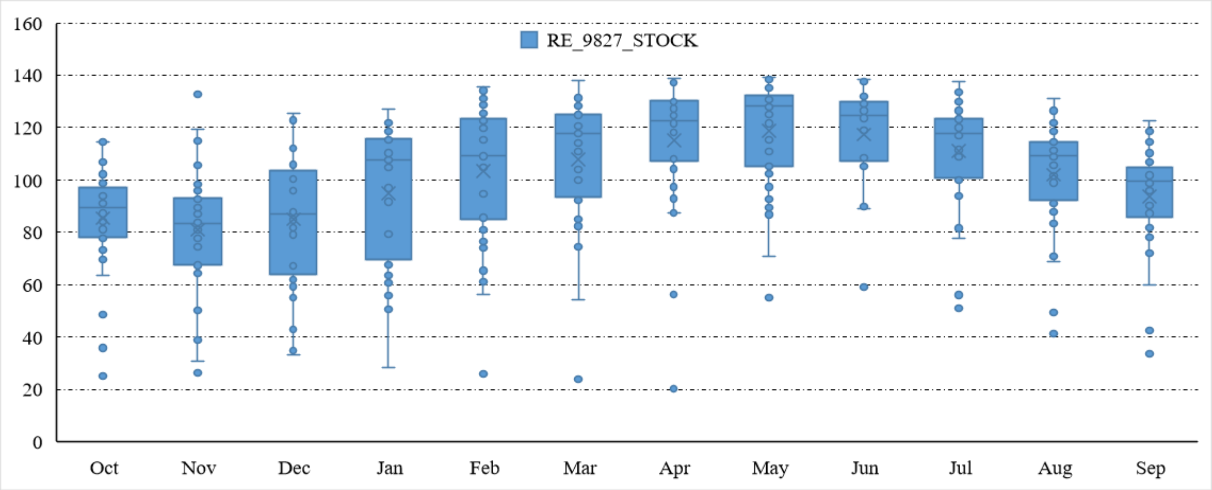
Source: Own work based on data from MAPAMA (2016b).

Figure 1.11. Ullivarri Reservoir (9827) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

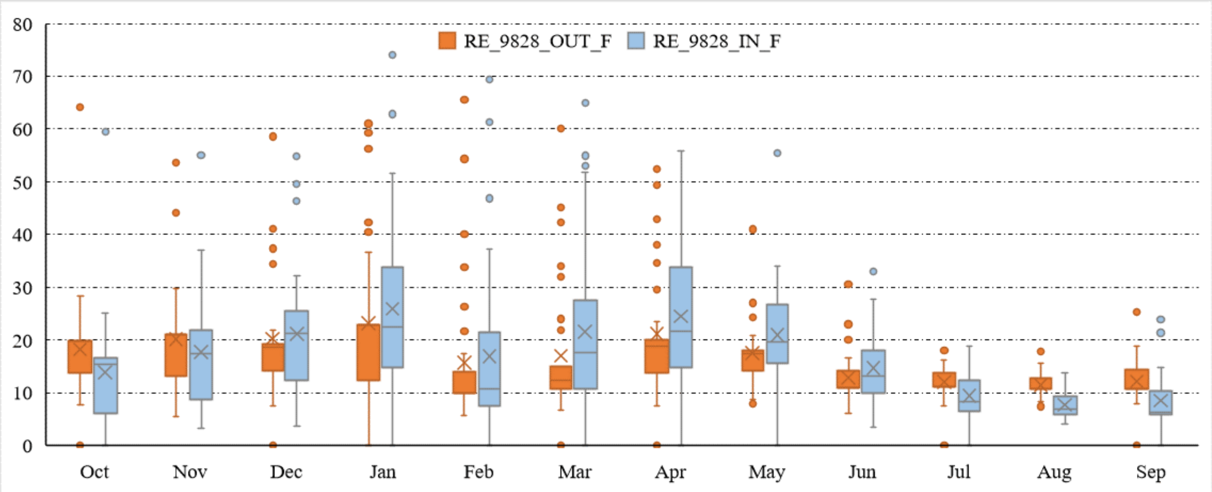
Figure 1.12. Ullivari Reservoir (9827) – Distribution of water stock (Hm^3)



Source: Own work based on data from MAPAMA (2016b).

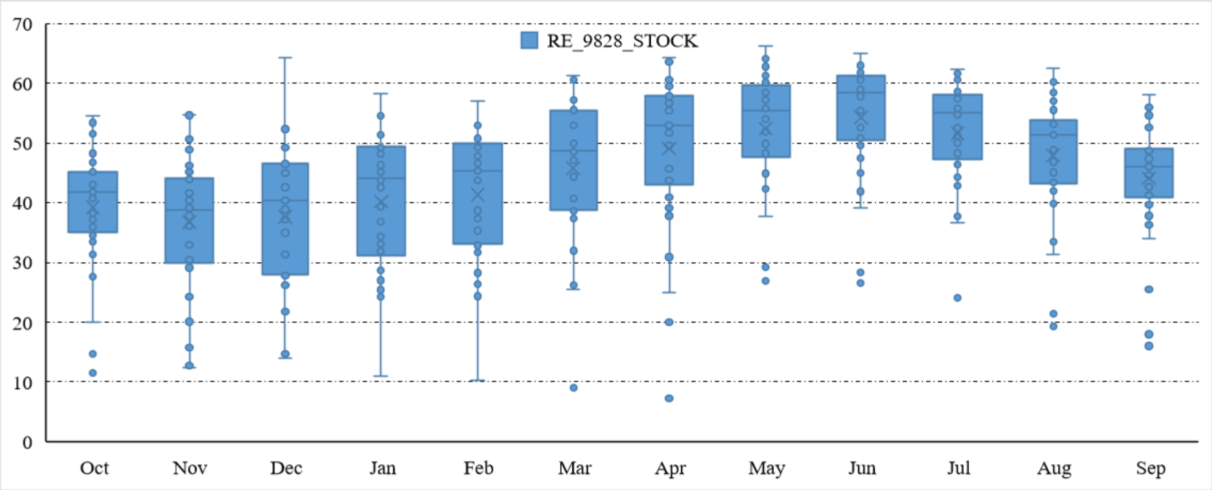
The maximum capacity of the Urrunaga reservoir is 72 Hm^3, and its average outflow is 202 Hm^3. The distribution of inflows and outflows is shown in Figure 1.13In this case, we may observe that the minimum outflows are around 10 Hm^3. The average stock held in this reservoir is 45 Hm^3, distributed as shown in Figure 1.14. The Urrunaga reservoir begins its recharge cycle in December, reaching maximum levels between May and June. Water inflows from then until the month of November are less than 10 Hm^3, while outflows increase to cover downstream needs.

Figure 1.13. Urrunaga Reservoir (9828) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.14 Urrunaga Reservoir (9828) – Distribution of water stock (Hm^3)

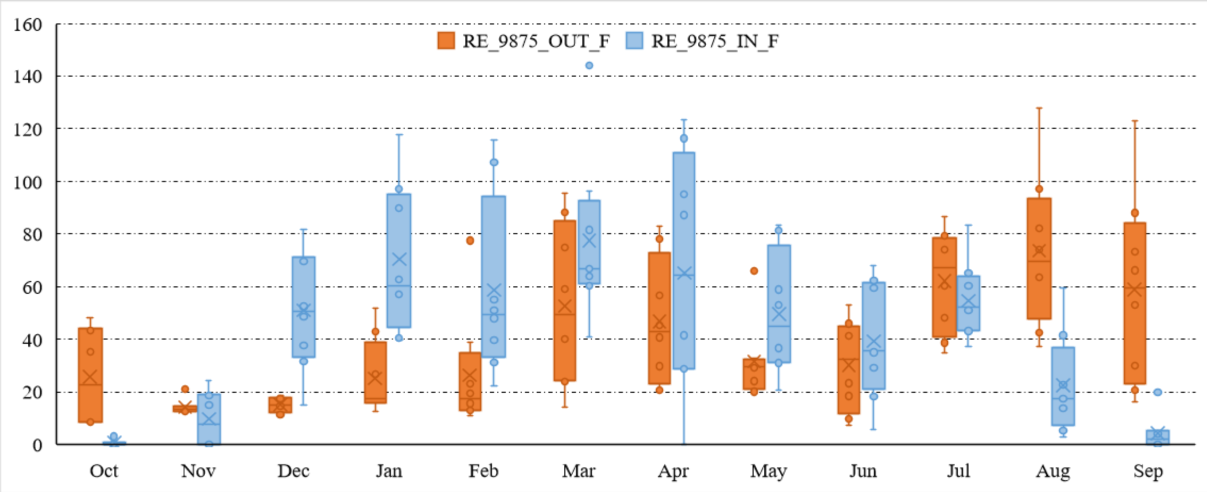


Source: Own work based on data from MAPAMA (2016b).

The town of Miranda de Ebro lies on the border between Burgos and La Rioja, through which the Ebro River between the towns of Haro and Alfaro, forming a border first with the Basque Country and eventually with Navarre. La Rioja has no major reservoirs, and water availability depends mainly on the Ebro, although the region has other sizeable streams, including the Najerilla, Iregua and Cidacos rivers. The left bank of the Ebro in this stretch belongs to Navarre. In the south of this Autonomous Community, water is taken directly from the Ebro for use by the Mendavia and Lodosa irrigation canals. The rest of the water used in the Ebro Valley in Navarre comes mainly from the western Pyrenees. The Canal de Navarra canal and the Canal de Bardenas help distribution of this water.

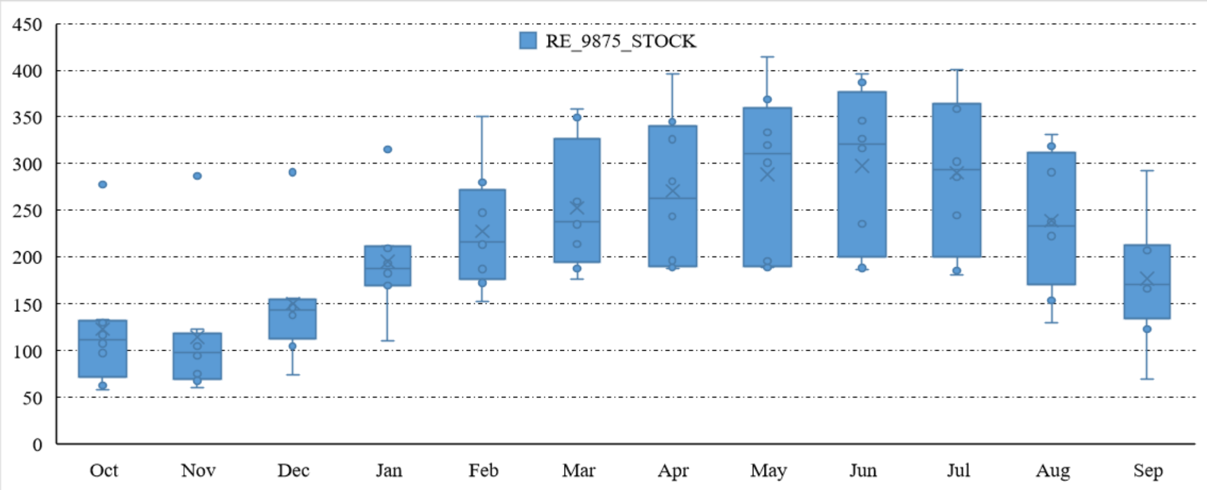
The Canal de Navarra takes water from the Itoiz reservoir (9875), commissioned in 2004. The distribution of inflows and outflows at this reservoir is shown in Figure 1.15 while the distribution of the average monthly stock in Figure 1.16. Inflows into this reservoir start in October, when they are practically nil, and rise until March or April, when they begin to fall again. Meanwhile, outflows follow a similar cycle similar to inflows, except in the summer period, when inflows dwindle almost to nothing but outflows increase to support downstream water needs. This difference between outflows and inflows over the summer until reduces the water stock held in the reservoir by 25% -30% of its capacity in October-November. The recharge cycle of the Itoiz reservoir therefore begins in the months of November and December and continues until June.

Figure 1.15. Itoiz Reservoir (9875) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.16. Itoiz Reservoir (9875) – Distribution of water stock (Hm^3)



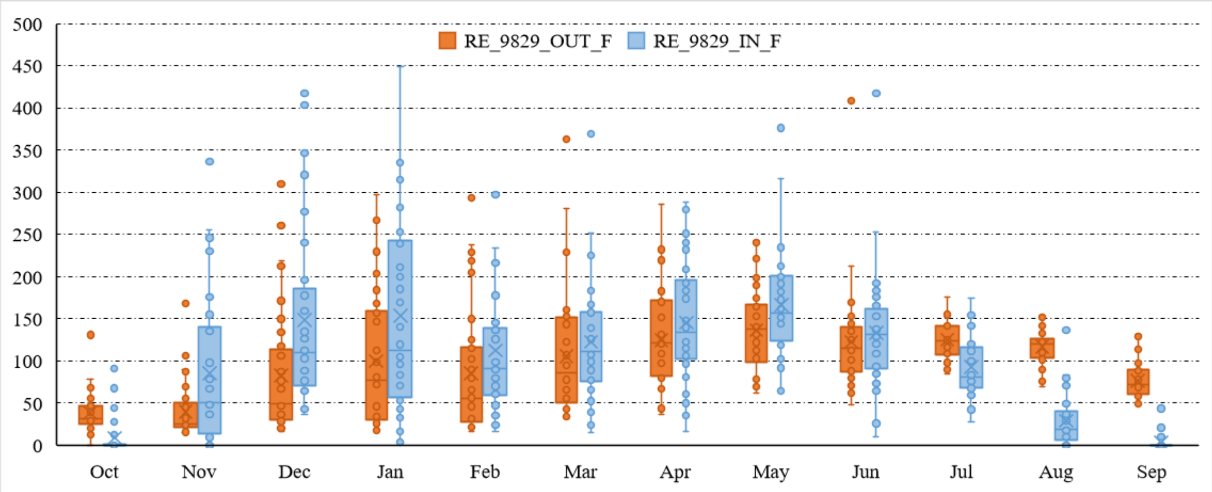
Source: Own work based on data from MAPAMA (2016b).

The Bardenas canal, which takes water from the Yesa reservoir (9829), supplies part of Navarre, although most of the water outflows from Yesa through the canal are actually used in Aragon. The Bardenas canal currently supplies more than 80,000 hectares and numerous towns in both Navarre and Aragon. As Figure 1.17 shows, the distribution of inflows and outflows at the Yesa reservoir is very similar cycle. According to Figure 1.17 and also Figure 1.18, which presents the monthly change in the average water stock held, a net outflow of water occurs between July and October, while the reservoir collects more water than it releases from November to June.

La Loteta reservoir was built to improve water quality and guarantee supply for the city of Zaragoza and neighbouring towns. Work was completed in 2008. It takes its waters from the Canal Imperial and the Canal de Bardenas (Yesa Reservoir) via the Sora channel.

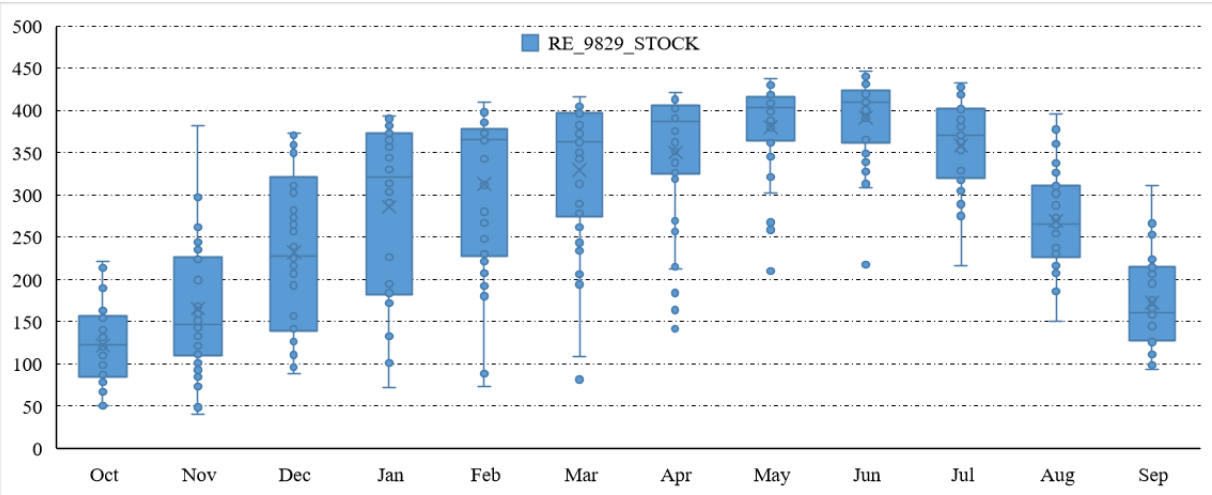
However, problems of salinity affecting its basin rendered it unsuitable for supply uses, and it was therefore decided to source the city's water supply continuously from Yesa and to use the Laverné reservoir (38 Hm^3) for regulation purposes. At present, then, the city of Zaragoza is supplied with water from the Canal Imperial, the Yesa Reservoir and the Ebro River, in variable proportions.

Figure 1.17. Yesa Reservoir (9829) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.18. Yesa Reservoir (9829) – Distribution of water stock (Hm^3)

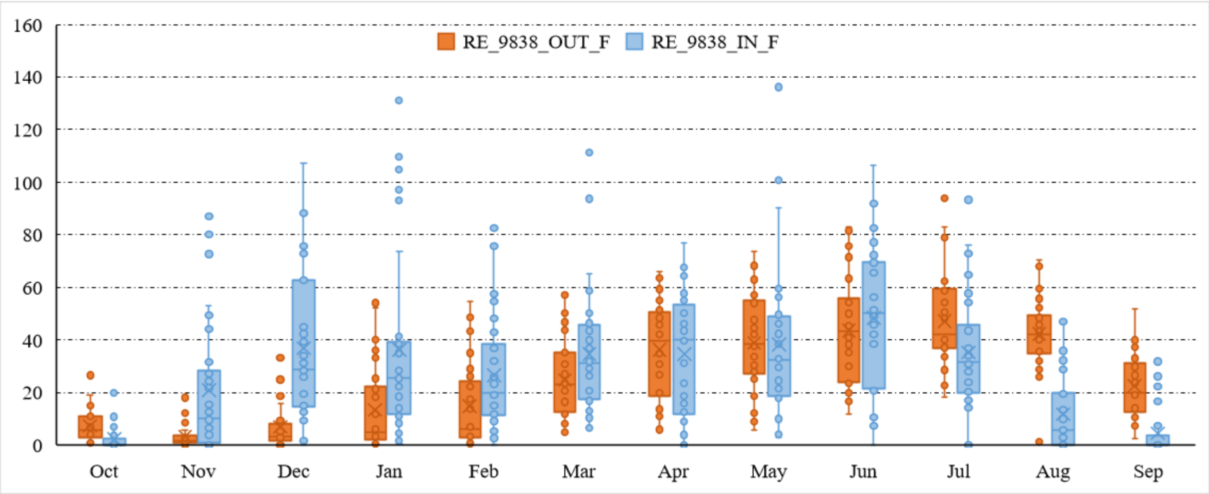


Source: Own work based on data from MAPAMA (2016b).

A dense network of canals exists in the last few kilometres before the Ebro leaves Navarre and the first few as the river enters Aragon, and this in turn means that the area has a high concentration of irrigated land. The Canal de Lodosa runs parallel to the Ebro on the river's right bank from the Navarrese municipality of Lodosa to its end in Aragon. Meanwhile, the Canal de Tauste and the Canal Imperial de Aragon take their waters from the Ebro after it passes through the town of Tudela in Navarre, These canals also run parallel to the river, one on its left and the other on its right bank. These canals were traditionally very important for Aragon, as almost as much as the Ebro itself in fact, but the bulk of the water now consumed in Aragon actually comes from the Pyrenees.

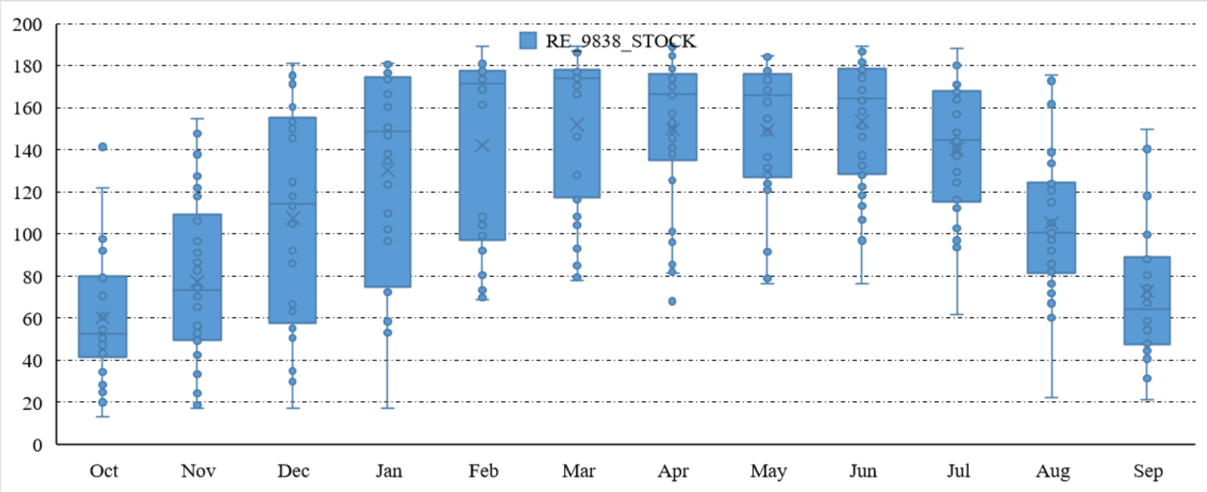
Apart from the Canal de Bardenas and the Yesa reservoir, the left bank of the Ebro in Aragon is largely supplied by waters from the Central Pyrenees, which recharge La Sotonera reservoir (9838), the reservoir system formed by Mediano (9846) and El Grado (9847), and the Barasona reservoir (9848). La Sotonera reservoir is located on the Sotón river, a tributary of the Gállego, which in turn flows into the Ebro close to Zaragoza. This reservoir and El Grado feed the Riegos del Alto Aragón irrigation scheme. Figure 1.19 and Figure 1.20 present the distribution of inflows and outflows, and the stock held in La Sotonera reservoir, which receives average inflows of between 20-40 hm^3 from December to July (around 50 hm^3 in June) but almost zero inflows in the remaining four months of the year. The water stock held in La Sotonera reservoir increases over the months from December to June and is gradually discharged between July and November.

Figure 1.19. La Sotonera Reservoir (9838) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

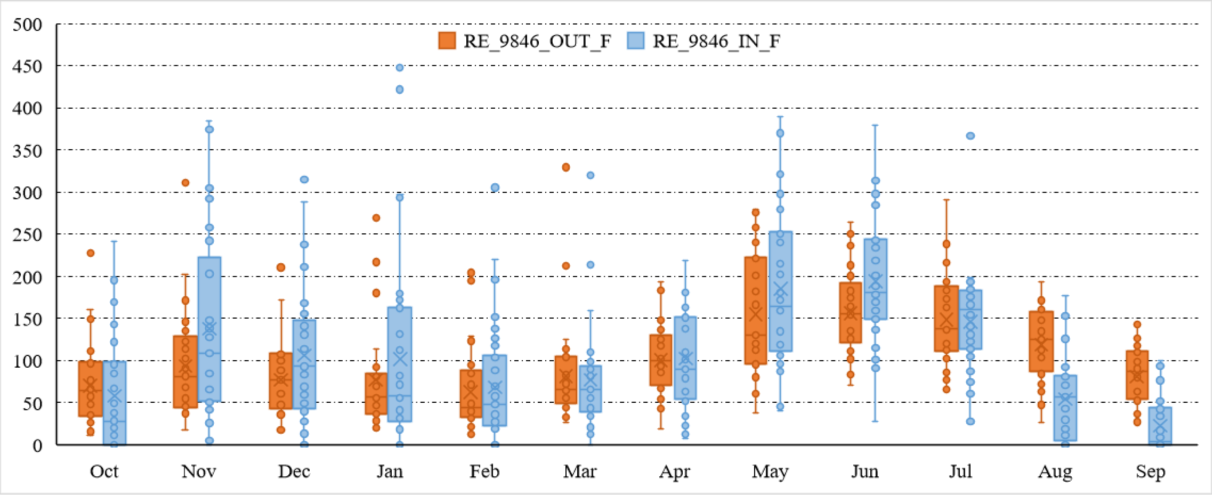
Figure 1.20. La Sotonera Reservoir (9838) – Distribution of water stock (Hm^3)



Source: Own work based on data from MAPAMA (2016b).

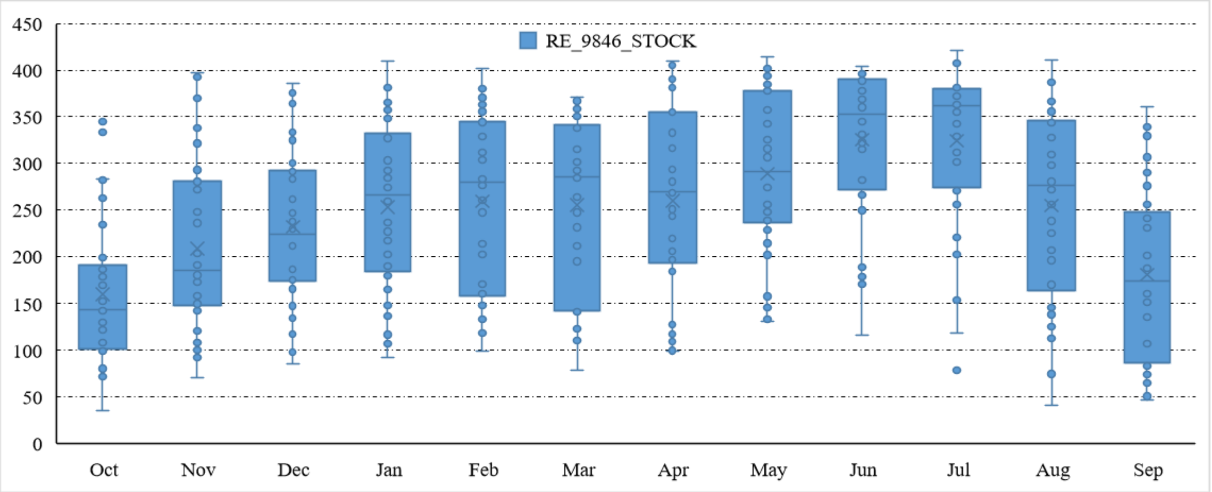
The binary system formed by the contiguous Mediano and El Grado reservoirs located on the Río Cinca also supplies the irrigation channels of the Alto Aragón scheme. The distribution of flows and the volume of water stored at these two reservoirs, are shown in Figure 1.21–Figure 1.24. As may be observed, El Grado reservoir holds a practically constant volume of water since inflows and outflows, which are determined by the management of the Mediano reservoir, are practically equal in quantity. The data for the Mediano reservoir reflect inflows from the Cinca watershed. This water is managed to ensure supplied for downstream uses. Because the two reservoirs are situated so close together and El Grado receives no significant contributions from any source other than the Mediano reservoir a little further upstream, we can study this reservoir system as if it were single facility. Figure 1.25 presents the distribution of inflows and outflows of this binary system, while Figure 1.26 shows the distribution of the water stock stored in the twin reservoirs. As may be observed, the reservoir system collects water from October to June but makes significant net discharges in the months of July and September.

Figure 1.21. Mediano Reservoir (9846) – Distribution of inflows and outflows (Hm^3)



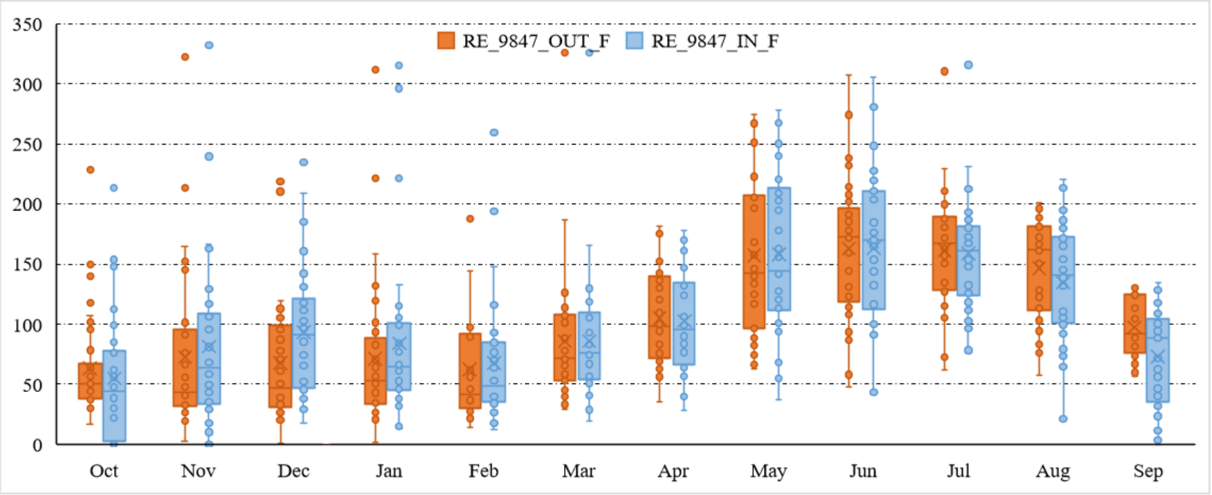
Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.22. Mediano Reservoir (9846) – Distribution of water stock (Hm^3)



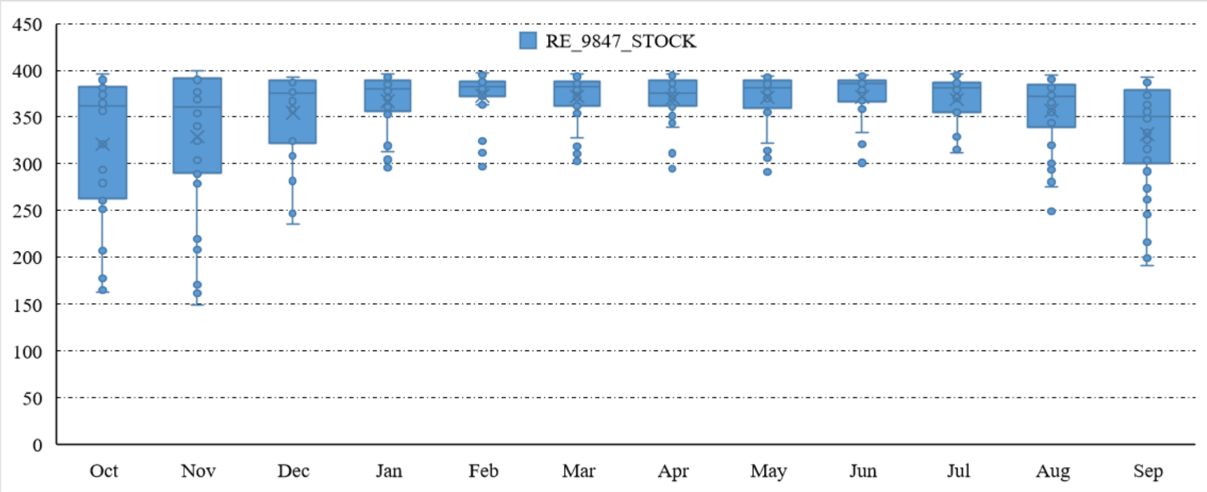
Source: Own work based on data from MAPAMA (2016b).

Figure 1.23. Grado I Reservoir (9847) – Distribution of inflows and outflows (Hm^3)



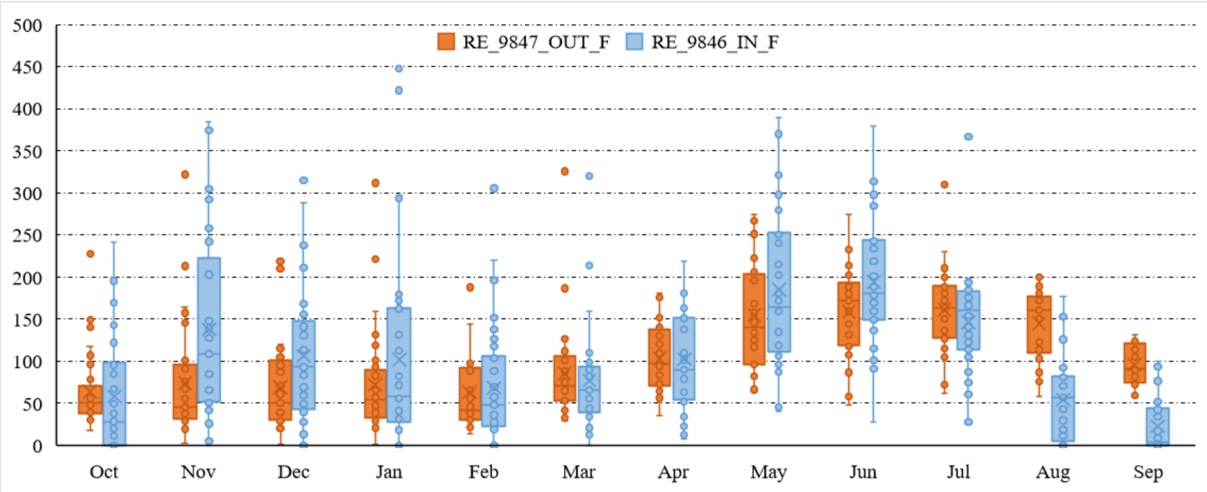
Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.24. Grado I Reservoir (9847) – Distribution of water stock (Hm^3)



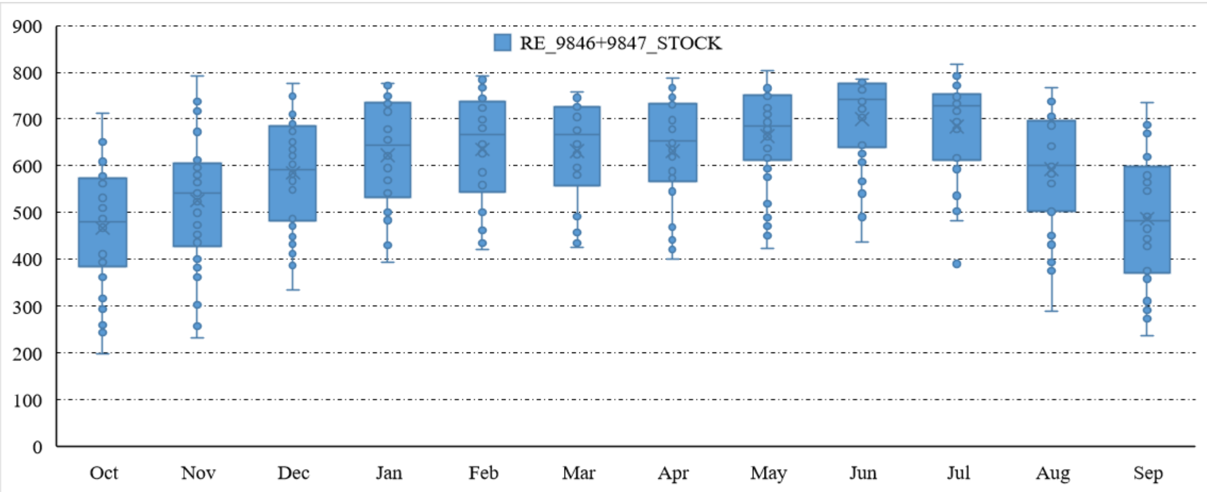
Source: Own work based on data from MAPAMA (2016b).

Figure 1.25. Grado I and Mediano System – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.26. Grado I and Mediano System - water stock distribution (Hm^3)



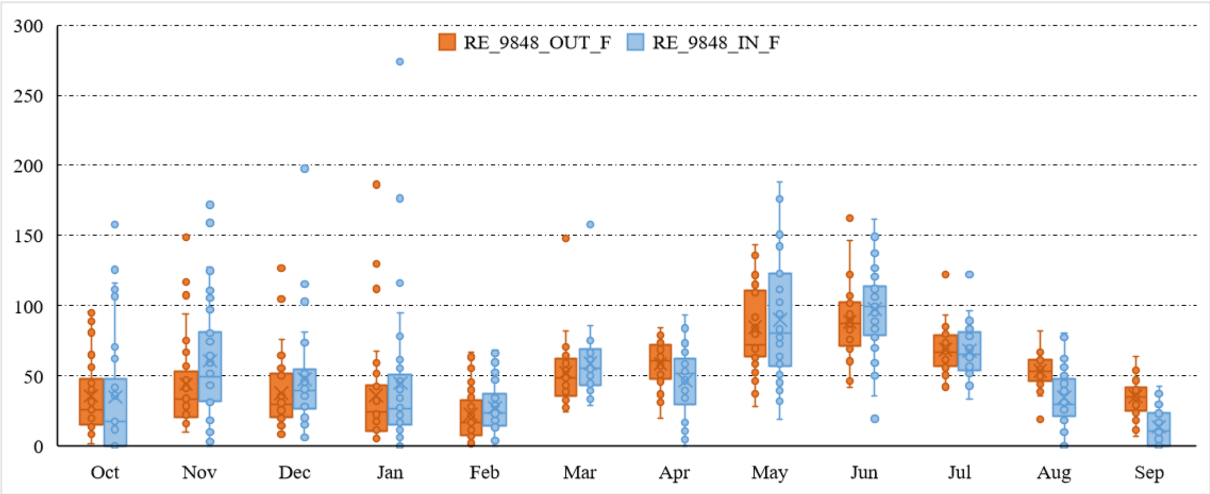
Source: Own work based on data from MAPAMA (2016b).

Also in the central Pyrenees, the Esera river, a tributary of the Cinca, feeds the Joaquín Barasona reservoir (9848), while the Noguera Ribagorzana river, already a tributary of the Segre, supplies the reservoir system formed by the Escales, Canelles, and Santa Ana reservoirs (codes 9850, 9851 and 9852 respectively). Both the Barasona reservoir and the Sana Ana reservoir feed the Canal de Aragón y Cataluña, which holds a concession of more than 100,000 hectares of land, approximately of which is in 60% Aragon and 40% in Catalonia.

Figure 1.27 shows the distribution of inflows and outflows at the Barasona reservoir, and Figure 1.28 reflects the distribution of water stocks. Barasona collects water from November to March but in April it makes a net discharge of water only to fill up again between May and June. The reservoir releases more water than it receives between July and October.

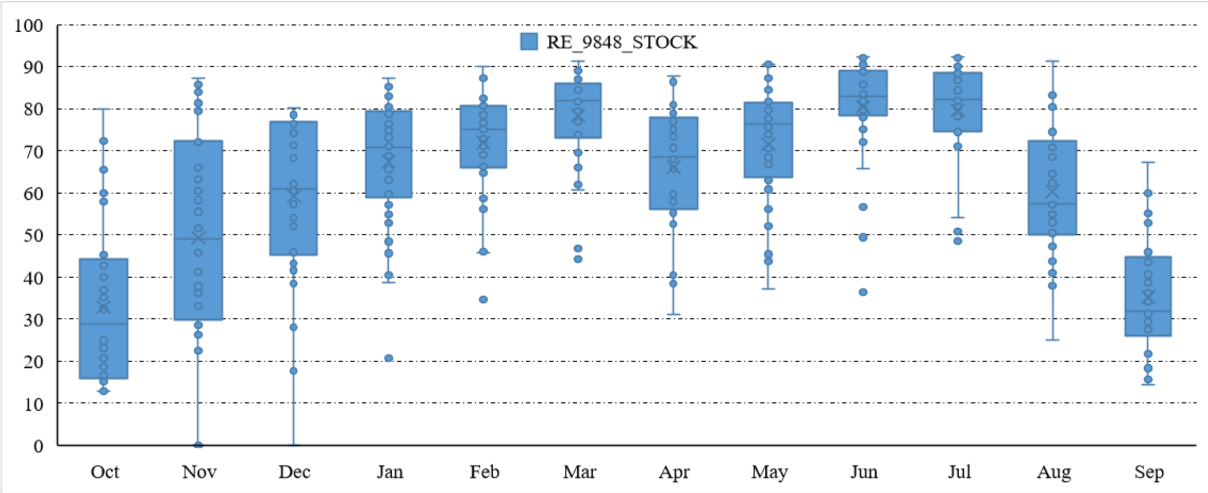
The reservoirs situated on in the different headwaters must guarantee flows to meet all of the different water needs downstream, including environmental requirements. After calculating these needs, they must capture enough water in the first part of the flow year to assure availability in the summer months. In the case of La Sotonera, the El Grado and Mediano system, and Barasona, we may observe that the reservoirs are filled between February and March. Stocks are then discharged between April and June based on snow level data to make room for inflows of melt water. Greater reservoir capacity at these points would therefore enhance the ERB's flow management capacity, providing greater water security in dry years.

Figure 1.27. Barasona Reservoir (9848) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

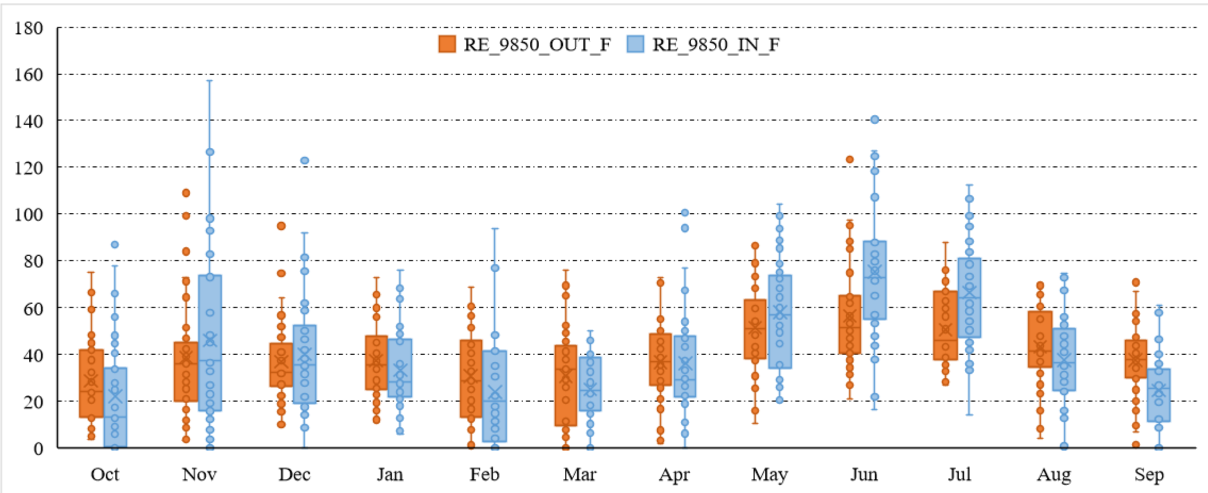
Figure 1.28. Barasona Reservoir (9848) – Distribution of water stock (Hm^3)



Source: Own work based on data from MAPAMA (2016b).

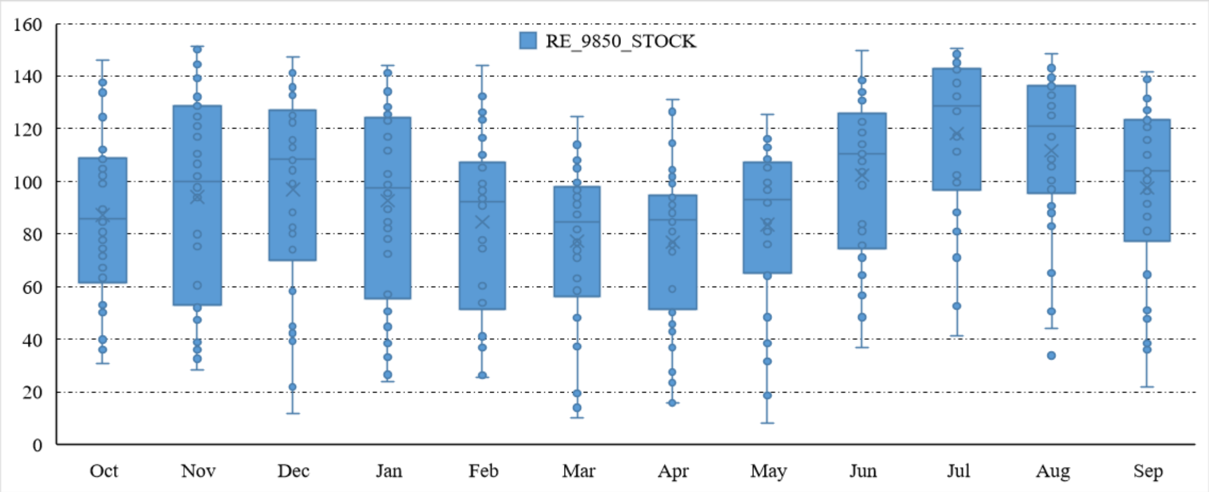
As mentioned above, the waters of the Noguera Ribagorzana River and its tributaries feed the reservoir system formed by the Escales (9850), Canelles (9851) and Santa Ana (9852) reservoirs. Figure 1.29 and Figure 1.30 refer to the first of these reservoirs, which has a maximum capacity of 150 Hm^3. As shown in Figure 1.29, inflows and outflows at Escales follow similar cycles. However, we may observe from Figure 1.30, which shows the monthly distribution of the water stock held in this reservoir, it does not follow the standard water recharge pattern in the early months of the hydrological year, and nor, in fact, does any of the three reservoirs that make up the system. Also, the reservoir is recharged between April and July, suggesting that it is affected by a late thaw.

Figure 1.29. Escales Reservoir (9850) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

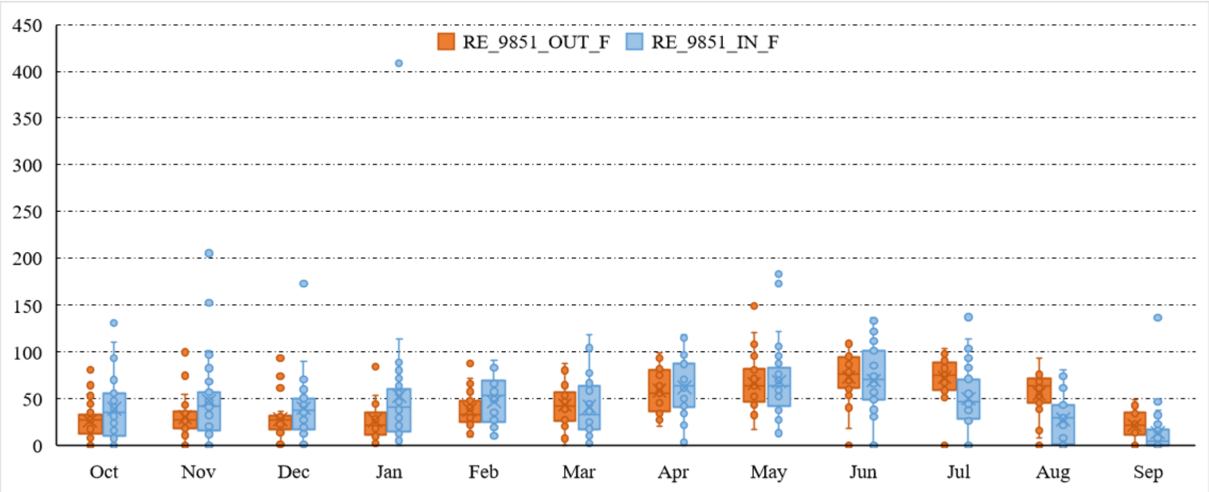
Figure 1.30. Escales Reservoir (9850) – Distribution of water stock (Hm^3)



Source: Own work based on data from MAPAMA (2016b).

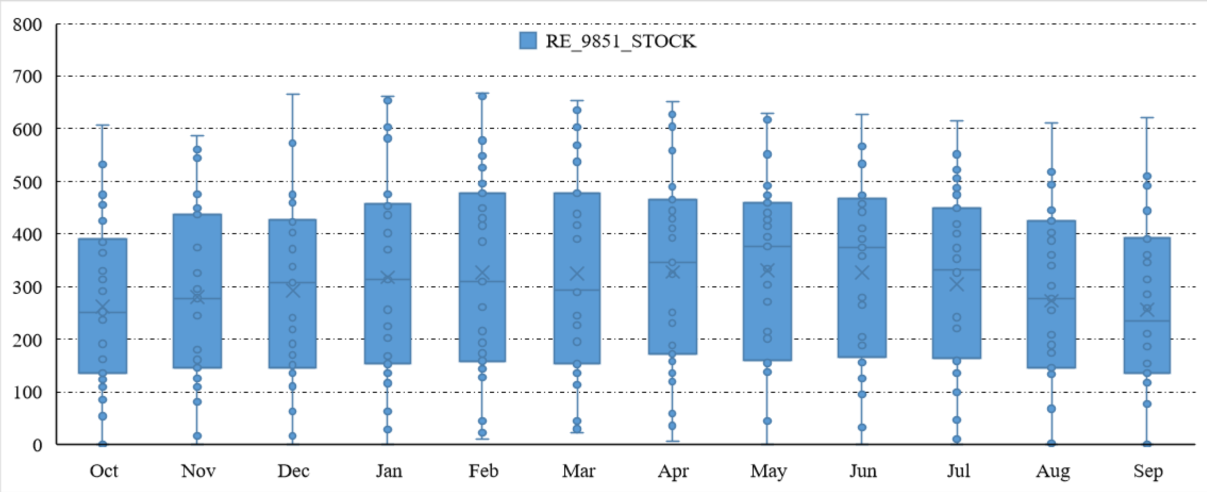
The next in this reservoir system is Canelles, which has a maximum capacity of 687 Hm^3. Inflows and outflows are represented in Figure 1.31. Once again, inflows and outflows follow a very similar cycle, although a pattern of net imbalances is observable in the summer months in this case. Figure 1.32 reveals significant variance in the monthly volumes of dammed water. Moreover, the average volume of water stored in the Canelles reservoir is below 50% of capacity all year round.

Figure 1.31. Canelles Reservoir (9851) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

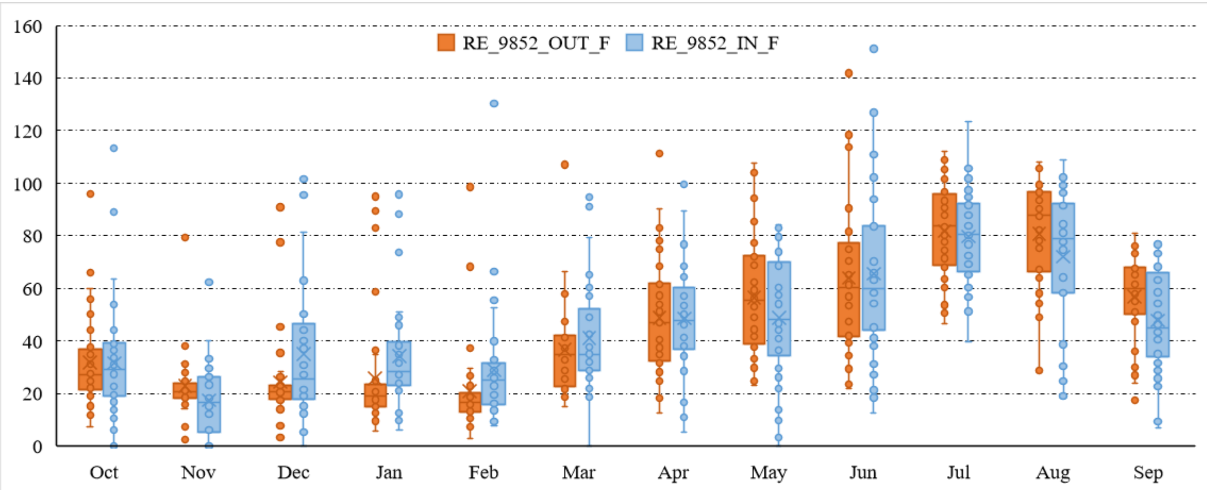
Figure 1.32. Canelles Reservoir (9851) – Distribution of water stock (Hm³)



Source: Own work based on data from MAPAMA (2016b).

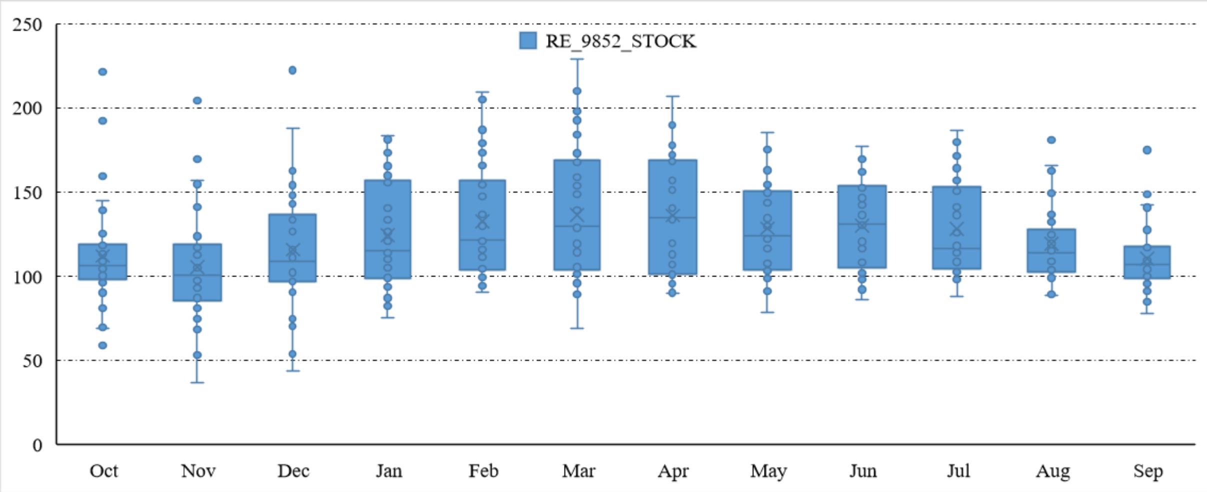
Santa Ana reservoir, which has a maximum capacity of 236 Hm³, completes the system of three reservoirs on the Noguera Ribagorzana river. This reservoir also supplies the Canal de Aragón y Cataluña canal system (together with Barasona reservoir) and feeds the Piñana Canal, which provides water for the city of Lleida. Figure 1.33 shows inflows and outflows at this reservoir. Once again, the pattern is very similar, although there is some recharging between December and April and small net discharges between May and November.

Figure 1.33. Santa Ana Reservoir (9852) – Distribution of inflows and outflows (Hm³)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.34. Santa Ana Reservoir (9852) – Distribution of water stock distribution (Hm^3)

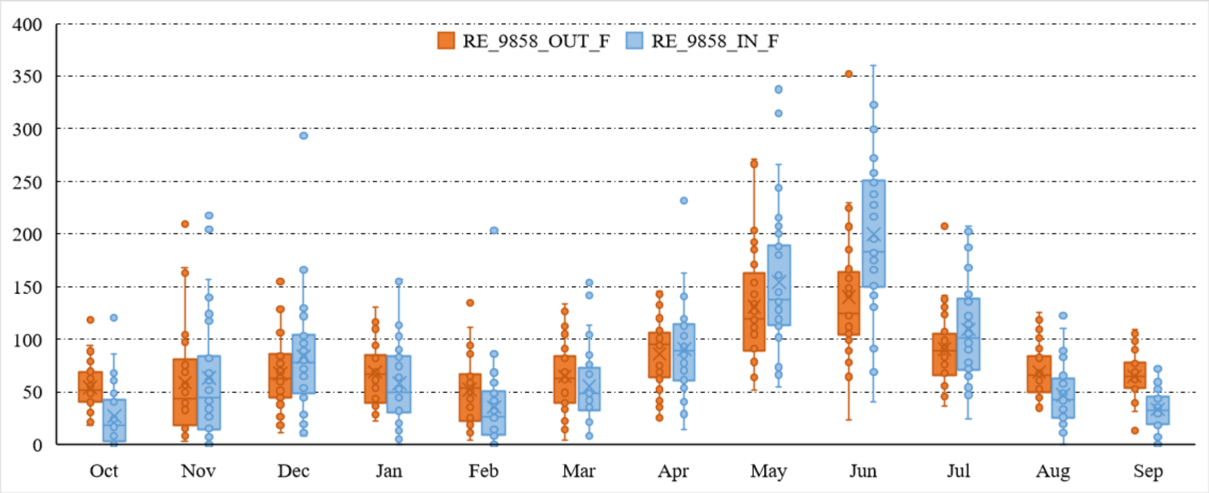


Source: Own work based on data from MAPAMA (2016b).

A little to the east of the Noguera Ribargorzana river we find the Noguera Pallaresa river, also a tributary of the Segre. Its reservoir system encompasses the Tremp (9858), Terradets (9859), and Camarasa (9860) reservoirs. Meanwhile, the Río Segre has two main reservoirs at Oliana (9862) and Rialb (9876), which directly supply the irrigation scheme associated with the Urgel canal. The Noguera Pallaresa river empties into the Segre in the San Lorenzo de Mongay reservoir (9861), which has a capacity of only 10 Hm^3 and supplies irrigation water via the auxiliary channel of the Urgel canal as well as domestic water to various towns.

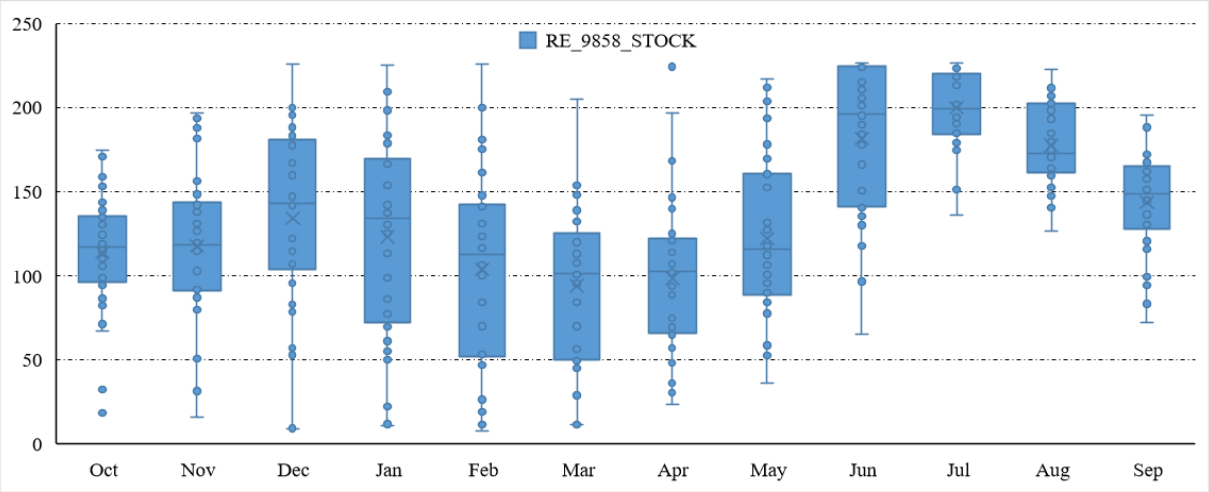
Figure 1.35 shows the distribution of inflows and outflows at the Tremp reservoir. The inflows consist of contributions to the watershed via the Noguera Pallaresa river.Figure 1.36, meanwhile, presents the distribution of average water stock. As may be observed, Tremp has two filling cycles due to its low storage capacity compared to the total annual inflows, as is also the case in the reservoir system as a whole. The reservoir is thus partially recharged in the months of November and December, only to proceed with a net discharge in the months of January to March and recharge again between April and July. The data for the Terradets reservoir are presented in Figure 1.37 and Figure 1.38. This reservoir has a capacity of only 33 Hm^3 of capacity, and it backs up and then releases the inflows received from the Tremp reservoir for hydroelectric use. The inflow and outflow data for Camarasa, the third reservoir included in this reservoir system, are presented in Figure 1.39. This figure and Figure 1.40 reflect a similar filling and discharge cycle to the Tremp reservoir.

Figure 1.35. Tremp Reservoir (9858) – Distribution of inflows and outflows (Hm^3)



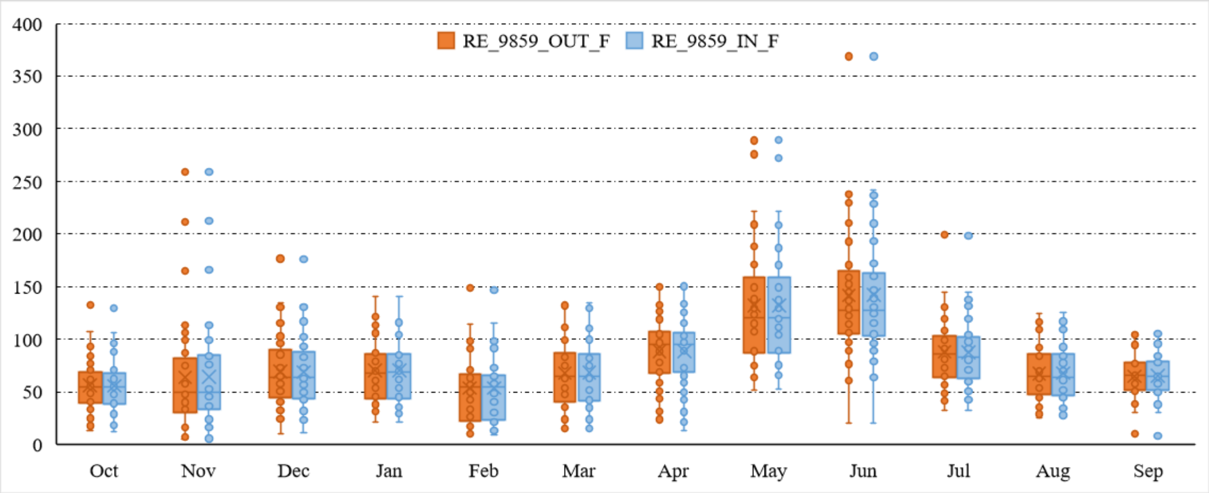
Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.36. Tremp Reservoir (9858) – Distribution of water stock (Hm^3)



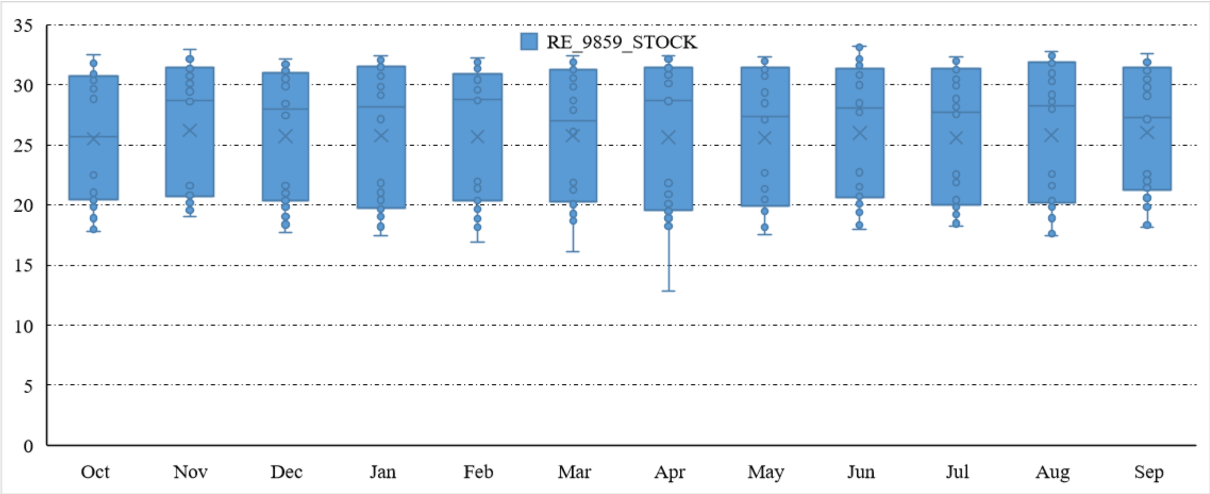
Source: Own work based on data from MAPAMA (2016b).

Figure 1.37. Terradets Reservoir (9859) – Distribution of inflows and outflows (Hm^3)



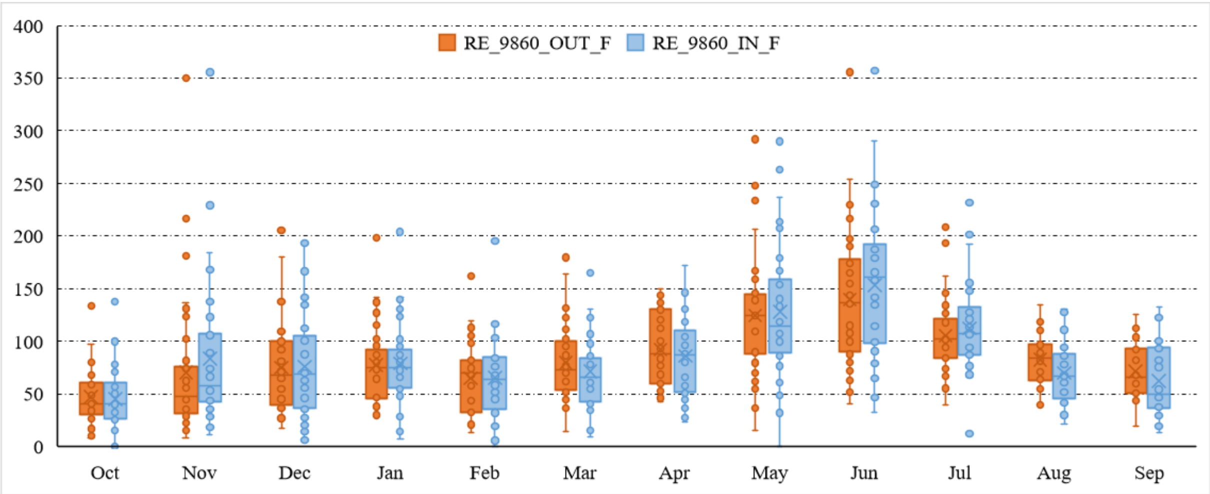
Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.38. Terradets Reservoir (9859) – Distribution of water stock (Hm^3)



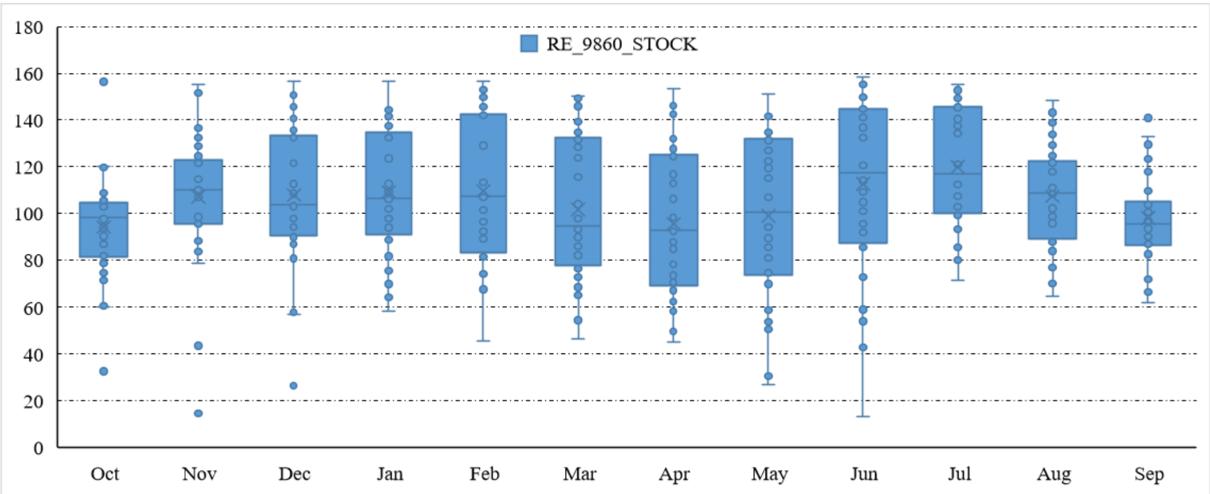
Source: Own work based on data from MAPAMA (2016b).

Figure 1.39. Camarasa Reservoir (9860) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.40. Camarasa Reservoir (9860) – Distribution of water stock (Hm^3)



Source: Own work based on data from MAPAMA (2016b).

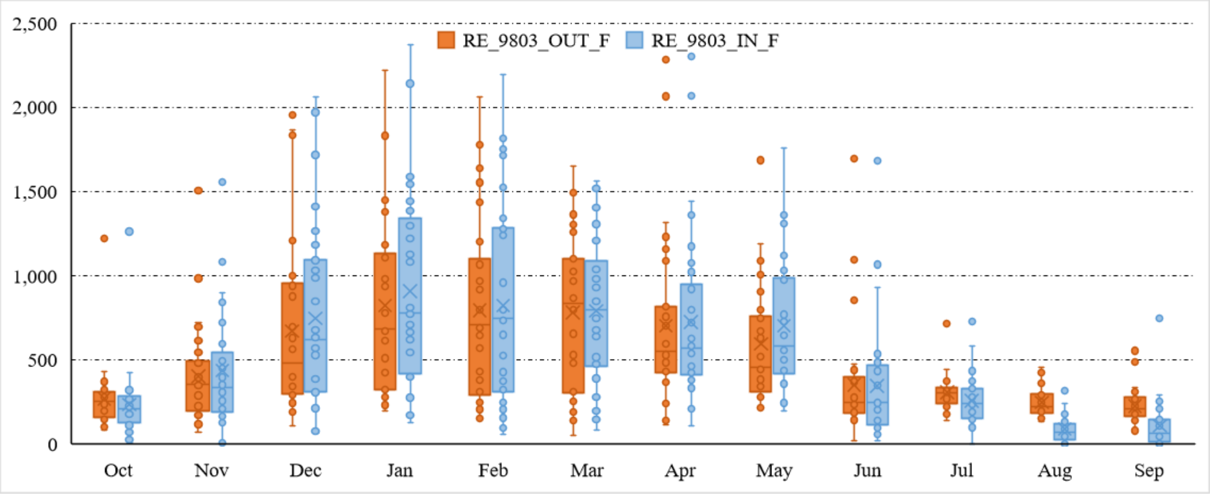
The most recently commissioned reservoir in the Eastern Pyrenees is Rialb reservoir on the Segre river, which provides enhanced water management capacity. Rialb has a capacity of 403 Hm^3 and a fluvial contribution of more than 800 Hm^3/year. Construction of the reservoir was completed in 2000, followed by a period of years to fill it. The distribution of inflows and outflows at this reservoir is not presented graphically to avoid the risk of misinterpretation.

On its way from Aragon to Catalonia, the waters of the Ebro are dammed first at Mequinenza (9803) to form the reservoir with the largest capacity in the whole of the Ebro River Basin, holding with 1,530 hm^3 of water. Mequinenza reservoir empties its waters into the much smaller Ribarroja (9804) reservoir (capacity of 210 Hm^3). Still just inside Aragon, Ribarroja collects the waters of the two tributaries with the largest flow in the Ebro Basin, the Cinca and the Segre. The Ribarroja reservoir drains in Catalonia, at the tail of the Flix reservoir, which has a capacity of only 11 hm^3. In this last stretch, the waters of the Ebro must still cool the Ascó nuclear power plant, feed the Xerta irrigation canals, which average annual water demand of more than 1,000 Hm^3, supply the Camp de Tarragona district by transfer, and maintain environmental flows of 3,500 Hm^3 at Tortosa.

The ERB Authority uses the Mequinenza reservoir to manage the lower stretch of the Ebro and make the necessary contributions to cover water needs. As shown in Figure 1.41, inflows and outflows at the reservoir are not very different in most months, although water stocks rise to their highest levels in the summer months. This is in part because the reservoir is used for winter flood protection and control, which means that it cannot be at maximum capacity at that time of year, and it also supports minimum flows in the river in the months from June to October, resulting in average annual outflows of about 400 Hm^3 in summer (Figure 1.42).

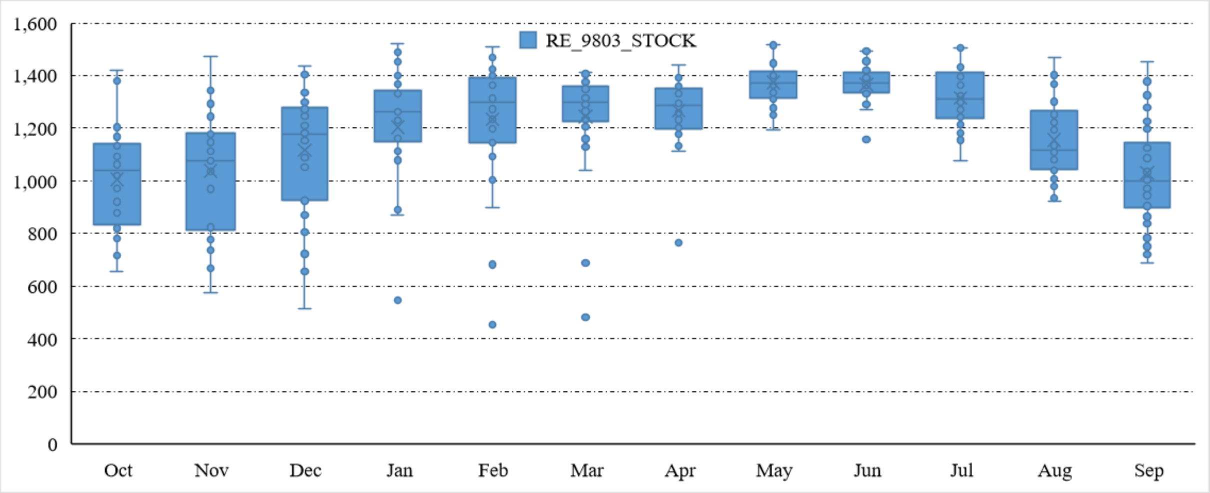
Ribarroja reservoir receives the outflows from Mequinenza and also the waters of two of the main tributaries of the Ebro, the Cinca and the Segre. As can be seen in Figure 1.43, inflows into the reservoir match outflows keeping the level of its waters, shown in Figure 1.44, more or less constant. Ribarroja therefore benefits from the absence of any management activity, a matter to which we will return in Chapter 3. Finally, the figures for Flix reservoir are presented Figure 1.45 and Figure 1.46. This reservoir has a very small capacity in relation to the inflows and outflows it supports, which are the practically equal. In view of this, Flix is not treated here as a reservoir properly speaking but rather as a gauging station.

Figure 1.41. Mequinenza Reservoir (9803) – Distribution of inflows and outflows (Hm^3)



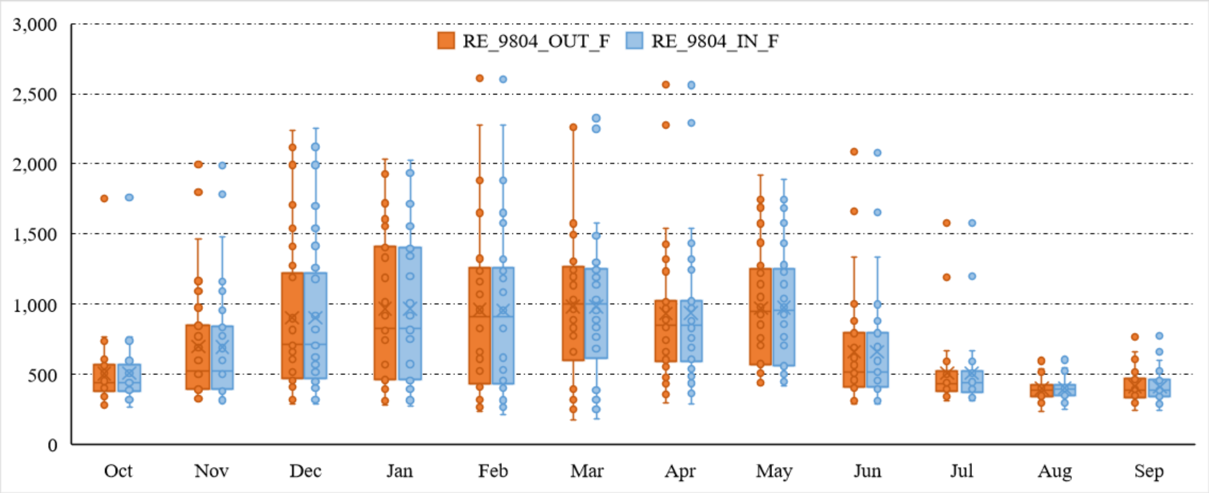
Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.42. Mequinenza Reservoir (9803) – Distribution of water stock (Hm^3)



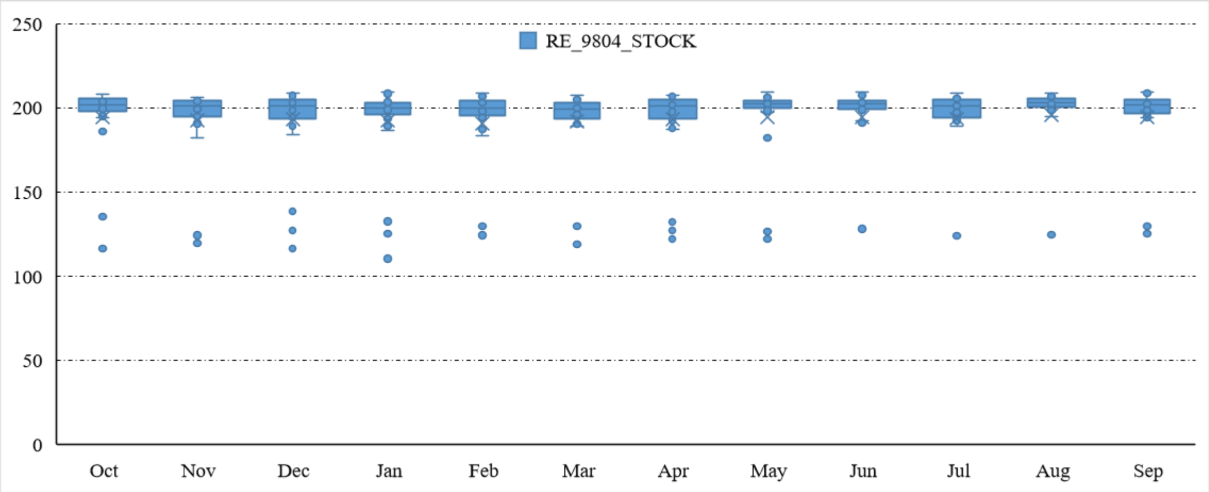
Source: Own work based on data from MAPAMA (2016b).

Figure 1.43. Ribarroja Reservoir (9804) – Distribution of inflows and outflows (Hm^3)



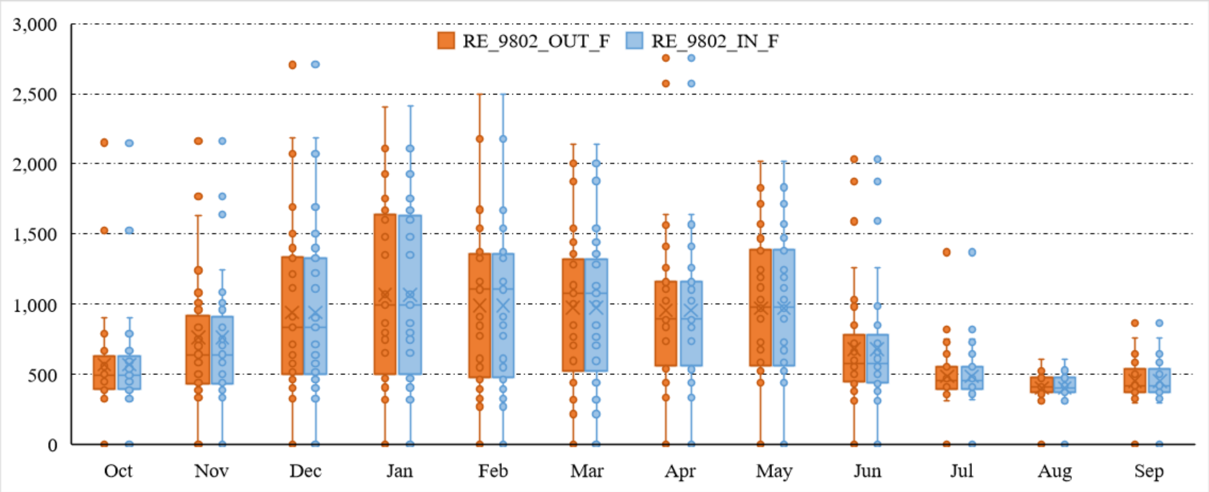
Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.44. Ribarroja Reservoir (9804) – Distribution of water stock (Hm^3)



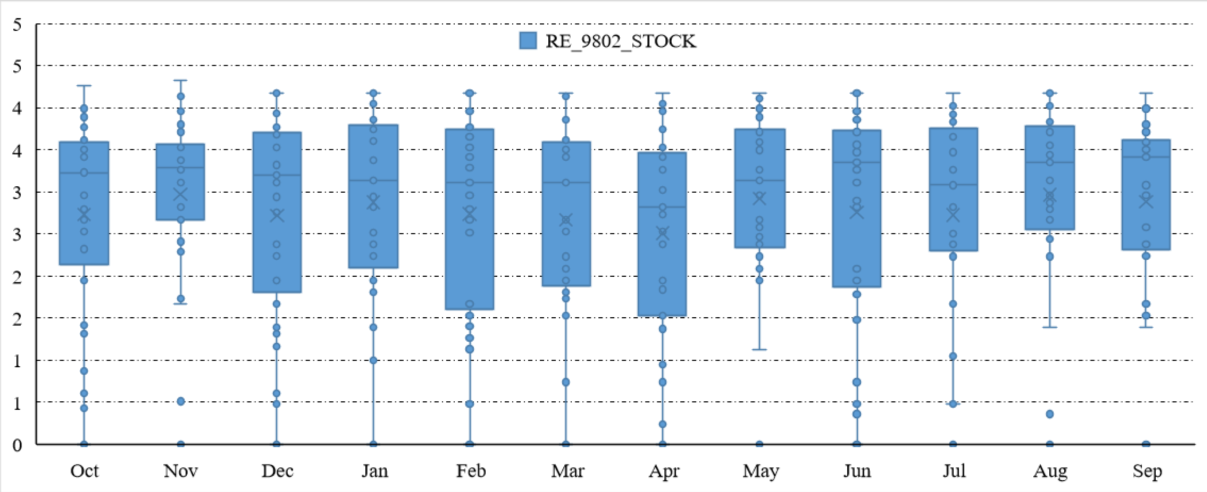
Source: Own work based on data from MAPAMA (2016b).

Figure 1.45. Flix Reservoir (9802) – Distribution of inflows and outflows (Hm^3)



Source: Own work based on data from MAPAMA (2016b). Orange represents outflows and blue inflows.

Figure 1.46. Flix Reservoir (9802) – Distribution of water stock (Hm^3)



Source: Own work based on data from MAPAMA (2016b).

The description of the Ebro River Basin made in this chapter reflects both its multiregional nature and some of the socioeconomic differences between its constituent Autonomous Communities. The socioeconomic database built for the purposes of this research at the municipal level is attached to this thesis in Excel format, and the main parameters used in are provided in the annex to this chapter. This database is used in Chapters 4 and 5.

As explained below, the ERB's water availability problems are not determined by annual availability, which would always be enough to satisfy all the water requirements of the Ebro Basin, but by the spatial and temporal distribution of flows over the course of the hydrological year and by the storage capacity of reservoirs. In this light, the description of flows provided in this chapter is crucially important, providing one of the key modelling and calibration bases discussed in Chapter 5. Figures Figure 1.9-Figure 1.46 present descriptive information on monthly flows at the different reservoirs based on data from the gauging yearbook (MAPAMA, 2016b), . This is a key issue for the analysis of water availability and water management, so much so in fact that one of the future lines of research proposed would address the relationships between transient inflow, storage and dam discharge conditions and water uses, given that differences in these patterns reveal not only fluctuations in rainfall and snowmelt, but also regional divergences in in water use and in the management role played by the reservoirs throughout the Ebro Basin.

Annex to Chapter 1

Construction of municipal level database for the Ebro River Basin

The research supporting this thesis involved the collection and calculation of numerous data at the municipal level. As explained above, the Ebro River Basin has been pared down in this thesis to include only its five most representative regions (Aragon, the Basque Country, Calatonia, La Rioja and Navarre) for the purpose of building both the ERB input-output table and the hydro-economic model.

The ERB as a whole includes a total of 1718 municipalities, of which 1480 belong to the regions modelled. As a result, some of the calculations made extend only to the 1480 municipalities of these representative regions, even though the database shows the data referring to all 1718 municipalities of the Ebro Basin. .

The municipal level database for the Ebro basin is attached to this Thesis in Excel format and is available upon request. As explained, the database referred to in this Annex was built up from other databases and using calculations based on data from other sources (Bureau Van Dijk, 2017; INE, 2018, 2015, 2011a, 2011b; MAGRAMA, 2013, 2011; Martínez-Cob, 2004). The database contains the information presented in the Table A1.6 and it also identifies the water use zone assigned to each municipality for Chapter 5.

Table A1.6. Data contained in the municipal level database of the Ebro basin

Variable	Unit	Data Source	Notes
Hectares sown, broken down into 18 groups of rainfed and irrigated crops (18 x 2 = 36 data per municipality)	Hectares	"Agrarian census of 2009" (INE, 2011)	1) Wheat ; 2) Other winter cereals (oats, rye, etc.); 3) Corn; 4) Barley; 5) Other summer/spring cereals (sorghum, millet, etc.); 6) Alfalfa; 7) Other fodder crops; 8) Industrial crops; 9) Citrus fruits; 10) Pome fruits; 11) Stone fruits; 12) Fleshy fruits; 13) Dried fruits; 14) Legumes; 15) Horticulture; 16) Olives; 17) Vines; 18) Rice
Annual water needs per hectare and crop type (only applies to irrigation) (18 data per municipality)	Cubic meters	"Review of the Net Water Needs of Crops in the Ebro Basin" (Martinez-Cob, 2004)	Water needs are calculated by county, so we have identified the Autonomous Community to which each municipality belongs. We use the water need data associated with the 80th percentile. Also, the annual irrigation water needs are extrapolated from the monthly irrigation water needs observed in this study.
Annual water needs by municipality and crop (only applies to irrigation) (18 data per municipality)	Cubic hectometers	Own calculations	Hectares planted by annual water needs per hectare and crop type
Estimated output (18 x 2=36 data per municipality)	Kilograms	Hectares planted and Statistical Yearbook of the MAGRAMA 2011	The average productivity per hectare was extrapolated from the data contained in the MAGRAMA yearbook, which are provided at the provincial level.
Output value (18 x 2=36 data per municipality)	Euros	Estimated production and farm gate prices* (IAEST, 2014)	* Prices received by farmers on the sale of agricultural produce and livestock. Years 1990-2013 - Average prices for the years 2008-2012 were applied
Livestock broken down into 7 groups (7 data per municipality)	Heads LU*	"Agrarian census of 2009" (INE 2011)	1) Cattle; 2) Sheep; 3) Goats; 4) Equine; 5) Pigs; 6) Poultry; 7) Rabbits LU * Livestock Units - Equivalences at www.INE.es
Ordinary result before taxes (29 sector groups) (29 data per municipality)	Thousands of euros	"Iberian Balance Analysis System (SABI). Online Database" (Bureau Van Dijk, 2017)	Aggregate figures for each CNAE (Spanish Classification of Economic Activities) were obtained by combining the municipal postcode with the INE code (Spanish National Statistics Institute). The CNAE codes were grouped based on the sectoral aggregation of the multi-regional table for the Ebro Basin (see Chapter 4). Data referring to the primary sector were rejected.
Results for the year (29 data per municipality)			
Farm income (29 data per municipality)			
Operating result (29 data per municipality)			
Personnel costs (29 data per municipality)			
Value added (29 data per municipality)			
Number of employees (29 data per municipality)	Jobs		
Gross Domestic Product (series 2000-2012)	Euros	Instituto Klein	The database to which we have had access contains the GDP and per capita GDP estimates made by the Instituto Klein for the years 2000, 2006, 2009 and 2012. The rest of the data was estimated by interpolation.
Gross Domestic Product per capita (serie 2000-2012)			
Population (2000-2018) (Total, male and female)	Inhabitants	INE	Official population figures at January 1 of each year

Chapter 2

Background and methodological notes

Academic interest in the resolution of water-related conflicts and in the valuation of water as an economic input and a natural resource has grown in recent years (Hipel et al., 2015), as it has become more widely recognized that it has no substitute and is essential for life and for any kind of development, while its value depends on both place and time (Hanemann, 2006). In this light, water problems are not confined merely to the trade-off between costs and benefits but also involve key social and political concerns. (Madani, 2010).

When the common resource is water, the logic of personal greed that underlies the tragedy of the commons (Hardin, 1968) clashes with the reality embodied by the irrigation collectives and tribunals of Spain, the oldest of which can trace their origins back as far as 200 BC (Sagardoy et al, 2001). The venerable Tribunal de les Aïgues in Valenciais over 1,000 years old and is heir to institutions dating back at least to the times of the Caliphate of Al-Andalus (Giner-Boira, 1997). Indeed, it is widely held that the existence of management organizations is essential to safeguard the condition and renewability of water resources, and to guarantee the interests of all stakeholders over the long term (Ostrom, 1990). Game theory, especially repeated games, are exceptionally well suited to the analysis of these situations(Aumann, 1964).

The international law association approved the “Helsinki Rules” (ILA, 1967) in 1966 to deal with the issues concerning the distribution of water in international river basins. However, every river basin and every potential conflict features its own particular issues, and each must therefore be addressed in its own terms. In actual fact, the distributions provided for in most water treaties are not based on law or hydrology but on socioeconomic variables that determine specific needs. (Wolf et al., 1999). It is, then, essential to identify the key socioeconomic variables and observe the interrelationships between them to ensure good water governance.

The more arid the riparian terrain, the more necessary it will be to share out water resources equitably and the greater the possibility that a given distribution could prejudice some users and unfairly benefit. Spain is a largely dry country and semi-arid or arid climate conditions prevail over approximately two thirds of its land according to an official report on desertification in Spain (MMA, 2008). Conflicts over water have existed throughout Spanish history, but Spain has also been a land of agreements; let us recall the contents of the Botorrita II plaque dating from the 1st century BC, which includes an agreement on water uses.

The inevitability of conflict and the need for agreement are still present in the Ebro Basin today. Moriondo et al. (2010) and a recent IPCC report (Hoegh-Guldberg et al., 2018) forecast highly adverse climate change impacts on water resources. For the ERB, it is argued, an increase of 1ºC in temperature combined with a 5% drop in precipitation would mean a reduction of around 20% in water availability. Meanwhile, Milano et al. (2013b)examine trends in water withdrawals and availability in light of water stress indices, highlighting the vulnerability of arid and semi-arid Mediterranean river basins to climate change between the present and 2050. As a matter of fact, increasing aridity has accelerated desertification in the ERB (Vicente-Serrano et al., 2012).

The following methodological approaches and tools are used in what follows to make an economic and environmental analysis of the ERB, assess possible conflicts between different water uses or users, and design environmental mitigation measures: 1) input-output framework, 2) game theory, 3) hydro-economic modelling, and 4) geographic information systems (GIS). The methodologies used are explained at the beginning of each chapter, but in the following sections we review the literature on these frameworks as they relate to water issues.

2.1. Input-output and water framework

Input-output tables (IOTs) lie at the core of the input-output framework, which is based fundamentally on supply and use tables and the implicit relationships they embody based on the macroeconomic relationships inherent in any economy. In fact, a symmetric IOT is merely a reorganization of the corresponding source and destination table under the implicit hypothesis of simple production (Eurostat, 2008). Symmetric IOTs can be made product by product or industry by industry depending on the objectives of the study concerned. Given our statistical sources, we use industry-based tables.

The supply table shows what sector or industry produces each type of good and the level of output. Meanwhile, the use table reflects the sectors or industries that consume each type of good in their own production processes, as well as the part of production intended to satisfy final demand. Finally, the symmetric table will tell us what goods (which we may define either as products or as the output of a given industry or sector) are inputs used in the production of each of the other goods existing in the economy.

Symmetric IOTs were initially developed at the national level as an accounting tool to show the economic transactions between the different agents and, ultimately, the interdependencies existing in a country’s economy. The geographical scope of the method was later extended to create multi-regional input-output tables (MRIOTs), which identify transactions between agents from different countries or regions while determining the regions of origin and destination of each exchange. MRIOTs have gained prominence in recent decades on the back of ever more intense globalization and the increasing availability of data. In short, interdependencies revealed show us the need that each of the productive sectors in an economy has for the others, as well as its relations with other economies (imports and exports).

Input-output models throw light on inter-sectoral and interregional structures and allow calculation of the total direct and indirect effects of shocks affecting different economic and environmental variables (White et al., 2015). They are therefore an important tool for the analysis of the potential impacts of policy proposals on production. However, the method permits not only investigation of the possible changes in output that a given measure could trigger, but also of the potential variation in other socioeconomic variables such as employment, consumption or exports. Furthermore, the model can be extended to address environmental assess effects. This is extensible to multi-regional input-output models, which add geographic and/or regional features to input-output models.

The input-output framework has been widely used to assess environmental impacts. For example, Leontief (1970) added a row and a column to obtain an environmental model in a simplified economy with two sectors, while Lenzen (1998) studied the greenhouse gas emissions embodied in goods and services. This methodology has also been widely used to study CO_2 emissions (Chang and Lin, 1998; Duarte et al., 2018a; Lenzen et al., 2004; Machado et al., 2001; Munksgaard et al., 2008), and in the specific case of water, it has also been enlisted to analyse the relationship between economic agents and water (Duarte et al., 2002; Lenzen and Foran, 2001; Velázquez, 2006; Wang et al., 2009) and to estimate the water footprint of different activities (Cazcarro et al., 2016a, 2014; Lenzen, 2009; Wang et al., 2013; Zhao et al., 2009) and the flows of embedded water or virtual water included in the goods produced by an economy (Antonelli et al., 2012; Chen et al., 2012; Dietzenbacher and Velázquez, 2007; Duarte et al., 2018b; Zhang and Anadon, 2014).

The methodology has also frequently been extended to create IOT-based computable general equilibrium (CGE) models. Models of this kind have also been widely used as a tool to study water-related topics. Among others, the United States Department of Agriculture developed a CGE (Robinson et al., 1990) for this purpose, while . Seung et al. (1999) developed another rather more specific CGE model to assess surface water distribution policies (creation of a water rights market) in Churchill County, Nevada. More recently Calzadilla et al. (2011, 2010) used global CGE models to analyse the sustainability of irrigated agriculture. Another notable example is the multi-regional CGE model designed by Wittwer (2012) and applied in Wittwer and Dixon (2013) to analyse water repurchase policies in the Murray Darling Basin under drought conditions. Other water-related CGE models have also been developed to address technological changes applied in irrigation water management and the distribution of agricultural production (Cazcarro et al., 2019; Philip et al., 2014).

2.2. Game Theory and water

Widely used in economics, Game Theory is an area of mathematics that uses formalized structures, to search for optimal strategies and study of the expected behaviour they imply. According to Gura and Maschler (2008), this is a relatively young branch of mathematics that dates back to the publication of *Theory of Games and Economic Behavior* de John von Neumann y Oskar Morgenstern in 1944. The history of game theory is briefly summarized in Tenorio-Villalón and Martín-Caraballo, (2015).

Game theory establishes a broad classification comprising competitive, bargaining and cooperative games. The literature on cooperative games and water is extensive. An example of the application of cooperative games to water can be found in Dinar y Howitt (1997), who test the acceptability and stability of the balance in cooperative games and discuss the two main reasons (economies of scale and internalization of externalities) why cooperation is preferable as a means of apportioning environmental control costs. Other works that apply cooperative games to address water issues include Abed-Elmdoust and Kerachian (2012), Liao and Hannam (2013) and Nikoo et al. (2012).

In the present context, consumptive water uses turn water into a semi-private good, and non-cooperative games will therefore take pride of place in this thesis, especially bargaining games. This is the approach taken in Atwi and Sánchez-Chóliz (2011), who analyse the water drawn from the River Jordan using negotiation games, finding that the current distribution is clearly improvable. Also, Sechi et al. (2013) use bargaining games to determine ideal core water distributions and compare them with the current distributions in southern Sardinia, Italy. Other papers to analyse water issues using non-cooperative games include Kerachian et al. (2010), Madani (2010), Wei et al. (2010) and Rafipour-Langeroudi et al. (2014).

Evolutionary game theory emerged in the work of Maynard Smith (1972) and Maynard Smith and Price (1973). Some relatively recent papers have used this dynamic form of game theory to analyse water issues. One such is Parsapour-Moghaddam et al. (2015), who combine evolutionary game theory and heuristics in a study of the Karoon river in Iran.

Cooperative water-related games have recently been used in Kahil et al. (2016b), who use a cooperative game theory framework that applies to the economic and environmental benefits of stakeholder cooperation to find the best water allocation in a context of diffuse payments in the Júcar River Basin in Spain. Likewise, Kerachian et al. (2010) apply fuzzy payment game theory to develop a model based on Rubinstein's negotiation model (Rubinstein, 1982) to resolve conflicts of interest arising between parties in relation to the joint use of surface and underground water resources. The study area chosen was the metropolitan area of Tehran (Iran). Another similar study applied to the Karoon River (Iran) is described in Abed-Elmdoust and Kerachian (2012).

Cooperative games have traditionally been used to address water problems because they provide an explanation of behaviour when the resource to be distributed is communal and finite (Jager et al., 2016). In fact, the presence of stakeholder groups can be key to assuring water availability and quality (Aumann, 1964; Ostrom, 1990).

2.3. Hydro-economic modelling

Hydro-economic models combine hydrological data with socioeconomic and environmental information to seek optimal water distributions among several agents, or to simulate hydrological events and estimate the resulting socio-economic or environmental impacts (Booker et al., 2012). One of the main strengths of these models is that they take consider time and space into account with regard both to the available water and to the water needs of the agents involved. Hydro-economic models are supported by water flow modelling based on the principles of water mass balance and of river flow continuity, which determine the volume of water available in the different river reaches (Cai et al., 2003). This involves the identification of nodes to determine the amount of the available water in each stretch of river at any given time and formulating equations to define the relationships between them. The nodes in the simplified hydrological scheme developed here and the relationships between them are based on the flows in the Ebro River Basin described in the section 1.2.

Hydro-economic models also draw on relevant socio-economic and environmental information, such as environmental needs, production, benefits, demand patterns and the water needs of individual sectors, as well as crop and land productivity data, the irrigation technologies used and so on. All socio-economic and environmental water uses are identified and associated with specific use nodes in the model of the Ebro River Basin described here. Specifically, the model integrates a broad range of socio-economic data including urban, industrial and farm water requirements measured in terms of domestic consumption, industrial output and monthly consumption per hectare for each crop grown month by month, as well as agricultural productivity, production costs of each sector and the like. This socioeconomic data is obtained from the multi-regional input-output table developed in Chapter 4 and from our municipal level database for the Ebro River Basin. Environmental requirements are modelled applying minimum flow restrictions throughout the schema, in line with the minimum flows established for specific sections and points in the Ebro River Basin, see annex 5 of CHE (2015b).

Scholars first began to combine economic benefit functions with hydrological concepts to determine optimal levels of use in arid regions in the 1960s and 1970s (Harou et al., 2009). Since then, these models have been closely linked to agriculture. For example they were used to maximize the benefit of farmers through the joint use of surface and ground water in the San Joaquin Valley (Burt, 1964), and Yolo County (Noel et al., 1980; Noel and Howitt, 1982), California, and in the economic optimization of groundwater use in Israel applying different water demand curves (Bear et al., 1968). Other hydro-economic models have been used to seek optimal management and distribution strategies for surface and groundwater in Pakistan (Rogers and Smith, 1970), California (Jenkins et al., 2004) and the Júcar Basin in Spain (Kahil et al., 2016c), among others. These models have mainly focused on agriculture, while taking account of the needs of other agents.

Hydro-economic models have also been used to study and propose solutions to international conflicts. Taking the Jordan Basin as their study area and in view of the installation of desalination plants by the state of Israel, Fisher et al. (2002), developed a software application containing hydrological and economic information to determine the shadow price of water in local population centres. Also in an international context, Ringler and Cai (2006) studied the Mekong River, which supplies water to 75 million people living in 6 different countries, seeking to improve social benefits by identifying trade-offs between irrigation, hydroelectric power plants, municipal and industrial uses, fishing, and wetlands.

Babel et al. (2005) developed a model that integrates a dam management module with economic and water distribution aspects as a means to seek optimal distributions between different agents, while the time-conditioned model proposed Bielsa and Duarte (2001) differentiates between distributions depending whether irrigation is or is not permitted in the period concerned. Finally, George et al. (2011) created a hydro-economic model to assess and determine the optimal allocation of water from the Musi River in India.

Models of this kind have also been used, among many other purposes, to evaluate possible water markets, calculate shadow prices and to assess the opportunity cost of establishing environmental flows in Spain (Pulido-Velázquez et al., 2008, 2006); to assess the benefits of possible water reallocation in the Murray-Darling Basin (Akter et al., 2014); to examine management and climate change adaptation policies in scarcity scenarios (Kahil et al., 2016a, 2015); to limit damage in the event of drought (Ward et al., 2006); and to study possible flooding impacts and their direct and indirect economic (Jonkman et al., 2008). A detailed review of the literature on hydro-economic models will be found in Harou et al. (2009).

As explained below, water availability problems are determined not by the annual availability of water, but by the distribution of flows over the year and by storage capacity. Hence, the model developed for the Ebro Basin is based on monthly flows from October 1 to September 30 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 behaviour of water demand more accurately.

2.4. Geographic information systems (GIS)

Geographic information systems (GIS) allow different layers of information to be superimposed on a map. The data in question may be related to physical and environmental variables (temperature, rainfall, slope, drainage area, etc.), hydrology (rivers, reservoirs, gauging stations, channels, etc.) or socio-economic variables (location of industries and infrastructure, production levels in a given area, etc.). Meanwhile, the combination of different variables in a single map will reveal the effects of the variables considered in the districts selected for examination and and/or on local industries (Cazcarro et al., 2016a).

Given their characteristics, GIS have played an important role in socio-economic and environmental analysis and planning (Malczewski, 2004). For example, Page et al. (1999) used GIS to examine the role of Maori participation in tourism and the implications of indigenous participation in tourist development, while Jonkman et al. (2008) applied the technique to estimate potential flood damage by looking at layers of land use and other economic data, as well as geographical and/or hydrological information. Finally, Hubacek and Sun (2001) also incorporated layers of information on biophysical attributes and demographic data to assess how different development pathways influence land use and commodity trade flows.

GIS is used here in combination with the methodologies described above, especially input-output models, in order to achieve a graphic representation of findings and to identify the areas and municipalities likely to be most affected by changes in water availability as an aid to interpretation and, in some cases, as a basis for compensatory policy proposals. Although GIS has rarely been used in conjunction with the input-output framework, Veen and Logtmeijer (2005) combined the technique with a bi-regional table to capture and visualize the total (rather than merely the direct) impact of possible flooding in the province of South-Holland (Netherlands). Meanwhile, Hallegatte et al. (2011) describe a similar study focused on the Copenhagen area, in which they use a GIS/IO combination to assess the overall impacts of rising sea levels on socioeconomic variables including jobs and value added. Grêt-

Regamey and Kytzia (2007) also use a combination of these tools to estimate the value of ecosystems as a service in an alpine region of Switzerland, while Haddad and Teixeira (2015) combine GIS with a spatial computable general equilibrium model to assess the potential impact of flooding caused by extreme precipitation. Finally, (Cazcarro et al., 2016a) use a multi-regional input-output framework in combination with GIS to locate the grey water footprint, allowing them to identify critical points and vulnerable areas.

Chapter 3

Environmental flow management:

an analysis applied to the Ebro River Basin

This chapter presents a case study of the flows and conflicts associated with the final stretch of the Ebro, comprising the land near the Mequinenza, Ribarroja and Flix reservoirs, which are the last on the river, and the environmentally sensitive area of the Ebro Delta.

The Ebro Delta makes a very interesting case study in both social and political terms not only in view of the minimum environmental flows required under the EU's Water Framework Directive, but also because of two unrelated but nonetheless important factors, namely the demands of the regional government of Catalonia (ACA, 2007; CSTE, 2015) and the very limited room for manoeuvre available for water management, since uses are already close to the maximum possible.

The demands of the Catalan regional government are impossible to meet, as will be shown through the simulations performed using actual flow data for recent decades. Based on the present analysis, however, it appears that the difficulty is not so much a matter of the equivalent annual volume sought by the nationalist political parties but the level of their monthly demands. Moreover, the continuation of the current management arrangements, which place the entire burden of regulation on the Mequinenza dam, implies very high environmental and social impacts both for the reservoir itself for the surrounding area. , Nevertheless, this responsibility could be shared with other reservoirs.

As we will also see, various potential solutions exist that would guarantee environmental flows in the Ebro Delta, but these would imply cooperation between all users and agents involved, including those in the middle and upper reaches of the river (which determine water availability at Mequinenza) and those in the final stretch in Catalonia (associated mainly with the use of water from Rialb reservoir).

This chapter strongly underscores the usefulness of agreements and negotiation between users and highlights the opportunities they could offer to improve water use and gain economic efficiency. It also to some extent determines the analysis presented in the next chapters, revealing that conditions in the last stretch of the Ebro are dependent on conditions further upstream and stressing the need for extensive geographical planning. At the same time, it points up the need to integrate the analysis of water flows with economic analysis to throw light on the problems and interdependencies existing in the ERB. This is the *raison d'être* for the fusion of hydrological and economic models described in Chapter 5. Finally, this chapter invites us to delve into possible conflicts between users, which is the key issue underlying all of the research supporting this thesis.

The content of this chapter is essentially the same as that of the article: Almazán-Gómez, M.A., Sánchez Chóliz, J., Sarasa, C. (2018): "Environmental flow management: an analysis applied to the Ebro River Basin". *Journal of Cleaner Production*, 182, 838-851. However, some changes have been made, mainly with regard to the renumbering of the sections, tables and graphs to adapt them to the numbering of the thesis. Meanwhile, the bibliography has been incorporated into the general thesis bibliography and the Abstract and Acknowledgments have been removed.

3.1. Introduction

The importance of water for life, for the environment, for human beings and for industries of all kinds is indisputable. However, the quality and availability of the resource are affected by numerous variables, including increases in upstream use and climate change (Alcamo et al., 2007; IPCC, 2014), spontaneous revegetation and so forth, all of which combine to diminish fresh water availability (Gerten et al., 2008). The European Water Framework Directive (WFD) was enacted partly in response to declining water availability (European Communities, 2000). In particular, the WFD requires member States to achieve good ecological status (GES) in all water bodies and river basins, and to establish Environmental Water Requirements (EWR) and regulate environmental flows (EF) in all of Europe's rivers, defining the quantity, timing and quality of the water flows necessary to ensure sustainability under variable conditions, see Acreman and Ferguson (2010). In this context, our study focuses on the final stretch of the Ebro River (Spain) analysing the competing EF and other economic uses in the Ebro Delta (a Biosphere Reserve).

In economic terms, EFs present a serious constraint, particularly for arid and semi-arid regions, because they reduce the volume of water available for consumption and condition agricultural and industrial uses (Bonsch et al., 2015). However, the GES of water bodies and river EF also provide environmental and economic benefits for users and non-users alike, see Ilija Ojeda et al. (2008), Loomis (2000), and Perni et al. (2012). In fact, environmental flows often generate new development opportunities in the areas affected, although can result in social conflict between potential users—see, for example, the work of Qureshi et al. (2010), who address the question of who should receive the profits and bear the costs implicit in any management of environmental flows.

Irrigation communities have long existed to regulate and share the precious resource that is water, some of them going back centuries, even millennia (Sagardoy, 2001). The Water Tribunal of Valencia, whose jurisdiction is a legacy from the time of Moorish rule in eastern Spain is an example. Despite the argument that human beings are often selfish and will sometimes exhaust and destroy shared resources (Gordon, 1954; Hardin, 1968), it seems when the resource is water that communal bodies in fact spring up to handle the tasks of conserving and allocating water, contrary to Hardin's "tragedy of the commons" theory.

Nevertheless, conflicts related with water do exist and when rivers or their basins do not lie entirely within the borders of a single nation, disputes can become bitter and ingrained (Wolf, 1998). Even under the same flag, water can become a source of conflict, as in the case of the Cauvery River in India; in California (Hanak et al., 2011); along the Colorado River (Fradkin, 1981); and in the last two decades in Spain, where the *Plan Nacional del Agua* directly affected Ebro water use and water transfers from the Tagus to the River Segura. The outline of the National Water Plan has been at the root of ongoing political wrangling ever since.

This study seeks the best solution to the water conflicts associated with the final stretch of the Ebro River (Spain), where water uses are already bumping up against their limits, as we shall see below. The Ebro River runs for 910 km in a south-easterly direction across northeast Spain to its delta on the Mediterranean coast midway between Barcelona and Valencia. It has the largest discharge of any Spanish river, and its drainage basin, at 85,500 square km, is also Spain's biggest. The Ebro River Basin provides water to more than three million people living in over 1,700 towns and villages, but it suffers from high levels of evapotranspiration, and low, irregular rainfall (Novau and Campo, 1995). Moreover, a slight decline in mean annual rainfall has been observed over the last eight decades (Valencia et al., 2015). According to (Milano et al., 2013a; Sánchez-Chóliz and Sarasa, 2015), in fact, a general downward trend in water availability is observable in the Ebro River Basin as a whole, a phenomenon that is strongly supported by statistics from the Tortosa gauging station. This only increases the pressure on water alternative uses.

The legal EFs in the Ebro Basin, and in particular for the Ebro Delta, are fixed and regulated by the Ebro Basin Authority (*Confederación Hidrográfica del Ebro* or CHE in its Spanish acronym), which is also responsible for the preparation, review and implementation of annual management plans for the Ebro River Basin. The process involves drawing up preliminary plans, which are submitted to public scrutiny by all stakeholders (irrigators, industry, local councils and environmental organizations) as required by the WFD ((Ballester and Mott Lacroix, 2016).

Water use on the final stretch of the Ebro River is a fiercely competitive matter. Not only do upstream uses compete with uses in the final stretch, but these downstream environmental and economic uses also vie with each other. Priorities include the water requirements to guarantee environmental conditions in the Ebro Delta (a Biosphere Reserve) and to control the salinization of its farmland. Reservoir GES is another prime environmental concern, especially at the Mequinenza dam. Key economic uses include irrigation and hydroelectric generating. Rice is the main irrigated crop in the Ebro Delta, and this traditional activity is essential to maintain the local flora and fauna. Water is also drawn off from Mequinenza reservoir for subsidized irrigation in neighboring wetlands (Aragonese Lower Ebro Plan). Finally, there are also several important hydroelectric power plants along the river's lower stretch of the river. For example, the Mequinenza power plant has approximate annual turbine capacity of some 4,800 hm^3 a year (equal to 75% of Mequinenza's annual inflows) generating capacity of 324,000 Kw and output equal to around 500 Gw-h).

Conflict with the autonomous region of Catalonia is a further issue affecting water management in relation to the Ebro Delta and most of the Segre River Basin, one of its main tributaries, both of which are within Catalonia's regional borders. The strong Catalan nationalist movement seeks secession from Spain and to turn Catalonia into an independent state. This has resulted in a largely contrarian policy on the part of the Catalan authorities reflected in uncompromising demands to guarantee environmental needs of the Delta while excluding Ebro reservoirs like Rialb, which is located in Catalonia and which the nationalist-controlled regional government hopes to appropriate exclusively for local irrigation and future transfers to the city of Barcelona.

A full study of this complex conflict is beyond the scope of this article, see Saez et al. (2015), but the key to any possible solution will involve the regulation criteria applied to the lower Ebro reservoirs. For this reason, we develop a water management model which allows us to simulate scarcity scenarios and measure environmental flow default rates. For the sake of simplicity, the model assumes that the volume of irrigation in the delta will remain constant, which allows us to exclude these uses from the analysis. We likewise assume that there will be no additional water demand for hydroelectric generating, since no-one today is lobbying for an increase of this activity. As a result of these constraints, our model focuses mainly on the hydrological aspects of the problem (dam reoperation) and Ebro Delta EF fulfilment. We also tackle the current management of environmental flows on the final stretch of the Ebro and assess possible alternatives to answer the question: Is there a management criterion that would assure Delta EFs and at the same time reduce water pressures on Mequinenza while maintaining current irrigation and hydroelectric uses are and allowing the completion of subsidized irrigation plans?

Environmental flows in the Ebro Delta, which are gauged at Tortosa, are currently regulated by the Mequinenza dam alone, although other options could be considered. In our case study, we look at three reservoirs situated in the final stretch of the Ebro River Basin, namely Mequinenza, Rialb and Ribarroja, which have respective capacities of 1,530, 403 and 210 hm^3. Other theoretical alternatives also exist, such as the El Grado and Barasona reservoirs for example, but they are not viable due to overuse of their water for irrigation and electric power generation and to their size.

We then go on to use game theory, especially bargaining games, alongside the management model developed in order to account for different institutional frameworks and assess the proposed alternatives. To this end, we develop utility functions based on the reservoirs' average levels and fluctuations obtained from the model so as to shed light on the opportunity costs associated with different management alternatives. Our research aims to contribute to the settlement of water conflicts and to foster more cooperative and equitable flow allocations in the final stretch of Spain's Ebro River Basin in order to assure the future development and sustainability of the area. This is achieved by linking a combination of methods based on a proposed water management model with game theory in order to account for the influence of different institutional frameworks.

The rest of the paper is organized as follows. Section 3.2 reviews the existing literature on water allocation. In Section 3.3, we analyse time series from the gauging stations covering a period of 50 years to establish a correlation between water inflow and outflow along the final stretch of the River Ebro as a basis for the development of our water management model.

Section 3.4 describes the initial results from our simulations, while the results obtained from the different game theory scenarios are outlined in Section 3.5. We end with a discussion of our main conclusions and policy recommendations in Section 3.6.

3.2. Review of the literature

Scholarly interest in water conflict resolution and in assessing water both as an economic input and natural resource, has increased in recent years (Hipel et al., 2015). As a consequence, numerous methodologies and models have been proposed to establish best water allocations based on the constant rise in calculation and data management capabilities, and on progressive developments in game theory.

To begin with, numerous hydro-economic models have been proposed to evaluate water allocation strategies, see for example George et al. (2011), and to analyse water-related issues such as inter-sector water allocation, water markets and pricing, conflict resolution, land-use management, climate change and drought among others. Various proposals of this kind have recently appeared, including Pulido-Velazquez et al. (2008), who develop a hydro-economic model to establish the shadow value of water and assess the opportunity cost of environmental requirements; Akter et al. (2014), who describe a hydro-ecological-economic model designed to assess water reallocation benefits in the Murray-Darling Basin (Australia); and Kahil et al. (2015) and Kahil et al (2016), who asses different possible water policies in scarcity and drought scenarios to handle climate change adaptation in arid/semi-arid regions. More details and a detailed review of the literature on hydro-economic models will be found in Harou et al. (2009). Alongside these models, we also find papers on the subject of dam reoperation, such as Bednarek and Hart (2005), who discuss how dam management could drive better biological status in tailwaters, and Watts et al. (2011), who show the importance of dam reoperation in the service of climate-change adaptation. These models and methodologies capture relevant technical, physical and economic information on irrigation and production technologies, water flows, the technical efficiencies of different uses, benefits, demand patterns and so forth.

Meanwhile, computable general equilibrium (CGE) models provide another tool which has been widely used to examine water management issues in recent years. Among others, a CGE model of the US economy developed by the USDA Economic Research Service (ERS) is presented in Robinson et al. (1990), while Seung et al. (1999) used a CGE model to evaluate surface water reallocation policies (water rights sales) at the Stillwater National

Wildlife Refuge in Churchill County, Nevada, and Calzadilla et al. (2010, 2011) develop a global CGE to analyse the sustainability of irrigation. Another frequently cited example of a multi-regional CGE model is The Enormous Regional Model or TERM designed by Wittwer (2012) and applied by Wittwer and Dixon (2013) to analyse water buyback policies in the Southern Murray Darling Basin under drought conditions. Other water-related CGE models have also been developed to address technological changes applied to irrigation water management, see Philip et al. (2014).

Hydro-economic and CGE models have been widely used to assess water allocations, and in this paper we have chosen to combine a water management model with game theory, and in particular with bargaining games, in order to address the impact of different institutional frameworks and to assess the contribution of the proposed alternatives to the attainment of environmentally sustainable solutions.

This combination of methods for the analysis of the Ebro Delta in Spain is in line with prior uses of game theory in conflicts of this type, such as the Graph Model for Conflict Resolution (GMCR), which uses game theory to find the best allocation within a user-friendly windows operating environment. GMCR is described in Hipel et al. (1997) and has been successfully applied to an environmental conflict in North America. Other similar models are the Interactive Computer-Assisted Negotiation Support system (ICANS) developed by Thiessen and Loucks (1992), which offers bargaining solutions for dynamic, multi-issue, multi-party negotiation problems, and the Water Allocation System (WAS) used to analyse the water situation in the Middle East (Fisher et al., 2002). We may note here that game theory provides an explanation for the kinds of communal, cooperative behaviour in question here (Jager et al., 2016), and it appears likely that the presence of stakeholder associations is a key guarantee of water availability and quality (Aumann, 1964; Ostrom, 1990). Cooperative games have recently been used in connection with water issues in Abed-Elmdoust and Kerachian (2012) to look for the best water allocation in a context of fuzzy payoffs, and in Kahil et al. (2016b), who use a cooperative game theory framework to show the economic and environmental benefits of cooperation for stakeholders in the Jucar River Basin (Spain). Other games have also been used for similar purposes in Kerachian et al. (2010), where a model is developed based on Rubinstein’s bargaining model (Rubinstein, 1982), to resolve conflicts of stakeholder interests in the joint use of surface and groundwater resources.

3.3. Data and Methodology

3.3.1 Data

As mentioned in the introduction, the legal environmental flows for the Ebro Delta at Tortosa gauging station, described in Table 3.1, are fixed and regulated by the Ebro Basin Authority. At a yearly volume equal to approximately 25% of the mean yearly runoff of 12,500 hm^3 from the Ebro River at Tortosa between 1984 and 2014, well above the level of 10% - 20% normally set for EWR, these EF volumes are very large and represent a significant constraint.

Table 3.1 Proposed environmental flows at Tortosa gauging station

	Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	August	Sep	Total
Minimum flow (m^3/s)	80	80	91	95	150	150	91	91	81	80	80	80	95.58*
Monthly contribution (hm^3)	214.27	207.36	243.73	254.45	369.36	401.76	235.87	243.73	209.95	214.,27	214.27	207.36	3,016.4

*Annual average, source: CHE (2014)

Our database includes daily data on water volumes measured at the gauging stations and water discharges from each reservoir situated in the Ebro River Basin from October 1964 to September 2014, obtained from the Gauging Yearbook (MAPAMA, 2016). However, the environmental flows we are concerned with are set monthly, and we have converted daily figures accordingly.

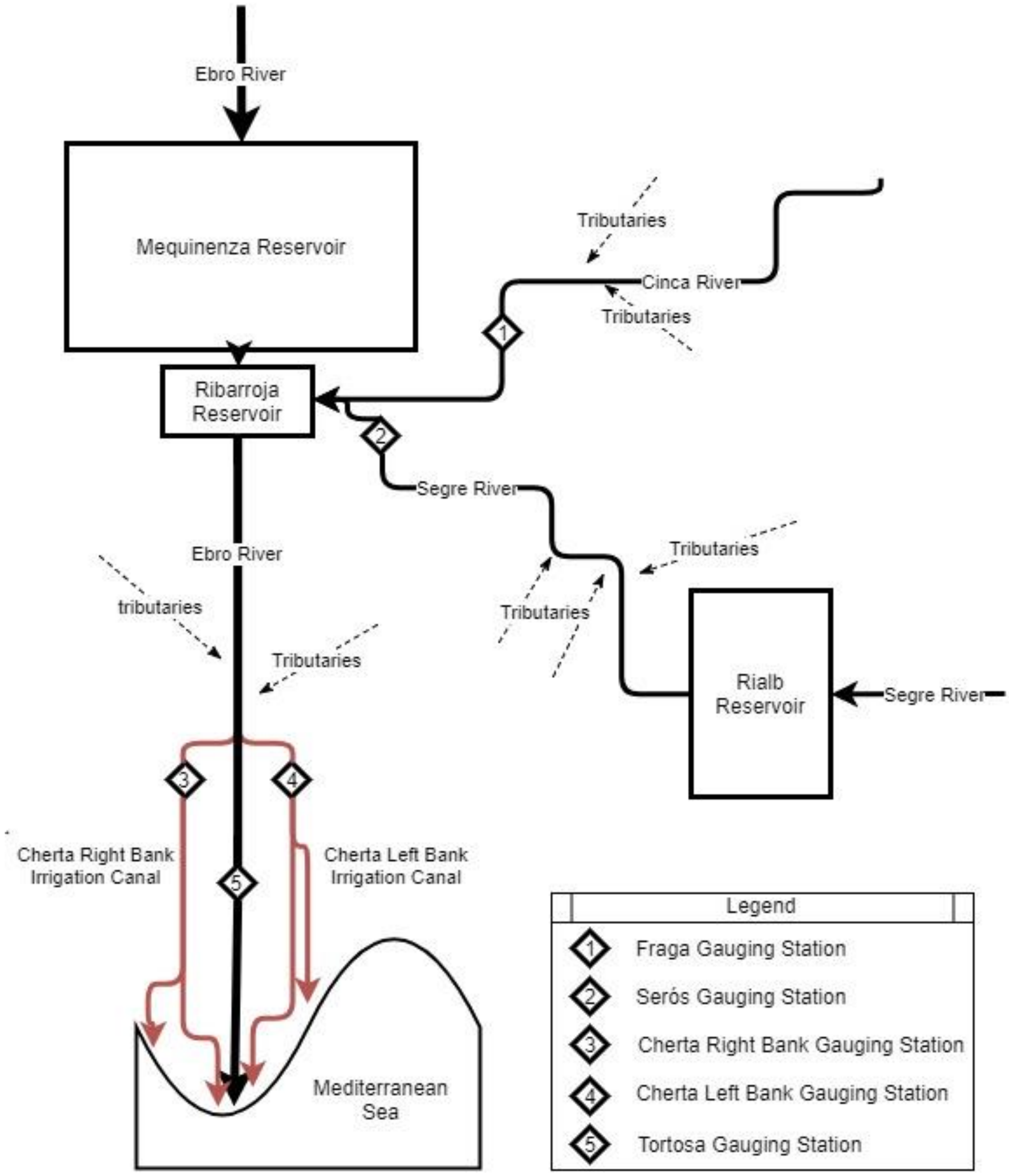
Meanwhile, the Ebro Delta environmental flows measured at Tortosa are managed solely on the final stretch of the Ebro River. Water inflow along the final stretch comes mainly from upstream and from the Ebro's two main tributaries, the Segre and the Cinca. Our analysis includes the Mequinenza, Rialb[1] and Ribarroja reservoirs, which have respective capacities of 1,530 Hm^3, 403 Hm^3 and 210 Hm^3. The Mequinenza dam collects water from upstream on the Ebro River, while Rialb reservoir receives water flows from the Upper Segre River. Meanwhile, both the River Cinca and the Segre flow into Ribarroja reservoir, where the outflow from Mequinenza also ends up, making Ribarroja a junction of the three rivers.

[1] Rialb is a new reservoir and the water inflow data comprise actual monthly figures from 1964-1981 (Ponts gauging station) and from 2000-2014 (Rialb reservoir). Meanwhile, annual data for Rialb between 1981 and 2000 were estimated by linear correlation with figures from Serós gauging station. Monthly data were assigned proportionally based on actual data for 2000-2014.

Figure 3.1 provides a schematic representation of the final stretch of the River Ebro; a map is provided in the Annex of this chapter (Figure A3.7).

The monthly water inflows at these three reservoirs, the flows gauged at Tortosa and the flows measured at Serós gauging station reduced by Rialb inflows represent the key variables in the water management model presented in the following subsection. Water inflows in the last stretch of the Ebro are shown in Table A3.10 in the Annex.

Figure 3.1 Schematic representation of the final stretch of the Ebro River. Own work.



3.3.2 Methodology

Using monthly data obtained by the gauging stations over the last 50 years (1964-2014), we shall establish a monthly correlation between *water inflow* in the final stretch of the River Ebro and *water outflow* (measured at Tortosa). The data used comprise inflows observed at Mequinenza and the flows measured at the Tortosa, Fraga and Serós gauging stations, see Table A3.11 in the Annex. However, this estimation suffers from two serious problems. One consists of the impact on the monthly flows measured at Tortosa over the last two decades from artificial floods released for regulation purposes from Mequinenza dam since 2002 in order to guarantee EF at Tortosa, as well as the continuous water demand for use in hydropower operations since 1964. The other is the lack, or relative unreliability, of data from the 1990s. For this reason, we finally opted to use only data covering the period 1964-1988 for our initial and auxiliary estimation. Moreover, this estimation was made on an annual basis to smooth the impact of artificial floods, monthly regulation and water demand for electricity generating.

We performed a regression applying the ordinary least squares (OLS) method to the annualized data, with the following result (Equation (3.1)).

$$\widehat{W}_t = 1.04\, W_t - 1{,}545.54 \quad ; \; R^2 = 0.944 \tag{3.1}$$

Where $\widehat{W}_t$ represents the estimated annual water outflow (measured at Tortosa) and W_t represents annual water inflow along the final stretch of the Ebro measured as the sum of inflow from Mequinenza reservoir and the inflows from the Fraga and Serós gauging stations. The estimated coefficient (1.04) means that water inflows should be increased by almost 4% to account for contributions from rainfall and minor tributaries. Meanwhile, the model constant suggests that withdrawals by irrigation canals plus other losses are around 1,545 hm^3 each year.

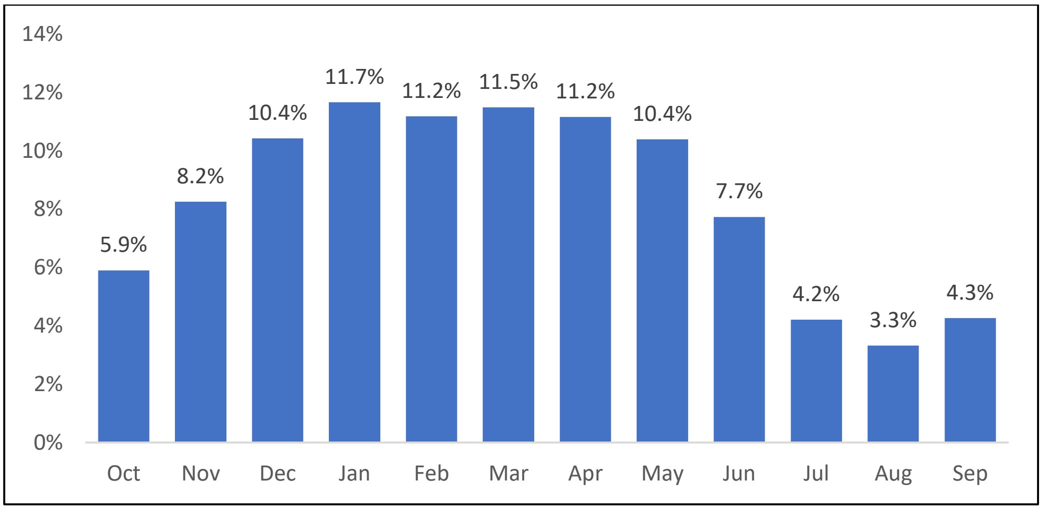
Starting from Equation (3.1), we can obtain the monthly flows at Tortosa used in the analysis and in our simulations as follows (Equation (3.2):

$$\widehat{W}_t^m = 1.04\, W_t^m + \alpha_m \quad ; \quad m = 1, \ldots, 12 \tag{3.2}$$

Where $\widehat{W}_t^m$ represents the estimated monthly water outflow in Tortosa, W_t^m represents the monthly inflows from Mequinenza, Fraga and Serós, the coefficient is the same as in (3.1); and the monthly constant, α_m, is obtained by dividing up the constant (-1,545.54 Hm^3) proportionally to the monthly flow data of the two main irrigation canals on the final stretch of the Ebro. These canals, both of which are located at Cherta (10 km upstream from Tortosa), have drawn off between 1,085 and 1,343 Hm^3 annually over the last 20 years

Meanwhile, the coefficient of 1.04 obtained in Equation (3.1) may initially seem an excessively tough hypothesis in this monthly extension, but we believe it to be acceptable, given the difficulty of obtaining better monthly coefficients from the data currently available. Keeping the coefficient means assuming that the monthly contributions from rainfall and tributaries in the final stretch of the Ebro are proportional to the monthly contributions in the rest of the river basin. This hypothesis also incorporates the expected monthly variation as shown in the monthly histogram from Figure 3.2, where we can see the monthly inflows in 1964-2014 as a percentage of total inflows obtained from the Gauging Yearbook for Mequinenza reservoir and Fraga and Serós gauging stations.

Figure 3.2. Monthly inflows in 1964-2014 as % of total inflows in the period



Meanwhile, the criteria applied to monthly distribution of the constant -1,545.54 Hm^3 allows us to assume that these withdrawals are proportional to their major component (i.e. withdrawals by the Cherta irrigation canals), which account for an average of approximately 80% according to data from the Gauging Yearbook. Table 3.2 presents the monthly values of the monthly constant α_m. This sharing criterion is consistent with the constant Delta irrigation assumed for the sake of simplicity.

Table 3.2. Determination of α_m

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Total
-158.98	-117.21	-102.14	-63.71	-44.94	-74.09	-146.47	-170.08	-166.88	-171.73	-168.85	-160.45	-1,545.54

Finally, let us consider the meaning of equations (3.1) and (3.2), and therefore of the water management model generated. Equation (3.1) describes a "theoretical flow" at Tortosa defined for a scenario where there is no regulation or intervention via artificial floods. It is not therefore a description of the natural stream, but an approximation to an annual flow without institutional intervention based on the data actually available. Equation (3.2) is an alternative to the available monthly data[2]. As we shall see, however, the referential scenario defined by equation (3.1) and equation (3.2) is useful, allowing us to answer the two main questions posed: Are current and regulated environmental flows acceptable? And, are fairer and more cooperative management alternatives possible?

Having obtained equations (3.1) and (3.2), we can now simulate and analyse alternative scenarios based on the actual data for the purposes described in the introduction. Significantly, the model allows restrictions to be placed on the admissible levels in reservoirs, so that we can assess falling water availability in line with the downward trend in measurements taken at Tortosa (Sánchez-Chóliz and Sarasa, 2015), caused by increases in upstream use, the effects of climate change and revegetation (Bielsa et al., 2011), among other factors. Finally, we can also assess compliance with the mandatory environmental flows established by the Ebro River Authority.

3.4. Results of alternative management scenarios

In this section, we will present two blocks of simulations. Firstly, we analyse the effects of scarcity scenarios designed in line with current debates and proposals based on the impact of climate change and the higher environmental flows demanded by Catalonia. We then examine our own proposed water management strategies to assure compliance with regulated environmental flows while maintaining current water uses in the Ebro Delta.

In order to study current water availability and compliance with regulated EF in the final stretch of the Ebro River, we may use equation (3.2) to simulate a monthly flow regime without dams or reservoirs in our first block of scenarios. Focusing on the possible future

[2] Hydroelectric uses are not included because they are assumed to remain constant. Experience over the last 20 years shows that hydroelectric uses have not posed a problem for Mequinenza in guaranteeing EF in the Ebro Delta. Moreover, no-one today is lobbying for a reduction of hydroelectric generating and recent plans do not provide for additional water demands in this area.

effects of climate change and the higher EF demanded by Catalonia, the different scenarios (results shown in Table 3.3) may be summarized as follows:[3]

- Current Flows (CF) Scenario. Monthly flows are defined by equation (3.2) and actual inflows obtained from the Gauging Yearbook. The environmental flows are obtained from CHE (2014), as shown in Table 3.1 above. This scenario approximates the actual figures while smoothing changes caused by regulation and increases in irrigation demand over the last two decades.
- Higher Environmental Flows (HEF) Scenario. This is similar to the CF scenario but it includes a 10% increase in environmental flow requirements. This scenario allows us to evaluate sensitivity to changes in EF.
- Scenario Lower Inflows due to Climate Change (LFCC) Scenario. Again, similar to the CF scenario but assuming a 20% fall in inflows due to the impact of climate change.
- HEF&LFCC Scenario. This combines scenarios "HEF" and "LFCC" and is consistent with the expected future situation due to tougher conditions.

Table 3.3. Natural stream simulation results

Scenario	Failed months		Failed years	
	Number	%	Number	%
CF	62	10.3%	0	0%
HEF	80	13.3%	0	0%
LFCC	132	22%	2	4%
HEF&LFCC	150	25%	2	4%

Source: Own work.

The "failed months" column refers to the number of months in which regulated environmental flows would not have been met by the flows obtained from the simulation, while "failed years" represents the number of years in which the total annual water volume measured at Tortosa would be lower than annual environmental flow requirements. The simulation covers 600 months from 1964 until 2014.

[3] The scenarios defined are intended rather to provide qualitative information (sensitivity analysis) than quantitative data, so the variations of 10% in Scenario HEF and of -20% in Scenario LFCC are merely arbitrary. However, 20% is in line with some forecasts of possible reductions in the stream flow of the Ebro River from 2040 onwards, (see, for example, Alvares et al., 2009).

In the Current Flows (CF) Scenario, there are 62 months in which environmental flow requirements could not have been met without human intervention, as shown in Table 3.3[4] Hence, compliance with the environmental flows established for the Ebro Delta in our model would be very difficult without infrastructure (reservoirs and dams), and water management is therefore crucial to meeting EF requirements. It also confirms the claim that Ebro water uses are already bumping up against its limits, as mentioned in the Introduction. Furthermore, the number of failed months increases in the other scenarios, which means that we should not expect any improvement in the coming decades, mainly because of climate change. This is a relevant finding, especially in view of proposals made by the Catalan Government (ACA, 2007; CSTE, 2015), which would impose much greater demands on the system, see Table A3.12 in the Annex.

We address our second block of simulations under this same framework, again using equations (3.1) and (3.2). Specifically, we analyse the impacts associated with two basic water management strategies. The first is *long-term regulation*, a soft alternative based on optimal monthly levels which are the same for every year and established by means of a conditional optimization procedure. This simulation is designed to achieve and maintain optimal monthly water levels for each reservoir every year. The second, *monthly regulation*, consists of making timely, targeted discharges to meet specific water and flow requirements so as to fulfil environmental flows. This second alternative may or may not be complementary with the first. The model optimization assumes as a constraint that the level of any reservoir must be above 50% of capacity in order to preserve ecosystems.

For the sake of simplicity, we shall take the Current Flows (CF) Scenario (which does not impose tougher requirements or reductions in water availability) as the base scenario for further simulations. In the case of both long-term regulation and monthly regulation, the optimization policy is implemented based on the data obtained from the Gauging Yearbook, and we simulate the potential impacts of the policy for each of the three reservoirs both separately and simultaneously.

The basic optimization constraints for these simulations consist of maximum and minimum reservoir levels. The maximum is determined by the spillway level, but the

[4] These flows represent approximately 25% of mean yearly runoff at Tortosa. Compliance would undoubtedly be greater if requirements were set lower. However, these stringent conditions have been collectively agreed by Ebro water users through the pertinent institutional mechanisms.

minimum level is merely posited at around 50% of each reservoir's capacity. This constraint is based on two criteria, no area should be strong disadvantaged in order to favour another, and discharges for all reservoirs should be limited so as to avoid harming the local flora and fauna and to favour tourism and residential development. When a reservoir does not participate in management measures in any simulation, its level is assumed to be fixed at 75% of total capacity in volume terms. When monthly regulation is handled jointly by more than one reservoir, meanwhile, we assume for the sake of simplicity that the water used is shared, 50% coming from Mequinenza, 33% from Rialb and 17% from Ribarroja. The proportions are 65% and 35%, respectively, when only Rialb and Ribarroja contribute.

The results associated with both long-term and monthly regulation strategies in different situations for the period 1964/1965-2013/2014 are reflected in Table 3.4, while the optimum monthly levels obtained from long-term regulation are provided in Table A3.13 in the Annex. Table 3.4 shows the results for the main variables modelled (i.e. reservoir level, water volume and number of EF failures) at Tortosa. In particular, the first and second columns indicate the reservoirs that shoulder the burden of long-term and monthly management of environmental flows, while the third reports the number of failures to comply with regulated EF. The fifth column shows the minimum water levels reached at each reservoir, and the sixth shows the simulated average level over the fifty years of the study period. The percentage of total capacity associated with the minimum and average levels is also given. This table also presents the values of the utility functions, which we will define later in Section 3.3.5.

Note that the Current Flows scenario in Table 3.3 is the same as the scenario in Table 3.4 involving no long-term or monthly regulation, so the number of failures is the same in both. Note also that some of the scenarios presented in Table A3.13 of the Annex match those long-term scenarios in Table 3.4 that do not involve any kind of monthly regulation, so that the number of failures coincides.

As may be observed from Table 3.4, when management policy is applied at only one reservoir, its water levels are lower than when management policy is implemented by all. Likewise, it is plain that long-term planning strategies implemented by one or more reservoirs reduce the number of failures compared to the CF scenario (see Table 3.3). However, long-term planning alone cannot assure EF compliance at all times, eventually making short-term planning inevitable.

Table 3.4 also reveals that all of the alternatives involving monthly regulation by one or more reservoirs display a zero failure rate, ensuring compliance with the environmental requirements of the Ebro Delta. This confirms the existence of different alternatives to fulfil EF at Tortosa assuming the current uses for irrigation and hydroelectric power plants. These alternatives could be achieved either by means of intervention at Mequinenza alone, CHE's current option, or by cooperation between reservoirs. In other words, cooperative options exist and they are efficient.

Finally, although monthly planning is sufficient to fulfil Tortosa EF requirements, the environmental impact on the regulating reservoir and the surrounding area can be very adverse, as water volumes occasionally fall below the minimum level of 50% established in our model. This happens especially if monthly planning is not carried out in partnership.

Table 3.4. Water Management Results 1964-2014

Long-term	Monthly	Fails	Reservoir	Minimum Level	Average Level	Standard Error (SE)	Unforeseen Deviation (UD)	Minimum Volume (%)	Average Volume (%)	U_i(SE)	U_i^*(UD)
All reservoirs	None	16	Mequinenza	111.64	115.50	2.75	0.19	62%	77%	112.75	115.31
			Rialb	419.42	422.55	2.12	0.31	67%	76%	420.44	422.24
			Ribarroja	64.50	66.84	0.91	0.00	60%	75%	65.93	66.84
	All reservoirs	0	Mequinenza	111.64	115.48	2.76	0.31	62%	76%	112.72	115.17
			Rialb	416.14	422.48	2.18	0.86	58%	76%	420.30	421.62
			Ribarroja	63.10	66.81	0.94	0.28	51%	75%	65.87	66.53
	Only Mequinenza	0	Mequinenza	110.88	115.46	2.77	0.50	59%	76%	112.69	114.96
			Rialb	419.42	422.55	2.12	0.31	67%	76%	420.44	422.24
			Ribarroja	64.50	66.84	0.91	0.00	60%	75%	65.93	66.84
	Only Ribarroja and Rialb	0	Mequinenza	111.64	115.50	2.75	0.19	62%	77%	112.75	115.31
			Rialb	410.26	422.40	2.39	1.57	44%	76%	420.01	420.83
			Ribarroja	61.34	66.78	1.04	0.61	42%	75%	65.74	66.16
Only Mequinenza	None	20	Mequinenza	111.27	114.80	2.51	0.03	61%	74%	112.29	114.77
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	All reservoirs	0	Mequinenza	110.47	114.78	2.50	0.21	58%	74%	112.28	114.57
			Rialb	417.49	422.42	0.52	0.73	61%	75%	421.90	421.69
			Ribarroja	64.92	66.96	0.22	0.30	62%	76%	66.74	66.66
	Only Mequinenza	0	Mequinenza	109.64	114.75	2.49	0.42	55%	73%	112.26	114.33
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	Only Ribarroja and Rialb	0	Mequinenza	111.27	114.80	2.51	0.03	61%	74%	112.29	114.77
			Rialb	411.74	422.33	1.10	1.53	48%	75%	421.23	420.80
			Ribarroja	62.41	66.92	0.47	0.66	47%	76%	66.45	66.26

Long-term	Monthly	Fails	Reservoir	Minimum Level	Average Level	Standard Error (SE)	Unforeseen Deviation (UD)	Minimum Volume (%)	Average Volume (%)	U_i(SE)	U_i^*(UD)
Only Ribarroja and Rialb	None	28	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	415.00	420.71	5.97	2.14	55%	72%	414.74	418.57
			Ribarroja	64.10	65.99	1.85	0.01	57%	70%	64.14	65.99
	All reservoirs	0	Mequinenza	113.90	115.46	0.18	0.26	70%	76%	115.28	115.20
			Rialb	411.19	420.59	5.97	2.47	46%	71%	414.62	418.12
			Ribarroja	63.06	65.94	1.84	0.35	51%	70%	64.11	65.59
	Only Mequinenza	0	Mequinenza	112.19	115.42	0.37	0.53	64%	76%	115.05	114.89
			Rialb	415.00	420.71	5.97	2.14	55%	72%	414.74	418.57
			Ribarroja	64.10	65.99	1.85	0.01	57%	70%	64.14	65.99
	Only Ribarroja and Rialb	0	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	403.77	420.46	6.05	3.09	32%	71%	414.42	417.37
			Ribarroja	61.88	65.89	1.86	0.76	44%	69%	64.03	65.13
None	None	**62 (CF)**	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	All reservoirs	0	Mequinenza	113.67	115.42	0.25	0.35	69%	76%	115.17	115.07
			Rialb	416.27	422.27	0.86	1.17	58%	75%	421.42	421.10
			Ribarroja	64.43	66.90	0.35	0.48	59%	76%	66.54	66.41
	Only Mequinenza	0	Mequinenza	111.70	115.35	0.52	0.71	62%	75%	114.83	114.64
			Rialb	422.50	422.50	0.00	0.00	76%	76%	422.50	422.50
			Ribarroja	66.99	66.99	0.00	0.00	76%	76%	66.99	66.99
	Only Ribarroja and Rialb	0	Mequinenza	115.49	115.49	0.00	0.00	76%	76%	115.49	115.49
			Rialb	408.84	422.02	1.81	2.49	41%	74%	420.21	419.53
			Ribarroja	61.21	66.79	0.77	1.06	41%	75%	66.01	65.72

Note: Levels are given in meters above sea level (m.a.s.l.). When no reservoir assumes any regulation, the scenario depicted is the same as CF in Table 3.3 Source: Own work.

3.5. Insights from game theory

According to Gura and Maschler (2008), "Game theory is a relatively young branch of mathematics that goes back to the publication of *Theory of Games and Economic Behavior* by John von Neumann and Oskar Morgenstern in 1944. Game theory undertakes to build mathematical models and draw conclusions from these models in connection with interactive decision-making: situations in which a group of people not necessarily sharing the same interests are required to make a decision". Moreover, any game is defined by four basic elements, namely: players, rules governing play, strategies for each player, and payoffs or utilities associated with the possible outcomes obtained from the strategies applied.

Game theory is widely used in economics because almost any economic process (or conflict) can be modelled as a game with players, rules, strategies and utilities, allowing researchers to identify and assess the different outcomes which arise from players' strategic behaviour, and then to establish the best allocations. In this work, we use non-cooperative and bargaining games to evaluate and compare the actual management of environmental flows on the final stretch of the Ebro River Basin and outcomes from the management alternatives described above.

We analyse the water conflict in terms of a game between two players, on the one hand, Mequinenza reservoir, and on the other, the duo formed by Rialb and Ribarroja reservoirs. The latter plays a less relevant role in the conflict in view both of its small capacity and of its geographical location (see Figure A3.7), and its evolution is strongly dependent on the strategies deployed by Mequinenza and Rialb. Both Rialb and Ribarroja are in Catalonia, making both reservoirs potentially members of a Catalan coalition. For all these reasons and for the sake of simplicity, we will from now on treat the conflicts as a two-player game and assume that Rialb and Ribarroja always apply the same strategies.

According to game theory, a conflict can be addressed in any one of three ways: 1) non-cooperative games (without negotiation or cooperation), 2) bargaining games (without cooperation), and 3) cooperative games. These three types of games represent different institutional scenarios (rules) or forms of interaction between agents.

In *non-cooperative games*, each agent seeks the best outcome for himself, regardless of any gain or loss for other players. The typical solution is the non-cooperative Nash equilibrium (Nash, 1951). In *bargaining games*, each player only considers his own benefit, but all are willing to engage in negotiation in order to increase their payoff (Nash, 1950). In a bargaining game framework, then, an efficient (Pareto optimum) solution for all players is needed to reach agreement. The Nash (Nash, 1950), and Kalai-Smorodinsky solutions (Kalai and Smorodinsky, 1975) are the most common.

Finally, the touchstone in *cooperative games* is joint benefit, although the possible allotment of outcomes is treated as secondary. Under the assumption of rationality, nobody should receive less from allocation than they could obtain individually. These games are usually solved by seeking a nucleus or nucleolus, or by means of Shapley Allotments (Shapley, 1988). The robustness of the equilibrium reached can be analysed using indexes developed for this purpose (Dinar and Howitt, 1997). We have not considered cooperative games in view of the social, economic and institutional context of the River Ebro, even though such games are generally applied in water-related scenarios.

3.5.1. Defining utility functions

The average water level and volume are good indicators of a reservoir's functioning, since both variables capture the same information and utility functions based on them provide similar results. We can, then, safely assume that adverse outcomes or losses for the agents increase when level values fall. On the other hand, fluctuations in water levels generally have a negative impact on growth and development. Moreover, they complicate tourist and residential development and a high variance can leave reserves at extremely low levels and cause irreversible impacts on flora and fauna. Hence, the standard errors for the levels observed provide a sure measure of these last adverse effects. In this context, a first type of utility functions for each reservoir was calculated by subtracting the standard error from the average level for the total period of our simulations (see Equation (3.3) below).

In order to avoid penalizing long-term regulation, we also develop other utility functions using the unforeseen deviation instead of standard error. These utility functions are designed to reflect the fact that the real damage to stakeholders can be calculated in terms of their expectations, if the agents know the expected level of each reservoir in advance. Unforeseen deviation is defined in a similar way to standard error using the expected level instead of the average level (see Equation (3.4)). The qualitative results obtained from both utility functions do not differ significantly, but (3.4) opens the way for future research incorporating more flexible scenarios.

Utility function with standard errors**:**

$$U_i = \bar{x}_{i,600} - \sigma_{i,600} \quad (3.3)$$

Utility function with unforeseen deviations**:**

$$U_i^* = \bar{x}_{i,600} - \sqrt{\frac{1}{600}\sum_{j=1}^{600}\left(x_{i,j}^e - x_{i,j}\right)^2} = \bar{x}_{i,600} - \sigma_{i,600}^{UD} \quad (3.4)$$

Where U_i and U_i^* represent the utilities for reservoir *i* obtained from our simulations; $\bar{x}_{i,600}$ is the average level for 600 months, from 1964 to 2014, and $\sigma_{i,600}$ is the standard error in these months; $x_{i,j}^e$ represents the fixed level in month *j* for reservoir *i* according to planned long-term regulation, see Table SI4 in the SI; $x_{i,j}$ represents the observed value for reservoir *i* in month *j* according to the simulation; and $\sigma_{i,600}^{UD}$ is the unforeseen deviation.

The values of our utility functions are shown in Table 3.4 and also in Table 3.5-Table 3.8. Table 3.4, presented in the previous section, shows the standard error and unforeseen deviation, respectively, in the seventh and eighth columns. The last two columns represent the two utility levels, U_i and U_i^* .

As shown in Table 3.4 and as expected, the maximum utility U_i for Mequinenza, 115.49 m.a.s.l., is reached in four situations, when the reservoir does not take on either long-term or monthly regulation. This happens regardless of what Rialb and Ribarroja do. The lowest utilities are found when Mequinenza assumes both types of regulation alone (112.26 for U_i and 114.33 for U_i^*), without assistance from Rialb or Ribarroja. In this case, the minimum level of reserves drops to 55% of total capacity. This level is environmentally unacceptable, though it is unfortunately the current institutional reality.

3.5.2 Non-cooperative games

In games of this type, players seek only to optimize their own utility. The values are shown in Table 3.4 and also in the payoff matrixes for Mequinenza and Rialb shown in Table 3.5-Table 3.8. Tables Table 3.5 and Table 3.7 show the payoff matrixes for the utility function with standard error U_i, while Tables Table 3.6 and Table 3.8 reflect those associated with U_i^* . The four tables (Table 3.5-Table 3.8) present four pure strategies or alternatives for each player based on the two basic planning alternatives discussed above, namely doing nothing (n), long-term regulation (L) only, monthly regulation only (M), and the combined strategy of long-term and monthly regulation (LM).

No conditions are imposed in Tables Table 3.5 and Table 3.6, assuming also that any alternative (n, L, M, or LM) is viable for any player. Therefore, the environmental flows will not be fulfilled if, for example, both players choose the strategy doing nothing (*n*). In both tables, a surprising first result is that the two alternatives which include long-term planning (L and LM) are strictly dominated by each of the other two (n and M) for both players. This also shows that long-term planning, according to the data for the whole period of 50 years used in the case study, is not a good alternative although it does reduce the number of failures. Hence, short-term and monthly planning without long-term planning is always better, revealing the need for an Ebro Basin Authority with "permanent" responsibility on water management.

Table 3.5. Non-cooperative Game - Mequinenza vs Rialb – Average level minus SE

	U	Rialb			
		n	L	M	LM
Mequinenza	n	**115.49; 422.50**	**115.49**; 414.74	**115.49**; 420.21	**115.49**; 414.42
	L	112.29; **422.50**	112.75; 420.44	112.29; 421.23	112.75; 420.01
	M	114.83; **422.50**	115.05; 414.74	115.17; 421.42	115.28; 414.62
	LM	112.26; **422.50**	112.69; 420.44	112.28; 421.90	112.72; 420.30

Table 3.6. Non-cooperative Game – Mequinenza vs Rialb -Average level minus UD

	U^*	Rialb			
		n	L	M	LM
Mequinenza	n	**115.49; 422.50**	**115.49**; 418.57	**115.49**; 419.53	**115.49**; 417.37
	L	114.77; **422.50**	115.31; 422.24	114.77; 420.80	115.31; 420.83
	M	114.64; **422.50**	114.89; 418.57	115.07; 421.10	115.20; 418.12
	LM	114.33; **422.50**	114.96; 422.24	114.57; 421.69	115.17; 421.62

Table 3.7. Non-cooperative Game - Mequinenza vs Rialb – Average level minus SE - feasible points

	U	Rialb			
		n	L	M	LM
Mequinenza	n	-	-	**115.49; 420.21**	**115.49**; 414.42
	L	-	-	112.29; **421.23**	112.75; 420.01
	M	**114.83; 422.50**	**115.05**; 414.74	115.17; 421.42	115.28; 414.62
	LM	112.26; **422.50**	112.69; 420.44	112.28; 421.90	112.72; 420.30

Table 3.8. Non-cooperative Game – Mequinenza vs Rialb – Average level minus UD - feasible points

	U^*	Rialb			
		n	L	M	LM
Mequinenza	n	-	-	**115.49; 419.53**	**115.49**; 417.37
	L	-	-	114.77; 420.80	115.31; **420.83**
	M	**114.64; 422.50**	114.89; 418.57	115.07; 421.10	115.20; 418.12
	LM	114.33; **422.50**	**114.96**; 422.24	114.57; 421.69	115.17; 421.62

The Nash equilibrium in Tables Table 3.5 and Table 3.6, is the solution in which no player takes on responsibility for management. This implies another relevant finding, namely that a non-cooperative approach would not assure compliance with environmental flows without an institutional framework to enforce environmental requirements and limit private economic uses.

Since such an authority does in fact exist in CHE, we can advance in the analysis by assigning zero values to the crossover strategies underlying non-compliance with environmental flows in order to evaluate the game outcomes by imposing compliance, see Table 3.7 and Table 3.8. Once again, the M strategy of both players strictly dominates their L and LM strategies in both payoff matrixes, making monthly planning better than long-term planning and again revealing the need for an Authority with "permanent" responsibility on water management. The game using standard errors (U_i), reflected in Table 3.7, has three Nash equilibriums. Two of them, M-n and n-M are pure strategies, and the other is a mixed strategy. The mixed strategy equilibrium implies a 99.74% probability that Mequinenza would contribute to monthly regulation (M), while there would be a 98.72% probability that Rialb would do so (M). Both figures are very close to one, so we can identify the third Nash equilibrium as one where all reservoirs play a part in monthly regulation, a collaborative solution close to the alternative M-M. By contrast, the solutions M-n and n-M are obtained in the absence of cooperation. We may recall here that M-n represents the current situation, where Mequinenza Reservoir alone shoulders the burden of regulatory environmental flows, dropping the minimum level of reserves to 62% of total capacity, which is environmentally unacceptable. In n-M we have a similar situation, Rialb and Ribarroja alone shoulder the regulation but reserves at both reservoirs fall to a minimum level of 41%, which again is environmentally unacceptable. In other words, the only solution compatible both with environmental water requirements and current economic uses is the cooperative solution between the three reservoirs. The same conclusion is reached using the utility function U_i^* and its unforeseen deviations, as may easily been seen from Table 3.8.

These three equilibria also point to another relevant social and institutional conclusion concerning the conflict with Catalonia. The two Catalan reservoirs, Rialb plus Ribarroja, could assure the fulfilment of regulated EF either by themselves (strategy n-M) or in partnership (mixed strategy). Thus, Catalonia would not need an agreement with the rest of Spain to fulfil the Ebro Delta EF, although the environmental cost to both reservoirs would be enormous.

This game can be also analysed from a "leader-follower" standpoint, where the leader would guide the game to the Nash Equilibrium that best suits it. Given the privileged geographical situation of Mequinenza reservoir and its size, the leader-follower Nash equilibrium would be (n-M), which would allow Mequinenza to maximize its level and utility. This is also the expected equilibrium if there is no cooperation between Catalonia and the rest of Spain, though it would be a bad solution as mentioned above.

3.5.3 Bargaining games

Bargaining games represent another potential application of game theory to the search for and evaluation of equilibrium, especially when utility transfers between players are possible. We do not assume any utility transfer between players in our game for the sake of simplicity, although in the actual economy there is indeed room for utility transfers between the players through investment in irrigation and infrastructure by the Spanish government or by tweaking the water use rights granted by the Ebro Basin Authority.

Furthermore, bargaining games allow analysis based on variations in bargaining power, allowing us to lay bare the institutional framework and power ratios underlying the current management of environmental flows. Policymakers might decide to assign different levels of bargaining power for a variety of reasons. For instance, greater bargaining power associated with Mequinenza could compensate the district’s population for having shouldered the burden of environmental stewardship until now. On the other hand, greater bargaining power associated with Ribarroja or Rialb could represent a framework within which to raise the bargaining power of the smallest reservoir’s users (farmers, villages, etc.).

The *status quo* (points of disagreement or payments which players expect to receive if they do not reach an agreement) is a basic element of bargaining games, and it usually reflects different institutional frameworks. We show results for two such possible frameworks. In the first we define the *status quo* as the utility associated with 50% of reservoir capacity (i.e. the level used to optimize long-term regulation), and in the second we take the worst feasible alternative for each player, i.e. the utility level that each player would obtain if it had to shoulder the burden of environmental flow management entirely on its own.

Under these conditions, the bargaining solutions of the game are obtained according to Nash (1950) through optimization of the product of utility gains. Specifically, the problem is solved for U_i as follows:

$$Max\ \prod_{i=1}^{2}(U_i - q_i^o)^{\alpha_i} = Max\ S[(U_i)] \quad ; \quad (U_i) \in \text{Bargaining set} \qquad (3.5)$$

Where (q_i^o) is the *status quo* chosen, α_i the bargaining power of player i, and $S[(U_i)]$ the utility isoquants associated with (U_i), and the bargaining set: $\{(U_i)|U_i \in \text{convex hull of points from Table 3.7; } U_i \geq q_i^o; \text{and Pareto optimum}\}$.
We have a similar equation for U_i^* , which is estimated based on the points from Table 3.8.

Table 3.9 shows the Nash Bargaining Equilibrium for both *status quo* alternatives using the two utility functions and various bargaining powers. Similar information is shown in Figure 3.3-Figure 3.6, where we may also observe the optimum isoquants for three pairs of bargaining powers and the *status quo* point where the axes cross. Figure 3.3 and Figure 3.4 represent the bargaining game using standard error utility functions (U), and Figure 3.5 and Figure 3.6 using unforeseen deviations functions (U^*).

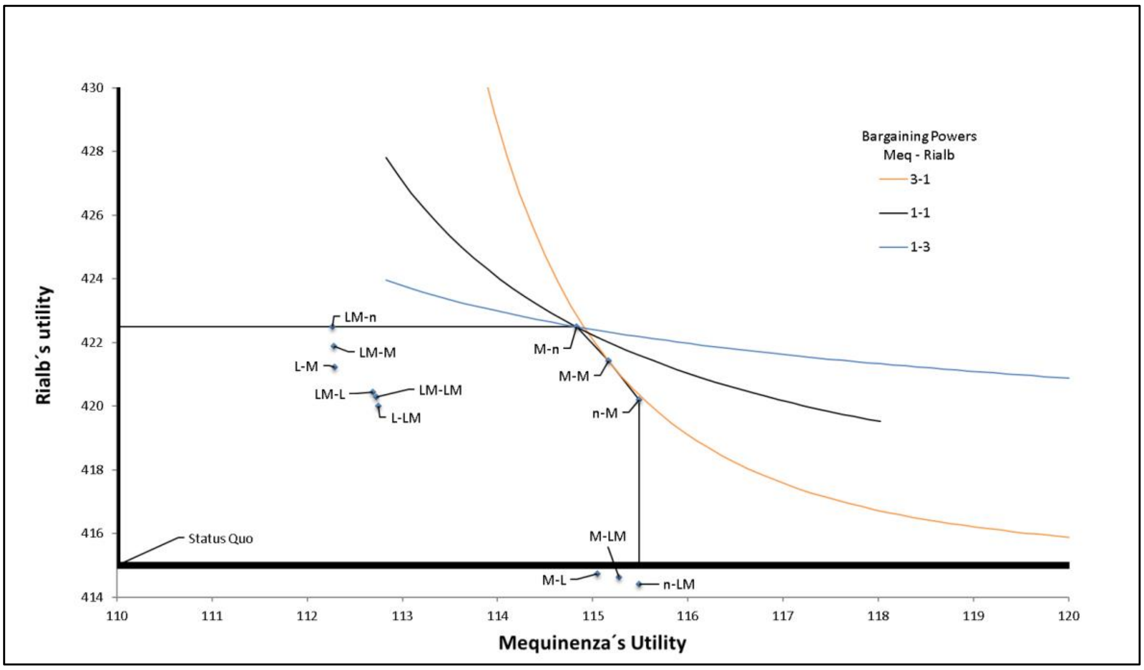
As shown in Table 3.9 and in Figure 3.3-Figure 3.6, the Nash bargaining equilibrium differs depending on the type of utility function (U or U^*) and the *status quo* used. When the utility associated with 50% water reserves is taken as the *status quo*, bargaining power becomes critical to the Nash Equilibrium. If the bargaining power of Rialb reservoir is higher than or equal to that of Mequinenza reservoir (cases 1-1, 1-2 and 1-3), the latter will take on full responsibility for management when the utility function used is U and the solution is M-n, and it also will shoulder the lion's share of the burden in the case of utility U^* with solutions M-n and LM-L. By contrast, if Mequinenza reservoir has significantly higher bargaining power (case 3-1), both players implement the Nash bargaining solution together so that cooperation is necessary, and the solution is close to M-M for the utility U, and to LM-LM for U^*. In other words, assigning increased bargaining power to Mequinenza shifts the game towards a cooperative equilibrium.

Fixing the *status quo* as the worst feasible alternative always leads to a cooperative solution. This *status quo* is too much for Rialb, forcing it to play a role that is similar to assigning higher bargaining power to Mequinenza, which results in a more favourable equilibrium for the latter than in the previous case for both utility functions. Assuming equal bargaining power in this case, the results are M-M for U and LM-LM for U^*.

Table 3.9. Bargaining Game Theory Equilibria, Mequinenza Reservoir vs Rialb Reservoir

Bargaining Power	Status Quo	Equilibria when U		Equilibria when U^*	
3-1	50% of capacity	115.168 - 421.416	M-M	115.167 - 421.619	LM-LM
2-1		114.827 - 422.50	M-n	114.96 - 422.237	LM-L
1-1		114.827 - 422.50	M-n	114.96 - 422.237	LM-L
1-2		114.827 - 422.50	M-n	114.635 - 422.50	M-n
1-3		114.827 - 422.50	M-n	114.635 - 422.50	M-n
3-1	Worst feasible alternative	115.324 - 420.83	Mixed equilibrium	115.308 - 420.828	L-LM
2-1		115.269 - 421.037	Mixed equilibrium	115.237 - 421.227	Mixed equilibrium
1-1		115.168 - 421.416	M-M	115.167 - 421.619	LM-LM
1-2		115.067 - 421.737	Mixed equilibrium	115.046 - 421.981	Mixed equilibrium
1-3		115.007 - 421.928	Mixed equilibrium	114.96 - 422.237	LM-L

Figure 3.3. Mequinenza vs Rialb – (U) - status quo at 50% capacity.



Note for Figures Figure 3.3-Figure 3.6: The black isoquant depicts equal bargaining power, while the orange isoquant depicts greater bargaining power (3/1) for Mequinenza and the blue one for Rialb.

Figure 3.4. Mequinenza vs Rialb – (U) - status quo at worst feasible alternative (114.83-420.21)

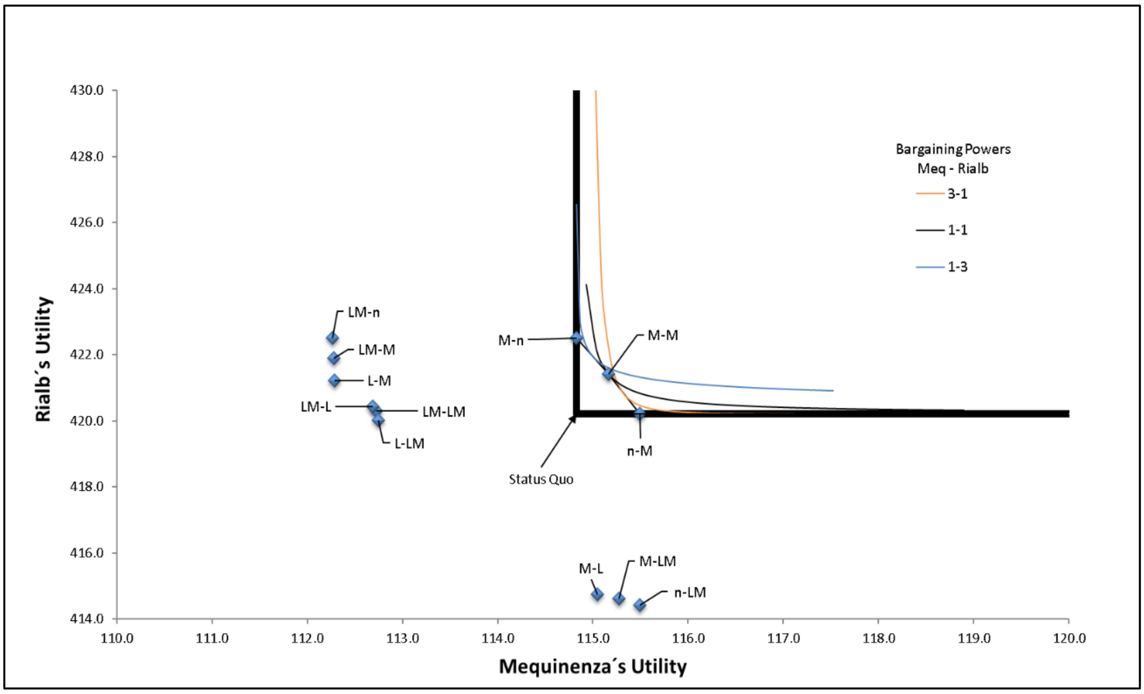


Figure 3.5. Mequinenza vs Rialb – (U^*) - status quo at 50% capacity

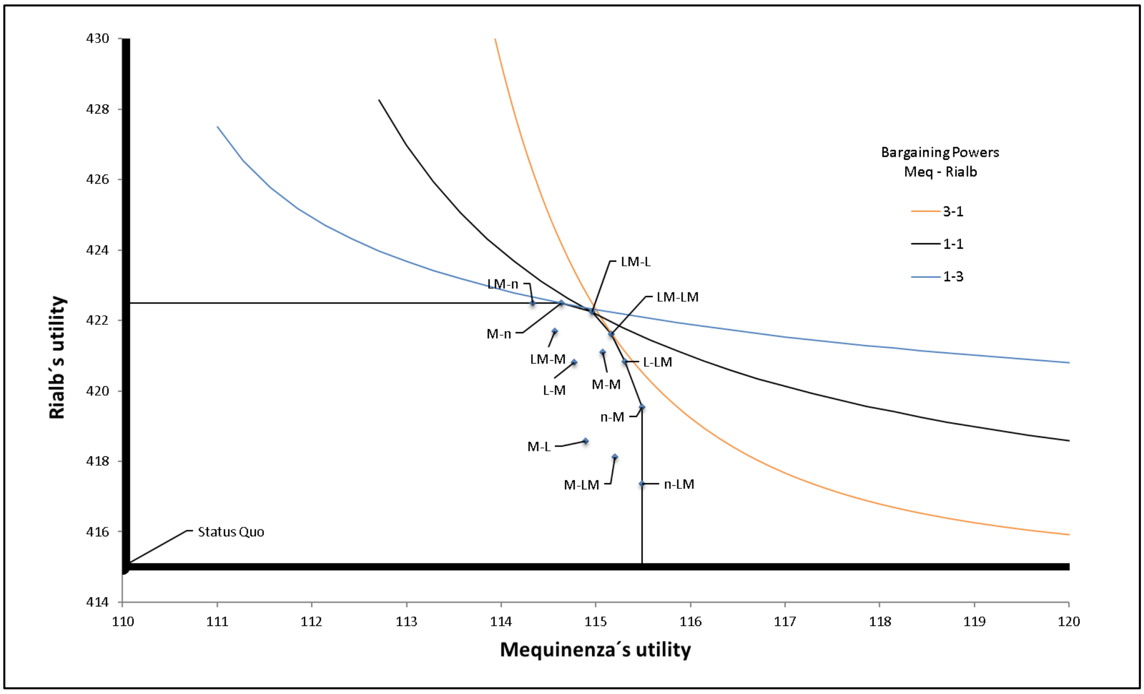
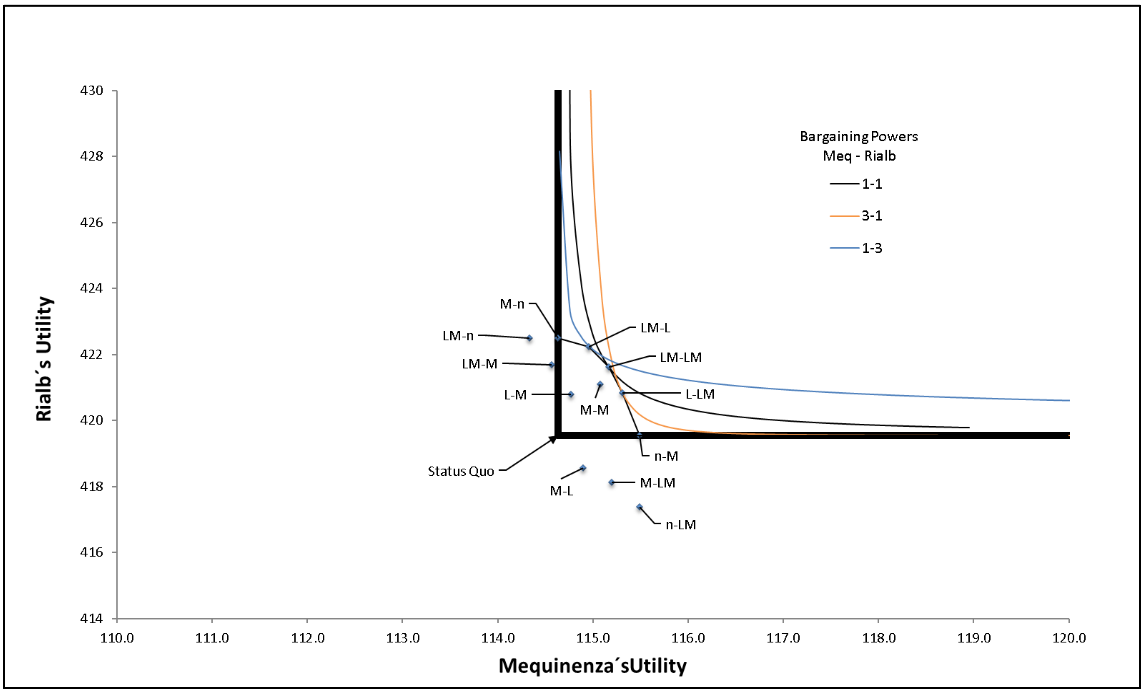


Figure 3.6. Mequinenza vs Rialb – (U^*) - status quo at worst feasible alternative (114.63-419.53)



3.6. Conclusions and discussion

The allocation of natural resources has been widely studied by economists. In this paper, we consider water uses and the alternative ways of avoiding possible conflict between economic agents and the environment, focusing our analysis mainly on water use in the final stretch of the Ebro River (Spain) in the period 1964-2014. We have developed a water management model to simulate and evaluate different flow management hypotheses, and we have also combined the results obtained from the simulations with non-cooperative and bargaining games for getting the best water allocations. We seek to answer three key questions: (i) Are current and regulated environmental flows for the Ebro Delta (a Biosphere Reserve) acceptable? (ii) Are the current economic use (mainly irrigation and hydroelectric generating) compatible with environmental requirements? (iii) Is there a fairer and more cooperative alternative for water management in the area than the current one?

The model is used to analyse four scenarios (CF, HEF, LFCC and HEF&LFCC) and two types of water planning (long-term regulation and monthly regulation), and eventually leading on to the examination of findings using non-cooperative and bargaining games.

In the CF scenario we assume no regulation (which is similar to assuming that there are no dams) and the first finding from this simulation is conclusive: compliance with the current EF in the River Delta would be almost impossible without infrastructure and dams. Hence, reservoir and dam management are necessary if we are to maintain the current economic uses with no or little effect on the environment. In other words, something similar to the Ebro Basin Authority (CHE) is necessary. A further conclusion from this scenario is that uses in the Ebro Basin are close their limits. This is very important in view the declining trend in Ebro Basin flows observed in recent decades and expected climate change impacts.

In scenario HEF we assume a 10% increase in current Ebro Delta EF and no regulation. The simulations reveal an increment in the failed months (80 versus 62 in the previous scenario). This demonstrates the difficulty of meeting the ever increasing demands made by the Catalan regional government in recent years. In scenario LFCC we simulate a 20% fall in inflows, to reflect the possible effects of climate change. Again, the failed months rise (150 months versus 62 in CF). Both of these scenarios once again confirm that water uses are already bumping up against their limits, and that an Ebro Basin Authority is needed, not to mention an improvement in water management policies.

The current water management policy deployed by the Ebro Basin Authority (CHE) is based on additional daily and/or monthly flows from Mequinenza reservoir, which ensures the water supply for economic activities while at the same time allowing compliance with environmental flows, except in occasional cases arising mostly in times of extreme drought. This is directly confirmed by the data and by our simulations. However, we consider that the current management structure is highly questionable as regulation is handled by Mequinenza alone, sometimes leaving the reservoir not just below the acceptable environmental level of 110 meters (representing 50% of capacity) but even below the level where irrigation water intakes are situated (105 meters above sea level), resulting in high financial, opportunity and environmental costs for the surrounding area, see Almazán-Gómez and Sánchez-Chóliz (2016).

For these reasons, we have evaluated two alternative water management strategies using our model. The first is *long-term regulation*, and it consists of establishing optimal monthly levels to be repeated each year. The second is *monthly regulation*, which requires occasional targeted discharges to fulfil EF requirements. Our results show that *long-term regulation* is useful because it reduces the number of months in which environmental flows cannot be fulfilled, but it is not enough for a full compliance with EFs. Hence, monthly regulation (additional daily or monthly discharges) is needed to comply with regulatory EFs in the Ebro Delta. Again, the results suggest that an institutional framework and a river basin authority are necessary to ensure that environmental and economic water demands in the area are met. As a final significant result, it would appear that compliance with Ebro Delta environmental flows does not depend exclusively on the reserves of Mequinenza reservoir. There are alternatives to the current management strategy, in which the burden is shouldered by Mequinenza alone, so that Rialb and Ribarroja could take part in flow management or even assume stewardship entirely. In other words, cooperative management strategies are viable.

We then used game theory to evaluate management strategy alternatives, designing utility functions based on the simulation results for each alternative and reservoir. Non-cooperative and bargaining games each with its own *status quo* and bargaining power parameters are used.

By analysing non-cooperative games, we have been able to ascertain that the current management structure (M-n), where Mequinenza reservoir shoulders the full burden of regulation, is a Nash Equilibrium, confirming its “rationality” under the current institutional rules, which accept as “normal” a high degree of environmental damage for Mequinenza reservoir and its surrounding district. Another Nash equilibrium is n-M, in which Rialb and Ribarroja take on the burden alone, again at a high environmental cost, making this too a bad alternative. However, these games have a third, mixed-strategy Nash Equilibrium supporting a more equitable and collaborative alternative. This is important because it confirms the existence of a technical basis for collaboration and for sharing the burden of monthly regulation together.

Bargaining games are a standard analytical tool when different Nash equilibria exist, because they allow us to select between efficient or Pareto-optimal alternatives. This type of analysis can be refined by changing the *status quo* (which we may associate with different institutional situations) and negotiating powers of each player. We have used two different parameters for the *statu quo*, five bargaining power pairs and two utility functions.

The solutions obtained from this analysis are crystal clear. Although the current management criteria represent a solution if Mequinenza's bargaining power is low, cooperative solutions become more probable the greater the negotiating power assigned to Mequinenza, or the greater the no agreement cost for Rialb and Ribarroja. This of course casts serious doubt on the fairness of the current institutional water management arrangements for the lower stretch of the Ebro River.

To sum up, let us consider the answers to our three key questions. First, increasing current regulated flows would be problematic in the medium and long term, especially considering the potential impacts of climate change and the difficulty of removing existing, vested water use rights in the Ebro Basin. Second, both economic (irrigation and hydroelectric generating) and environmental uses are viable assuming current EFs. Third and finally, fairer cooperative solutions do exist, which involve sharing regulatory burdens and relieving the pressure on the Mequinenza area. Moreover, these solutions could promote and increase irrigation in the area by releasing draw-offs for other uses from this reservoir.

The methodology employed in this study represents merely the first step in a complex analysis that could easily be extended to the whole Ebro River Basin and indeed to other river basins in Spain and elsewhere. This paper merely provides a baseline for the study of socio-economic effects throughout the Ebro Basin and a point of departure for economic policy proposals.

Annex of Chapter 3

Table A3.10. Water inflow in the Ebro last stretch

Period	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1964-1965	1,022.68	1,028.06	1,538.76	1,755.78	1,009.21	2,306.56	1,211.11	663.75	421.91	352.95	239.80	462.55
1965-1966	2,024.96	2,298.23	2,699.50	2,065.23	2,391.16	2,111.07	1,641.52	1,391.18	1,505.06	689.72	525.54	502.28
1966-1967	1,153.30	3,669.75	2,532.41	1,480.00	874.62	1,421.27	1,005.06	790.70	652.32	414.05	301.91	362.90
1967-1968	505.05	2,270.12	2,266.65	2,886.16	1,490.02	1,441.85	1,629.69	1,411.57	1,258.53	492.17	557.15	624.99
1968-1969	564.29	732.52	1,238.24	1,246.58	1,030.73	3,312.46	3,157.57	2,578.61	1,834.26	1,013.79	556.31	923.44
1969-1970	918.75	756.73	2,249.51	3,077.98	1,973.23	1,739.95	781.90	1,028.70	986.36	452.88	379.47	398.93
1970-1971	541.44	592.10	727.52	749.02	906.56	1,154.87	2,085.15	3,890.83	2,447.14	1,123.29	671.09	600.27
1971-1972	836.82	1,058.39	1,648.31	1,847.78	3,158.38	2,272.42	1,746.32	1,949.31	1,988.61	1,004.51	683.70	1,585.18
1972-1973	1,399.09	1,329.04	1,364.54	1,539.82	1,762.58	1,307.83	945.18	801.09	1,522.77	457.60	439.86	487.70
1973-1974	501.11	568.30	803.10	1,031.21	1,216.45	2,495.33	1,988.79	1,162.35	887.30	807.05	457.89	1,089.02
1974-1975	1,248.37	1,735.72	1,285.97	1,047.72	1,217.29	1,389.57	1,993.21	1,443.34	1,858.45	591.83	493.56	776.95
1975-1976	751.43	1,110.05	1,339.76	694.11	1,579.26	928.34	1,108.03	713.01	431.23	368.52	338.82	407.19
1976-1977	770.35	1,166.49	1,396.56	2,067.69	1,791.58	1,219.53	1,127.91	3,233.80	2,833.12	1,314.56	990.59	556.56
1977-1978	1,110.57	1,052.05	1,372.87	1,719.38	3,669.58	2,947.47	1,980.60	2,288.51	1,381.08	725.55	397.50	492.58
1978-1979	484.31	415.52	770.55	2,418.84	3,781.57	2,082.86	2,407.46	1,690.98	2,541.22	747.86	386.57	468.60
1979-1980	910.06	1,149.77	1,366.09	1,808.21	1,684.25	1,491.89	1,187.27	1,140.35	1,041.33	505.72	296.72	488.72
1980-1981	744.95	715.12	1,925.94	2,102.38	910.45	953.34	1,176.25	1,199.48	638.89	605.20	294.38	336.67
1981-1982	493.76	391.41	1,159.98	1,650.01	1,262.13	1,641.33	734.22	603.13	672.82	288.18	388.95	485.12
1982-1983	775.64	1,816.83	2,619.94	1,262.76	1,232.25	1,544.68	1,701.16	932.57	593.06	488.71	626.46	614.58
1983-1984	433.82	632.75	946.72	1,223.67	1,332.17	1,126.26	1,281.82	1,797.31	1,536.06	368.89	299.21	354.51
1984-1985	597.73	1,800.58	1,457.43	1,588.45	1,399.72	1,277.98	1,011.40	1,465.53	847.31	505.74	377.68	284.06
1985-1986	467.86	329.29	332.93	837.61	1,122.77	1,046.80	1,274.83	1,230.11	448.86	308.37	184.97	416.36
1986-1987	482.38	491.20	653.62	838.34	1,239.37	717.64	1,295.06	562.00	253.84	517.22	255.51	368.25
1987-1988	1,085.56	1,006.41	1,319.61	1,381.95	1,938.25	1,350.99	2,691.07	1,825.66	1,937.25	1,178.15	420.56	398.90
1988-1989	646.06	638.93	583.04	545.03	462.64	688.50	1,103.70	822.31	677.76	554.38	412.00	434.82
1989-1990	470.92	596.07	626.01	708.88	637.56	431.13	1,017.15	814.95	677.20	418.18	381.30	416.62
1990-1991	661.37	642.77	952.85	1,010.85	758.41	1,345.79	1,832.79	2,070.51	717.17	493.60	379.18	516.24
1991-1992	663.93	1,170.75	865.79	574.86	541.51	635.02	1,745.74	823.71	1,200.88	802.39	594.57	614.34
1992-1993	1,929.05	2,184.43	2,375.37	1,079.61	830.41	1,114.28	954.85	1,266.00	747.20	483.02	429.11	527.04
1993-1994	960.41	973.34	1,555.33	2,302.57	1,522.12	1,044.91	1,422.09	1,078.91	646.66	427.77	340.28	391.79
1994-1995	817.75	1,493.82	1,025.30	2,224.89	1,214.09	1,778.07	720.25	707.70	553.29	433.35	318.13	335.82
1995-1996	479.65	557.13	1,044.99	2,520.82	2,285.40	1,639.62	1,092.42	1,180.39	834.91	478.91	372.78	446.68
1996-1997	570.99	988.49	2,986.82	3,356.91	1,582.42	878.27	743.22	864.91	1,070.75	723.02	475.35	459.94
1997-1998	398.04	709.02	2,351.09	1,820.78	1,003.17	806.74	908.93	1,143.54	812.79	326.39	318.67	404.61
1998-1999	746.84	520.18	872.01	883.55	1,055.58	955.02	525.57	974.31	368.56	317.51	357.36	525.92
1999-2000	580.50	923.04	1,014.48	692.65	567.69	367.23	984.02	1,226.69	754.98	323.75	362.08	342.77
2000-2001	676.84	1,047.81	1,309.54	2,167.19	1,721.57	2,524.33	888.21	1,261.33	507.55	426.26	327.82	383.76
2001-2002	376.50	458.90	348.38	395.82	492.69	446.38	442.96	621.74	316.35	222.71	270.74	420.26
2002-2003	439.59	667.44	1,122.99	1,058.01	1,311.88	1,646.65	764.64	1,074.31	376.94	196.85	268.70	584.09
2003-2004	605.33	1,367.57	1,703.07	1,796.36	973.98	1,538.25	1,779.92	1,617.70	648.23	355.74	292.43	594.61
2004-2005	507.73	834.18	849.21	978.21	979.69	998.75	1,020.61	613.86	250.84	187.69	189.78	265.55
2005-2006	360.30	689.06	745.88	1,084.06	510.85	1,426.65	748.02	481.00	268.22	187.29	174.74	382.37
2006-2007	397.26	539.94	770.44	402.90	1,006.67	1,420.10	2,743.45	1,212.17	532.55	285.56	306.52	326.37
2007-2008	376.88	299.44	410.24	500.82	327.93	672.26	1,227.05	1,649.81	2,075.07	482.40	440.36	532.63
2008-2009	494.49	1,039.84	1,414.04	1,203.94	2,315.29	1,367.25	1,196.86	982.67	418.02	303.41	355.71	429.13
2009-2010	425.83	691.35	692.61	1,694.37	1,513.87	1,223.11	920.22	1,180.65	1,075.58	361.28	296.49	390.52
2010-2011	442.90	619.71	842.57	788.28	618.76	1,283.98	691.49	423.82	448.76	288.65	290.28	309.22
2011-2012	277.74	572.35	500.52	409.54	574.86	346.00	522.28	746.59	284.71	212.70	164.65	223.17
2012-2013	660.38	511.27	1,026.14	1,969.59	2,989.20	2,334.91	2,222.72	1,762.02	2,013.52	617.83	417.67	461.21
2013-2014	574.00	893.15	768.73	1,419.70	1,897.62	2,014.28	1,532.78	719.35	575.25	637.14	551.43	701.40

Source: Own Work

Table A3.11. Data used to obtain Equation 1

Year	Tortosa	Mequinenza Inflow	Serós	Fraga
1964-1965	10,785.73	7,624.62	2,323.22	2,065.26
1965-1966	18,816.62	11,327.42	4,050.17	4,467.83
1966-1967	13,883.79	9,472.55	2,836.52	2,349.23
1967-1968	15,599.95	10,645.44	3,329.89	2,858.60
1968-1969	17,557.78	9,568.28	3,874.63	4,745.87
1969-1970	14,437.70	10,138.78	2,347.57	2,258.00
1970-1971	14,359.16	8,118.89	3,656.91	3,713.45
1971-1972	19,455.67	11,045.90	5,005.75	3,728.06
1972-1973	12,780.94	8,090.21	2,096.71	3,170.18
1973-1974	11,826.04	6,686.06	2,924.66	3,397.14
1974-1975	13,709.29	9,065.34	3,184.83	2,831.79
1975-1976	8,455.10	6,319.82	1,896.25	1,553.64
1976-1977	15,476.04	10,523.06	4,102.75	3,842.91
1980-1981	9,444.57	8,041.70	2,369.95	1,191.42
1981-1982	7,456.03	5,378.26	2,547.64	1,845.10
1984-1985	12,411.19	7,958.35	2,660.84	1,994.35
1985-1986	6,922.30	5,174.68	1,407.81	1,418.28
1986-1987	6,995.17	4,702.33	1,278.12	1,693.97
1987-1988	18,114.95	10,826.21	2,615.80	3,092.34

Source: Own Work

Table A3.12. Catalonia Government proposals through some of its agencies for Tortosa Environmental Flows

	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Average m^3/s**	**Annual contribution (hm^3)**
Environmental Flows Fixed by Ebro River Basin Authority CHE (2014)														
Flow required m^3/s	80	80	91	95	150	150	91	91	81	80	80	80	95,58	
Contribution hm^3	214,27	207,36	243,73	254,45	369,36	401,76	235,87	243,73	209,95	214,27	214,27	207,36		3.016,40
ACA (2007) for drought years														
Flow required m^3/s	87	135	248	285	327	276	336	396	252	167	116	103	227,03	
Contribution hm^3	233,02	349,92	664,24	763,34	805,2	739,24	870,91	1.060,6	653,18	447,29	310,69	266,98		7.164,68
ACA (2007) for medium years														
Flow required m^3/s	119	202	359	388	436	360	428	500	342	198	150	135	300,97	
Contribution hm^3	318,73	523,58	961,55	1.039,2	1.073,6	964,22	1.109,3	1.339,2	886,46	530,32	401,76	349,92		9.497,95
ACA (2007) for wet years														
Flow required m^3/s	207	317	449	468	511	526	569	623	453	254	187	210	397,45	
Contribution hm^3	554,43	821,66	1.202,6	1.253,4	1.258,2	1.408,8	1.474,8	1.668,6	1.174,	680,31	500,86	544,32		12..542,47
CSTE (2015) for drought years														
Flow required m^3/s	84	153	204	143	166	212	329	303	268	147	107	120	186,13	
Contribution hm^3	224,99	396,57	546,39	383,01	408,76	567,82	852,77	811,55	694,65	393,72	286,59	311,04		5.877,86
CSTE (2015) for medium years														
Flow required m^3/s	124	219	249	219	260	283	410	410	310	180	132	151	245,19	
Contribution hm^3	332,12	567,65	666,92	586,57	640,22	757,99	1062,7	1098,1	803,52	482,11	353,55	391,39		7.742,89
CSTE (2015) for wet years														
Flow required m^3/s	192	326	396	321	316	410	475	413	368	212	166	178	314,16	
Contribution hm^3	514,25	844,99	1060,6	859,77	778,12	1098,1	1231,2	1106,2	953,85	567,82	444,61	461,38		9.920,94

Source: Own work from CHE (2014), ACA (2007) and CSTE (2015)

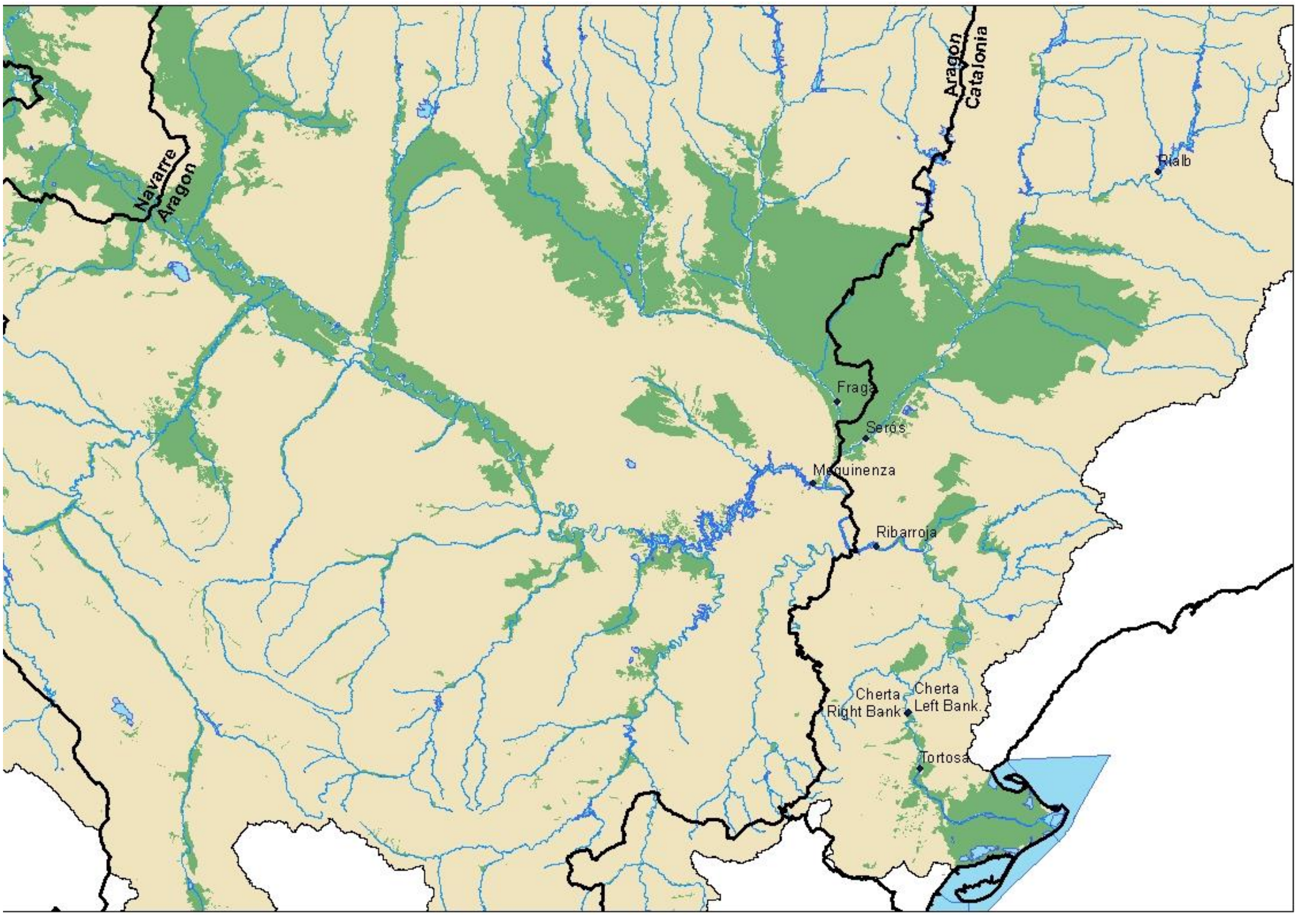
Note: Table A3.12 shows the Environmental Flows legally fixed by the Ebro River Basin Authority in its first rows, and the proposals of the Catalonian government through two of its agencies in the following rows. The Catalonian proposals are divided in three: proposals for drought years, for medium or normal years, and for wet years. By columns are listed the Environmental Flows fixed or proposed for each month and the contribution that this flow suppose per month. The last two columns show the annual average flow and the minimum annual contribution that the Environmental Flows suppose or would suppose.

Table A3.13. Optimal monthly fixed levels (m.a.s.l.) in the long-term regulation

Apply management policy		Fails	Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	August	Sept
All reservoirs	Mequinenza	16	112.40	111.65	115.29	116.14	116.63	115.24	116.47	121.00	119.98	115.93	112.23	113.40
	Rialb		421.05	422.19	426.39	421.37	423.69	421.39	426.53	422.36	419.71	423.24	424.40	419.42
	Ribarroja		66.59	66.02	67.19	67.12	67.46	66.72	67.60	67.10	66.51	68.40	67.03	64.50
Only Mequinenza	Mequinenza	20	111.28	113.58	113.57	115.06	115.97	113.23	115.63	118.85	119.51	116.48	113.22	111.35
	Rialb		422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50
	Ribarroja		67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00
Only Ribarroja and Rialb	Mequinenza	28	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50
	Rialb		423.03	415.00	415.00	415.00	415.00	426.89	428.37	428.56	429.89	428.23	419.16	415.04
	Ribarroja		64.10	64.31	64.28	64.29	64.10	67.15	67.50	68.36	69.92	65.36	66.05	66.55
Any Reservoir	Mequinenza	62	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50	115.50
	Rialb		422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50	422.50
	Ribarroja		67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00	67.00

Note: Fails' column refers to the number of months that EF would not been fulfilled among the 600 months studied. Source: own work.

Figure A3.7. Map of the study area



Chapter 4

Effects of water re-allocation in the Ebro river basin:

A multiregional input-output and geographical analysis.

One of the main objectives of this chapter is to develop a suitable tool for the interregional and inter-sectoral analysis of the Ebro River Basin (ERB), based on a socioeconomic description of the area. Given our interest in water, however, it will also be necessary to extend this description in environmental terms, so as to identify the relationships existing between socioeconomic variables and water in the ERB.

To this end, we may build a multi-regional input-output table for the ERB. As mentioned above, input-output tables are available as a quantitative accounting instrument in Spain at the national level, but they also been calculated at the level of the Autonomous Communities although with less continuity. These regional tables, the World Input-Output Database (WIOD), interregional trade information and other statistical sources are used to construct the multi-regional input-output table for the ERB.

The model created here provides two key tools for the socioeconomic and environmental analysis of the ERB, which will also serve as the basis for the next chapter. The first is the input-output table for the ERB itself, which is attached to this thesis in Excel format and is also available on request. This table is, to the best of the author’s knowledge, the first to be constructed for a river basin based on physical rather than administrative constraints. The second tool produced is the weighting matrix here called matrix **M**, which will allow estimation of the municipal distribution of the results obtained from the input-output model associated with the Ebro Basin input-output table.

Using the ERB input-output table, we have been able to verify the trade-off between water savings and value added in the basin. This trade-off is not evenly distributed, so that some municipalities win while others lose as calculated using the sector-region weighting matrix (**M**). Meanwhile, graphic representation using GIS data is used to aid in the interpretation of results, given that the ERB consists of 1,480 municipalities.

The content of this chapter is essentially the same as that of the article: Almazán-Gómez, M.A., Duarte, R., Langarita, R., Sánchez Chóliz, J., (2019): *Effects of water re-allocation in the Ebro river basin: A multiregional input-output and geographical analysis*. Journal of Environmental Management, 241, 645-657. However, some changes have been made, mainly with regard to the renumbering of the sections, tables and graphs to adapt them to the numbering of the thesis. Meanwhile, the bibliography has been incorporated into the general bibliography of the thesis and the Abstract and Acknowledgments have been removed.

4.1. Introduction

Water is indispensable for life, for the environment, for human beings, and for industry (Sepehri and Sarrafzadeh, 2018). Freshwater quality and availability are affected by several variables, such as increases in upstream use (Alcamo et al., 2007), or global warming and revegetation (Bielsa and Cazcarro, 2014). These factors are leading to a global decrease in freshwater availability (Gerten et al., 2008). Climate change and food safety are important challenges for human and economic development. Thus, the mitigation of the impact of climate change, and the design of patterns for sustainable consumption and production are among the primary societal challenges (United Nations, 2015).

Fresh water is a natural resource whose value depends on place and time (Hanemann, 2006), since water transport or intra-basin water transfers are expensive. So, given the importance of water and the costs of its transportation, this paper aims to study water use and the water footprint (WF) from a river basin perspective, considering both the physical and administrative contexts.

Specifically, we study the water flows in the Ebro river basin (ERB), which is the largest in Spain (85,500 Km^2), representing 15% of the Spanish extension, and whose basin hosts 7.3% of the Spanish population and 8.53% of Spanish GDP. The Ebro River runs for 910 km in a south-easterly direction across northeast Spain, to its delta on the Mediterranean coast midway between Barcelona and Valencia. It has the largest discharge of any Spanish river (average 9,281 hm^3/year), and its drainage basin, at 85,500 square km, is also Spain's largest. The ERB provides water to more than 3 million people, living in over 1,700 towns and villages, and is one of the most representative semi-arid river basins of the Mediterranean (Milano et al., 2013a). Moreover, according to Valencia et al. (2015), a downward trend in water availability is observable in the ERB, as in other Mediterranean basins (Milano et al., 2013b) and other basins around the world (Gerten et al., 2008).

Regarding the agriculture sector, the ERB represents a very important area. In the ERB, most crop areas, 17,690 km^2, are rainfed, while 5,744 km^2 are irrigated land (INE, 2011). The primary sector is the most water-demanding sector, with more than 4,500 hm^3/year of a total of 5,000 hm^3/year used (CHE, 2014). The ERB water is regulated via an extensive network of dams (Tena et al., 2017) and canals. They allow for the allocation of the water where orography and weather promote the better development of agrarian activities. Another main feature of this basin is that it contains, in part or in whole, nine autonomous communities of Spain (see Table 4.1 and Figure 4.1).

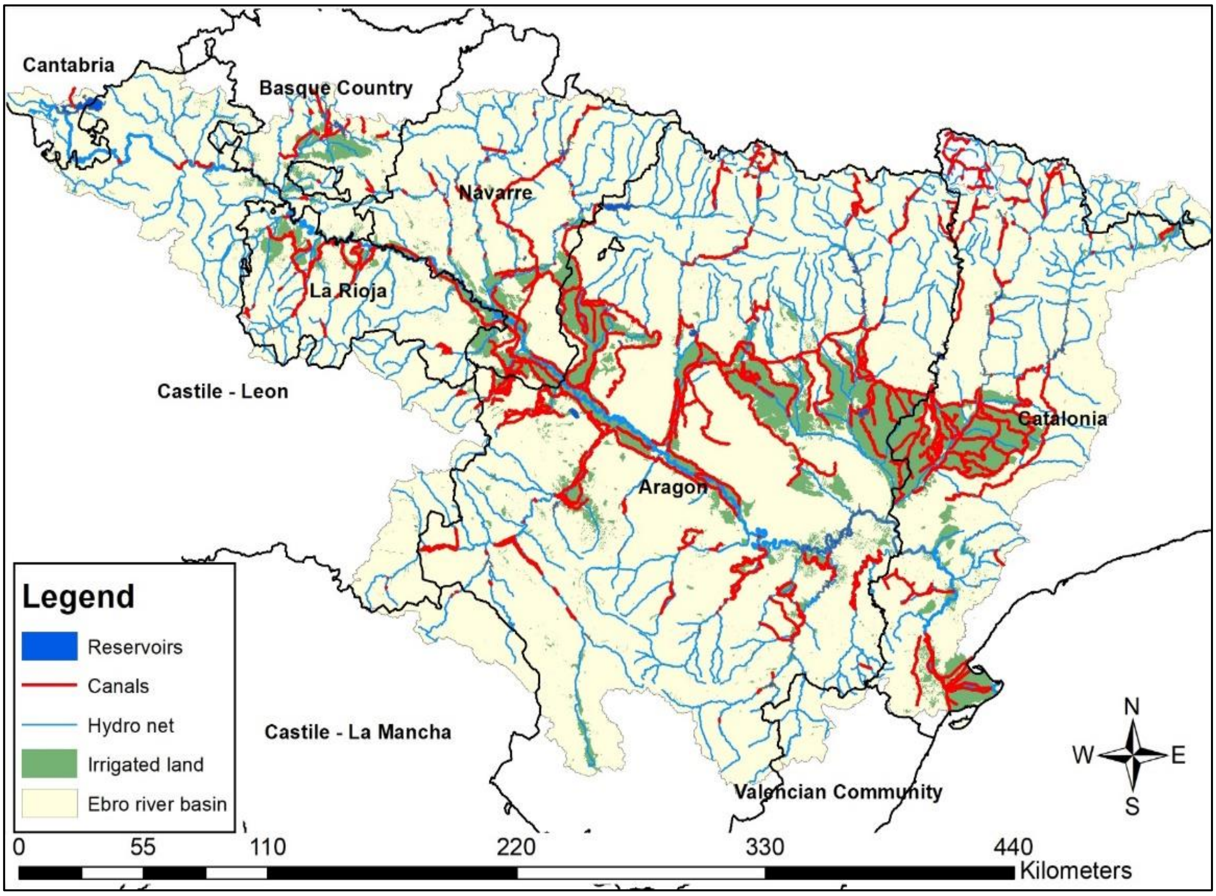
In order to propose measures to reduce the WF in the basin and to estimate the socioeconomic effects at the municipal level, we combine the input-output framework with Geographical Information Systems (GIS). The use of the input-output methodology is justified by the significant literature in this field. The input-output framework has been largely used to assess environmental impacts: Leontief (1970) added a row and a column to obtain an environmental model. Lenzen (1998) used the IO framework to study the greenhouse gases embodied in goods and services.

Table 4.1. Autonomous Communities in the Ebro River Basin

Autonomous Community	Total area (km^2)	Area within the basin (km^2)	Basin within the autonomous. Comm.	Part in the basin
Aragon	47,720	42,111	88.25%	49.21%
Catalonia	32,091	15,635	48.72%	18.27%
Navarre	10,390	9,229	88.83%	10.79%
Castile-Leon	94,227	8,148	8.65%	9.52%
Rioja	5,045	5,023	99.56%	5.87%
Basque country	7,230	2,678	37.04%	3.13%
Castile-la Mancha	79,462	1,119	1.41%	1.31%
Valencian Community	23,254	851	3.66%	0.99%
Cantabria	5,327	775	14.55%	0.91%

Source: Ebro River Basin Authority (CHE, 2014)

Figure 4.1. The Ebro River Basin. Northeast of Spain



Source: Own work. data obtained from MAPAMA (2016).

Emissions of CO_2 have been analysed using this methodology in several works. Munksgaard et al. (2008) used the input-output framework to measure emissions of CO_2 at national, city, and household level. Roibás et al. (2018) used the input-output framework to determine the carbon footprint from a consumer-responsibility perspective, in Galicia, a Spanish region. Long et al. (2018) used the world input-output database (WIOD) to compare levels of embodied CO_2 in the international trade of China and Japan. Acquaye et al. (2017) used the WIOD database to develop a global multiregional input-output model to analyse certain supply chains and their effects on CO2, water consumption, and pollution, among other environmental variables.

This framework is also used to analyse the inter-agents water relationship. Duarte et al. (2002) employed the hypothetical extraction method to analyse the behaviour of the productive sectors as direct and indirect water-consumers in the Spanish economy. There are other papers focused on water pollution or the WF. Lenzen (2009) demonstrated that input-output analysis can be useful in analysing virtual water flows, applying the analysis to a case study of the Australian state of Victoria. Wang et al. (2013) evaluated the WF and the virtual water trade for the case of Beijing, China. Cazcarro et al. (2016) used the input-output framework to analyse the foreign tourism WF. White et al. (2015) also studied the Haihe River Basin's WF and water stress, using a hydro-economic multisectorial model.

There are other papers focused on analysing embodied water trade-flows. Antonelli et al. (2012) analysed green and blue virtual water 'flows' for the Mediterranean Region using the input-output framework. Chen et al. (2012) simulated the global network of embodied water flow, using a top-down approach of input-output simulation for the globalized economy in 2004. Cai et al. (2017) developed a multiregional model for China to analyze the grey water virtual flows among 30 Chinese regions.

In this paper, we construct a multi-regional input-output (MRIO) table for the ERB for 2010 to assess the WF. Since the primary sector, and more specifically crop production, is the largest water consumer in the ERB, we disaggregate it into 36 crops (18 irrigated and 18 rainfed), 6 livestock groups, and the rest of the primary sector (forestry, fishing, and auxiliary activities).

MRIO models usually cover direct and indirect impacts at the country or regional level. However, socioeconomic and environmental impacts take place in much more specific areas. For this reason, we develop a strategy to downscale the MRIO model results at the municipal level, using GIS software. We construct a downscaling matrix using data at the municipal level, such as land use, yields, livestock and other industry outputs, water requirements by production, etc.

The novelty of this paper is the construction of the MRIO model for the Ebro river basin and its link with information at the municipal level and GIS. This MRIO model, to the best of our knowledge, is the first developed for this important area in terms of agriculture, which can be identified as NUT-1[5]. The analysis in this paper shows the utility of these tools for policymakers in determining the effects of policies on certain socioeconomic variables, and the areas where the effects will be most evident. In this sense, apart from the novelty of constructing an MRIO model for the Ebro river basin, this work goes further in the research, linking it with local information. Moreover, its link with GIS allows the display of the affected areas in a map, which opens a way for the interpretation of results and the identification of the affected areas. This becomes especially interesting when designing possible policies at the district level or for collaboration between municipalities.

The rest of the paper is structured as follows: in Section 4.2 we explain the methodology and we show the data used for the analysis. Section 4.3 presents the main results, and particularly

[5] The Ebro river basin has more than 3 Million inhabitants and is part of two Spanish NUT-1: ES2 (Northeast) and ES5 (East).

the results at the municipal level, for two scenarios, which include changes in water withdrawals and value added. Sections 4.4 and 4.5 contain the discussion and conclusions.

4.2. Materials and methods

4.2.1. MRIO model for the Ebro River Basin

MRIO tables usually describe the sale and purchase relationships between regions, producers, and consumers within an economy. They show the interdependencies among industries, agents, and regions (sellers by rows, buyers by columns), as we will see later. The construction of the MRIO table for the Ebro river basin consists of several steps, which are explained below.

First, from the world input-output database (WIOD) (Timmer et al., 2015) we obtain the global MRIO table for 2010 and we aggregate it to obtain an MRIO table with three regions: Spain, rest of EU, and rest of World. As noted earlier, one feature of the Ebro basin is that it contains, in whole or in part, nine autonomous communities of Spain, which are, by alphabetical order, Aragon, Basque-Country, Cantabria, Castile-La Mancha, Castile-Leon, Catalonia, La Rioja, Navarre, and Valencian Community. This leads us to develop a multiregional analysis, and we approach the ERB as the part within the basin of the five most representative regions. Attending to the smaller sizes of the area inside the basin, we discard Castile-la Mancha, Valencian Community, and Cantabria regions. We also discard Castile-Leon, since we consider that the socioeconomic data of that whole autonomous community do not accurately describe the part of the region within the basin (this part of the autonomous community represents less than 7% of the value added of Castile-Leon and its population). So, for the multiregional analysis, we approach the Ebro river basin as those parts of Aragon, Catalonia, Navarre, La Rioja, and Basque Country that fall inside the basin.

Second, we divide the Spanish table into six smaller tables, according to the regions conforming to the Ebro basin: Aragon, Basque Country, Catalonia, Navarre, La Rioja and rest of Spain. To divide the national table into these six regions, we use the Regional IOTs, the table of Aragon has been obtained from Pérez and Parra (2009), the Basque country table from Eustat (2015), the Catalonia table from IdesCat (2012), the table of Navarre from IEN (2011), and La Rioja table from IELR (2011). We also used data from the Spanish Statistical Office (INE, 2017), the c-intereg database (Llano et al., 2010) to see interregional imports and exports, data from the Spanish Institute for Foreign Trade (ICEX, 2016) to identify international trade at regional level, and data from a previous multiregional model developed for Spain (Cazcarro et al., 2013). In order to facilitate the following disaggregation, explained below, we also disaggregate the primary sector of all Spanish regions (ERB regions and rest of Spain) into 3: agriculture, livestock, and the rest of the primary sector.

Third, to harmonize the table, we apply the improved version of the GRAS algorithm of Lenzen et al. (2007). The GRAS algorithm is an updating method developed by Junius and Oosterhaven (2003), commonly used in the literature to balance tables, which consists of a Generalization of the updating/regionalization RAS method (Stone and Brown, 1962). GRAS is an improvement with respect to the RAS, since it allows the updating of non-squared tables and, in addition, accounts for the existence of negative elements, both in the original table and in the data to be adjusted[6].

Fourth, since the five regions considered are not completely within the basin, we divide the regional IO tables into two sub-tables, the intra-basin and the trans-basin. To this end, we use the Analysis System of Iberian Balances database (Bureau Van Dijk, 2017). From this database, we obtain, at municipal level, firms-data, such as gross output (approached by operating income), value added, labor force, zip code, etc. Then, we use proportions to estimate the gross output that corresponds to the intra-basin regional IO tables.

To balance these last estimations, we use the GRAS algorithm again. Once we have determined the data that compose the regional IO tables of the ERB, we calculate the rest of Spain IO table by subtraction. Then, to harmonize the MRIO table, we apply the GRAS algorithm once more.

Finally, due to our interest in water, for the ERB regions we have disaggregated the primary sector into 43 activities: 36 different crop productions (18 irrigated and 18 rainfed), 6 livestock groups, and the rest of the primary sector, which covers forestry, fishing, and auxiliary activities. To disaggregate, we take into account land-use data from the last agrarian census (INE, 2011), yield-data from MAGRAMA (2011), crop-prices obtained from the "price received by farmers and ranchers" survey (IAEST, 2013) and "Technical and economic data of agricultural holdings in Aragon" (MAGRAMA, 2013). Then, we use the GRAS algorithm to balance the table and to obtain the final estimation. As a result, the MRIO table of the ERB

[6] The maximization problem of Junius and Oosterhaven (2003) is: Max: $\sum_j \sum_i |x_{ij}| ln \frac{x_{ij}}{a_{ij}}$; and we use the improved version of Lenzen et al. (2007), whose optimization problem is: Max: $\sum_j \sum_i \ |a_{ij}| \frac{x_{ij}}{a_{ij}} ln \left(\frac{x_{ij}/a_{ij}}{e} \right)$; both subject to: $\sum_i x_{ij} = u_i$; $\sum_j x_{ij} = v_j$; $\sum_i u_i = \sum_j v_j$; $\forall i, j$

Where x_{ij} is the new component of the table placed in row *i* and column *j* and a_{ij} is the old component, also known as "prior", v_j is the new sum by rows of column *j* and u_i is the new sum by columns of row *i*.

takes into account 428 productive sectors, as can be seen in Table SI1 of the Supplementary Information: 69 (36 crops + 6 livestock + 1 rest of primary sector + 26 non-primary sectors) sectors by 5 regions; 29 (1 crop production + 1 livestock + 1 rest of primary sector + 26 non-primary sectors) from rest of Spain; and 27 sectors (primary sector is not disaggregated) by 2 regions (rest of EU and rest of World), and 32 components of final demand: 4 (Households, Government, Gross capital formation, and Changes in inventories and valuables) by 8 regions. Then, the final structure of the MRIO table of the Ebro basin is the following (Figure 4.2), with the 6 Spanish regions plus rest of EU, plus rest of World:

Figure 4.2. Structure of the MRIO table of the Ebro river basin

$x_{i,j}^{1,1}$	…	$x_{i,j}^{1,8}$	$y_{i,d}^{1,1}$	…	$y_{i,d}^{1,8}$
⋮	$x_{i,j}^{r,s}$	⋮	⋮	$y_{i,d}^{r,s}$	⋮
$x_{i,j}^{8,1}$	…	$x_{i,j}^{8,8}$	$y_{i,d}^{8,1}$	…	$y_{i,d}^{8,8}$
v_j^1	v_j^s	v_j^8			

In Figure 4.2 $x_{i,j}^{r,s}$ are the components of the intermediate inputs matrix X (denoting the intersectoral trade), composed of submatrices $X^{r,s}$. Each $x_{i,j}^{r,s}$ represents the sales from sector i of region r to sector j of region s. r and s indices, from 1 to 8, indicate Aragon, Catalonia, Navarre, Basque country, La Rioja, rest of Spain, rest of European Union, and rest of World respectively. Indices i and j represent sectors (see Table A4.7 in the Annex). $y_{i,d}^{r,s}$ represents the components of the final demand matrix Y, also composed of submatrices $Y^{r,s}$. Each $y_{i,d}^{r,s}$ represents the sales from sector i of region r to component d of the final demand of region s. Index d, from 1 to 4, are Households, Government, Gross capital formation, and Changes in inventories and values respectively. v_j^s represents the value added of sector j in region s.

Reading the table by columns, we can observe the productive structure of each sector of each region, and the dependencies of other sectors of other regions. Meanwhile, reading it by rows, we can observe the destination of the production. Since the table represents a closed economy (the whole world), sums by columns coincide with sums by rows (see equation (4.1)).

$$\sum_r \sum_i x_{i,j}^{r,s} + v_j^s = \sum_z \sum_u x_{j,u}^{s,z} + \sum_z \sum_d y_{j,d}^{s,z} = x_j^s \ ; \ \forall i,j,r,s,d,u,z \qquad (4.1)$$

Where x_j^s represents the total output of sector *j* from region *s*. From the MRIO table of the ERB (figure 2) we obtain the matrix of technical coefficients, **A**, which represents direct needs from sector *j* per Euro produced by sector *i*, and whose components are the $a_{i,j}^{r,s}$ calculated following equation (4.2). we can describe the multiregional links in a matrix form (equation (4.3)).

$$a_{i,j}^{r,s} = \frac{x_{i,j}^{r,s}}{x_j^s} \quad (4.2)$$

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{Y}\mathbf{e} \leftrightarrow \mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}\mathbf{e} = \mathbf{L}\mathbf{y} \quad (4.3)$$

Where **I** is the identity matrix (428x428), **Y** is the final demand matrix, **e** is a (32x1) column vector of ones, $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ is the Leontief inverse, which indicates the inputs generated by sector *i* incorporated directly or indirectly to sector *j* per euro of final demand of sector *j*, **x** is the (428x1) Gross Output vector, $\mathbf{y} = \mathbf{Y}\mathbf{e}$ is the final demand aggregated vector $\left(y_i^r = \sum_s \sum_d Y_{i,d}^{r,s}\right)$, which includes different kinds of final demand: households, investment, government expenditures, and exports.

4.2.2. Environmental extension: Blue and green water

The definition of WF is close to the concepts of embodied water and virtual water (Hoekstra and Chapagain, 2008). Embodied water is the water necessary to produce a good or service (direct) and the water needed to produce the goods and services involved in its productive process (indirect) (see Chapagain and Orr, 2009). The term "virtual water" is synonymous with "embodied water", but generally refers to embodied water traded as virtual water flows. This indicator takes into account both direct and indirect water use (Hoekstra et al., 2009).

In these terms, there are three kinds of WF: blue, green, and grey (see Hoekstra et al., 2009 and Mekonnen and Hoekstra, 2010). The blue WF refers to the volume of freshwater consumed and/or evaporated in the production process (supply chain) of a good or service, when water comes from a freshwater body (surface or groundwater). The green WF refers to the rainwater stored in the soil as soil moisture evapotranspirated (consumed) by plants when they are part of a productive process. The grey WF refers to pollution (not to consumption) and is defined as the amount of freshwater required to assimilate the load of pollutants. Blue and green water are directly associated with water consumption and water availability (Veettil and Mishra, 2018), so, we will focus on these two.

The direct water used by a sector refers to the direct water consumption of the sector and it is only a part of the WF, or the embodied water. However, knowing the water needed by sector per euro of total production, we can obtain the virtual water flow matrix using the input-output framework (Roibás et al., 2017). The virtual water flow matrix shows by rows the origins of embodied water, and by columns the destination of the water embodied (see Table 4.3). Thus, totals by rows (usually last column) identify the water used from the region and sector identified by each row; and totals per column (usually the last row) identify the WF.

The data for direct water used have been obtained from the world input output database (see Genty et al., 2012). This dataset is provided for 40 regions and 35 industries, for the period 1995-2009. We estimate the 2010 data, following equation (4.4):

$$\frac{d_{j,2010}^{s}}{x_{j,2010}^{s}}-\frac{d_{j,2009}^{s}}{x_{j,2009}^{s}}=\frac{d_{j,2009}^{s}}{x_{j,2009}^{s}}-\frac{d_{j,2008}^{s}}{x_{j,2008}^{s}};\ d_{j,2010}^{s}=x_{j,2010}^{s}\left(2\frac{d_{s,2009}^{s}}{x_{j,2009}^{s}}-\frac{d_{s,2008}^{s}}{x_{j,2008}^{s}}\right) \tag{4.4}$$

Where $d_{j,t}^{s}$ represents the direct water used by sector *j* in region *s* and year *t*, and $x_{j,t}^{s}$ represents the gross output of sector *j* in region *s* and year *t*. To estimate the direct water used by the ERB regions and the rest of Spain, for non-primary sectors, we assume the same direct water used over output ratio $\left(d_{j,2010}^{s}/x_{j,2010}^{s}\right)$ for Spain. For primary sectors, we use land use data (INE, 2011), proportions and coefficients from Cazcarro et al. (2014) and Chapagain and Hoekstra (2004), and water-needs data at the county level from Martinez-Cob (2004); thus, we are also able to estimate the water used in each municipality for feeding each crop. Then, for further actions, we calculate both vectors, direct blue water per euro and direct green water per euro, following equation (4.5). These vectors are called unit requirements.

$$w_{\mathrm{j}}^{s}=\frac{d_{\mathrm{j},2010}^{s}}{\mathrm{x}_{\mathrm{j},2010}^{s}} \tag{4.5}$$

Thus, we are able to extend environmentally the model using these vectors to obtain the virtual water matrix (**V**) of the ERB (see equation (4.6)). To this end, we use $\hat{\mathbf{w}}$ and $\hat{\boldsymbol{y}}$ which are the vector of unit requirements of water (blue or green), and the vector of final demand ($\mathbf{y}=\boldsymbol{Ye}$) diagonalized respectively. **V** (428x428) is the virtual water matrix which shows the embodied water traded between sectors and regions.

$$\mathbf{V}=\hat{\mathbf{w}}\mathbf{L}\hat{\mathbf{y}} \tag{4.6}$$

4.2.3. Downscaling: from regions to municipalities

As the effects on water resources are usually located in small and specific areas, and MRIO models usually show environmental impacts at a country or regional level only, we propose to extend the MRIO analysis with GIS layers and municipal information. In this way, we will be able to estimate the water used in specific hotspots, to understand those hotspots and their locations, to propose policies at the municipal level, and so on.

We make use of the Bureau Van Dijk (2017) database, since it contains information at the municipal level, sector by sector, about output and other relevant variables, for all sectors except the primary, to discern the proportion that the output of each sector in each municipality represents over the output of each region and sector. To estimate the percentages of the primary sector, we use own-elaboration data that distinguish between irrigated and rainfed crops and take into account the area dedicated to each crop at the municipal level, as well as different yields by region. Data on crop production and livestock have been calculated using the 2009 census (INE, 2011), with yields from MAGRAMA (2011), and prices from IAEST (2013).

We have used these proportions to estimate the parts of the regional IO tables that are included in the basin (mentioned in Section 4.2.1) and to develop the matrix **M**. Matrix **M** (1480x428) contains, by columns, the percentage that the output of each of the 1,448 municipalities represents over the gross output of each sector in its region. Once we have matrix **M**, following equation 5.7, we can determine, by sector, the gross output at the municipal level, $\mathbf{X_m}$ (1480x428) using the output vector of the MRIO model, diagonalized. Moreover, substituting $\hat{\mathbf{x}}$ by $\hat{\mathbf{w}}\hat{\mathbf{x}}$ in equation (4.7), we can allocate blue or green water used at the municipal level. Also, we develop unit requirements vector of value added, to estimate the municipality distribution of this macro-magnitude. We use this vector in the same way that we use the water-related ones.

$$\mathbf{X_m} = \mathbf{M}\hat{\mathbf{x}} = \mathbf{M}\widehat{\mathbf{Ly}} \ ; \ \mathbf{W_m} = \mathbf{M}\hat{\mathbf{w}}\hat{\mathbf{x}} = \mathbf{M}\hat{\mathbf{w}}\widehat{\mathbf{Ly}} \qquad (4.7)$$

4.3. Results

4.3.1. MRIO table for the ERB and virtual water flows

As introduced in the Methodology section, input-output tables represent the economic flows among sectors and regions. They show by rows the origin of the products or services, and by column the sectors or the final demand agents that purchase them. As noted earlier, the intersectoral trade shows the structural links and dependencies among sectors and regions. Commonly, the last rows depict taxes, value added (VA), and output (as the sum of the intermediate inputs and value added), by sector or region represented in each column. Table 2 depicts the aggregated MRIO table that shows the economic flows in the regions of the Ebro Valley and the trade among the regions: Aragon (ARA), Catalonia (CAT), Navarre (NAV), Basque country (B_C), La Rioja (RIO), and including for each region the trade flows with rest of Spain (R_SP), rest of European Union (R_EU), and rest of world (R_W).

The output of the ERB in 2010 was €179,337 million, which represents 8.8% of Spanish gross output, while the VA of the ERB, €77,711 million, represents 8.0% of Spanish VA. The ERB output can be divided into intermediate inputs (€69,736 million), 38.9%, final demand (€68,151 million), 38%, and exports (€41,450 million), 9.6% to rest of Spain, 10.2% to rest of European Union, and 3.4% to rest of World. The ERB imports goods and services amounting to €44,201 million: 49.4% from rest of Spain, 35.2% from rest of European Union, and 15.4% from rest of World. So, The ERB is a net importer region. The largest producer in the ERB is Aragon (€69,820 million), followed by Navarre and Catalonia. Aragon imports from the rest of ERB €4,544 million, and its main commercial partner is Catalonia. Navarre and Catalonia have an output of €37,474 million and €33,830 million respectively, and their main trading partner is Aragon.

Following equation (4.6), we obtain the virtual water flows. Table 4.3 shows the virtual flows of blue plus green water by regions. The virtual water flow matrices show the embodied resource, that is to say, the water in the different regions and sectors, directly and indirectly incorporated in the various steps of the production supply chain. Similarly that input-output tables, the virtual flow matrices show the origin of the resource by rows, and the destination by column. Then, the column sums over the rows show the total water used in production by the corresponding sector or region (the water footprint). Meanwhile, the row sums over the columns can be interpreted as the total water requirements (virtual water) for each sector and region according the final demand.

As can be seen, the table of blue plus green virtual water flow shows that the ERB is a net importer of embodied water. The ERB uses 14,437 hm^3 from its water, while the ERB embodies 15,908 hm^3 of virtual water in its production. Thus, the ERB is a net importer of virtual water, which is common in Mediterranean countries due to the usual consumption patterns (Steen-Olsen et al., 2012). Aragon, which uses 48% of the total ERB water used by production activities, produces goods and services that amount only to 39% of ERB output. Similarly, Catalonia (part of which is within the ERB) uses 30% of the ERB water, while the region produces 19% of the ERB goods & services (see Table 4.4). In fact, both regions produce "water-intensive" products, mainly crops and livestock, in a higher proportion than the others. On the other hand, Navarre and Basque Country use 10% and 3%, respectively, of the ERB water used and they generate 20.9% and 12.6% of the ERB gross output, respectively.

Some socioeconomic and water-related variables, separated by sector and region, can be seen in Table 4.4. In general, the highest output by region are services and industry. The service sector is the largest in Aragon, Catalonia, and La Rioja, where the output of the service sector represents between 43% and 45%. In Navarre and Basque Country, the sector with the largest output is industry, at close to 50% in both regions. In these two regions (Navarre and Basque Country), the weight of the primary sector is much lower than in the other three regions, not only in terms of production, but also in value added, which is mostly concentrated in the service sector, which represents more than half of the value added in every single region. The region whose service sector weight is lowest is Basque Country, 54% of value added; in contrast, the Aragonese service sector represents 63%. The distribution of the main socioeconomic variables differs among regions and sectors. We can identify Basque Country and Navarre as industrial regions, where the primary sector has a significantly lower weight than the other three regions. Within the primary sector, livestock is an activity that distinguishes among regions; it represents 2.5% and 4.6% of the output of Aragon and Catalonia, respectively, while in the other regions it represents less than 1%.

Table 4.2. MRIO Table of the Ebro River Basin Aggregated by regions (Million €)

		Intermediate inputs								Final demand							
		Ebro River Basin					R_SP	R_EU	R_W	Ebro River Basin					R_SP	R_EU	R_W
		ARA	CAT	NAV	B_C	RIO				ARA	CAT	NAV	B_C	RIO			
Ebro River Basin	ARA	23,039	381	691	277	294	5,705	4,005	1,237	27,100	85	173	44	92	1,768	4,011	918
	CAT	2,590	11,963	676	417	126	1,371	599	333	1,041	12,517	269	84	30	530	892	394
	NAV	961	56	12,314	432	271	2,412	2,694	917	327	16	12,252	105	119	860	2,920	817
	B_C	656	93	1,019	7,137	254	1,755	963	567	175	23	272	7,190	70	797	1,046	570
	RIO	337	16	392	129	5,216	1,269	485	109	221	6	116	93	5,730	676	628	201
	R_SP	4,952	1,773	2,361	2,567	1,165	749,522	70,826	52,200	4,369	734	2,444	877	600	867,677	60,568	36,343
	R_EU	4,161	2,581	3,002	1,515	521	83,497	9,617,703	1,083,494	1,142	1,611	754	222	47	54,090	10,034,073	839,005
	R_W	1,038	2,025	539	729	264	72,633	1,101,714	37,428,689	527	1,236	223	186	38	31,126	500,772	35,346,951
	TAX	716	159	337	174	176	29,748	474,182	556,354								
	VA	31,371	14,784	16,144	9,210	7,339	911,066	10,454,248	35,364,788								
	OUTPUT	69,820	33,830	37,474	22,587	15,626	1,858,978	21,727,419	74,488,687								

Table 4.3. Blue plus green virtual water flows by regions (hm^3)

	ARA	CAT	NAV	B_C	RIO	TOTAL ERB	R_SP	R_EU	R_W	TOTAL EXPORTED	TOTAL = Direct water
ARA	4,594	316	413	66	33	5,422	1,253	209	116	1,578	6,999
CAT	632	2,535	69	32	7	3,276	707	165	168	1,040	4,316
NAV	99	7	1,085	33	13	1,237	194	53	31	278	1,515
B_C	17	2	23	311	11	364	54	15	7	75	440
RIO	50	5	58	39	744	896	212	37	22	270	1,167
TOTAL ERB	5,393	2,865	1,648	481	808	11,195	2,419	478	344	3,242	14,437
R_SP	935	295	459	296	136	2,122	67,155	3,105	1,917		74,299
R_EU	285	215	129	95	79	803	4,273	489,733	38,260		533,069
R_W	496	579	277	275	161	1,789	15,273	177,454	9,592,907		9,787,423
TOTAL IMPORTED	1,716	1,090	865	666	376	4,713					
TOTAL = WF	7,109	3,955	2,513	1,148	1,184	15,908	89,120	670,770	9,633,429		

Table 4.4. Socioeconomic and environmental variables in the ERB regions (million €, jobs and hm^3)

Region	Sector	Output	VA	Direct blue water used	Direct green water used	Apparent blue water productivity
Aragon	Irrigated crops	830	633	1,887	2,208	0.34
	Rainfed crops	615	469	0	2,494	-
	Livestock	1,719	388	131	0	2.96
	Rest of primary sect.	115	58	23	74	2.52
	Industry	27,729	6,997	13	0	538.23
	Construction	7,171	2,920	170	0	17.18
	Services	31,641	19,473	0	0	-
Catalonia	Irrigated crops	839	605	1,513	1,860	0.40
	Rainfed crops	233	168	0	651	-
	Livestock	1,559	332	119	0	2.79
	Rest of primary sect.	74	35	15	48	2.33
	Industry	11,642	2,753	8	0	344.13
	Construction	4,359	1,619	103	0	15.72
	Services	15,125	9,087	0	0	-
Navarre	Irrigated crops	354	255	359	493	0.71
	Rainfed crops	279	201	0	538	-
	Livestock	363	65	28	0	2.32
	Rest of primary sect.	26	14	5	17	2.80
	Industry	18,221	4,643	10	0	464.30
	Construction	2,772	1,350	66	0	20.45
	Services	15,460	9,344	0	0	-
Basque Country	Irrigated crops	41	28	67	79	0.42
	Rainfed crops	99	68	0	188	-
	Livestock	190	57	14	0	4.07
	Rest of primary sect.	5	3	1	3	3.00
	Industry	11,258	3,055	8	0	381.88
	Construction	3,278	962	78	0	12.33
	Services	7,715	4,872	0	0	-
La Rioja	Irrigated crops	339	211	374	502	0.56
	Rainfed crops	188	117	0	201	-
	Livestock	84	54	6	0	9.00
	Rest of primary sect.	33	16	7	21	2.29
	Industry	6,167	1,997	7	0	285.29
	Construction	2,071	692	49	0	14.12
	Services	6,745	4,172	0	0	-

Source: Own Work

Of the water used in production, 4,589 hm^3 of a total 5,059 hm^3 of blue water are consumed by the primary sector, 464 hm^3 is used by construction sector, and the rest, 46 hm^3, by industry. Apart from that, the primary sector also uses 9,378 hm^3 of green water. Irrigated crops use 83% of the blue water used in the ERB, distributed irregularly among regions; Aragon and Catalonia irrigators together use 67% (3,400 hm^3) of the blue water used in the ERB. Irrigators from La Rioja and Navarre use a similar amount of blue water, which, in sum, represents 14.5% of the total. Basque Country irrigators use only 67 hm^3 blue water, which is only 1.3% of the total. The construction sector uses 9.24% of the blue water, with no differences among regions in relative terms. Livestock activities consume 2.6% of blue water in Aragon, and 2.3% in Catalonia, while the other three regions consume 1% in total.

We divide value added by direct blue water to obtain the apparent blue water productivity. In the whole ERB, the apparent blue water productivity in irrigated crop production is 0.41 €/m^3, in livestock, it is 3 €/m^3, in construction, it is 16 €/m^3, and in industry 422 €/m^3. Considering these values of apparent blue water productivity and taking into account the proportions of blue water used, we focus on crop production to propose alternatives to save water and deal with possible reductions in water availability. The apparent blue water productivity in the ERB for irrigated crops is not the same in the five regions. In Aragon it is 0.33 €/m^3, in Catalonia 0.40 €/m^3, in Navarre 0.71 €/m^3, in Basque Country it is 0.42 €/m^3, and in La Rioja 0.56 €/m^3. These differences could be caused by the intensity of use, the crop mix (land use) and the productivity of the combination of factors (land, water, capital, and labour) of each crop in each region. The intensity of use can be obtained from Table 4.4, while the crop mix can be seen in Table A4.8 in the Annex. Production in euros (tons multiplied by price) for each crop and each region can be seen in Table A4.9 in the Annex.

We can satisfy the same final demand and reduce the blue WF, substituting the final demand of sectors and regions that provoke a higher WF in the ERB, by demand of the same sectors in the regions that provoke the lowest WF. Table 4.5 summarizes the data for irrigated crop production embodiments in final demand. The third column identifies the embodied blue water (the blue WF) in one euro of final demand, by sector and region, from the Ebro river basin, and the fourth column identifies the blue WF caused outside the ERB (rest of Spain, Rest of European Union, and Rest of the World) per euro of final demand. The fifth and sixth columns identify the green WF. Columns 7 and 8 show the embodiments of value added per euro of final demand and where that value added is generated.

As can be seen, the coefficients of the same crop differ by region. These coefficients capture the total effect, that is to say, the direct effect plus the indirect effect. While the direct effect captures the direct use of the resource (blue or green water) or the value added generated, the indirect effect captures the resource embodied in the different stages of the production process; that is, it depends on the productive structure of the region itself and of the regions providing the inputs.

Given the primary character of agricultural goods, the direct effect represents the larger part of the total effect, with the differences in the coefficients depicted in Table 5 being, in great part, associated with the direct effect. The differences in the requirements of water per Euro are mainly motivated by the factors affecting direct water productivities, that is by the climate, by the differences in the productivity of the land, and by the difference in prices.

Using the data in Table 4.5, we propose two scenarios, in which we re-allocate the final demand of crop production, looking to reduce the blue WF, and maximizing the value added. In these scenarios, we use the same strategy: for example, in scenario 1, we identify for each crop, the region that, per euro of final demand, provokes the lowest blue WF in the ERB and the region that provokes the highest blue WF in the ERB. Then, we move €100,000 from the final demand of this crop of the region with the highest WF to this crop in the region that has the lowest WF[7]. In scenario 2, we are looking to maximize value added, so we move €100,000 of final demand from the regions with the lowest value added per unit to the regions with the highest. Results can be seen in Table 4.6.

As can be seen in Table 5.6, we can satisfy the same final demand of each crop, saving water (first scenario) or having a higher value added (second scenario). The first scenario shows that we could save 1.06 hm^3 of blue water and 1.32 hm^3 of green water; however, value added would decrease by around €44,000 in the basin. This means that saving a cubic hectometre of blue water would cost around €41,500 in terms of value added in the whole of

[7] In scenario 1, we subtract €100,000 from the final demand of Aragon's wheat (because it has the largest wheat blue WF coefficient) and we add €100,000 to the final demand of La Rioja's wheat (because it has the largest wheat Blue WF coefficient); we subtract €100,000 from the final demand of Catalonia's corn and add €100,000 to the final demand of Navarre's corn; we subtract €100,000 from the final demand of Aragon's barley and we add €100,000 to the final demand of Navarre's barley; and so on.

the ERB. The second scenario looks to increase the VA by €97,000, while the blue water and green water also increase, by 0.6 hm^3 and 0.85 hm^3 respectively. These scenarios show the opportunity cost, in the cases where we prioritize one objective. Choosing other crops to reallocate their final demand, other trade-offs appear and, since the model we use is linear, other combinations are possible. We use these two scenarios as examples, to show the capabilities of combining the MRIO table with data at the municipal level and GIS software, and their utility for policymakers. Knowing the trade-offs between environmental and socio-economic variables at global and local level is indispensable for policy makers. Policy makers should also know where and how their decisions will have an effect. For this reason, we developed in 5.3.2 a strategy to locate the impacts.

Table 4.5. Embodiments per euro of final demand in irrigated crop production

	crop	Blue WF (m^3/€)		Green WF (m^3/€)		Value Added (€/€)	
		In ERB	Abroad	In ERB	Abroad	In ERB	Abroad
Aragon	Wheat	1.9557	0.0036	3.2038	0.0184	0.9860	0.0359
	Corn	2.0764	0.0034	2.2841	0.0174	0.9881	0.0343
	Barley	2.0108	0.0032	3.5168	0.0162	0.9877	0.0345
	Alfalfa	1.8899	0.0070	2.1157	0.0360	0.9471	0.0678
	Other fodder	1.4444	0.0052	3.2109	0.0268	0.9613	0.0558
	Pome fruits	2.0107	0.0096	2.2058	0.0494	0.9221	0.0884
	Stone fruits	3.7135	0.0086	4.2648	0.0438	0.9327	0.0796
	Horticulture	1.2208	0.0053	1.7080	0.0271	0.9681	0.0507
	Rice	2.3562	0.0053	2.1028	0.0270	0.9684	0.0505
Catalonia	Wheat	1.5125	0.0042	2.5569	0.0257	0.9461	0.0556
	Corn	2.7667	0.0026	3.2343	0.0155	0.9565	0.0450
	Barley	1.3153	0.0041	2.4365	0.0247	0.9409	0.0600
	Other fodder	0.4969	0.0095	1.2183	0.0582	0.9024	0.0983
	Citrus frits	1.5693	0.0075	2.4461	0.0456	0.8975	0.1007
	Pome fruits	1.7059	0.0107	1.9603	0.0655	0.8899	0.1102
	Stone fruits	3.1482	0.0083	3.6395	0.0506	0.8997	0.0996
	Horticulture	2.1577	0.0070	2.9720	0.0429	0.9179	0.0827
	Olive	1.5726	0.0104	2.7501	0.0634	0.8867	0.1131
	Grapevine	0.5584	0.0107	0.7402	0.0652	0.8920	0.1082
	Rice	1.6216	0.0070	1.3651	0.0428	0.9179	0.0827
Navarre	Wheat	0.9676	0.0016	2.4972	0.0078	0.9610	0.0373
	Corn	1.4639	0.0013	1.5306	0.0063	0.9674	0.0320
	Barley	0.7437	0.0017	2.7647	0.0083	0.9568	0.0408
	Other fodder	0.2658	0.0048	0.6091	0.0232	0.9198	0.0727
	Pome fruits	1.4602	0.0039	1.7321	0.0186	0.9161	0.0755
	Stone fruits	1.7466	0.0043	2.1309	0.0209	0.9187	0.0735
	Horticulture	1.3993	0.0029	1.8264	0.0139	0.9474	0.0491
	Grapevine	0.5749	0.0046	0.8816	0.0220	0.9152	0.0763
	Rice	1.5755	0.0029	1.3872	0.0138	0.9481	0.0485
Basque Country	Industrials	0.1627	0.0217	0.2452	0.1006	0.8512	0.1379
	Pome fruits	1.0271	0.0232	1.2393	0.1070	0.8430	0.1458
	Stone fruits	3.7018	0.0125	4.4697	0.0576	0.8519	0.1355
	Rice	2.2691	0.0133	2.0028	0.0616	0.8815	0.1088
La Rioja	Wheat	0.9435	0.0058	1.7624	0.0294	0.8801	0.1015
	Barley	1.1066	0.0081	1.9108	0.0414	0.8642	0.1167
	Industrials	0.2045	0.0174	0.2615	0.0872	0.8422	0.1393
	Pome fruits	1.0176	0.0186	1.1750	0.0938	0.8017	0.1769
	Stone fruits	1.8355	0.0170	2.2843	0.0857	0.8111	0.1678
	Horticulture	1.4359	0.0159	1.9403	0.0800	0.8302	0.1499
	Olive	0.7262	0.0172	1.4836	0.0870	0.8111	0.1678
	Grapevine	0.3286	0.0168	0.5732	0.0845	0.8166	0.1624

Source: Own Work

Table 4.6. Irrigated crops final demand reallocation results

Scenario	Blue WF (m3)		Green WF (m3)		Value Added (€)	
	In ERB	Abroad	In ERB	Abroad	In ERB	Abroad
Scenario 1	-1,057,266	2,297	-1,323,459	8,249	-43,724	26,364
Scenario 2	596,768	-6,129	852,749	-31,245	96,990	-67,740

Source: Own Work

4.3.2. Downscaling the MRIO results; locating the impacts

In the previous section, we have seen the trade-off between water and value added in the whole basin. This trade-off exists because of the differences between regions. However, the socio-economic gains or losses occur in more specific areas. Moreover, the ERB has depopulation problems: the ERB represents 15% of the Spanish surface area, but only has 7.3% of the Spanish population. Moreover, 400 of the 1,400 municipalities considered contain 90% of the ERB population. For this reason, it is even more important to know the socio-economically affected areas by measures on a more local scale.

MRIO tables usually tell us about environmental impacts at the country or regional level. Thus, to identify the hotspots and quantify the socio-economic impacts and environmental damage in specific areas, we develop a methodology to allocate the standard MRIO model results among municipalities (Section 4.2.3). Since we are considering more than 1,400 municipalities, we analyze the results through GIS software (disaggregating results by municipality and also by sector are available on request).

Using equation 4.7, we have determined the blue and green water used at the municipal level, as well as the value added and its variations through the two scenarios previously depicted. Figure 4.3 shows the changes in blue water used when we reallocate the final demand of crops among regions to reduce blue water (first scenario). Figure 4.4 is related to the first scenario and shows the changes in value added at the municipal level.

As can be seen in Figure 4.3, the reallocation of final demand of crops in the first scenario provides a solution that mainly water would be saved in the middle-east and middle-west of Aragon, the west of Catalonia, and in the Ebro Delta. The areas that would increase water withdrawals are, mainly, the south of Navarre and the east of La Rioja. Changes in VA associated with scenario 1 can be seen in Figure 4.4, which shows that the areas where the VA would decrease (in red) are mostly the same areas where blue water is being saved.

Reductions in water consumption entail reductions in output and in VA, although each municipality is affected in a different way, due to their crop mix and also their water requirements per euro of production.

Figure 4.5 and Figure 4.6 depict the changes in blue water used and in VA at the municipal level, respectively, when we re-allocate final demand of crops among regions to increase the VA in the whole basin (second scenario). As can be seen in Figure 4.5, in this scenario, the saving-water areas are mostly in La Rioja, and the intensification of water extractions would be primarily in mid-Aragon. Figure 4.6 shows the municipalities where VA increases (green zones) and where it decreases (red zones). As noted earlier, the areas where water use decreases are the areas where VA decreases, and vice-versa. In relative terms, the water withdrawal variations at the municipal level entailed in these scenarios are small. They can be seen in Figure A4.7 and Figure A4.8 in the Annex. So, these scenarios do not significantly increase the water stress.

Figure 4.3. Changes in blue water used. Total impact on blue water (direct plus indirect) of scenario 1 at the municipal level

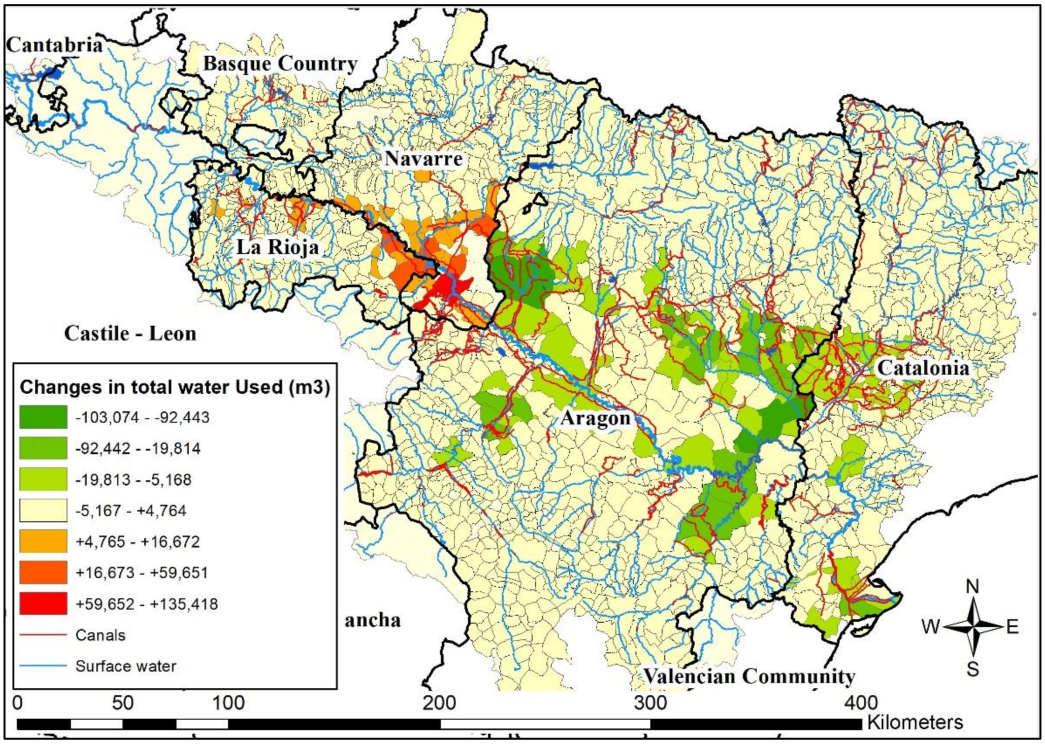


Figure 4.4. Changes in value added. Total impact on value added of scenario 1

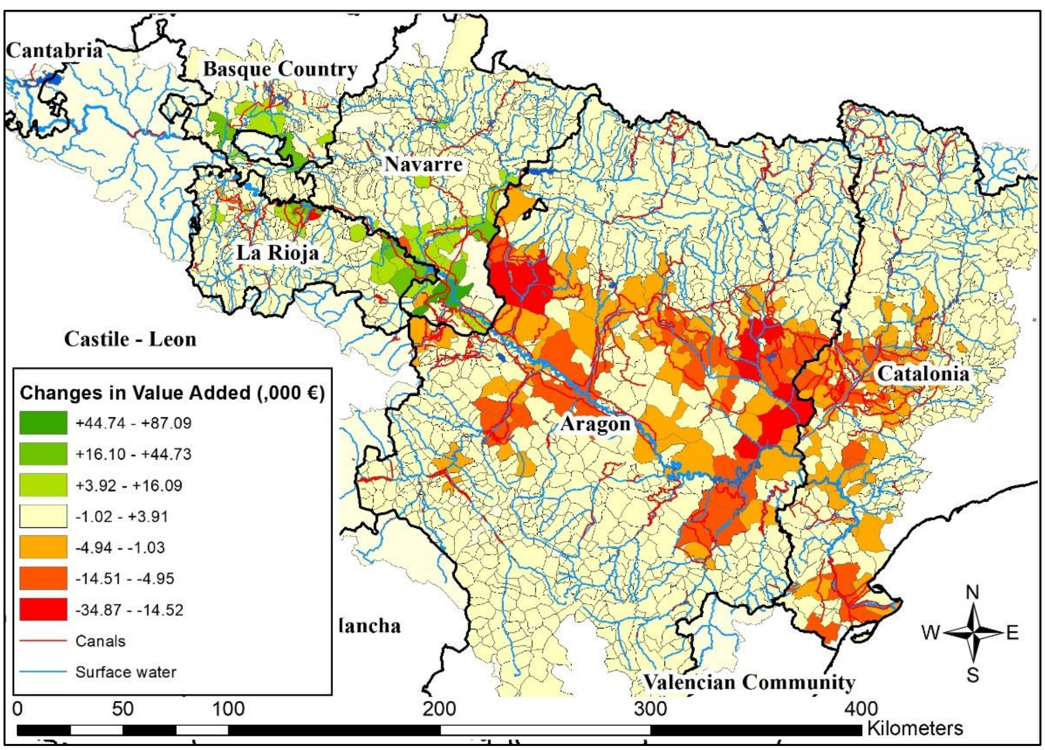


Figure 4.5. Changes in blue water used. Total impact on blue water (direct plus indirect) of scenario 2

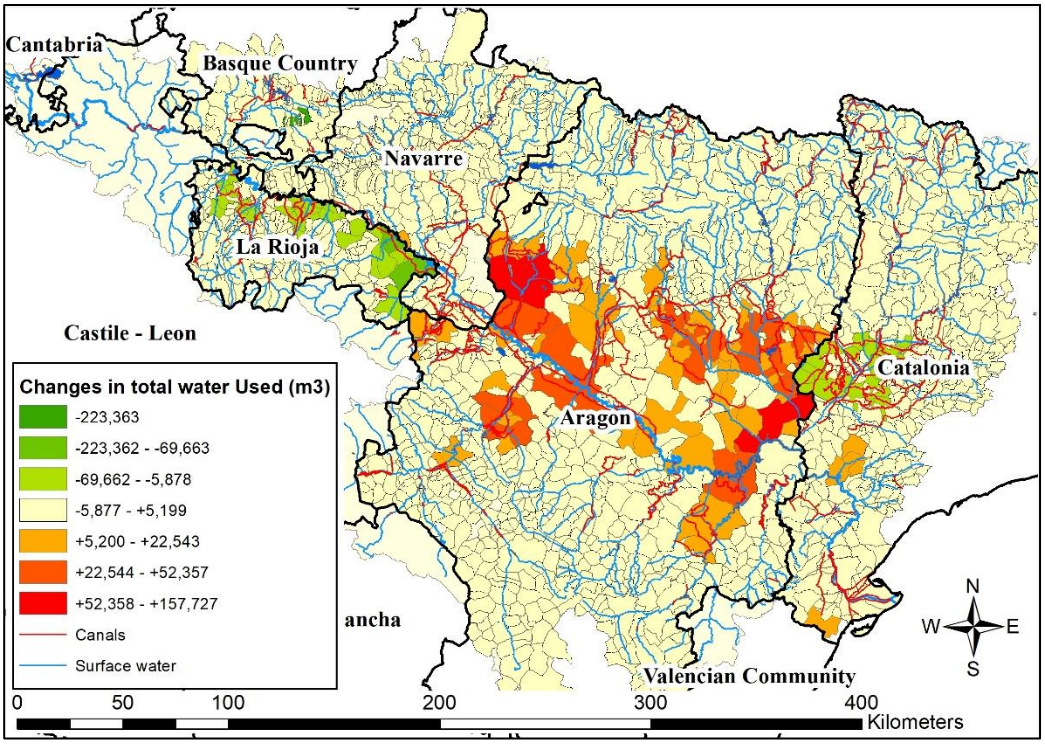
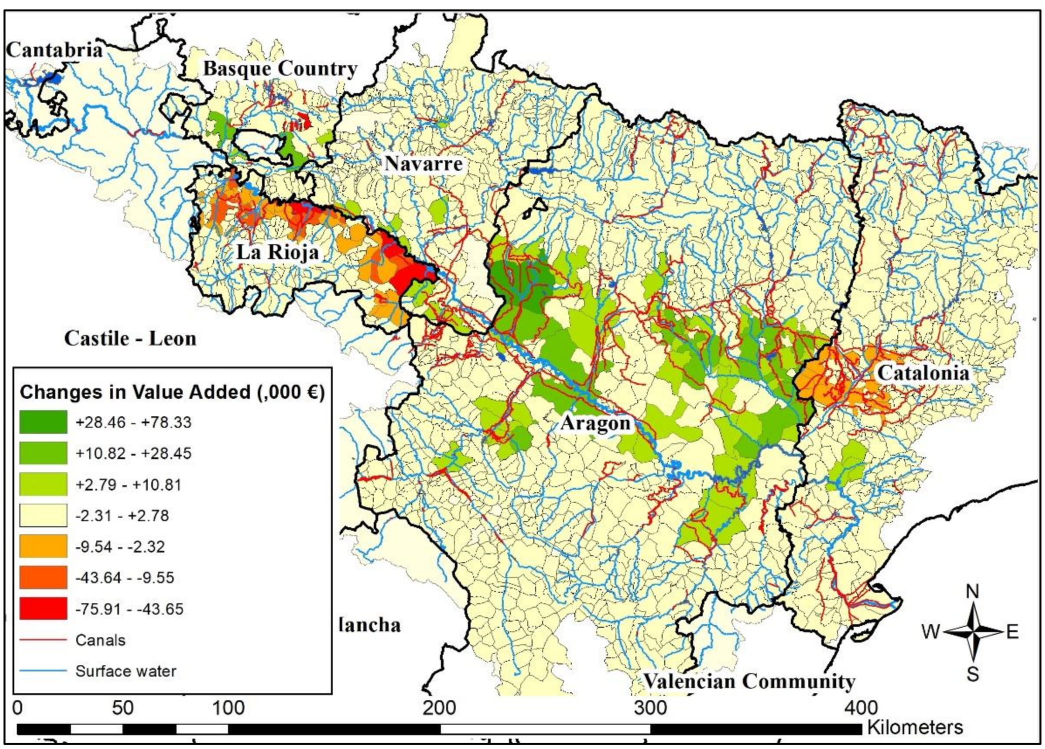


Figure 4.6. Changes in value added. Total impact on value added of scenario 2



4.4. Discussion and conclusions

In the Ebro river basin, water use is already bumping up against its limits. Moreover, different stakeholders are clamouring for greater environmental flows that would imply unaffordable blue water use reductions, see Chapter 3 and Crespo et al. (2018). So, looking for more sustainable patterns, policy makers should propose measures to save water, and local gains and losses should be considered when a policy is being considered.

In this work, we develop a multiregional analysis using the input-output framework in the Ebro river basin (ERB). We build a multiregional input-output table, with the primary sector disaggregated. This integrated table and the associated model represent an important result in themselves, since, to the best of our knowledge, they are a first for this large basin. The MRIO table of the ERB considers 8 regions, the 5 regions that make up the basin and 3 regions that represent the rest of the world. The table shows the interdependencies among the different sectors of different regions, and knowledge of these relationships could help to anticipate the impacts of certain policies.

The environmental extension of the model, with water satellite accounts, allows us to depict the virtual water matrices. These matrices tell us about the embodied water flows, which we consider a very useful tool for environmental management. According to our data, the ERB uses 5,059 hm^3 of blue water and 9,378 hm^3 of green water for production. However, the final demand of the ERB products leads to a blue WF of 4,700 hm^3 and a green WF of 11,208 hm^3. These data show that, in water-embodied terms, the ERB is exporting blue water and importing green water. Tables Table 4.2 and Table 4.3 show the input-output table for the ERB, and the blue-plus-green virtual water matrix of the ERB, respectively, aggregated by regions. Table 4.4 shows some socio-economic and water-related data at the sectoral level.

The five ERB regions that we take into account differ - not only by size, but also by their productive structures. Table 4.4 is useful to characterize the region, and also notes the differences between regions in the ERB. From this table, we can also conclude that crop production is the most water-dependent sector. In addition, Table A4.8 and Table A4.9 in the Annex show the number of hectares dedicated to each irrigated crop and its production, respectively. The ERB uses around 4,200 hm^3 of blue water in crop production, representing 83% of the total water withdrawals.

For irrigated crops, we calculate the embodiments per euro of final demand of blue water, green water, and value added, as can be seen in Table 4.5. From our point of view, these coefficients are significant because they include direct plus indirect effects. We focus only on irrigated crop production, because they have the highest coefficients of blue water, so they have a greater capacity to reduce or to increase the blue WF in the ERB, per euro of final demand. These capacities differ among the regions, so when we consider crops as homogeneous goods, and move final demand of crops with a high blue water coefficient to the same crop of another region that has a lower blue WF per euro of final demand, we satisfy the same final demand, but with a lower WF. As can be seen in Table 4.5, we have calculated the coefficients of blue water, green water, and value added.

Taking into account the coefficients in Table 4.5, we propose two scenarios that reallocate final demand of crops among regions. The first scenario aims to save blue water in the ERB, moving €100,000 of final demand of the crop and region that show the highest blue water coefficient to the final demand of the crop with the lowest blue water coefficient. According to our data, the ERB could save around 1 hm^3 of blue water and satisfy the same final demand. However, as can be seen in Table 4.6, this 1 hm^3 has an opportunity cost in value added terms, suggesting that we should apply other (compensatory) policies to focus on increasing value added when implementing water-saving policies. Note that we focus on the trade-offs between water savings and value added in the Ebro river basin and the spatial distribution of the impacts. For the sake of simplicity and to cover cases with reduced water-uses, in our simulations we chose a small amount of water, 1 hm^3, since it is enough to appreciate the trade-offs. In the case of a real policy, the quantities would be higher, such as 100 hm^3, 200 hm^3, and even more.

Knowledge of the trade-off between socio-economic and environmental variables is indispensable for policy makers; moreover, we consider that knowing the specific location of the impacts is also useful; more information leads to better decisions and proposals for compensatory measures. Therefore, we have developed a strategy to downscale the results at the municipal level. The downscaling process uses a matrix of percentages to estimate the allocation of the regional output. When we can allocate the output at the municipal level, we can also allocate other variables using “unit requirement vectors”. In Section 4.3.2 we show the estimations of the impacts of the scenarios proposed. Following the first scenario, saving

1 hm^3 of blue water could cost around €41,500 of value added if we look at the whole basin. However, there are municipalities that would reduce their value added by more than €30,000 (e.g., Ejea de los Caballeros, in Aragon, in scenario 1 loses €34,900 of VA) and others that would gain value added (e.g., Tudela, in Navarre, in scenario 1 gains €87,000 of VA). As expected, due to direct effects, municipalities that gain the most VA are those that grow the crops with increased final demand. The municipalities that lose the most VA are those growing the crops with decreased final demand. However, there are some municipalities that have gains, or suffer losses, that do not grow certain crops because of the indirect effects. We also show the spatial distribution of the environmental and socio-economic effects of the scenarios proposed at the municipal level, using GIS software.

These tools and results can be useful for policy makers when considering re-allocating water. The tools provided represent a contribution in themselves, since they are useful in policy analysis, and the analysis of the scenarios illustrates the utility of the tools provided in this paper, for policymakers to analyse specific areas where the effects will be felt.

We are aware of the limitations of the study, but we trust the usefulness of multiregional and multisectoral models to analyse the socio-economic and environmental effects of any policy. Moreover, the link with GIS layers allows us to study local effects. One future line of research is the proposal of more realistic scenarios and their analysis using the tools provided in this paper, evaluating not only the effects on socio-economic variables but also the specific places where the effects will be felt.

This work is extensible to other basins and provides a tool for policymakers to estimate not only socio-economic and environmental total impacts, but also where the impacts will be felt. In another future line of research, this MRIO table can be used to calibrate a computable general equilibrium (CGE) model, with which it would be possible to analyse more specific policies of change, as well as local effects. The flexibility of this kind of model also allows us to create links with a hydro-economic model, which is another future line of research.

Annex of Chapter 4

Table A4.7. Sectors in MRIO table

ISIC Rev3.1		Sector in table	
A01	(1.1) crops production irrigated crops (1.101-1.118)	1.101	Wheat
		1.102	Other Winter cereals (oats, rye, etc…)
		1.103	Corn
		1.104	Barley
		1.105	Other summer/spring cereals (sorghum, millet, etc…)
		1.106	Alfalfa
		1.107	Other fodder
		1.108	Industrial crops
		1.109	Citrus frits
		1.110	Pome fruits
		1.111	Stone fruits
		1.112	Fleshy fruits
		1.113	Dried fruits
		1.114	Legumes
		1.115	Horticulture
		1.116	Olive
		1.117	Grapevine
		1.118	Rice
	(1.1) crops production rainfed crops (1.119-1.136)	1.119	Wheat
		1.120	Other Winter cereals (oats, rye, etc…)
		1.121	Corn
		1.122	Barley
		1.123	Other summer/spring cereals (sorghum, millet, etc…)
		1.124	Alfalfa
		1.125	Other fodder
		1.126	Industrial crops
		1.127	Citrus frits
		1.128	Pome fruits
		1.129	Stone fruits
		1.130	Fleshy fruits
		1.131	Dried fruits
		1.132	Legumes
		1.133	Horticulture
		1.134	Olive
		1.135	Grapevine
		1.136	Rice
	(1.2) Livestock	1.21	Cattle
		1.22	Sheep
		1.23	Goat
		1.24	Horses
		1.25	Porcine
		1.26	Others (Rabbits, poultry)

ISIC Rev3.1	Sector in table	
A02 -A03	1.3	Forestry and logging & Fishing and aquaculture & related service activities
B & C19	2	Mining and quarrying & Manufacture of coke and refined petroleum products
D35	3	Electricity, gas, steam and air conditioning supply
C10-C12	4	Manufacture of food products, beverages and tobacco products
C13-C15	5	Manufacture of textiles, wearing apparel and leather products
C16	6	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17-C18	7	Manufacture of paper and paper products & Printing and reproduction of recorded media
C20-C21	8	Manufacture of chemicals and chemical products & Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	9	Manufacture of rubber and plastic products
C23	10	Manufacture of other non-metallic mineral products
C24-C25 & C29-C33	11	Manufacture of basic metals & Manufacture of fabricated metal products, except machinery and equipment & Manufacture of motor vehicles, trailers and semi-trailers & Manufacture of other transport equipment & Manufacture of furniture; other manufacturing & Repair and installation of machinery and equipment
C26- C28	12	Manufacture of computer, electronic and optical products & Manufacture of electrical equipment & Manufacture of machinery and equipment n.e.c.
E36-E39	13	Water collection, treatment and supply & Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
F	14	Construction
G45	15	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	16	Wholesale trade, except of motor vehicles and motorcycles
G47	17	Retail trade, except of motor vehicles and motorcycles
I	18	Accommodation and food service activities
H49-H51	19	Land transport and transport via pipelines & Water transport & Air transport
H52-H53	20	Warehousing and support activities for transportation & Postal and courier activities
K64-K66	21	Financial service activities, except insurance and pension funding & Insurance, reinsurance and pension funding, except compulsory social security & Activities auxiliary to financial services and insurance activities
L68	22	Real estate activities
J58-J63	23	Publishing activities & Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities & Telecommunications & Computer programming, consultancy and related activities; information service activities
M72	24	Scientific research and development
M69-M71 & M73-M75 & N	25	Legal and accounting activities; activities of head offices; management consultancy activities & Architectural and engineering activities; technical testing and analysis & Advertising and market research & Other professional, scientific and technical activities; veterinary activities & Administrative and support service activities
O & P & Q	26	Public administration and defence; compulsory social security & Education & Human health and social work activities
R & S & T & U	27	Other service activities & Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use & Activities of extraterritorial organizations and bodies

Table A4.8. Land use for irrigated crop production (hectares)

	Aragon	Catalonia	Navarre	Basque Country	Rioja	TOTAL
Wheat	33,872	13,787	9,274	17	3,954	62,606
Other Winter cereals	1,424	2,033	973	0	108	4,636
Corn	58,972	23,915	12,898	18	747	98,702
Barley	34,932	13,128	8,670	70	3,711	60,552
Other summer	770	0	0	0	0	862
alfalfa	69,525	0	0	14	765	70,304
Other fodder	14,557	30,108	7,566	0	253	52,686
Other industrial crops	5,175	374	1,833	66	510	8,027
citrus frits	0	9,008	0	5	0	9,049
pome fruits	7,965	0	0	5	2,832	10,952
stone fruits	21,139	0	0	1,183	1,564	23,904
Fleshy fruits	43	39,055	2,727	2,043	21	44,883
Dried fruits	3,545	3,931	830	124	553	9,208
Legumes	3,604	119	1,050	21	163	4,957
Horticulture	3,312	2,160	7,968	2	7,367	20,812
Olive	6,675	12,748	2,706	0	2,481	25,150
Grapevine	4,312	4,325	10,480	0	11,473	30,591
Rice	12,892	21,548	2,080	0	0	36,520
Total Irrigated Land	282,716	176,239	69,055	3,568	36,502	574,401

Source: own work with data from Agrarian census (INE, 2011)

Table A4.9. Irrigated crop production (,000 Euros)

	Aragon	Catalonia	Navarre	Basque Country	Rioja	TOTAL
Wheat	30,818	13,686	9,603	18	4,280	59,773
Other Winter cereals	688	1,364	666	0	81	2,843
Corn	119,246	39,519	26,566	15	1,210	191,084
Barley	26,479	12,135	6,703	54	2,837	48,234
Other summer	633	0	0	0	0	709
alfalfa	110,768	0	0	15	884	111,667
Other fodder	13,708	60,156	30,396	0	630	105,394
Other industrial crops	1,136	90	888	648	4,590	7,371
citrus frits	0	38,504	0	7	0	38,561
pome fruits	60,535	228,174	10,553	9,532	29,427	339,364
stone fruits	193,938	130,659	14,238	3,494	15,622	358,098
Fleshy fruits	0	320	6	81	0	407
Dried fruits	3,708	3,927	760	139	619	9,391
Legumes	5,003	114	1,356	15	170	6,659
Horticulture	29,385	25,415	86,344	27	75,245	216,428
Olive	5,721	13,472	3,715	0	3,260	26,771
Grapevine	6,665	12,603	20,278	0	23,960	63,506
Rice	23,245	42,013	4,512	656	0	70,427
Total Irrigated Land	631,676	622,153	216,583	14,702	162,816	1,656,688

Source: own work. Using Agrarian census (INE, 2011), Land yield from MAGRAMA, (2011) and prices from IAEST, (2013) In Figure A4.7 and Figure A4.8 Green colour depicts the areas in which the water withdrawals would decrease.

Figure A4.7. Changes in water withdrawals at the municipal level in relative terms in scenario 1

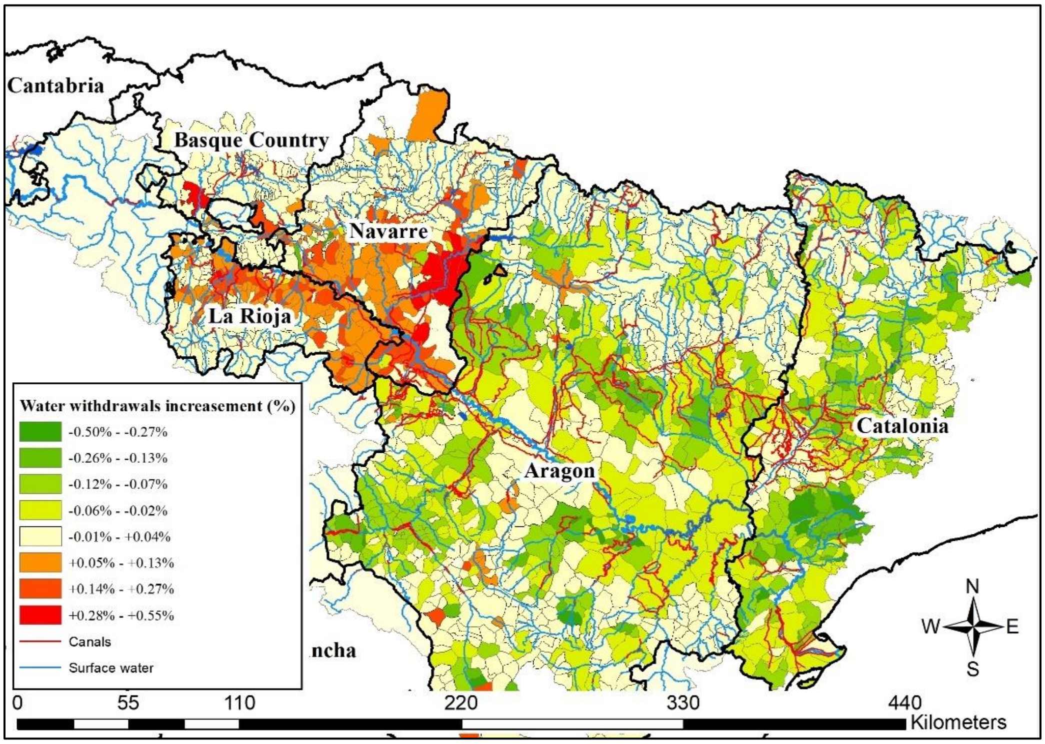
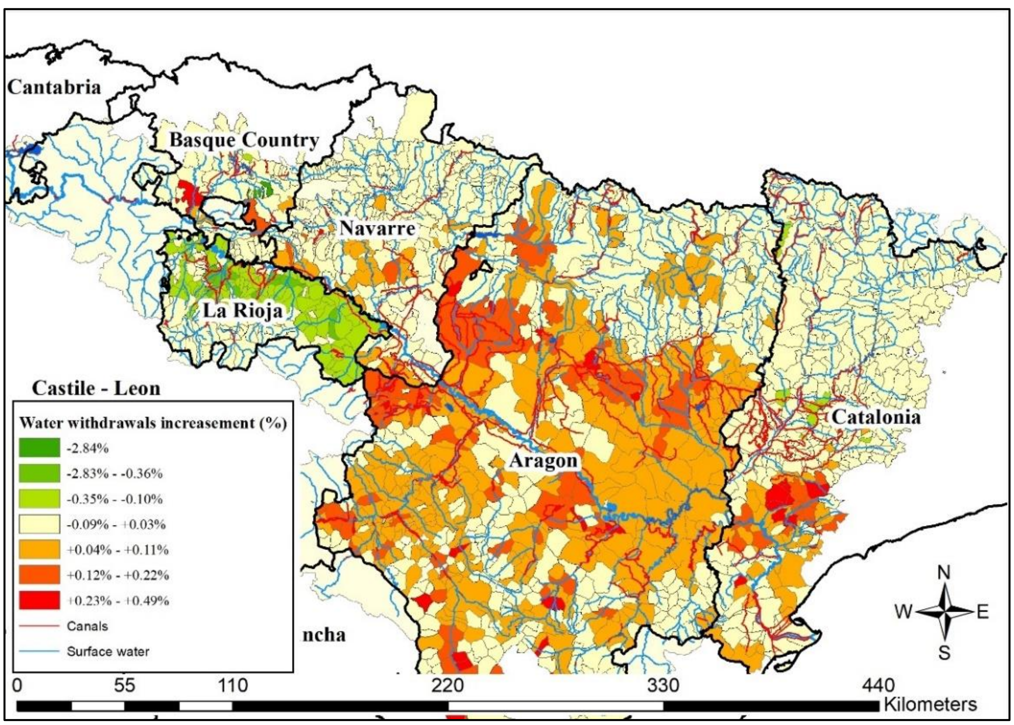


Figure A4.8. Changes in water withdrawals at the municipal level in relative terms in scenario 2



Chapter 5

An input-output and hydro-economic model to assess socioeconomic impacts

Fresh water is an essential natural resource for life but also for economic development, and its value depends on place and time (Hanemann, 2006). In this light, then, water and water management issues must be addressed in a context of temporal and spatial variability. Furthermore, the amount of water available for use at any given place and time will depend on both upstream uses and downstream commitments.

For these reasons, the next step in this thesis will be to develop a hydro-economic model for the Ebro basin that is compatible with the multi-sectoral input-output model developed in the previous chapter. Chapter 3, meanwhile, describes a simple water flow model for the lower Ebro, which confirms that the management of environmental flows in this last stretch is carried out almost entirely from Mequinenza reservoir, where the river begins its final journey down to the Delta. This model produced two key findings with regard to water uses and flows in the Ebro Basin: 1) annual flows are not representative of the problems involved in the supply of water for all uses; and 2) environmental planning is the responsibility of all agents and the entire area comprised within the river basin, and it cannot, in general, be made to depend on a single flow or reservoir.

Meanwhile, Chapter 4 develops a multiregional model of the Ebro River Basin (ERB) using the input-output framework, which covers the entire basin with the exception of certain very small regions in terms of area and/or population. As mentioned in Chapter 4, the input-output framework allows us the use of satellite accounts to link socio-economic and environmental data. However, water use data and variations due to possible shocks are not usually subject to availability restrictions in traditional input-output modelling, and even where they are, the constraints concerned do not take into account either monthly flows or flows through the territory, or indeed the resulting restrictions on water availability.

Our objective in this chapter is to link the water flow modelling methodology with the input-output framework, which would be an important scientific step insofar as no such integration has not been attempted before to the best of the author's knowledge. In this way, we will be able to analyse the successive uses of water in the geographical area studied and the water and economic dependencies that exist in the basin, and to observe the impacts of different economic activities (and therefore of consumption and exports) on the ERB's overall water system.

Linking the modelling and IO methodologies permit the inclusion of restrictions on water availability, in the multiregional model (Chapter 4), making it dependent on the monthly flows observed in the ERB, along with previous uses and environmental needs. We use monthly rather than annual water flow data because some months offset others eliminates and/or obscures many of the restrictions that actually exist, as explained in Chapter 3. This is because the commonest and most relevant bottlenecks occur month by month, or at least in periods shorter than a full year. Based on the monthly flows data, it was observed that maintaining current uses requires active management even without assuming reductions in the volume of available water. Since the problems of water availability in the Ebro basin are not due to overall annual water availability but rather by the variations in water availability over the course the year and by storage capacity, a monthly time scale was adopted for the analysis of both water flows and water demand. This captures more precisely all of the overarching economic, social and environmental relations between the regions comprised within the Ebro Basin, and their relations with the rest of Spain, the European Union and the rest of the world. This allows a more focused approach and assessment of the effects of farming and agricultural water use, which vary very significantly over the course of the year. Meanwhile, this overview should also permit a more accurate analysis of the medium- and long-term effects of climate change in the Ebro Basin.

The main results of this chapter were presented at the 27th International Input-Output (IIOA) Conference held in Glasgow in July 2019, and at the 14th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES) held in Dubrovnik in October 2019.

5.1. Geographical structure and water flows

The input-output and hydro-economic models of the ERB used in this thesis is include both hydrological and socio-economic components, physical and environmental constrains, and an optimization equation. Meanwhile, the hydrological schema used is a node-link network associated with the water flows, in which nodes represent geographical points where different flows join and/or diverge around physical units impacting the stream system, and links represent the hypothetical water stream relationship between the nodes. Since ground water is used relatively little in the ERB (CHE, 2016), we use surface water hydrological components only. The model is constrained by physical and environmental restrictions such as the water availability in each head flow, the monthly EF bounds along the river's course, and reservoir capacity levels.

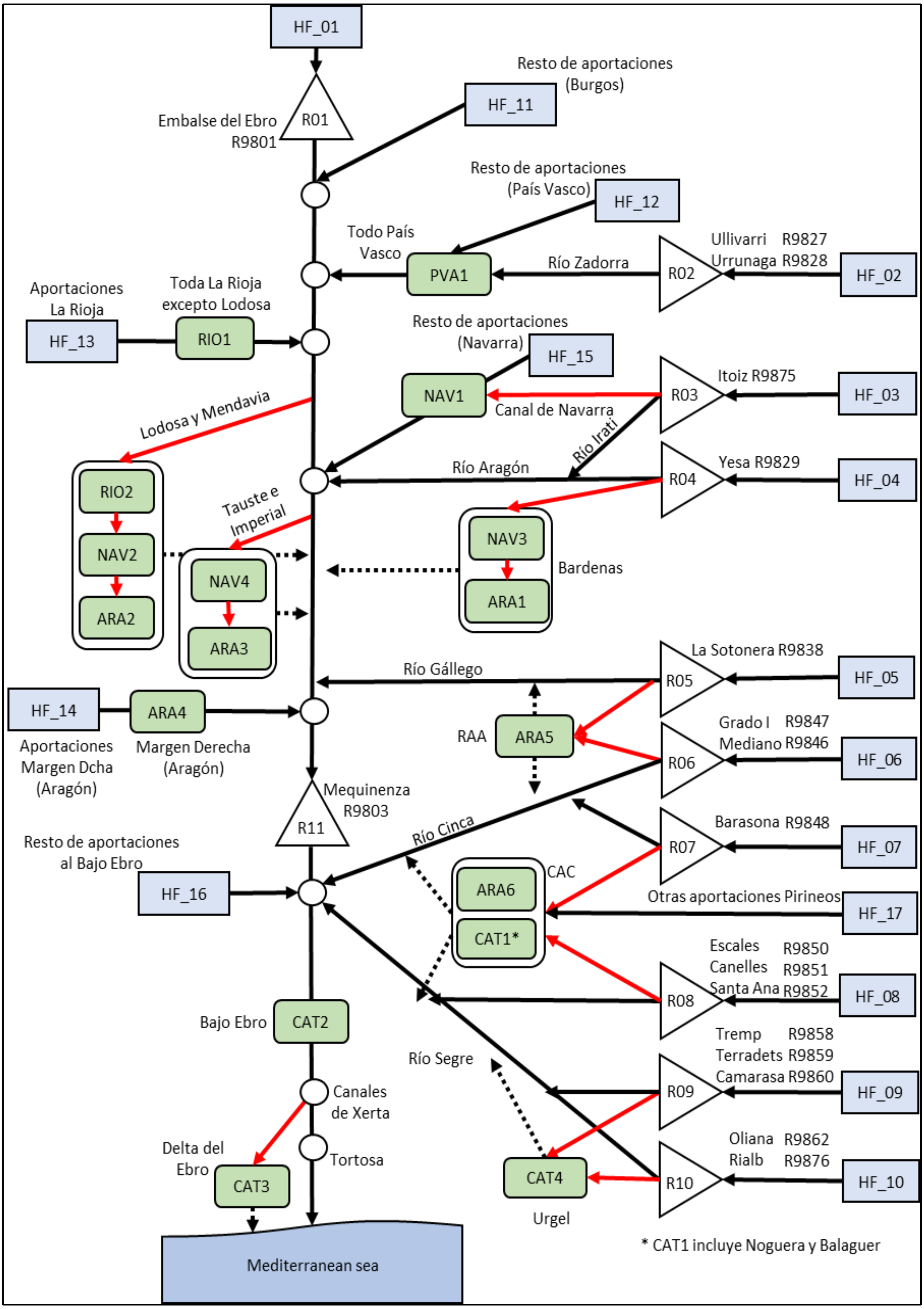
To capture the whole basin flows, the schema splits the five Autonomous Communities into 17 areas or regions in order to capture all flows throughout the whole of the river basin. These regions share common water sources (tributaries, runoff and so on) and several points of water-use, as shown in Figure 5.1. This figure depicts the ERB water flows considered in the model schematically, based on the actual surface flows presented in Chapter 1. The triangles in Figure 5.1. represent reservoirs, while the green rectangles represent areas of water use and the circles are capacity gauging stations. The black arrows represent the river's natural course and the red arrows water diversions/canals, while the dotted arrows identify water returns. These components are discussed in detail below.

5.1.1. 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, headwaters HF_05 to 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 (see also Figure 6.2 and the paragraph dealing with this reservoir in the next section), while incoming water from the Río Segre (HF_06) is stored and managed by the Grado-Mediano system of reservoirs, which together with La Sotonera supply the Riegos del Alto Aragón canals as well as downstream requirements on the Gállego and Cinca rivers.

Figure 5.1. General outline of the surface water network of the Ebro River Basin



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 to HF_10 are headwaters that directly some reservoir 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 to 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 towards 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 labelled PVA1, which comprises the entire area of the Basque Country belonging to the Ebro Basin.[8] 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 water use zone RIO1, comprising all municipalities in La Rioja except those supplied by the Lodosa Canal.

Similarly, head flow HF_14 identifies right bank contributions in Aragon (Rivers Jalón, Huerva, Guadalope and other streams.), while water use zone ARA4 groups all of

[8] Water use zones are described in section 5.1.3.

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 towards the Ebro. These contributions are treated as usable in zone NAV1 zone in Navarre.

According to 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 to 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/requirements estimates based on the irrigation land declared in the last available agricultural census (INE, 2011) and estimated 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, 2018).

5.1.2. Canals and reservoirs

The Ebro River Basin has 125 reservoirs larger than 1 Hm^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 as shown in Figure 5.1.

Reservoirs are labelled using codes along similar lines to head flows. For example, Ebro reservoir in Cantabria (assigned code 9801 in the gauging yearbook) collects water from the HF_01 head flow and it is therefore labelled 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 modelling, 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 5.1), we identify only 6 reservoirs for the province of Huesca and the Catalan Pyrenees (R05 to 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 below and represented in Figure 5.2 and Figure 5.3.

La Peña and Ardisa reservoirs are both small (capacity 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 presented in Figure 5.2, water entering reservoir R05 and leaving the Ardisa dam which does not pass Gauging Station GS9012 plus fringe water at Gauging Station GS9255. The capacity of R05 is that of La Sotonera reservoir (186 Hm^3), which is part of the "Riegos del Alto Aragón" (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.

Figure 5.2. Schema of reservoirs in Huesca province and Catalonia (Gállego, Cinca and Segre)

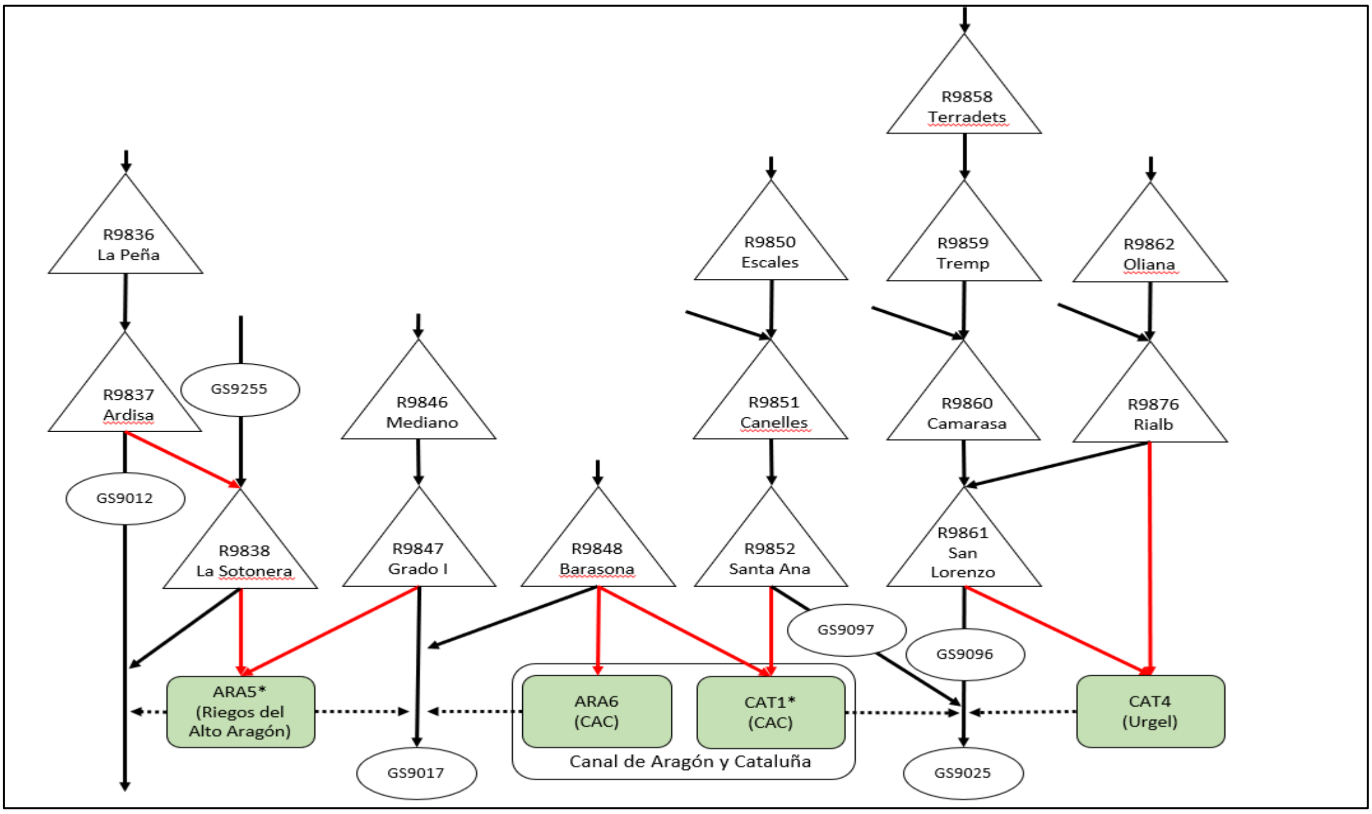
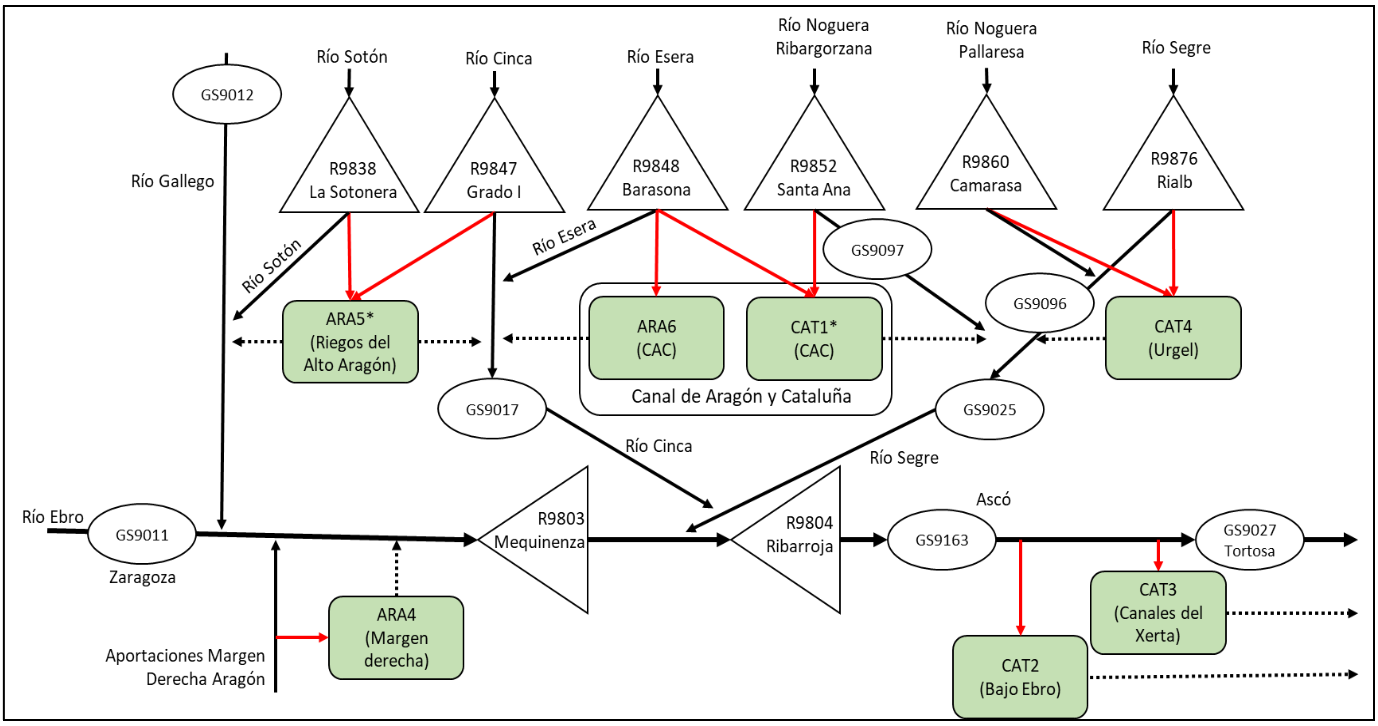


Figure 5.3. Schema of middle and lower Ebro



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.

The reservoir labelled R07 in the schema is Barasona reservoir. Together with the Noguera Ribagorzana reservoir system (Escales, Canelles and Santa Ana reservoirs) identified as R08, Barasona supplies the water used in zones ARA6 and CAT1, comprising mainly the irrigation water serving zone the users of the 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 5.1 at the Mequinenza-Ribarroja system, which does not collect any water from the Rivers Cinca and Segre, whose waters meet further downstream.

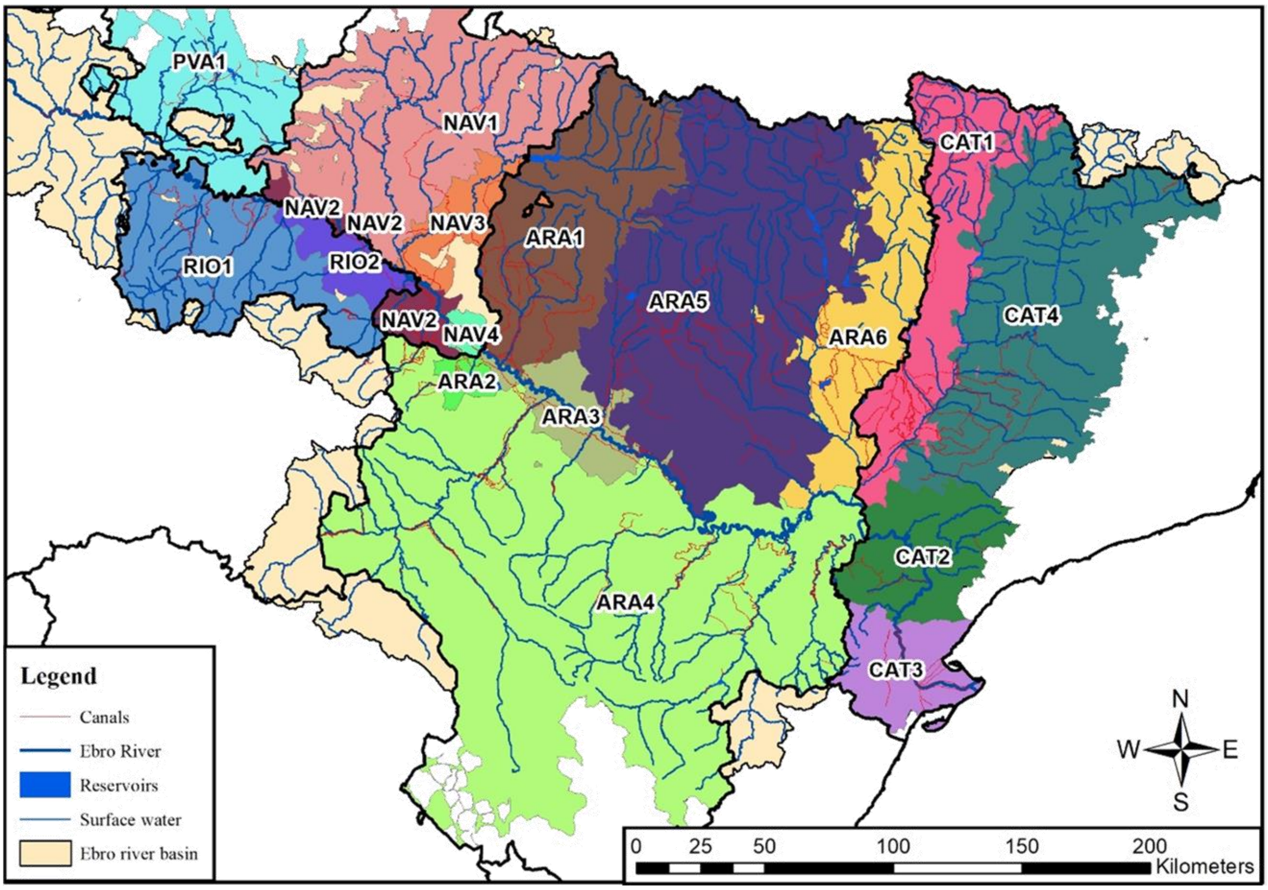
The capacity of the reservoirs in our model is the sum of the impoundment capacities they represent in reality. However, upper and lower monthly storage thresholds of 90% and 30% of capacity are also established in the model for operational (maximum level) and environmental (minimum level) reasons. Moreover,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

5.1.3. Water use zones

In terms of physical geography, the Ebro River Basin actually includes parts of 9 Autonomous Communities and 1,724 municipalities. As modelled 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 of1,480 municipalities. In order to combine the hydro-economic model with the input-output framework, meanwhile, the water zones modelled 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. The annex to Chapter 1 lists all of the municipalities modelled and the water use zones with each is associated. Meanwhile, the zones resulting from the aggregation procedure are represented in the Figure 5.4 and the key water use data for each grouping is shown in Table 5.1

Figure 5.4. Water use zones in the Ebro River Basin



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 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 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 domestic, industrial and farm use, and they 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.

Table 5.1 Consumptive water use 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 use (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	2.0
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	5135	4200	860	75.2

Source: Own work

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 are supplied by the Lodosa canal and ARA3 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 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.

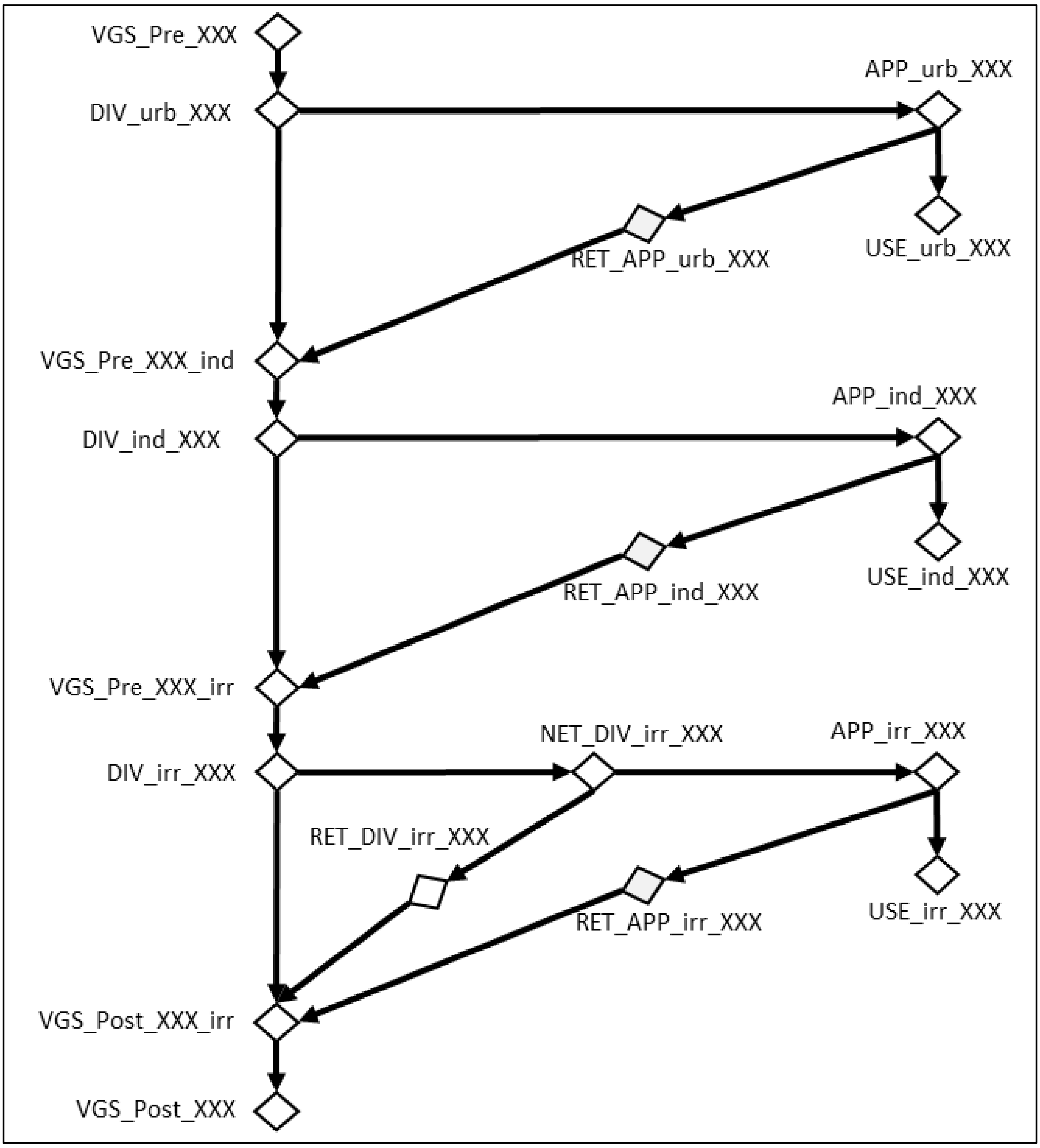
CAT1 comprises mainly the Catalan municipalities supplied by the Canal de Aragón and Catalunya and some other located further the north. CAT2 represents the Catalan municipalities downstream of the Ribarroja reservoir. CAT3 consists of the municipalities of the Ebro Delta, which are mainly supplied by 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 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 labelled RIO2.

Let us now consider the movement of water within the zones defined in the model. This is reflected schematically in Figure 5.5, 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 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, labelled VGS_post_XXX.

Figure 5.5. Schematic pattern of flows in water use zones



The water available for use in each water use zone is the sum of all water flows received from upstream (i.e. upstream flows net of water used). Figure 5.5 shows a schematized zone in which the initial node is labelled VGS_Pre_XXX, where XXX denotes the water-use zone, and the last node is labelled 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 node DIV_urb_XXX for urban use (APP_urb_XXX), while the rest flows on to 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 sub-schema is split at node APP_urb_XXX between actual consumption (USE_urb_XXX) and water returned to the river basin (RET_APP_urb_XXX) at node 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 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 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.

5.2. Hydro-economic equations

Having described the hydrological schema, let us now go on to consider the hydro-economic equations supporting the model. This discussion is divided into two subsections, the first of which explains the equations and restrictions defining the water supply conditions established in section 5.1, and the second the constraints on water demand, consisting of the different economic activities carried on and the objective function.

5.2.1. Water flow equations and environmental and physical constrains

The schematic hydrological model of the ERB is based on the principles of water mass balance and continuity of river flow, which determine the volume of water available in the different reaches of the river and water stocks held in reservoirs (equations (5.1)-(5.4)). The available water can be used for socioeconomic activities subject to the environmental restrictions established (equation (5.4)). This is formulated in general terms applicable to all nodes[9] represented in Figure 5.1 and Figure 5.5.

Specifically, equation (5.1), which represents surface flow continuity, means that the water entering a given node $w_{in_{d,m}}$ each month is the sum of all water arriving from upstream, whether its source is a head flow or other nodes. The head flows entries (HF) that appear in equation (5.1) are zero if they node in question does not have an associated head flow.

Equation (5.2) represents the available water after use and it must be positive. The water leaving nodes where there is no consumption is equal to the input water. However, the water consumed in the water use zones is subtracted at the nodes where it is used, so that the outgoing water volume represents the difference between inflows and consumption. Note that only consumptive use in Figure 5.5 occurs at nodes USE_urb_XXX, USE_ind_XXX and USE_irr_XXX.

Equation (5.3) is the mass balance equation for reservoirs, meaning that the water impoundment in the reservoirs each month is equal to the previous month's stock plus inflows, less outflows. Finally, equation (5.4) represents environmental flows. This equation applies only to the nodes for which environmental flows are defined, which are those represented in Table 5.2. These four equations determine the available water for use at the different nodes given the physical and environmental restrictions mentioned below.

$$w_{in_{d,m}} = \sum_j \beta_{j,d} w_{out_{j,m}} + HF_{d,m} \quad (5.1)$$

[9] In our modelling, the volumes of water passing from one node represent the flows of the Ebro River Basin. In reality, therefore, these nodes represent geographical areas of differing size and nature such as river stretches, reservoirs, and water use zones.

$$w_{out_{d,m}} = w_{in_{d,m}} - USE^{URB}_{d,m} - USE^{IND}_{d,m} - USE^{IRR}_{d,m} \quad (5.2)$$

$$S_{r,m} = S_{r,m-1} + \sum_j \beta_{j,r} w_{out_{j,m}} - w_{out_{r,m}} \quad (5.3)$$

$$w_{out_{d,m}} \geq E^{min}_{d,m} \quad (5.4)$$

Where $w_{in_{d,m}}$ is the water inflow at node “d” in month “m”; $w_{out_{j,m}}$ 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 $HF_{d,m}$ is the runoff entering node “d” in month “m” (head flows). Meanwhile, $USE^{URB}_{d,m}$ is the urban/domestic (drinking and sanitation) water consumed at node “d” in month “m”; $USE^{IND}_{d,m}$ is the water consumed by “other industries” (i.e. all productive activities except irrigated farming) at node “d” in month “m”; and $USE^{IRR}_{d,m}$ represents the evapotranspiration of irrigation at node “d” in month “m”. $S_{r,m}$ is the water stored at reservoir node “r” in month “m”. Finally, $E^{min}_{d,m}$ is the minimum EF established for node “d” in the month “m”.

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. Secondly, 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 (5.4) 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, 2015). Additional environmental flows equal to 25% of 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 1980-2013 data from the gauging stations yearbook. The minimum flows established for the hydrologic components of the model are shown in Table 5.2.

The first set of constraints in Table 5.2 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.

Table 5.2. Minimum flow constraints (hm^3)

Variable	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Notes
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
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

The second set of constraints 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 Canal09, 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 environmental flows. These are situated in the water use zones (3rd set of constraints) and along the river itself (4th set of constraints, represented as circles in Figure 5.1). 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.

Water use and return flow equations

The equations forming the next block (5.5)-(5.9) address the points where water is used, linking consumption to the socio-economic activities discussed in section 5.2.2. Equation (5.5) identifies the net irrigation water requirements (discounting returns) in each water use zone, $USE_{d,m}^{IRR}$, calculated as the sum of net requirements for each crop ($USE_{d,m}^{IRR,c}$). These net irrigation water requirements therefore depend on water needs per hectare of each crop 'c' in each water use zone ($Wr_{d,m}^{c}$) and the hectarage 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 returns flows, although they are omitted for simplicity's sake in Figure 5.5. This allows different ratios to be set for each crop between applied water, evapotranspiration and water returns so as to capture different efficiencies in the water use by crop.

Likewise, equation (5.6) represents the water used by the different industrial sectors of polygon 'd' in month 'm' ($USE_{d,m}^{IND}$) , which is the sum of the water used by other industries[10] "f" in zone "d" ($USE_{d,m}^{IND,f}$). This consumption depends on the water needed to produce one unit of output 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.

[10] "Industry" means all productive sectors of the economy including services, with the exception of irrigated farming.

The irrigation water requirements for each crop and their monthly distribution ($\mathrm{Wr}_{d,m}^{c}$) were estimated based on the data provided by Martínez-Cob (2004). The water requirements of other industries (Wr_{d}^{f}) were obtained from the WIOD database (Genty et al., 2012).

Equation (5.7) estimates domestic water consumption. Drinking and sanitation water in each water use zone is calculated based on a fixed coefficient per capita ($\mathrm{Wr}^{percapita}$) and the population ($\mathrm{Pop}_{d,m}^{URB}$). According to ERB data (CHE, 2015), the per capita domestic water requirement is set at 319 litres per day. Furthermore, 100% efficiency is assumed for mains transportation of both domestic and industrial water, together with returns of 80% on applied water (APP_urb and APP_ind nodes) (CHE, 2015a). Meanwhile, equations (5.8) and (5.9) establish returns on irrigation in each region ($\mathrm{RET}_{d,m}^{IRR}$) as the sum of returns on each irrigated crop ($\mathrm{RET}_{d,m}^{IRR,c}$) and returns from industry ($\mathrm{RET}_{d,m}^{IND}$) as the sum of returns from each individual industry ($\mathrm{RET}_{d,m}^{IND,f}$). The model does not take account of specific situations involving the reuse of irrigation returns, and this consumption is included in general uses.

$$\mathrm{USE}_{d,m}^{IRR} = \sum_c \mathrm{USE}_{d,m}^{IRR,c} = \sum_c \mathrm{Wr}_{d,m}^{c} * \mathrm{h}_{d}^{c} \tag{5.5}$$

$$\mathrm{USE}_{d,m}^{IND} = \sum_f \mathrm{USE}_{d,m}^{IND,f};\ \mathrm{USE}_{d,m}^{IND,f} = \frac{\mathrm{Wr}_{d}^{f} * \mathrm{Q}_{d}^{f}}{12} \tag{5.6}$$

$$\mathrm{USE}_{d,m}^{URB} = \mathrm{Wr}_{d,m}^{percapita} * \mathrm{Pop}_{d,m}^{URB} \tag{5.7}$$

$$\mathrm{RET}_{d,m}^{IRR} = \sum_c \mathrm{RET}_{d,m}^{IRR,c} \tag{5.8}$$

$$\mathrm{RET}_{d,m}^{IND} = \sum_f \mathrm{RET}_{d,m}^{IND,f} \tag{5.9}$$

5.2.2. Behavioural functions for economic activities and objective function

As explained above, consumptive water demand by region is subdivided into three categories in the model, comprising irrigation, other industrial uses and other domestic uses. Let us begin with the equations describing the economic behaviour of irrigation water use and then go on to discuss other industrial and domestic use. For the sake of simplicity, it will be assumed that the value of one unit of any good or service is one euro so as to extract the maximum socio-economic data from the MRIO table for the ERB explained in the previous chapter.

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” $\left(\phi_{i,c}^{r,d}\right)$, are constant and can be obtained from the ERB input-output table. Hence, the non-labour cost per hectare (ϕ_c^d) is also constant. See equation (5.10).

$$\phi_{i,c}^{r,d} = \frac{x_{i,c}^{r,d}}{h_c^d} \quad ; \quad \phi_c^d = \frac{\sum_r \sum_i x_{i,c}^{r,d}}{h_c^d} \tag{5.10}$$

Where $x_{i,c}^{r,d}$ is the annual demand from farmers growing crop ‘c’ in ‘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 the zone ‘d’. ϕ_c^d is the annual cost per hectare of crop ‘c’ in the zone ‘d’. This information is obtained directly from or is compatible with the MRIO built for modelling purposes.

A decreasing irrigation production function is proposed in line with the usual approach taken in the literature, 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 equation (5.11)), 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 equation (5.11). Wages are included in profits.

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

$$\psi_c^d = \beta_0^{c,d} + \beta_1^{c,d} h_c^d \tag{5.11}$$

$$\pi_c^d = \left(\psi_c^d - \phi_c^d\right) h_c^d \tag{5.12}$$

The objective function of the model is to maximise farm profits on all irrigated crops in the river basin $\left(\text{Max: } \sum_d \sum_c \pi_c^d\right)$ as a proxy for the maximization of value added subject to the relationships and constraints mentioned above. The value added by other activities was not included.

Equation (5.13) 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 obtained from the multirregional table described in Chapter 4.

$$\pi_f^d = Q_f^d - \sum_r \sum_i x_{i,f}^{r,d} \tag{5.13}$$

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

An economic optimization process is assumed to take place in all industries before and after a possible shock, as specified in the balance requirement of the multi-regional table. This represents a general balance and it therefore optimizes the well-being of the different agents concerned. This approach was adopted so as not to complicate the process of estimating and adjusting the various scenarios unnecessarily, although it is the author's intention to address the full integration of the water and multi-sectoral models in the future, incorporating changes in the yield of all activities associated with water availability. By way of example, if a water scarcity event were to reduce the water available for irrigation by h%, domestic water and industrial water availability would also fall by s%, which would undoubtedly be less than h%.

The general model (hydrological model plus MRIO table) accounts for all water uses and requires that the equilibrium conditions of the multiregional model be verified before and after simulations. As we may recall, the coefficients representing the blue water requirement per unit of output of each sector were calculated in the previous chapter. Also, the annual output in each zone in each activity multiplied by these coefficients are the annual blue water withdrawals (see equation (5.6)). Meanwhile, water withdrawals for domestic uses will depend on the population of each region (equation (5.7)), and the population will in turn depend on jobs (equation (5.14)). A fixed ratio is assumed between employment and population in each water use zone.

$$Pop_{d,m} = \alpha_d E_d = \alpha_d \sum_f E_f^d + \alpha_d \sum_c E_c^d \tag{5.14}$$

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 and industrial employment conditions the population settled each region and district. Population data were obtained from INE (2018), and employment data were obtained from various regional input-output tables (Eustat, 2015; IAEST, 2016; IdesCat, 2012; IELR, 2011; IEN, 2011). The employment data used match the data appearing in the multiregional table constructed in Chapter 4.

5.3. Input-Output framework and socioeconomic impacts

5.3.1. Adaptation of the multiregional model to the zone structure

The regional input-output table for the Ebro Basin described in Chapter 4 has five main regions and is weighted by a matrix at the municipal level. However, none of the information it contains fits the water use zones defined in the hydrological model. Therefore, before calculating the integrated model, it will be necessary to move from a matrix comprising the 5 regions of the ERB to one including all 17 zones included in the hydro-economic model.

Matrix **M** (see section 4.2.3) contains the sectoral weightings of the 428 industries included in the MRIO built in Chapter 4 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 were aggregated based on the definition of the zones (data on the 1,480 municipalities and the associated zones will be found in the Annex to Chapter 1) in order to obtain 17 vectors**,** one for each zone, representing the associated sectoral weightings, which we will call ($\mathbf{s^r}$) **(** 1x428**)**, where the super-index 'r' denotes the zone in question. Three additional vectors were then added to the initial 17 to represent the rest of Spain, the European Union, and the rest of the world. These are weightings used to distribute the data contained in the MRIO for the Ebro Basin described in Chapter 4.

The matrices $\mathbf{Z^{rs}}$**(428x428)**, which represent the inter-sectoral trade between zones "r" and "s", were obtained from equation (5.15). These sub-matrices make up the matrix of intermediate inputs **Z (8560x8560)**. In equation (5.15), **Z (428x428)** is the matrix of intermediate inputs in the Ebro Basin, $\mathbf{\hat{s}^r}$ is the diagonal vector of weightings for region 'r' and $\mathbf{\hat{s}^s}$ is the diagonal vector of weightings for region 's'. A similar method applying the relevant percentages is applied to allocate vectors (output, value added, taxes, employment, etc.) and obtain the final demand matrix:

$$\mathbf{\hat{s}^r Z \hat{s}^s = Z^{rs}} \ ; \ \mathbf{\hat{s}^r Y = Y^r} \qquad (5.15)$$

The application of this equation or distribution method to the rows and columns of the multiregional input-output table for the ERB provides an initial approximation, which implies the assumption 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 or Catalonia).

5.3.2. Direct and indirect impacts on socioeconomic variables

Having rendered the multi-regional model compatible with the hydro-economic model, we may now the estimation of impacts using the integrated model. For the sake of brevity, let us focus on how to obtain the relevant changes in outputs.

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 multi-regional input-output table denoted by $\mathbf{T_0}$**,** which represents an I-O type general equilibrium. These variables verify the fundamental relationships of the model:

$$\begin{gathered}\mathbf{x_0} = \mathbf{A_0} + \mathbf{y_0} \leftrightarrow \mathbf{x_0} = (\mathbf{I} - \mathbf{A_0})^{-1}\mathbf{y_0} \\ (1,1,\ldots,1)\,\mathbf{v_0}\,\hat{\mathbf{x}}_\mathbf{0} = \mathbf{y_0}\,(1,1,\ldots,1)^\mathbf{T}\end{gathered} \tag{5.16}$$

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 **x** for irrigation, which will in turn lead to associated changes in value added , in the hectarage planted 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 (equation (5.17)). 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 output (equation (5.18)), so that the new matrix of technical coefficients $\mathbf{A_1}$ can be obtained.

$$a_{i,j,1}^{r,s} = a_{i,j,0}^{r,s}\,\frac{x_{j,0}^{s}}{x_{j,1}^{s}}\,\frac{h_{j,1}^{s}}{h_{j,0}^{s}}\;;\;\forall\, j \in c \tag{5.17}$$

$$a_{i,j,1}^{r,s} = a_{i,j,0}^{r,s}\;;\;\forall\, j \notin c \tag{5.18}$$

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 multi-regional model $\mathbf{T_1}$, which must verify the following basic relationships (equation (5.19)).

$$\mathbf{x_1} = \mathbf{A_1} + \mathbf{y_1} \leftrightarrow \mathbf{x_1} = (\mathbf{I} - \mathbf{A_1})^{-1}\mathbf{y_1}$$
$$(1,1,\dots,1)\,\mathbf{v_1}\,\hat{\mathbf{x}}_\mathbf{1} = \mathbf{y_1}\,(1,1,\dots,1)^\mathbf{T} \quad (5.19)$$

If the two equilibriums, $\mathbf{T_0}$ and $\mathbf{T_1}$, are known, we can obtain

$$\Delta\mathbf{x} = \mathbf{x_1} - \mathbf{x_0};\ \Delta\mathbf{A} = \mathbf{A_1} - \mathbf{A_0};\ \Delta\mathbf{y} = \mathbf{y_1} - \mathbf{y_0};\ \Delta\mathbf{v} = \mathbf{v_1} - \mathbf{v_0} \quad (5.20)$$

This would allow calculation of the impacts on the integrated model, which clearly have a dual origin, to wit changes in intermediate inputs in the irrigation sector and the shift in income from irrigation. This means that we can analyse the outcome as a double impact, one associated with changes in the intermediate inputs required for irrigation and other caused by a demand shock.

Equations (5.16), (5.19) and (5.20) support this, showing that:

$$\mathbf{x_1} = \mathbf{A_0}\,\mathbf{x_1} + \Delta\mathbf{A}\,\mathbf{x_1} + \mathbf{y_1} \leftrightarrow \mathbf{x_1} = (\mathbf{I} - \mathbf{A_0})^{-1}\,(\Delta\mathbf{A}\,\mathbf{x_1} + \mathbf{y_1}) \quad (5.21)$$

$$\Delta\mathbf{x} = \mathbf{x_1} - \mathbf{x_0} = (\mathbf{I} - \mathbf{A_0})^{-1}\,(\Delta\mathbf{A}\,\mathbf{x_1} + \mathbf{y_1}) - (\mathbf{I} - \mathbf{A_0})^{-1}\mathbf{y_0}$$
$$= (\mathbf{I} - \mathbf{A_0})^{-1}\,(\Delta\mathbf{A}\,\mathbf{x_1} + \Delta\mathbf{y}) \quad (5.22)$$

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[11].

Given the relations defining the new balance $\mathbf{T_1}$, we may now obtain the vectors $\mathbf{x_1}$ and we $\mathbf{y_1}$. Based on (5.22) we can obtain the following expression,

$$\Delta\mathbf{x} = [\mathbf{I} - (\mathbf{I} - \mathbf{A_0})^{-1}\Delta\mathbf{A}]^{-1}\,(\mathbf{I} - \mathbf{A_0})^{-1}[\,\Delta\mathbf{A}\,\mathbf{x_0} + \Delta\mathbf{y}] \quad (5.23)$$

This shows that increases in output for each new scenario simulated will also depend on 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

[11] As Dietzenbacher (2005) argues in his reply to Oosterhaven and Stelder, impacts of this kind can be likened to changes in final demand equal to the corresponding changes in output.

the way in which these reductions are transmitted to demand that is important[12]. This process depends on the social and institutional framework, and it should not be ignored or played down. Let us assume a very simple dependency (though more complex options are possible) and, returning to equation (5.19), represent the economy in the form of two blocks, irrigation and other sectors. This representation is shown in Figure 5.6 and represented by equations (5.24) and (5.25), which describe the new equilibrium after the water shock simulation, where irrigation is denoted by subscript 1 and other industries by subscript 2.

Figure 5.6. Reorganized structure of input-output table

$\mathbf{A_{11}\hat{z}_1}$	$\mathbf{A_{12}\hat{z}_2}$	$\mathbf{Y_1}$
$\mathbf{A_{21}\hat{z}_1}$	$\mathbf{A_{22}\hat{z}_2}$	$\mathbf{Y_2}$
$\mathbf{v_1'\hat{z}_1}$	$\mathbf{v_2'\hat{z}_2}$	

$$\mathbf{z_1} = \mathbf{A_{11}z_1} + \mathbf{A_{12}z_2} + \mathbf{y_1} \tag{5.24}$$

$$\mathbf{z_2} = \mathbf{A_{21}z_2} + \mathbf{A_{22}z_2} + \mathbf{y_2} \leftrightarrow \mathbf{z_2} = (\mathbf{I} - \mathbf{A_{22}})^{-1}(\mathbf{A_{21}z_1} + \mathbf{y_2}) \tag{5.25}$$

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). Therefore, $\mathbf{y_2}$ is the final demand observed in the initial input-output table proportionally reduced by the percentage fall in farm incomes. In this light, equation (5.25) can be applied to calculate the output of this scenario for all non-irrigated activities $\mathbf{z_2}$.

Once we know $\mathbf{z_2}$, equation (5.24) obtains $\mathbf{y_1}$, so that the equilibrium is completely determined. In this equilibrium, meanwhile, the value added by irrigation will always be $\mathbf{v_1'z_1}$, irrespective of the institutional criterion have chosen to determine $\mathbf{y_2}$.

5.3.3. Downscaling and depicting results with GIS

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

[12] Knowledge of the elasticities of goods and farm incomes would allow this gap to be bridged.

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

As in Chapter 4, these percentages were used to obtain matrix $\mathbf{M}$ (1480x8560), 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 matrix $\mathbf{M}$, equation (5.26) can be calculated to determine, gross output per industry at the municipal level, $\mathbf{X_m}$ (1480x8560). Meanwhile, equation (5.27) allocates socioeconomic variables at the municipal level, $\mathbf{v_m}$.

$$\mathbf{X_m} = \mathbf{M}(\mathbf{I}-\mathbf{A})^{-\mathbf{1}}\hat{\mathbf{y}} = \mathbf{ML}\hat{\mathbf{y}} \tag{5.26}$$

$$\mathbf{v_m} = \mathbf{M}\hat{\mathbf{v}}\hat{\mathbf{x}}^{-\mathbf{1}}\mathbf{Ly} \tag{5.27}$$

Where $\hat{\mathbf{y}}$ is the final demand vector and its hat denotes a diagonalized vector is diagonalized, which is a common feature of input-output frameworks; $\mathbf{L} = (\mathbf{I}-\mathbf{A})^{-\mathbf{1}}$ is the Leontief inverse; $\mathbf{M}$ (1480x8560) is the municipal allocation matrix; $\mathbf{X_m}$ (1480x8560) 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; $\mathbf{v}$ is a generic vector containing the socioeconomic data examined (value added, jobs, blue water, etc.); and $\mathbf{v_m}$ is the column vector (1480x1) reflecting the value of the variable at the municipal level.

5.4. Scenarios and Results

The following discussion describes three scenarios in order to demonstrate the combination of the hydro-economic models with the input-output framework. In the first (S1), the inflows of water into the basin are set at a level equal to a year made up of the median monthly inflows for each head flow based on the monthly observations from October 1980 to September 2013). This median water year results in an annual inflow of 11,495 Hm^3. The monthly inflows are presented in the Table 5.3. Meanwhile, the environmental flows for the whole basin are set at 25% of the median upstream flow (25% of the sum of all upstream headwaters in a median water year).

Given the nature of this scenario, the situation it reflects is close to what might be expected month by month in reality, and it is therefore more representative than the calibration scenario, which is based on actual water conditions in 2010, a year with above-average water availability. Meanwhile, environmental flows were set at 25% of the sum of the median upstream water, which raises the environmental requirements applicable throughout the entire catchment area to a similar level to the environmental requirements imposed in the Ebro Delta.

In S1, maximizing the value added by irrigated through the water 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 uses observed in 2010, which clearly are the same as in S1, as shown in Table 5.4. The other two scenarios are explained below.

Table 5.3. Water inflows in Scenario 1 (hm^3)

	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	14.0	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	309.0
HF_03	1.2	18.9	48.6	62.8	51.0	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	111.0	134.5	157.3	131.0	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	312.0
HF_06	66.7	110.5	97.0	67.4	55.9	70.0	92.2	168.1	184.5	161.0	71.1	42.4	1,186.8
HF_07	35.9	51.6	39.3	30.9	23.5	55.0	53.3	80.5	99.5	65.3	30.9	16.9	582.6
HF_08	22.0	30.8	41.0	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	35.0	40.0	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	-14.0	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	54.0	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	135.0	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	113.0	44.3	32.8	-13.0	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	1,372.0	1,494.5	947.6	458.3	332.6	11,494.8

Table 5.4. Consumptive water uses in Scenario 1 (hm^3)

Zone	Domestic	Industrial	Irrigation	Total
ARA1	0.7	22.5	314.0	337.3
ARA2	0.1	3.3	13.3	16.6
ARA3	21.0	138.3	158.7	318.0
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	76.0	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	119.0	344.8	468.7
NAV1	12.2	82.9	60.9	156.0
NAV2	1.4	11.6	111.5	124.4
NAV3	0.5	9.3	87.5	97.4
NAV4	0.3	4.7	35.0	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	4,229.0

5.4.1. Scenario 2

Having defined the comparative framework (S1), let us examine the effects of an increase in ecological flows at all points to 50% of the natural flow in a median water year. This is the second scenario (S2), which implies, at least, an equal distribution between consumptive uses and environmental uses because at least 50% of the water entering the river upstream of every control point in the river basin each month is reserved as environmental flow. Since the median annual flow is 11,495 Hm^3 (Table 5.3), the volume required at the Ebro Delta in this scenario is 5,747 Hm^3, leaving another 5,747 Hm^3 available for consumptive use, which is 1,517 Hm^3 higher than the 4,230 Hm^3 of consumptive use found in the base scenario (Table 5.4). As may be observed in Table 5.5, however, consumptive use actually falls by 341 Hm^3 to 3,888 Hm3 in this scenario (S2). This table also shows that the increase in environmental flows imposes a restriction on consumptive use for irrigation, which would imply the loss of more than 6,500 jobs and value added worth almost €250 million in the economy as a whole. These findings are obtained in two stages, first from the hydrological part of the model, which reflects impacts on irrigation in the ERB, and second as a result of the recalculation of the multi-sectoral and multiregional equilibrium applying the procedures described above.

Table 5.5. Changes in VA and jobs in S2 at the level of the Autonomous Communities

	All Sectors				Irrigated farming					
	VA (,000 €)	Emp. (jobs)	VA %	Emp. %	VA (,000 €)	Emp. (jobs)	VA %	Emp. %	Water Hm^3	Water %
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	-2.00%
Navarre	-2,409	-43	-0.015%	-0.016%	-465	-11	-0.18%	-0.18%	-1	-0.30%
Basque C.	-1,117	-21	-0.012%	-0.012%	0	0	0.00%	0.00%	0	0.00%
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 %. RSP = Rest of Spain, REU = Rest of European Union, ROW, Rest of World

If we look only at the ERB, the impact is just over €190 million in terms of value added and involves the destruction of more than 4,500 jobs. These losses are concentrated in particular in Aragon and Catalonia. In percentage terms, Aragon suffers by some way the greatest impact, losing just under 0.5% of value added and just 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 the continual increases in minimum flows required at each control point along the river.

The impact on irrigated farming is shown on the right of the table. As can be seen, this effect is much larger in percentage terms, and Aragón once again stands out, losing value added worth almost €80 million and more than 2,000 primary sector 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 euros 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 in 130 jobs, a loss that is actually worse than Catalonia's in percentage terms. Finally, in irrigated farming in Navarre suffers relatively little and the Basque Country comes off entirely unscathed because it has no irrigated farm sector.

Finally, the last two columns of the table show the impact on water consumption in each region in this scenario. Once again, Aragón suffers by far the biggest impact with a reduction of nearly 300 Hm^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 Hm^3 or 2% of its total water use. Finally, irrigation water use in La Rioja shrinks by almost 7%, although this is only 16 Hm^3 in absolute terms.

As explained in Chapter 4, aggregate results may understate the local impacts of policy initiatives. To prevent this, a strategy was developed to estimate effects at the municipal level, as explained in section 5.3.3. Given the significant geographic component of such local effects, they are shown graphically the better to reflect the areas impacted. Values of less than 1% are omitted.

Figure 5.7 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 may 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, 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 5.7 shows that local losses are almost 30% in some rural municipalities with a very agrarian economy. Figure 5.8 shows job losses in scenario 2 compared to the benchmark scenario. Again, the municipalities with the highest job losses largely overlap with those suffering the sharpest falls in value added, and even the percentages.

Figure 5.7. Changes in VA in Scenario 2 (all sectors)

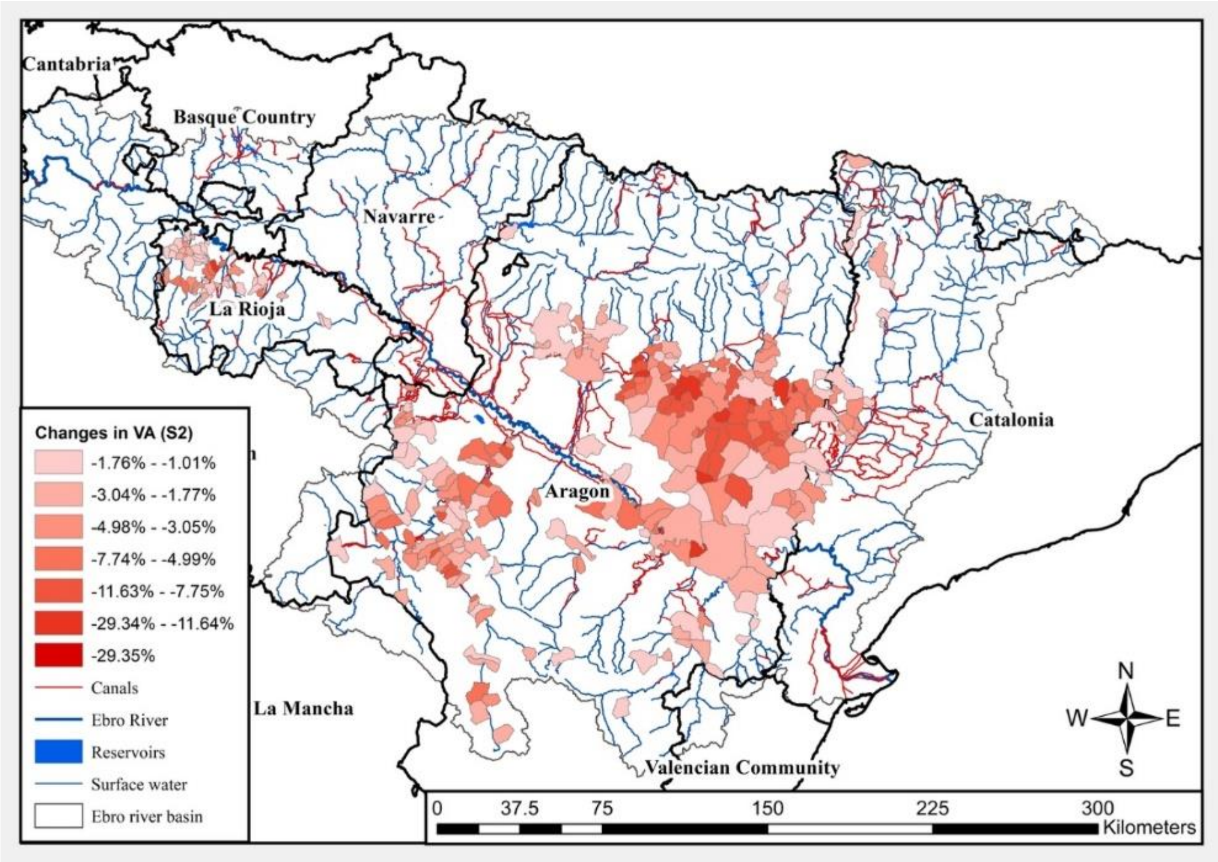
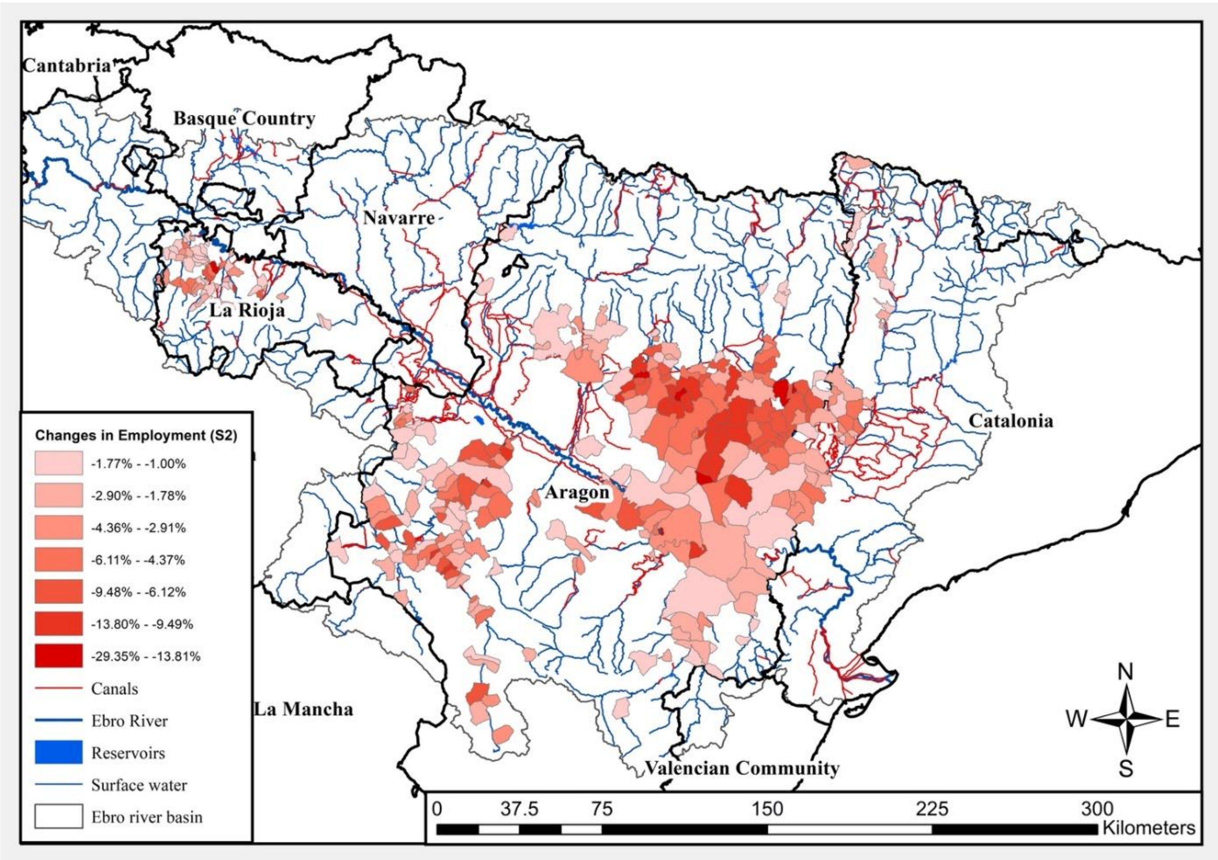


Figure 5.8. Changes in employment in Scenario 2 (all sectors)



Having established the overall economic impact at the municipal level (taking into account all sectors), let us now consider how this scenario would impact irrigation in each municipality. Figure 5.9 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 in the previous paragraph.

For the sake of simplicity, this discussion will focus on the aggregate value added and employment destroyed in irrigated farming. However, the individual results of the model for each municipality and activity are provided in Table A4.7, which could be used to calculate the distribution of individual impacts on each crop or activity.

Aside from socio-economic impacts, Figure 5.9 shows the areas where the pressure on water resources is greatest and water management options would not be sufficient to meet demand in the baseline water use scenario constructed using observations for 2009-2010. Figure 5.9 thus reveals which areas would be forced to cut their production of irrigated crops and by how much. As may be observed, pressure on water resources is higher than in the rest of the Ebro Basin in practically in the whole 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 consumptive uses observed in 2010 under the conditions set forth in this scenario, and it is therefore safe to say that resource pressure is less in these areas. Consumptive uses at the level of water use zones and the differences with the scenario S1 are presented in Table 5.6, which reveals that water use zones that would suffer the most from the imposition of an ERB-wide 50% environmental flow requirement as posited in this scenario would be ARA4, ARA5, ARA6, CAT1 and RIO1.

Figure 5.9. Changes in VA from irrigated farming - Scenario 2

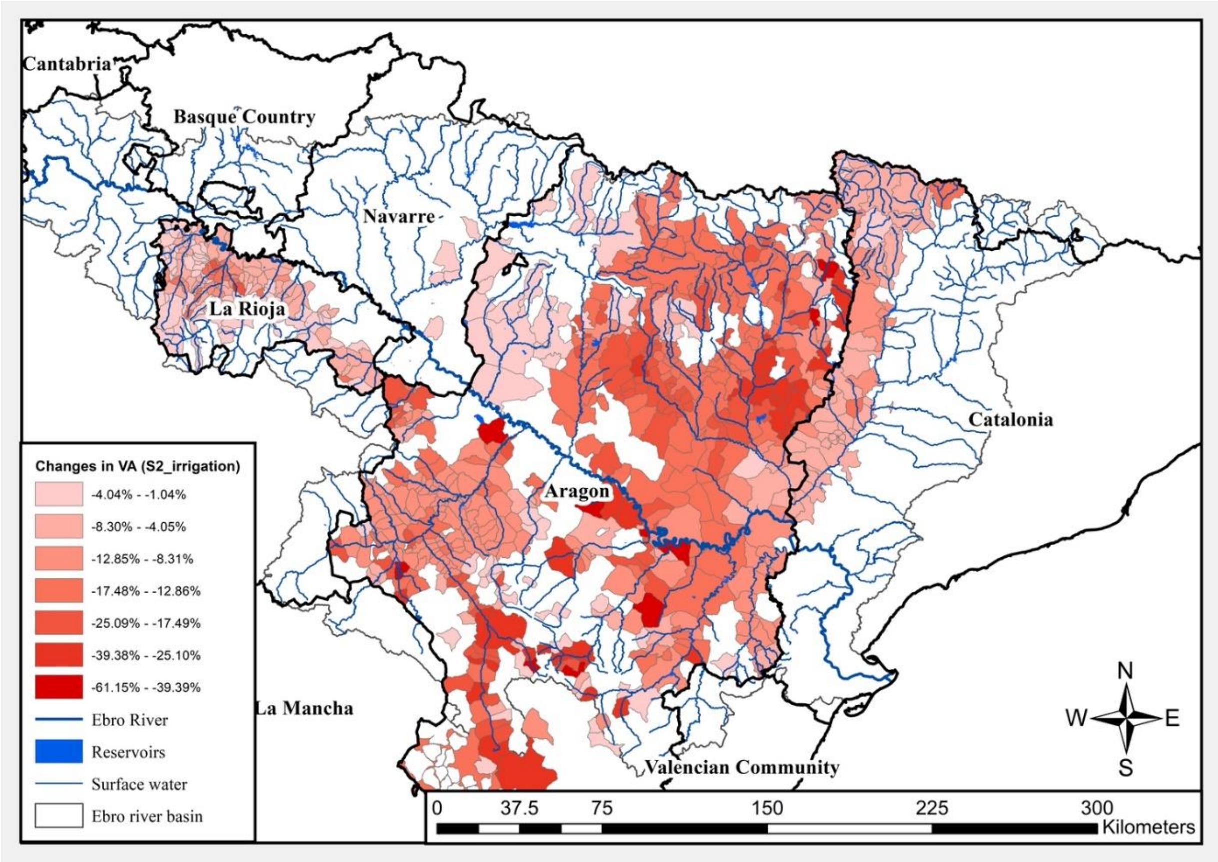


Table 5.6. Water used (consumptive uses) in Scenario 2 (hm3)

Zone	urban	Industrial	Irrigate	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	0%
ARA3	21.0	138.3	158.7	318.0	0.0	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	76.0	260.2	343.3	-27.1	-7.31%
CAT2	0.5	9.2	79.9	89.5	0.0	0%
CAT3	2.7	40.4	380.3	423.4	0.0	0%
CAT4	4.9	119.0	344.8	468.7	0.0	0%
NAV1	12.2	82.9	60.9	156.0	0.0	0%
NAV2	1.4	11.6	111.5	124.4	0.0	0%
NAV3	0.5	9.3	86.2	96.1	-1.2	-1.28%
NAV4	0.3	4.7	35.0	39.9	0.0	0%
PVA1	7.2	101.5	27.1	135.8	0.0	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	0%
Total	75.1	860.3	2,952.8	3,888.1	-340.9	-8.06%

5.4.2. Scenario 3

The third scenario (S3) proposed refers to 2004-2005, a drought year in which farms suffered badly. The water inputs from HF_01 - HF_10 used in this scenario were extracted from the gauging yearbook (MAPAMA, 2016b) for . The rest of the head flows (HF_11 - HF_17) were assumed to vary in line with the proportional variation in the sum of head flows HF_01 – HF_10 compared with the calibration year. The monthly distribution of the head flows used in S3 results in a total annual inflow of 8,981 Hm^3 as shown in Table 5.7, significantly less than the annual median water year inflow of 11,495 Hm^3. Though it might at first sight appear that this water availability would be enough in annual terms to meet environmental flow requirements and satisfy the consumptive uses observed in 2010, this is not actually the case in view of the monthly data, which are fundamental for the study of all agricultural activities. In this scenario, we keep the environmental flow requirement established in Scenario 1 (25% of incoming upstream flow in a hypothetical year made up of median months).

Table 5.7. Water inflows in Scenario 3 – 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	1045	840	1,077	1,204	656	270	203	8,971

The results of the model, aggregated by Autonomous Community, are shown in Table 5.8. The first 4 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 irrigation, revealing much larger impacts in relative terms in Aragon (30%) and Catalonia (12%). The overall reduction in water use totals 835 Hm^3, mainly concentrated in Aragon.

The areas affected in the first instance by the conditions of Scenario 3 can be identified via Table 5.9, which shows consumption 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). 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 in RIO1 (La Rioja), clearly due reduced availability. The last column of Table 5.9 shows a steep fall in water use in percentage terms, particularly 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).

Table 5.8. Changes in VA and jobs in S3 at the level of the Autonomous Communities

	All Sectors				Irrigation					
	VA (,000 €)	Emp. (jobs)	VA %	Emp. %	VA (,000 €)	Emp. (jobs)	VA %	Emp. %	Water Hm^3	Water %
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 C.	-2,422	-46	-0.026%	-0.026%	0	0	0.00%	0.00%	0	0.00%
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								

Table 5.9. Water used (consumptive uses) in Scenario 3 (hm^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	0%
ARA3	21.0	138.3	158.7	318.0	0.0	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	284.0	-11.3	-3.81%
CAT1	7.0	76.0	166.4	249.3	-94.0	-27.38%
CAT2	0.5	9.2	79.9	89.5	0.0	0%
CAT3	2.7	40.4	380.3	423.4	0.0	0%
CAT4	4.9	119.0	344.8	468.7	0.0	0%
NAV1	12.2	82.9	60.9	156.0	0.0	0%
NAV2	1.4	11.6	111.5	124.4	0.0	0%
NAV3	0.5	9.3	81.4	91.3	-4.8	-5.01%
NAV4	0.3	4.7	35.0	39.9	0.0	0%
PVA1	7.2	101.5	27.1	135.8	0.0	0%
RIO1	5.8	55.1	62.7	123.6	-4.0	-3.14%
RIO2	1.7	13.8	67.5	83.1	0.0	0%
Total	74.8	860.3	2,459.3	3,394.4	-493.7	-12.70%

Let us now focus on the spatial distribution of the decline in value added and job losses represented in Figure 5.10 and Figure 5.11 respectively, which outline 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, 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 losses of up to 50% in value added and/or employment. We also see sharp falls in value added and jobs in some municipalities in the north-east 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.

Figure 5.12 presents changes in the value added by irrigated farming only. The impact on the municipalities of the Basque Country is zero, and likewise in Navarre except for the municipalities served by the Bardenas canal, which sustain a fall of less than 10% in the value added by irrigated farming, a percentage similar to the loss of value added observable in La Rioja. In contrast, the Aragonese and Catalan municipalities associated with the Aragón y Catalunya Canal are generally severely hit by the conditions of water scarcity posited in S3, suffering steep falls in the value added generated by irrigation.

Figure 5.10. Changes in VA in Scenario 3 (All Sectors)

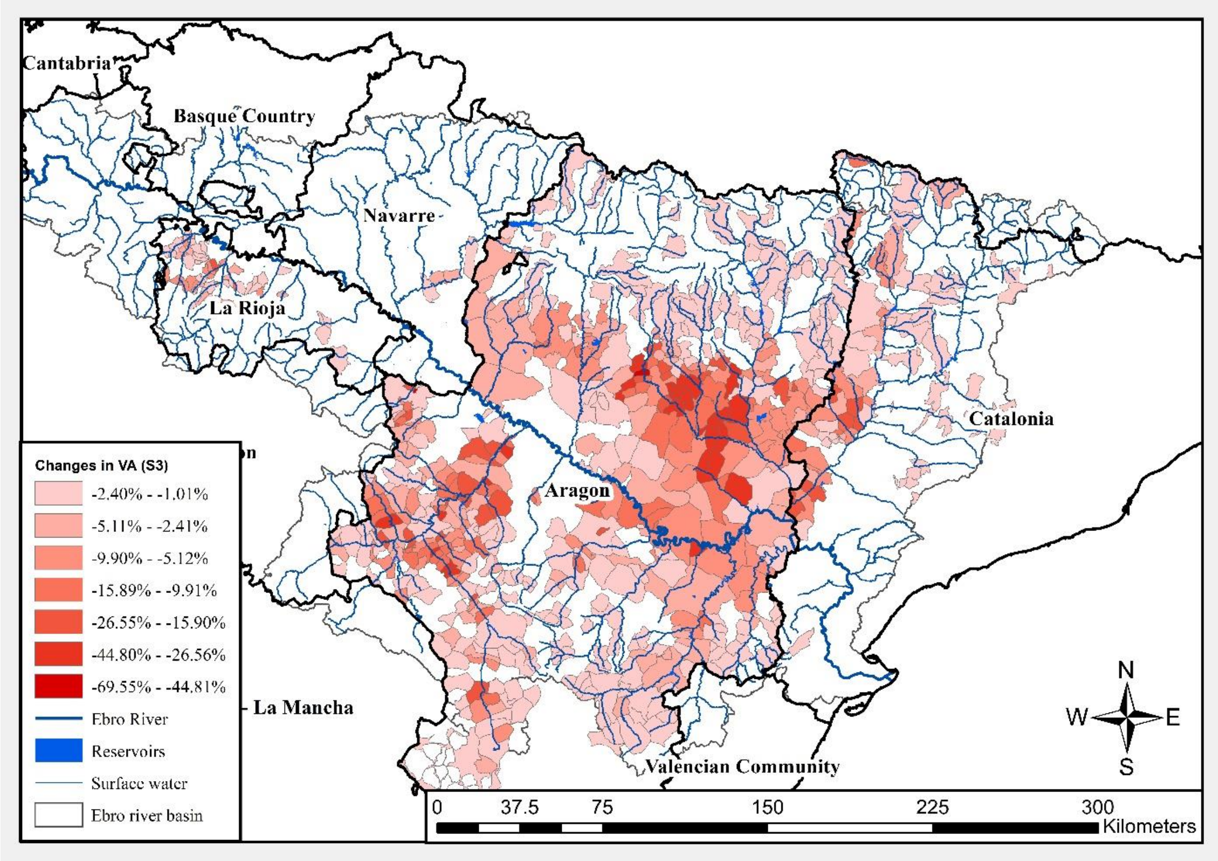


Figure 5.11. Changes in jobs in Scenario 3 (All Sectors)

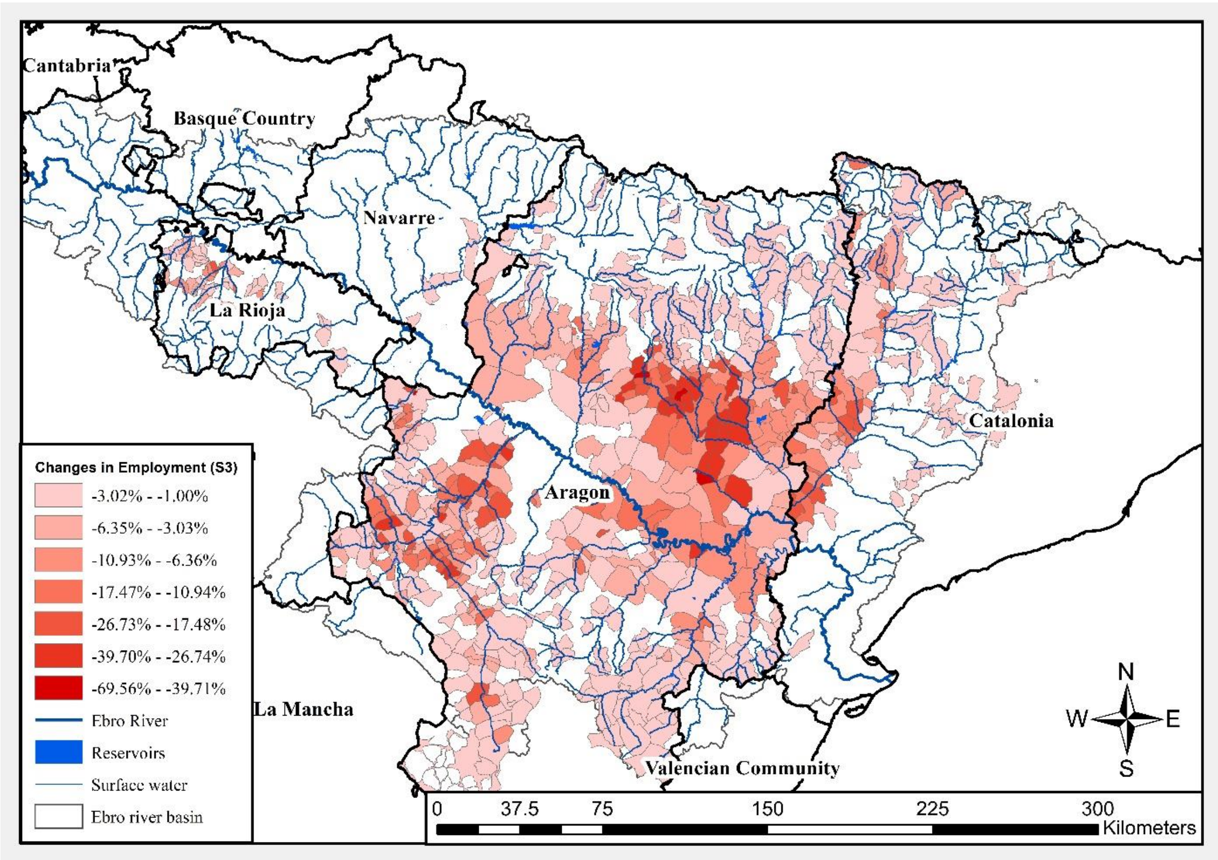
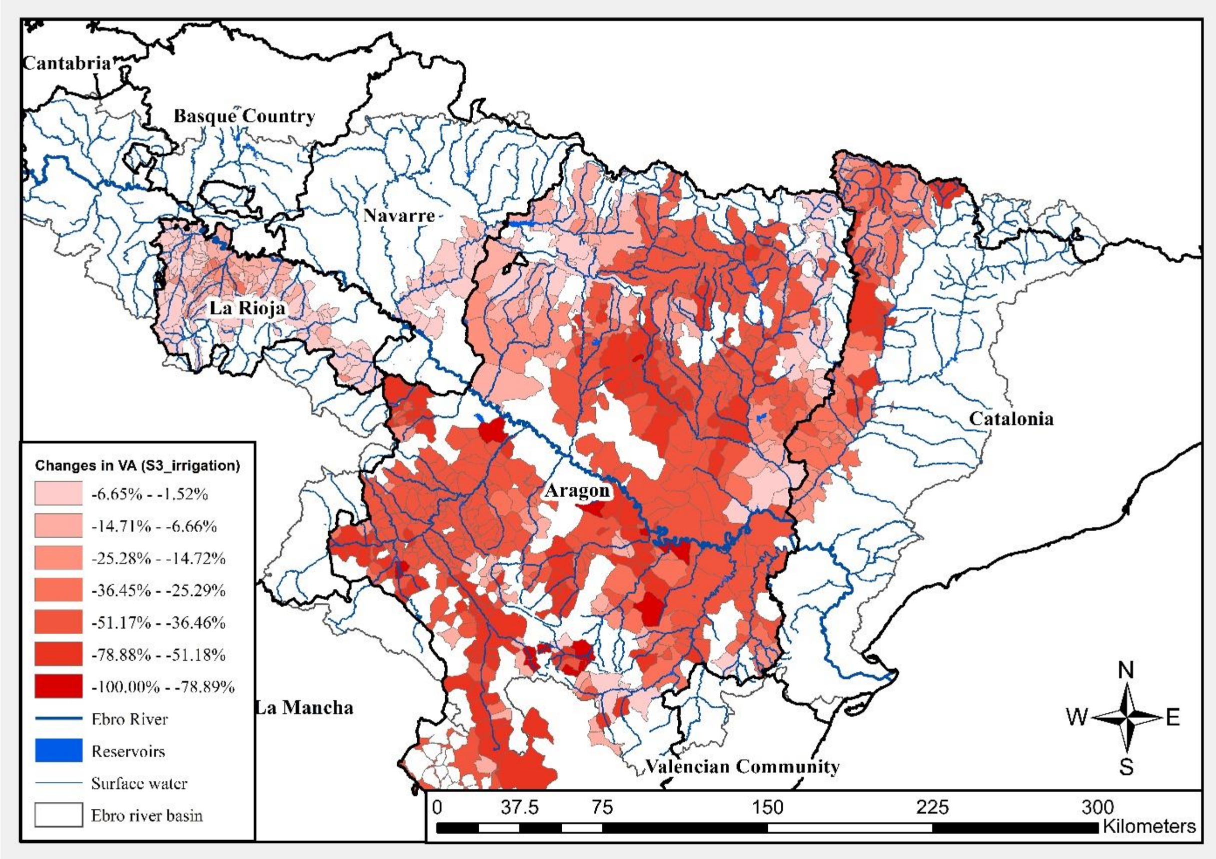


Figure 5.12. Changes in VA in irrigated farming - Scenario 3



5.5. Final remarks

The availability of fresh water for use at a given point in time and space depends on numerous physical and meteorological variables, as well as previous uses and environmental requirements, and the object of this chapter has therefore been to treat the entire river basin as the hydrological planning unit in order to expand the water flow modelling techniques explained in Chapter 3 to the ERB as a whole, while combining the water model obtained with the multiregional input-output framework developed in Chapter 4 to obtain a multi-regional and multi-sectoral hydro-economic model. The tool developed in this chapter thus allows assessment of the impact of different water availability scenarios and environmental flow conditions on socioeconomic variables at the level of the Autonomous Communities (political regions) forming the ERB, the water use zones included in each region and down to individual municipalities.

The hydrological model developed for the ERB is a simplification of the surface water flows in the Ebro Basin described in Chapter 1. Nevertheless, the picture it provides 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 by the principles of water mass balance and continuity of river flow, which determine the volumes of available water at each use or control node.

Meanwhile, the hydro-economic model described stands out from others of its kind insofar as it combines and integrates monthly hydrological data with the socioeconomic data obtained from the multi-regional and multi-sector input-output framework explained in Chapter 4, as well as the available municipal-level information.

The model is versatile, allowing the simulation of varying scenarios involving different water availabilities in each head flow or area, as well as changes in environmental requirements, water demand conditions (for example by assuming higher temperatures), gains in the efficiency of irrigation, the construction of new dams and or alterations to existing infrastructure (e.g. regrowth or demolition of dams) and changes in industrial water needs.

Meanwhile, the hydro-economic, multi-regional and multi-sectoral model of the Ebro Basin reveals how different hydrological scenarios impact value added and jobs, allowing analysis not only at the regional but also at the zonal and municipal level. This chapter, then, demonstrates the potential of the model created by positing two hydrological scenarios and calculating the results on value added and jobs both at the municipal level and by industry. These findings are then 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 consumptive use and added value/jobs. This trade-off depends on the temporal and spatial variability of the resource, and it affects each of the municipalities in the basin in a different way. However, impacts on rural employment are directly attributable to the association between farm jobs and irrigation. When farmers cannot plant their land because insufficient water is available for irrigation, these jobs simply disappear in the absence of crop substitution or technological adaptation. This is, of course, a very restrictive assumption, although it may be acceptable in the medium-term.

The model does not take into account groundwater flows and/or useor the smaller reservoirs in the basin. This is a weakness that will addressed in the future. However, the observed results of the proposed scenarios clearly reveal 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 was observed in in

Aragon in the same scenario. According to our model, then, increased consumptive use would be possible without negative effects in the Basque Country, Navarra, the Noguera Pallaresa watershed, the Segre River catchment area, and/or further downstream in the Ebro Basin.

In our analysis we focus on the impacts observable within the Ebro Basin, which are relatively larger. Nevertheless, the multiregional nature of the general model would allow the estimation of changes in value added and jobs in the rest of Spain, the EU, and the world. In the simulated scenarios, it was assumed for the sake of simplicity that foregone agricultural output (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 relevance of the model's global framework in the case in point, 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 take water availability into account at all times at each point throughout the ERB (or any other river basin modelled).

Summary and conclusions

The introduction of this thesis presents the subject and main goals of the research undertaken, explaining the importance of both water availability and freshwater management in a context of climate change and economic globalization. More specifically, the project was designed to contribute to the literature in both methodological and empirical terms. From the methodological point of view, aim was to create a combination of high-capacity tools to simulate scenarios and impacts at the macro and micro levels, while linking the economic and environmental components of the models used. At the empirical level, these instruments were adapted to address the relationships between economic agents and the potential conflicts existing in the Ebro River Basin, an area of special economic and environmental interest in Europe given the current context of climate change and globalization. Meanwhile, the results of this research and the model developed are directly applicable to other Mediterranean regions, pending future research partnerships and projects.

The essentially descriptive first chapter begins with a multiregional, socioeconomic and hydrological portrayal of the Ebro River Basin and the relationships existing within it. This chapter analyses the main uses made of water in the ERB, paying special attention to agriculture and above all to irrigated farming. Meanwhile, the description of surface water flows focuses on the main reservoirs, most of which are located at the headwaters of the Ebro's main tributaries, providing key data on water inflows into its basin. The annex to the first chapter also provides key information related with the construction of a municipal-level database for the Ebro Basin, itself an important product of this doctoral research. The database is attached to this thesis in Excel format and is also available upon request. It contains a wealth of information about the availability and use of water in the Ebro Basin, and a future study is planned to address the relationships between the timing of reservoir inflows, storage conditions, discharges and water uses, since the differences in these patterns reveal variances not only in rainfall and melt water but also in water use and the role played by dams in water management throughout the ERB.

The second chapter presents the input-output framework, game theory and hydro-economic modelling techniques, by way of an introduction to the main methodological approaches applied and combined in the ensuing chapters. In addition to these methodologies, geographic information systems (GIS) are used to obtain data/results at the municipal level. The input-output framework has been widely used in environmental analysis and it constitutes the main basis and guide for this thesis. Given the marked multi-regional character of the Ebro basin, these methods were used, among other matters, to develop the multi-regional and multi-sector input-output table for the Ebro basin, a significant contribution from this research in itself. Game theory has also been widely used to study the economics of natural resources, not least water. This thesis uses competitive and bargaining games to evaluate different water management alternatives in for the final stretch of the Ebro, which is taken as a case study. Hydro-economic modelling consists of a series of techniques used to determine water flows and estimate the volume of available water in the different sections of a river sections, and to shed light on relevant socio-economic and environmental issues. These models thus integrate and relate physical, socioeconomic and environmental information. The specific hydro-economic model built here for the Ebro Basin using monthly data is again a significant result, insofar as no other such model currently exists for the region to the best of the author’s knowledge. In view of the importance of geography in water studies, geographic information systems were also used in this research to visualize simulation results at the municipal level and reveal the geographic component of impacts, a technique that could be very useful in the design of compensatory measures to offset or mitigate any adverse effects of policy initiatives.

The third chapter addresses the flows and conflicts associated with the final stretch of the Ebro, which includes the land near Mequinenza, Ribarroja and Flix, the last reservoirs on the river, and the Ebro Delta, an environmentally sensitive biosphere reserve. A water flow model representing the lower Ebro, was developed to this end, along with a series of alternatives to the current system of flow management, which involves discharges of water from Mequinenza reservoir to comply with environmental flows. The application of game theory to the scenarios simulated and alternatives evaluated produced various relevant findings. In the first place, it was shown that annual flow data are too limited to be of much help in the examination of water uses and restrictions, and that this type of analysis needs to be addressed using at least monthly data. This was done in the case study. Another key finding was that current water uses are close to their limit, and that ongoing active and water management using dams and canals is necessary to guarantee that water flows throughout the basin satisfy current socio-economic and environmental water needs. In this light, current management arrangements appear more than a little questionable. Flows are currently managed by means of discharges of water from the Mequinenza dam when there is any shortage in the Delta, resulting in extreme variations in the level of this reservoir, which is environmentally damaging harm and hinders development in the surrounding area. For this reason, we consider that Mequinenza reservoir should not continue to be the sole solution for the flow and demand problems arising in the Delta. Moreover, alternatives to the current management set-up do actually exist, which basically involve sharing regulatory burdens and relieving the pressure on the Mequinenza area. Moreover, these solutions could help farmers in the area around the reservoir by releasing draw-offs for irrigation.

Chapter three sets the tone for the following chapters by highlighting the need for more geographically extensive planning and for the integration of hydrological and economic model to throw light on problems and interdependencies both in the river basin as a whole and locally.

Chapter four describes and explains the construction of the multi-regional and multi-sectoral input/output table for the Ebro River Basin. This IO table is a key analytic tool for the investigation of interregional and inter-sectoral interdependencies in the Ebro Basin, allowing a more detailed and accurate socioeconomic description that takes account of water demands. This table includes data for the five regions of the ERB and three further regions representing the rest of Spain, the EU and the world. Given our interest in water, the primary sector in the ERB regions was broken down into 43 activities, comprising 36 different crops (18 irrigated and 18 rainfed), 6 livestock groups, and the rest of the primary sector, which covers forestry, fishing, and ancillary activities. The construction of this multi-regional input/output table, which is attached to this thesis involved a laborious and intensive process of data collection and processing, since information was needed at the municipal level for all of the industries, crops and livestock groups taken into account. This undertaking produced the database presented in the Annex to Chapter 1, which was later used to estimate the results of the scenarios simulated at the municipal level. Meanwhile, the input-output table produced as part of this doctoral research is an important empirical contribution, given the lack of any previous multiregional IO table for the Ebro Basin, as far as the author is aware. Since the multiregional input-output framework offers data at the regional level, this Chapter describes a strategy to downscale the results offered by the input-output framework to the municipal level. This involved building a matrix of sector-region weightings at the municipal level, allowing the distribution of results to be estimated at the municipal level and then represented using GIS to facilitate geographic analysis. This weightings matrix, which is available on request, is used in Chapters 4 and 5 of the present thesis, although it could equally be applied in other studies.

To demonstrate the potential of this combination, a water saving policy was proposed and its impact at the municipal level was evaluated to reveal the trade-off in terms of value added and jobs that it implies. The combined analytic tool comprising the input-output table, the municipal-level weightings matrix and GIS shows with some precision just where the impact of a given policy will be most intense, a key consideration to determine whether a policy should be implemented as proposed, whether compensatory measures may be needed to offset adverse effects, and if so, in what municipalities and districts. The range of possible policy options is broad (two examples are examined in Chapter 5), and every alternative has a different impact. In this light, we consider that the contribution made in this chapter could be highly relevant for decision-making at the local level while maintaining a global perspective.

As explained in Chapter 4, the satellite accounts used in the input-output framework can be used to link socio-economic and environmental data. However, the data on water use and the variations caused by possible shocks in traditional input-output modelling are rarely subject to water availability restrictions, and even where they are, such constraints do not take into account monthly and geographical flows or the availability restrictions they entail. Chapter 5 therefore takes the model one step further by combining hydrological modelling with the input-output framework to build a multi-sectoral and multiregional hydro-economic model for the Ebro River Basin. This is a relevant and novel methodological contribution, insofar as no integration of this kind has been tried before. This fifth chapter is, then, based on the findings reached in the previous chapters and it is a clear continuation of Chapters 3 and 4. Furthermore, the hydrological model of the Ebro Basin used in Chapter 5 is a generalization of the surface water flows in the basin described in Chapter 1, taking into account the consumptive uses made by all agents. Since annual flows are not representative of water supply problems, meanwhile, the model is built on a monthly scale.

The hydro-economic model built in Chapter 5 allows simulation of different hydrological scenarios to show their socioeconomic effects at the municipal level, which is to say the impacts on the main macroeconomic variables and jobs in a context of general equilibrium.

As explained in Chapter 5, the results of the model depend largely on the variation in final consumption produced by the rise or fall in farm incomes produced by a given policy proposal. Hence, the range of results is as broad as the range of preferences that can be assumed for farmers in each region. For simplicity's sake, it was assumed in this chapter that the decline in consumption of each product caused by any fall in farmers' income will be proportional product by product to the available data on household consumption in each region according to the 2010 input-output table described in Chapter 4. As a future line of research, it is proposed to delve further into farm income elasticities in order to define a dynamic institutional framework for the economy, in which the role of agricultural products is paid more heed.

To demonstrate the potential of the model, two situations involving a reduction in the availability of water for consumptive use were simulated to observe the impacts on value added and jobs at both the regional (Autonomous Community) and municipal levels. The results observed in these scenarios clearly that water use for irrigation in the Basque Country and Navarre in the base year (2010) did not exert significant pressure on the water available in other regions, but the opposite was the case in Aragon According to the model, then, consumptive uses could be increased in the Basque Country, Navarre, the Noguera Pallaresa watershed, the Segre River, and/or in the Ebro without adverse effects.

The model does not take into account groundwater flows and/or uses, or the smaller reservoirs in the Ebro Basin, leaving the extension of the multi-sector and multi-regional hydro-economic model to groundwater for future research because this would imply significant changes to the hydrological model and would present a major challenge in terms of data collection, processing and calibration.

Furthermore, the model only takes into account direct impacts on irrigation due to the reduced availability of water for consumptive use. However, other activities may be affected by the management and availability of water, even if they do not involve any direct consumptive use. Hence, another future line of research could be to include all economic activities in the hydro-economic modelling process, paying special attention to hydroelectric generating. This would establish a solid basis for the design of policy proposals and the estimation of impacts on the water-energy-food nexus, as well as allowing the formalization and calibration of general equilibrium models.

To sum up, this thesis contributes to the literature in both methodological and empirical terms, opening up new avenues for future research. From the methodological standpoint, the integration of hydro-economic modelling and the input-output framework makes it possible to generate new long-term scenarios on the basis of which to assess key issues such as the resilience of different regions to the impacts of climate change, and the possible trajectories of change in rural areas and irrigation schemes driven by climatic and institutional conditions. Empirically, the detailed information obtained on inter-sectoral and inter-territorial relations in the Ebro River Basin constitutes a valuable starting point for the evaluation of economic and environmental policies. In fact, we intend that the tools we have developed in this thesis be of help in decision-making, and we will work to build a framework for the co-production of knowledge with agents to favour the formulation of growth strategies and the development of new models of governance related to water in the basin.

Resumen final y Conclusiones

En la introducción de esta tesis presentábamos la motivación y los principales objetivos. Allí exponíamos la importancia del agua dulce y su gobernanza en un contexto de cambio climático y globalización. En concreto, nos planteábamos como objetivos contribuir a la literatura en dos vías de trabajo. Desde el punto de vista metodológico, aportando una combinación de herramientas de gran capacidad para simular escenarios e impactos a nivel macro y micro, ligando las componentes económicas y ambientales. A nivel empírico, adaptando estos instrumentos al estudio de las relaciones entre los agentes, los potenciales conflictos, en un área de especial interés económico y climático en Europa, como es la cuenca del Ebro. Los análisis y resultados a nivel de cuenca tienen un gran interés hoy en día debido al contexto de cambio climático y economía global en el que estamos inmersos. Es más, este trabajo tiene aplicaciones para otras regiones mediterráneas, trabajo que queda pendiente de futuras colaboraciones en proyectos sobre esta área.

Para conseguir estos objetivos, el primer capítulo, de carácter fundamentalmente descriptivo, caracteriza la cuenca del Ebro y sus relaciones en un contexto multirregional, socioeconómico y también hidrológico. En este capítulo hemos analizado los usos principales que se hacen del agua en la cuenca del Ebro, prestando especial atención a la producción agrícola. Seguidamente, hemos descrito los flujos superficiales del agua, de aquí queremos destacar el análisis que hemos realizado sobre los embalses más relevantes, muchos de ellos situados en las cabeceras de las principales corrientes hídricas, por lo que, en gran medida, nos informan del agua entrante en la cuenca. Además, en el anexo de este primer capítulo encontramos detalles sobre la construcción de la base de datos a nivel municipal de la cuenca del Ebro, que ha sido una base importante para el desarrollo de esta tesis; esta base de datos se adjunta a esta tesis en formato Excel y también está disponible bajo petición. Haciendo uso de estos datos, y de cara a conocer aún mejor la disponibilidad y el uso del agua en la cuenca, para un estudio futuro, nos queda pendiente abordar las relaciones entre regímenes temporales de las entradas en los embalses, el almacenamiento y el desembalse con los usos; ya que las diferencias en sus patrones revelan, además de diferencias de pluviosidad y deshielo, diferencias también en los usos y en el papel que toman los embalses como reguladores a lo largo de la cuenca.

El segundo capítulo presenta las principales metodologías de trabajo, que se irán aplicando y combinando en los siguientes capítulos: que son el marco input-output, la teoría de juegos, y la modelización hidro-económica; estas metodologías acompañadas de los sistemas de información geográfica (GIS) nos aportan datos a nivel municipal. El marco input-output ha sido ampliamente usado en los análisis de medioambientales y es una base y una guía en esta tesis. Nosotros lo usamos en su vertiente multirregional y multisectorial debido al marcado carácter multirregional de la cuenca del Ebro. De hecho, hemos elaborado la tabla multirregional y multisectorial input-output de la cuenca del Ebro, que es un resultado en sí misma. La Teoría de Juegos también ha sido ampliamente utilizada en la economía de los recursos naturales, y concretamente en la economía del agua. En esta tesis hemos utilizado los juegos competitivos y de negociación para evaluar distintas alternativas de gestión del agua en el caso particular del tramo bajo del agua. Por su parte, la modelización hidro-económica se apoyan en la modelización de flujos hídricos, que determinan el volumen de disponibilidad de agua en los diferentes tramos fluviales, y en información socioeconómica y medioambiental relevante; de esta manera, los modelos hidroeconómicos integran y relacionan información física, socioeconómica y medioambiental. El modelo hidroeconómico que hemos construido para la cuenca del Ebro de escala mensual, es de nuevo un resultado en sí mismo, pues, hasta dónde llega nuestro conocimiento, no existe un modelo hidroeconómico para la cuenca del Ebro a escala mensual. El estudio del agua tiene un gran componente geográfico y por ello nos apoyamos también en los sistemas de información geográfica, que nos permiten visualizar los resultados de nuestras simulaciones a escala municipal; de esta manera podemos ver también el componente geográfico en los impactos, algo que puede resultar de utilidad en la elaboración de políticas de mitigación o compensatorias.

En el tercer capítulo de esta tesis abordamos el caso particular de los flujos y conflictos asociados con el tramo final del Ebro, que incluye las tierras cercanas a los últimos embalses del río, Mequinenza, Ribarroja y Flix y una zona especialmente sensible desde el punto de vista medioambiental, el delta del Ebro (reserva de la biosfera). Para ello, hemos elaborado un modelo de flujos hídricos que representa el tramo bajo del Ebro, y hemos elaborado distintas alternativas a la gestión actual, que no es otra que desembalsar puntualmente desde el embalse de Mequinenza el agua necesaria para cumplir con los caudales medioambientales. Hemos simulado diferentes escenarios y evaluado las distintas alternativas en ellos mediante la teoría de juegos, llegando a varias conclusiones relevantes. Por una parte, hemos visto como los flujos anuales dan información muy limitada a la hora de los usos y restricciones de agua, siendo necesario abordar este tipo de análisis con datos, al menos mensuales. Así se ha hecho en esta tesis. Otro hecho importante que se pone de manifiesto es que los usos de agua actuales están cerca del límite, y que es necesaria una gestión activa y permanente del agua a través de los embalses y canales, para garantizar de los flujos de agua a lo largo de la cuenca y así satisfacer los usos hídricos actuales, ya sean estos socioeconómicos o medioambientales. Como resultado encontramos también que la gestión actual, consistente en el desembalse desde el embalse de Mequinenza cuando falta agua para su uso en el Delta, es de una justicia al menos discutible, pues lleva a este embalse a variaciones muy elevadas en los niveles, que perjudican y complican su desarrollo. Por ello, consideramos que el embalse de Mequinenza no debe seguir resolviendo en solitario los problemas y exigencias del Delta, pues existen alternativas a la gestión actual que implican compartir las cargas regulatorias y aliviar la presión en el área de Mequinenza. Además, estas soluciones podrían promover e incrementar el riego en el área al liberar extracciones para otros usos de este embalse.

Este capítulo guía en cierta manera los capítulos siguientes, pues nos lleva a buscar una planificación más extensa geográficamente y nos impulsa a integrar los flujos hídricos con las actividades económicas, como forma de comprender mejor los problemas y las interdependencias.

En el cuarto capítulo avanzamos en la construcción de la tabla multirregional y multisectorial de la cuenca del Ebro. Esta tabla es una herramienta clave para analizar las interdependencias interregionales e intersectoriales de la cuenca del Ebro, que nos permite además avanzar en la caracterización socioeconómica de ésta, y tener en cuenta las demandas hídricas. Esta tabla tiene en cuenta 5 regiones de la cuenca del Ebro y tres regiones que representan el resto del mundo. Debido a nuestro interés en el agua, para las regiones ERB hemos desglosado el sector primario en 43 actividades: 36 producciones de cultivos diferentes (18 de regadío y 18 de secano), 6 grupos de ganado y el resto del sector primario, que abarca la silvicultura, la pesca y actividades auxiliares. Esta tabla input-output multirregional se anexa a esta tesis en formato Excel. La construcción de esta tabla ha sido laboriosa e intensiva en lo que respecta a la obtención y tratamiento de datos, pues ha requerido datos a nivel municipal de todas las industrias y de los cultivos y grupos de ganado tenidos en cuenta. De hecho, esto motivó la construcción de la base de datos que se presenta en el anexo del capítulo 1 y que posteriormente usamos para estimar los resultados a nivel municipal. De vuelta a la tabla input-output de la cuenca del Ebro, queremos destacar que, es un resultado importante de la presente tesis, pues no existía, hasta donde llega nuestro conocimiento, una tabla input-output multirregional para esta cuenca hidrográfica. El marco input-output multirregional nos ofrece en todo caso datos a nivel regional, por ello, en este capítulo hemos desarrollado una estrategia para escalar hasta el nivel municipal los resultados que nos ofrece el marco input-output. Hemos construido una matriz de pesos sector-región a nivel municipal, que nos permite estimar el reparto de los resultados a nivel municipal y su representación a través de GIS, que facilita el análisis geográfico. Esta matriz de pesos se usa en los capítulos 4 y 5 de esta tesis pudiéndose también usar para otros análisis, y que está disponible bajo petición.

Para demostrar la potencialidad de esta combinación, hemos planteado una política de ahorro de agua y hemos evaluado su impacto a nivel municipal, revelando el *trade-off* en términos de valor añadido y empleo que implica dicha política. La herramienta que forman la combinación de la tabla input-output, la matriz de pesos a nivel municipal, y GIS, permite conocer dónde se concentrará el impacto de una determinada política, algo que consideramos clave para determinar si dicha política debe llevarse a cabo y en caso de ser necesario, establecer medidas compensatorias sobre los municipios o comarcas más afectados. Muchas son las políticas que se pueden pensar (dos ejemplos de su posible explotación se ven en el capítulo 5), y cada una de ellas tiene un impacto distinto. Por ello consideramos que la aportación de este capítulo puede ser relevante para la toma de decisiones a nivel local con una necesaria perspectiva global.

Como hemos visto en el capítulo 4, el marco input-output nos permite, a través de las denominadas cuentas satélite, vincular datos socioeconómicos y medioambientales. Sin embargo, los datos de uso de agua y las variaciones respecto a posibles shocks, en la modelización input-output tradicional, no suelen estar sujetos a restricciones de disponibilidad, y de estarlo, estas restricciones no tienen en cuenta los flujos mensuales, su discurrir por el territorio y las restricciones de disponibilidad de agua que surgen de ambos hechos. Por ello, dando un paso más, en el capítulo 5, conjugamos la modelización hidrológica con el marco input-output para construir un modelo hidroeconómico multisectorial y multirregional para la cuenca del Ebro, siendo esta integración una aportación metodológica relevante y novedosa porque dicha esta integración no se había hecho anteriormente. Este quinto capítulo toma como premisas algunos de los hallazgos/conclusiones que hemos obtenido de los capítulos anteriores, y es una continuación clara de los capítulos 3 y 4, mientras que la forma en la que modelamos la hidrología en la cuenca del Ebro es una generalización de los flujos del agua superficial en la cuenca descritos en el capítulo 1 y tiene en cuenta los usos consuntivos que realizan todos los agentes. Además, como los flujos anuales no son representativos de la problemática a la hora de suplir los usos, el modelo que hemos construido es de escala mensual.

El modelo hidroeconómico construido en el capítulo 5 permite simular diferentes escenarios hidrológicos y ver, como ya hiciéramos antes, el impacto socioeconómico a nivel municipal, es decir, el impacto sobre las principales variables macroeconómicas y el empleo en un contexto de equilibrio general.

Como hemos podido observar en el capítulo 5, los resultados del modelo dependen en gran medida de la variación en el consumo final que se produce por la caída en la renta de los agricultores. Esto nos lleva a un abanico de resultados tan amplio como amplio es el abanico de preferencias que podamos asumir para los agricultores de cada región. Por simplicidad, en este capítulo, hemos supuesto que la caída en el consumo de cada producto que se produce por la caída en la renta de los agricultores es proporcional producto a producto con los datos que tenemos como consumo de los hogares de cada región. Sin embargo, esto nos lleva a plantear como futura línea de investigación, el profundizar en las elasticidades renta de agricultores y en la necesidad de definir un marco institucional y dinámico de la economía, marco donde se tenga más en cuenta el papel de los productos agrarios.

Para demostrar su potencialidad, hemos supuesto dos escenarios de menor disponibilidad de agua para uso consuntivo y hemos visto los impactos sobre el valor añadido y el empleo a nivel autonómico y a nivel municipal. Los resultados observados de los escenarios planteados apuntan claramente a dos hechos, los usos de regadío en País Vasco y Navarra que nos constan para el año 2010 no ejercen una presión significativa sobre el agua disponible en dichas regiones; mientras que en Aragón observamos lo contrario. Según nuestro modelo, de incrementarse los usos consuntivos, estos pueden incrementarse sin efectos negativos en País Vasco, en Navarra, en la Noguera Pallaresa y el Segre, y/o en el curso del Ebro.

Nuestro modelo no contempla los flujos y/o los usos de agua subterránea, ni tiene en cuenta los embalses de menor capacidad de la cuenca, por lo que queda pendiente la extensión del modelo hidroeconómico multisectorial y multirregional a las aguas subterráneas, lo que implicará importantes cambios en la modelización hidrológica y representará un gran reto en lo que respecta a la obtención y tratamiento de datos y en la calibración.

Por otro lado, el modelo sólo tiene en cuenta los daños directos que pueda recibir el regadío por la menor disponibilidad de agua para su uso consuntivo; no obstante, otras actividades, incluso las que no realizan un uso consuntivo, pueden verse afectadas por la gestión y disponibilidad geográfica del agua. Ello hace que otra futura línea de investigación sea incorporar todas las actividades económicas en la modelización hídrica, prestando especial atención a la hidroeléctrica. De esta manera, tendríamos una base sólida para estimar impactos y proponer políticas sobre el nexo agua, energía y alimentación, que además podría ser una base también para formular y calibrar modelos de equilibrio general.

En definitiva, la tesis contribuye a la literatura en dos vertientes, metodológica y empírica, abriendo nuevas vías de avance que trataremos de seguir en el futuro cercano. Desde el punto de vista metodológico, la integración de la modelización hidro-económica y el marco input-output permite generar nuevos escenarios de largo plazo con los que evaluar aspectos tan importantes como la resiliencia de las regiones ante los impactos del cambio climático, posibles trayectorias de cambio en el medio rural y en el regadío ante cambios en las condiciones climáticas e institucionales. Desde el punto de vista empírico, el detalle obtenido sobre las relaciones intersectoriales e interterritoriales en la Cuenca del Ebro constituye un punto de partida de gran valor para evaluar políticas económicas y ambientales. De hecho, pretendemos que las herramientas que hemos desarrollado en esta tesis sean de ayuda en la toma de decisiones, y trabajaremos en lo sucesivo en construir un marco de coproducción de conocimiento con los agentes para favorecer la formulación de estrategias de crecimiento y el desarrollo de nuevos modelos de gobernanza relacionados con el agua en la cuenca.

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