TESIS DE LA UNIVERSIDAD DE ZARAGOZA

2022

115

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Hydroeconomic Analysis of the Sustainable Use of Land and Water Resources under Droughts and Climate Change

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ISSN 2254-7606

Prensas de la Universidad
Universidad Zaragoza

Servicio de Publicaciones

ISSN 2254-7606

Universidad Zaragoza 1542

Tesis Doctoral

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Autor

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UNIVERSIDAD DE ZARAGOZA
Escuela de Doctorado

Programa de Doctorado en Economía

2022

UNIVERSIDAD DE ZARAGOZA

FACULTAD DE ECONOMÍA Y EMPRESA

DEPARTAMENTO DE ANÁLISIS ECONÓMICO

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Zaragoza, marzo de 2022

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Autor

Daniel Crespo Estage

Tesis presentada para optar al grado de Doctor por la Universidad de Zaragoza

Dirigida por el
Doctor José Albiac Murillo y la Doctora Encarna Esteban Gracia

Facultad de Economía y Empresa

Zaragoza, marzo de 2022

“ ‘When someone seeks,’ said Siddhartha, ‘then it easily happens that his eyes see only the thing that he seeks, and he is able to find nothing, to take in nothing. [...] Seeking means: having a goal. But finding means: being free, being open, having no goal.’ ”

Siddhartha, Hermann Hesse

A mi familia

Agradecimientos

Esta tesis es el resultado material de mis estudios de doctorado; el resultado inmaterial lo atesoro en mí, en forma de experiencia y conocimiento. En este periplo, he encontrado el sustento de muchas personas e instituciones que han contribuido al trabajo con esfuerzo, conocimiento y cariño. A todos ellos quiero expresar mi más sincero agradecimiento.

En primer lugar, me gustaría agradecer a mis directores de tesis, el Doctor José Albiac y la Doctora Encarna Esteban, la confianza que han depositado en mí. Pepe: gracias por el esfuerzo, dedicación y empeño en tu trabajo; gracias por el conocimiento que me has trasmitido y por la perspectiva que he adquirido mirando a través de tus ojos; gracias por enseñarme el valor de la paciencia, la constancia y la resiliencia. Encarna: gracias por enseñarme el valor de ser resolutivo, eficaz y determinado, valores que me has demostrado con tu ejemplo; gracias por tu experiencia y conocimiento; gracias por el apoyo y equilibrio que me has dado cuando más lo necesitaba. Pepe y Encarna: gracias por posibilitar el inicio de un nuevo camino.

Quiero agradecer también al Instituto Nacional de Investigación Agraria (INIA) la concesión de una beca predoctoral para la formación de personal investigador en el Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA). Gracias al apoyo del INIA y del CITA he podido continuar con mi formación, asistir a congresos y cursos, y realizar estancias en el extranjero.

Agradezco al Doctor Ariel Dinar, de la Universitity of California, Riverside (EEUU), su ayuda, disponibilidad y contribución en esta tesis. Al Doctor Taher Kahil, del International Institute for Applied Systems Analysis (Austria), le quiero agradecer el conocimiento que me ha trasmitido en modelización hidroeconómica, la técnica que fundamenta la metodología de esta tesis. Además, destaco y agradezco la notable contribución del Doctor Kahil en esta tesis. Al Doctor Andrea Castelletti, del Politecnico di Milano (Italia), le quiero agradecer la experiencia y conocimiento de modelos basados en agentes que me ha enseñado.

Doy las gracias por la ayuda técnica y el apoyo que he recibido por parte de los especialistas María Ángeles Lorenzo y Daniel Isidoro (CITA), Pablo Bruna (CTA), Rogelio Galván y Miguel Ángel García Vera (CHE) y Javier Tapia (Universidad de Zaragoza).

Gracias también a todos los compañeros del CITA que me han ayudado y acompañado estos últimos años, especialmente a Jorge, Brenda, Bea, Maite, Marian, Farida, Lola, Irene, Inés, Fran, Belinda, Álvaro, Fatma, Petjon. En particular, me gustaría agradecer el apoyo de Chicho (Eduardo Notivol), Safa Baccour y Manuel Resano, que han sido compañeros y amigos en este viaje.

En el CITA he encontrado amigos a los que quiero expresar especialmente mi agradecimiento. Alejandro: quiero que sepas que sí somos amigos. Yuri: tu cuenta de jarras no está liquidada; iré a cobrarlas pronto. Octavio y Wafa: habéis hecho del CITA un lugar hermoso; gracias por vuestra amistad y compañía.

Quiero agradecer a mis amigos su amistad y apoyo incondicional; en especial a Peri, Nico, Mati, Beatriz, Pablo, Natasha, Miguel Ángel, Agustín, Vanesa, Fran, Chus, Carlos, África y Prisca. Sin vosotros no hubiese sido capaz de hacer esta tesis.

A Consuelo le quiero dar gracias por el amor y la calma que me da.

Por último, quiero agradecer a mi familia: a mi madre Maite y mi padre José María; a mis hermanas, Susana, Marta y Raquel; a mi abuelo José; a mis sobrinos, Jonathan y Ana. Gracias por el apoyo incondicional, por la comprensión y el aguante en los momentos difíciles. Pero, sobre todo, gracias por el amor y cariño que me habéis dado y tanto he necesitado para realizar esta tesis. Esta tesis os la dedico especialmente a vosotros.

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Chapter 1

1. Introduction

Water scarcity is a global concern in many basins, because it may result in substantial damages to human societies and the environment. Water scarcity results in economic losses, ecosystems degradation, conflicts among stakeholders, and even hunger among very poor populations in some locations. Water scarcity is the consequence of unbalances in many basins around the world between the escalating water demand and the water available. The main drivers of the global expansion of water demand are population growth, economic development, and changing consumption patterns, which have increased water withdrawals seven-fold in the last century (AQUASTAT, 2010) with further increases around 20-30% expected for 2050 (Boretti and Rosa, 2019). Population growth will increase food demand and agricultural withdrawals, which currently account for 70% of water use with even higher levels in arid and semi-arid regions. Other economic sectors will also increase the demand for water in response to global growth in income and population.

Excessive water withdrawals from human activities jeopardize aquatic ecosystems and the sustainability of water systems. The erosion of ecosystems intensifies the hazards of biodiversity losses, extreme events, and go beyond critical tipping points, triggering irreversible damages and adverse changes (Bond et al., 2008). Recognizing aquatic ecosystems as legitimate water usage will increase water competition by limiting water available for other uses. However, the protection of ecosystems is essential for maintaining the essential goods and services provided to human societies. These goods and services from aquatic habitats are largely determined by the biophysical status of habitats, which is being extensively damaged by the escalating competition for water from human activities. The current depletion of hydrological systems worldwide is hampering the sustainability and viability of ecosystems, deteriorating both the quantity and quality of environmental goods and services.

1.1. Water Scarcity, Droughts and Climate Change

Droughts are natural hazards that threaten the reliability of water systems and undermine water based economic activities. Agricultural production, hydropower generation and urban supply are the most impacted sectors from droughts, with substantial economic losses estimated at €9 billion per year in Europe (Cammalleri et al., 2020) and $8 billion per year in the USA (NOAA, 2021). In addition, water-dependent ecosystems are stressed under drought conditions, compromising long-term environmental sustainability. In Europe, the countries with large drought damages in billion euros per year are Spain (1.5), Italy (1.4) and France (1.2), although future damages would depend on the increase in the global warming temperature, with damages increasing up to five times for a +3°C scenario (Feyen et al., 2020).

Climate change impacts in southern Europe and the Mediterranean region will aggravate drought events by increasing their frequency, intensity and duration, and the resulting economic and environmental damages. The mounting vulnerability of water systems to droughts will require the adaptation of water management to these worsening drought conditions.

Schewe et al., (2014) indicate that climate change impacts on water resources are quite large, even for small increases in temperature. The combination of population and income growth and climate change will exacerbate water scarcity problems requiring strong policy interventions to contain the scalating demand. If countries do not prepare for climate change, the risk of water stress will affect a large number of people (Oki and Kanae, 2006). Robust water systems will be needed in basins where economic activities are closely linked to climate conditions, in order to reduce uncertainties in water availability and economic damages (Dolan et al., 2021).

The impact of droughts is determined by their frequency, duration and intensity and by the capacity of the water system to withstand adverse events. Assessing the sustainability of river basin management requires evaluating the performance of the water system under alternative policy options and a wide variety of drought scenarios. Extreme droughts are low-frequency climate events, but they are not well represented in climate projections. Synthetic stream flows that replicate historical and projected weather conditions should be generated to identify vulnerabilities of the water system and adequate mitigation policies.

Water scarcity problems coupled with deficient management in basins and flawed water policies result in conflicts among stakeholders. Water-related conflicts have been steadily growing worldwide since the mid-20th century (Dinko, 2022). Urban water security, irrigation water access, hydropower generation, environmental flows and transboundary basins bring about disputes over the control of water resources. Water scarcity travels downstream, since the water available along basins depends on upstream inflows and withdrawals, and on local inflows of tributaries. Any change in upstream withdrawals impacts on downstream stakeholders.

Conflicts within countries are more frequent than conflicts between countries (Dinko, 2022; Munia et al., 2016), although conflicts between countries are more difficult to solve and may even threaten peace (UN Water, 2020). Climate change will intensify water stress in arid and semiarid regions that already experience water scarcity (Munia et al., 2020), increasing the risk of conflict. Equitable distribution of water through institutional arrangements reduces the risk of water conflicts, which could have serious consequences for populations in low-income economies (Gunasekara et al., 2014). Successful management solutions involve negotiations between upstream, downstream and sector stakeholders in basins, which involve adequate collective action at local and basin levels. Sustainable water policies require reconciling upstream, downstream and sectoral interests, while protecting the environmental benefits provided by ecosystems (Munia et al., 2016).

1.2. Water Management

Resilient and robust water systems that promote social, economic, and environmental goals are needed to confront mounting future uncertainties. Sustainable water management seeks social well-being, by meeting both human water demands and ecosystem biodiversity that secure environmental goods and services (Poff et al., 2016). Water management is essential to address adaptation and mitigation of climate change, because of the linkages with land use and energy generation (Miralles-Wilhelm, 2022). The uncertainties in water planning call for identifying governance alternatives that could enhance the performance of water systems under climate change conditions.

Economic growth and environmental protection involve the adequate distribution of water among economic sectors and ecosystems (Candido et al., 2022). A coordinated institutional response to water scarcity problems is an important challenge in coming decades, which requires accommodating climate change risks into local adaption plans, ensuring local autonomous responses (Leal Filho et al., 2022). An enhanced understanding of the interactions between human activities and the environment is needed in the management of water systems (Ryu et al., 2009), where water allocations satisfy efficiency, equity, and sustainability objectives (Wang et al., 2008).

Water management is challenging, especially in arid and semi-arid regions, where drought spells involve large economic costs and environmental damages. Climate change, economic growth, and the growing willingness of society to protect the environment result in trade-offs between economic activities that sustain human populations and environmental flows that sustain ecosystems, resulting in a wicked management challenge. Ward (2007) distinguish between supply and demand side water management policies. Supply-side management measures increase human access to water but often encompass large environmental damages, with engineering schemes such as interbasin transfers, reservoirs, irrigation districts, urban networks, water treatment facilities or seawater desalination plants, which require quite large investments in water infrastructure. Demand-side management measures deal with water shortages by curbing water demand and could include water pricing, water markets, water reuse, command and control, or stakeholders' collective action. Water scarcity has temporal and spatial dimensions, and therefore water management cannot be a static process. Water management should be under constant revision incorporating emerging conditions and knowledge, in order to allocate water under multiple uncertainties and trade-offs.

Water markets enhance private benefits by reallocating water from low to high profitable water uses, with welfare gains for buyers and sellers. However, environmental sustainability and social equity have been mostly disregarded, as the cases of water markets in Chile and Australia indicate. The success of water markets depends on institutions (Grafton et al., 2011a), and accounting for environmental goals would increase transaction costs significantly reducing private benefits and trading volume (Connor and Kaczan, 2013). A more efficient water allocation among economic sectors and the environment would improve sustainable water use and could be also an instrument for long-term social equity (Xu et al., 2019).

The economic value of water use in agriculture is lower than in other sectors, at around one order of magnitude, and water trading will improve economic efficiency. Water markets involve well-defined property rights, transport infrastructure for trading, and strong institutions. Institutions will not only enforce trading rules, but also must account for the third party impacts of trading, mostly in the form environmental impacts (D'Odorico et al., 2020). Disregard of the public good, common pool resource, and natural monopoly characteristics of water resources will lead to significant failures that compromise welfare gains (Grafton et al., 2011b). Also, water trading moves water from low-value to high-value crops in areas with higher irrigation efficiency. This could result in the reduction of stream flows in basins, an issue known as the "paradox of irrigation efficiency" (Grafton et al., 2018). The high transaction cost and lack of infrastructure hamper the efficient allocation of water markets, while market structure and bargaining power are important determinants of equity. The transfer of water rights threatens employment in selling areas jeopardizing the equity objective of water management (Bajaj et al., 2022).

Sustainable water management involves protecting environmental flows that support the ecological status of water dependent ecosystems. However, the benefits of ecosystem services are still hardly considered in river basin management. The complexity of biophysical processes and the non-trivial interactions between ecosystems and hydrological components prevent the estimation of benefits (Smakhtin et al., 2004). Additionally, the lack of information and knowledge on ecosystem interactions and dynamics precludes the assessment of ecosystems responses to streamflow, and the ensuing environmental benefits. These complexities lead to assuming simplified ecosystem response functions, in order to incorporate environmental benefits into water management decisions. At present the water management problem is only addressed in not many countries with minimum environmental flows, which are set up to avoid further deterioration of ecosystems in basins. Environmental flows are usually administrative assignments to certain reaches or gauge stations along river basins, based on simplified conjectures of the interactions between ecosystem status and stream flows.

1.3. Objectives of the research and methodology

The main objective of the thesis is developing an integrated hydroeconomic model of the Ebro basin for water policy analysis. The model is used to assess the impacts from droughts and water scarcity in the context of climate change. The results and policy implications can be used as guides for other semiarid and arid regions, facing similar water scarcity problems. The results provide information to stakeholders and decision makers on the impacts of droughts and climate change, and how different water management alternatives could contribute in addressing their effects. The sustainability of the Ebro water system is analyzed taking into account the reliability, resilience and vulnerability of the irrigation sector, together with the protection of water dependent ecosystems.

Mathematical models that reproduce the temporal and spatial interactions of water use are the basis for hydroeconomic analysis. These models optimize and simulate water systems to identify trade-offs in water uses by sector and spatial location. Many water related problems can be examined, such as economic growth, water supply, climate change adaptation and mitigation, flood control damage or environmental flows (Ward, 2021). The enhancement of water system resilience, to reduce losses from water shortages, involves actions that include expanding dam storage, water reuse, seawater desalination, water pricing, and water trading (Ward, 2022). Hydro-economic analysis incorporates multiple disciplines such as biophysical processes, economic activities, or aquatic ecosystems in a framework capable of addressing the temporal and spatial dimensions of the water scarcity problem. In this regard, hydro-economic analysis can contribute to solve water scarcity problems, giving answers to water management concerns.

The main investigation is displayed in three chapters (chapters 2 to 4), where hydroecomic analysis is used to address climate change and water management issues. The Ebro basin in Spain is our case of study, although findings could be useful for other arid and semi-arid basins with similar economic and climatic characteristics. The study compares water management alternatives and their contribution to the sustainability of the water system, by achieving both the protection human water security and ecosystem biodiversity from the impacts of water scarcity, droughts, and climate change. The findings in the Ebro could contribute to the water policy advancements in basins around the world facing water scarcity problems and worsening ecosystem degradation, such as basins in the Mediterranean region, the Middle East and Central Asia, Southwestern United States, or Australia.

The first study in Chapter 2, presents the hydroeconomic model of the Ebro Basin. The integrated model links three components: the reduced form hydrological component, the regional economic component, and the environmental component. The reduced form hydrological component is calibrated by including non-observed variables to close the mass balance between estimated and observed stream flows. The economic regional component is calibrated with positive mathematical programming (PMP), reproducing the observed water and land use under baseline conditions. This method assumes that farmers maximize benefits from water and land use, and the first order conditions are used for calibration. The constraint of minimum environmental flow at the river mouth represents the environmental component. The model is used to analyze the spatial and sectoral distributions of water under drought conditions, comparing the economic instrument of water markets with the institutional instrument of stakeholders' cooperation. Compliance with environmental flows in the river mouth is evaluated by taking different priorities for water allocation between upstream and downstream regions. Under alternative policies, the analysis identifies the impacts of droughts and water scarcity, and their distribution among regions and sectors.

In Chapter 3, the use of water by ecosystems is included in the hydroeconomic model. Representing the benefits of ecosystems requires linking the health of ecosystems with hydrological variations, and also determining the economic value of the ecosystem services. The integration of environmental benefits into the hydroeconomic model is the method for capturing the interactions between private benefits (provided by economic activities) and public benefits (provided by ecosystems). The simulation of water distribution under drought conditions is used to evaluate water policies that combine economic and institutional instruments.

The environmental component of the model links the benefits that ecosystems provided to society, the environmental status, and the stream flows that sustain the aquatic ecosystem. The relationship between environmental conditions and stream flows is established and calibrated by previous studies on the involved biophysical processes. The Ebro Basin Authority has used these studies to settle the minimum environmental flows in the basin.

The environmental component includes the representation of health status and subsequent environmental benefits, covering the main sections of the river basin. This is an significant improvement over previous hydroeconomic literature, where the environmental representation is limited to certain parts and specific locations of rivers. The environmental representation captures the spatial interaction between water allocations for economic activities and for ecosystems. The hydroeconomic model has been used to analyze the trade-offs between private and public benefits provided by economic activities and ecosystems. The analysis of water management alternatives contributes to identify suitable water allocations that maintain the water system in good status.

The third study in Chapter 4 is an enhancement of the hydroeconomic model presented in Chapter 2. The hydroeconomic model includes the temporal dimension, adding dynamic aspects to the model presented in Chapter 2, and the time step has been changed from yearly to montly. The main dams in the basin are included in the model, allowing the simulation and evaluation of water policy alternatives through multiple time periods. Dam capacity, water inflows into the basin, and dam operation and evaporation are some of the variables that incorporate the model to represent dams.

The temporal scale of the hydroeconomic model is monthly, promoting the analysis of a variety of drought spells, from several months to multiple years. The hydroeconomic model compares the sustainability of the water system under changing climatic conditions. As a result of climate change, in arid and semi-arid areas, such as the Ebro basin, drought events will be more intense, frequent, and longer. Therefore, the economic and environmental impacts of droughts will be aggravated under these conditions.

Climate change simulations rely on historic data, climate change projections, and on an advance method of water inflow simulation called Copulas. This method fits the joint distribution of two consecutive months to capture their interdependence. The advantage of this procedure is that it can generate stream flows that replicate historical and projected climatic conditions with long-lasting and more intense droughts.

Uncertainty and risk related to drought and climate change are identified by the cumulative distribution functions of water availability and benefit losses. The analysis reveals the exposition of the water system to losses, and then alternative policies are considered for reducing the impacts of droughts and climate change. Under these management policies, the reliability, resilience, and vulnerability of the water system are evaluated to confront water scarcity from climate change.

This thesis presents some methodological and empirical innovations over previous studies on water scarcity. The hydroeconomic analysis conducted here shows the relevance of the integrated modeling of water resources in order to advance sustainable management at basin scale. Sustainable outcomes require adequate information of the complex processes underlying the water cycle in basins, for an accurate assessment of the environmental and economic trade-offs. The representation of environmental benefits and climate change undertaken in this research contributes to the strengthening of the hydroeconomic modeling methodology. Empirically, the results show the superiority of institutional cooperation for sustainable water management, in relation to other policies such as water markets or investments in irrigation efficiency. The research informs about the contribution of different water management options in reducing the risks of economic and environmental impacts from climate change.

1.4. Introducción

La escasez de agua es un problema emergente en muchas cuencas en el mundo, que puede ocasionar daños sustanciales a la sociedad y al medio ambiente. La escasez de agua produce pérdidas económicas, degradación de los ecosistemas, conflictos entre los usuarios del agua e incluso hambrunas en poblaciones de regiones muy pobres. La escasez de agua en las cuencas es el resultado de los desequilibrios entre la creciente demanda de agua y el agua disponible. Los principales factores de la expansión global de la demanda de agua son el crecimiento de la población, el desarrollo económico y el cambio en los patrones de consumo, que han multiplicado por siete las extracciones de agua en el último siglo (AQUASTAT, 2010) con aumentos adicionales del 20-30% en 2050 (Boretti y Rosa, 2019). El crecimiento de la población ampliará la demanda de alimentos y las extracciones para regadío, que actualmente representan el 70% del uso del agua y mayores porcentajes en las regiones áridas y semiáridas. Otros sectores económicos también aumentarán la demanda de agua por el crecimiento de los ingresos y la población mundiales.

Las extracciones excesivas de agua de las actividades humanas ponen en peligro los ecosistemas acuáticos y la sostenibilidad de los sistemas de agua. La degradación de los ecosistemas y las pérdidas de biodiversidad pueden llegar a sobrepasar puntos críticos que desencadenen daños irreversibles y transformaciones adversas (Bond et al., 2008). El reconocimiento de los ecosistemas acuáticos como usuarios legítimos del agua intensificará la rivalidad por el agua al limitar la disponibilidad para otros usos. Sin embargo, es necesario proteger los ecosistemas para poder mantener los bienes y servicios medioambientales que son esenciales para la sociedad. Estos bienes y servicios que proporcionan los hábitats acuáticos dependen de su estado biofísico, que está siendo gravemente deteriorado por la creciente rivalidad por el agua de las actividades humanas. La actual sobreexplotación de los sistemas hidrológicos a nivel global amenaza la sostenibilidad y viabilidad de los ecosistemas, deteriorando tanto la cantidad como la calidad de los bienes y servicios medioambientales.

1.5. Escasez de agua, sequías y cambio climático

Las sequías son fenómenos naturales que amenazan la fiabilidad de los sistemas de agua, con perjuicios para las actividades económicas basadas en el agua. La producción agrícola, la generación de energía hidroeléctrica y el suministro urbano son los sectores más afectados por las sequías, con pérdidas económicas sustanciales que se estiman en 9.000 millones de euros al año en Europa (Cammalleri et al., 2020) y 8.000 millones de dólares al año en los Estados Unidos (NOAA, 2021). Además, los ecosistemas dependientes del agua se deterioran en condiciones de sequía, lo que compromete la sostenibilidad medioambiental a largo plazo. En Europa, los países con mayores daños por sequía son (en 10^9 €/año); España (1,5), Italia (1,4) y Francia (1,2). Los futuros daños dependeran del aumento de temperatura por el calentamiento global, con daños hasta cinco veces mayores enun escenario de aumento de 3 °C (Feyen et al., 2020).

Los impactos del cambio climático en el sur de Europa y la región mediterránea agravarán los eventos de sequía por el incremento de su frecuencia, intensidad y duración, y en consecuencia las pérdidas económicas y los daños medioambientales. Esta creciente vulnerabilidad de los sistemas de agua a las sequías obligará a adecuar la gestión del agua a condiciones más desfavorables.

Schewe et al., (2014) indican que los impactos del cambio climático en los recursos hídricos son considerables, incluso para pequeños aumentos de temperatura. La combinación de crecimiento de población y renta, y de cambio climático agravará los problemas de escasez de agua que requerirán poner en marcha intervenciones políticas decididas para poder contener la creciente demanda. Si los países no se preparan para el cambio climático, el riesgo de estrés hídrico afectará a gran parte de la población (Oki y Kanae, 2006). En las cuencas donde las actividades económicas están estrechamente vinculadas a las condiciones climáticas, se necesitarán sistemas de agua robustos que reduzcan la incertidumbre en la disponibilidad de agua y los daños económicos (Dolan et al., 2021).

El impacto de las sequías está determinado por su frecuencia, duración e intensidad y por la capacidad del sistema hídrico para soportar eventos adversos. La evaluación de la sostenibilidad de la gestión de las cuencas hidrográficas implica evaluar el rendimiento del sistema hídrico bajo diferentes políticas de gestión y una amplia variedad de escenarios de sequía. Las sequías extremas son eventos climáticos con baja frecuencia, que no están bien representados en las proyecciones climáticas. La generación sintética de caudales de entrada en el sistema que reproduzcan condiciones climáticas históricas y proyectadas permite identificar las vulnerabilidades del sistema de agua y la adecuación de las políticas a la mitigación.

Los problemas de escasez de agua, junto con una mala gestión de las cuencas y políticas de agua deficientes, dan lugar a conflictos entre los usuarios del agua. Los conflictos relacionados con el agua han aumentado progesivamente en todo el mundo desde mediados del siglo XX (Dinko, 2022). La seguridad urbana del agua, el acceso al agua del regadío, la producción de energía hidroeléctrica, los caudales medioambientales y las cuencas transfronterizas motivan disputas por el control de los recursos hídricos. La escasez de agua se traslada aguas abajo, ya que el agua disponible a lo largo del río depende de las entradas y extracciones aguas arriba, y de las entradas locales de los afluentes. Cualquier cambio en las extracciones aguas arriba afecta a usuarios aguas abajo.

Los conflictos dentro de los países son más frecuentes que los conflictos entre países (Dinko, 2022; Munia et al., 2016), aunque los conflictos entre países son más difíciles de resolver e incluso pueden amenazar la paz (ONU Agua, 2020). El cambio climático intensificará el estrés hídrico en regiones áridas y semiáridas que ya experimentan escasez de agua (Munia et al., 2020), aumentando el riesgo de conflicto. La distribución equitativa del agua mediante acuerdos institucionales reduce el riesgo de conflictos por el agua, lo que podría tener importantes consecuencias para las poblaciones con economías de renta baja (Gunasekara et al., 2014). Las soluciones exitosas de gestión requieren negociaciones entre los usuarios aguas arriba, aguas abajo y los sectores de la cuenca, lo que implica una adecuada acción colectiva a nivel local y de cuenca. Las políticas sostenibles de agua conllevan conciliar los intereses aguas arriba, aguas abajo y sectoriales, al tiempo que protegen los beneficios medioambientales proporcionados por los ecosistemas (Munia et al., 2016).

1.6. Gestión del agua

Los sistemas de agua resilientes y robustos son necesarios para promover objetivos sociales, económicos y medioambientales queafronten las crecientes incertidumbres futuras. La gestión sostenible del agua busca el bienestar social, satisfaciendo tanto las demandas humanas de agua como la biodiversidad de los ecosistemas que aseguran bienes y servicios medioambientales (Poff et al., 2016). La gestión del agua es esencial para abordar la adaptación y mitigación del cambio climático, debido a los vínculos con el uso de la tierra y la generación de energía (Miralles-Wilhelm, 2022). La incertidumbre en la planificación del agua conlleva identificar alternativas de gobernanza que mejoren el rendimiento de los sistemas de agua en condiciones de cambio climático.

El crecimiento económico y la protección del medio ambiente supone una distribución adecuada del agua entre los sectores económicos y los ecosistemas (Candido et al., 2022). Una respuesta institucional coordinada a los problemas de escasez de agua es un desafío importante en las próximas décadas, que requiere acomodar los riesgos del cambio climático en los planes locales de adaptación, asegurando respuestas autónomas a nivel local (Leal Filho et al., 2022). En la gestión de los sistemas de agua es preciso comprender mejor las interacciones entre las actividades humanas y el medio ambiente (Ryu et al., 2009), para que las asignaciones de agua satisfagan los objetivos de eficiencia, equidad y sostenibilidad (Wang et al., 2008).

La gestión del agua es un desafío considerable, especialmente en las regiones áridas y semiáridas, donde los períodos de sequía provocan grandes costes económicos y daños medioambientales. El cambio climático, el crecimiento económico y la progresiva voluntad social de proteger el medio ambiente dan lugar a soluciones de compromiso entre las actividades económicas que sostienen las poblaciones humanas y los caudales medioambientales que sostienen los ecosistemas, lo que supone todo un desafío de gestión. Ward (2007) distingue entre las políticas de oferta y demanda en la gestión del agua. Las medidas de gestión de la oferta aumentan el acceso humano al agua, pero a menudo conllevan grandes daños medioambientales. Se trata de proyectos de ingeniería como trasvases entre cuencas, embalses, polígonos de riego, redes urbanas, instalaciones de tratamiento de agua o plantas de desalinización de agua de mar, que requieren grandes inversiones. Las medidas de gestión de la demanda acometen la escasez de agua contrayendo la demanda mediante los precios del agua, los mercados de agua, la reutilización, el mando y control, o la acción colectiva de los usuarios. La escasez de agua tiene dimensiones temporales y espaciales, y por tanto la gestión del agua no puede ser un proceso estático. La gestión del agua debe estar en constante revisión incorporando las condiciones y conocimientos emergentes, a fin de asignar el agua bajo múltiples incertidumbres y contrapartidas.

Los mercados del agua mejoran los beneficios privados al reasignar el agua de usos poco rentables hacia usos de alta rentabilidad, que generan ganancias de bienestar para compradores y vendedores. Sin embargo, la sostenibilidad medioambiental y la equidad social suelen ser ignorados, como indican los casos en los mercados de agua en Chile y Australia. El éxito de los mercados de agua depende de las instituciones (Grafton et al., 2011a), y la incorporación de objetivos medioambientales incrementa los costes de transacción y puede reducir significativamente los beneficios privados y el volumen de intercambio (Connor y Kaczan, 2013). Una asignación más eficiente del agua entre los sectores económicos y el medio ambiente mejora el uso sostenible del agua y también puede mejorar la equidad social a largo plazo (Xu et al., 2019).

El valor económico del uso del agua en la agricultura es menor que en otros sectores, en torno a un orden de magnitud, por lo que los intercambios de mercado mejoran la eficiencia económica. Los mercados del agua suponen derechos de propiedad bien definidos, infraestructura de transporte para el intercambio de agua einstituciones sólidas. Las instituciones no solo deben hacer cumplir las reglas del mercado, sino que también deben tener en cuenta los impactos a terceros de los intercambios, en especial los impactos medioambientales (D'Odorico et al., 2020). Las características de bien público y bien comunal del agua, y las tecnologías de utilización del agua con economías de escala e indivisibilidad que resultan en monopolios naturales, conducen a fallos de mercado importantes, y dificultan las ganancias de bienestar (Grafton et al., 2011b). Además, los intercambios de agua entre cultivos de bajo valor a cultivos de alto valor y mayor eficiencia de riego, pueden provocar la caída de caudales en los ríos. Este problema que crea el aumento de la eficiencia de riego se denomina la "paradoja de la eficiencia de riego" (Grafton et al., 2018). El alto coste de transacción y la falta de infraestructuras dificultan la asignación eficiente de los mercados de agua, mientras que la estructura del mercado y el poder de negociación afectan a la equidad. La transferencia de derechos de agua supone una amenaza para la actividad económica y el empleo de las zonas que venden agua, poniendo en peligro el objetivo de equidad de la gestión del agua (Bajaj et al., 2022).

La gestión sostenible del agua supone proteger los caudales medioambientales que sustentan el estado ecológico de los ecosistemas dependientes del agua. Sin embargo, los beneficios de los servicios ecosistémicos apenas se consideran en la gestión de los hídricos. La complejidad de los procesos biofísicos y las interacciones entre los ecosistemas y la hidrología dificultan la estimación de los beneficios (Smakhtin et al., 2004). Además, la falta de información y conocimientos sobre las interacciones de los ecosistemas impide evaluar la respuesta de los ecosistemas al caudal de los ríos, así como estimar los beneficios medioambientales. Estas dificultades llevan a asumir funciones de respuesta de los ecosistemas simplificadas, para incorporar los beneficios medioambientales en las decisiones de gestión del agua. En la actualidad, en muchos países, el problema de la gestión del agua se aborda con caudales medioambientales mínimos, que se establecen para evitar la degradación de los ecosistemas. Los caudales medioambientales suelen ser asignaciones administrativas en ciertos tramos o estaciones de medición, basadas en supuestros simplificados de las interacciones entre el estado del ecosistema y el caudal en el tramo del río.

1.7. Objetivos de la investigación y metodología

El principal objetivo de la tesis es desarrollar un modelo hidroeconómico integrado de la cuenca del Ebro, para analizar las políticas de gestión de agua. El modelo se utiliza para evaluar los impactos de las sequías y la escasez de agua en el contexto de cambio climático. Los resultados y las implicaciones de política pueden utilizarse como guía para otras regiones semiáridas y áridas, que se enfrentan a problemas similares de escasez de agua. Los resultados proporcionan información a los usuarios del agua y a los responsables en la toma de decisiones sobre los impactos de las sequías y el cambio climático, y sobre la contribución de las diferentes alternativas de gestión para abordar sus efectos. La sostenibilidad del sistema de agua del Ebro se analiza teniendo en cuenta la fiabilidad, resiliencia y vulnerabilidad del sistema de agua en relación al regadío y a la protección de los ecosistemas dependientes del agua.

Los modelos matemáticos que reproducen las interacciones temporales y espaciales del uso del agua son la base del análisis hidroeconómico. Estos modelos optimizan y simulan los sistemas de agua para identificar las soluciones de compromiso entre sectores y localizaciones espaciales del uso del agua. Los problemas relacionados con el agua que se pueden analizar son numerosos, como el crecimiento económico, el suministro de agua, la adaptación y mitigación del cambio climático, el daño del control de inundaciones o los caudales medioambientales (Ward, 2021). La mejora de la resiliencia del sistema de agua para reducir las pérdidas por escasez, requiere de acciones como la expansión del almacenamiento en presas, la reutilización del agua, la desalación del agua, los precios del agua, y los mercados de agua (Ward, 2022). El análisis hidroeconómico incorpora múltiples aspectos, como los procesos biofísicos, las actividades económicas o los ecosistemas acuáticos, en un marco capaz de abordar las dimensiones temporales y espaciales del problema de la escasez de agua. En este sentido, el análisis hidroeconómico puede contribuir a resolver problemas de escasez de agua, dando respuestas a los desafíos de gestión.

La investigación principal se presenta en tres capítulos (capítulos 2 a 4), en los que se utiliza el análisis hidroeconómico para abordar el cambio climático y los problemas de gestión del agua. El caso de estudio es la cuenca del Ebro, aunque los resultados pueden ser útiles en otras cuencas áridas y semiáridas con características económicas y climáticas similares. El estudio compara las alternativas de gestión del agua frente a los impactos de la escasez de agua, las sequías y el cambio climático, examinando la contribución de las alternativas a la sostenibilidad del sistema de agua y la protección tanto de la seguridad del uso de humano del agua como de la biodiversidad de los ecosistemas.. Los resultados en el Ebro pueden contribuir a mejorar la gestión en otras cuencas con escasez de agua y degradación de los ecosistemas, como las cuencas de la región mediterránea, Oriente Medio y Asia Central, el suroeste de los Estados Unidos o Australia.

El primer estudio del Capítulo 2, presenta el modelo hidroeconómico de la Cuenca del Ebro. El modelo integrado vincula tres componentes: el componente hidrológico en forma reducida, el componente económico regional y el componente medioambiental. El componente hidrológico en forma reducida se calibra mediante variables de holgura que representan variables no observadas entre caudales estimados y observados. Las variables de caudal cumplen con los principios de equilibrio de masas y continuidad entre tramos. El componente económico regional se calibra con programación matemática positiva (PMP), reproduciendo el uso observado del agua y la tierra del periodo base. Este método asume que los agricultores maximizan los beneficios del uso del agua y la tierra, y utiliza las condiciones de primer orden para la calibración. La restricción del caudal medioambiental mínimo en la desembocadura del río representa el componente medioambiental. El modelo se emplea para analizar la distribución espacial y sectorial del agua en condiciones de sequía, y compara el instrumento económico de los mercados del agua con el instrumento institucional de cooperación entre los usuarios del agua. El cumplimiento de los caudales ambientales en la desembocadura del río se evalúa asumiendo diferentes prioridades de asignación de agua entre las regiones aguas arriba y aguas abajo. Bajo distintas políticas de asignación , el análisis identifica los impactos de las sequías y la escasez de agua, y su distribución entre regiones y sectores.

En el Capítulo 3, se incluye en el modelo hidroeconómico el uso del agua de los ecosistemas. La representación de los beneficios de los ecosistemas precisa determinar en primer lugar la relación entre el estado de salud de los ecosistemas y las variaciones de caudal en los ríos, y en segundo lugar determinar el valor económico de los servicios de los ecosistemas según el estado de los ecosistemas. La incorporación de los beneficios ambientales en el modelo hidroeconómico permite capturar las interacciones entre los beneficios privados (proporcionados por las actividades económicas) y los beneficios medioambientales (proporcionados por los ecosistemas). La simulación de la distribución de agua en condiciones de sequía sirve para evaluar las políticas de agua basadas en instrumentos económicos o en instrumentos institucionales.

El componente medioambiental del modelo representa los beneficios de los ecosistemas, a partir del estado de los ecosistemas que depende de los caudales en los tramos de los ríos. La relación entre las condiciones de los ecosistemasy los caudales de los ríos se establece y calibra mediante la información de estudios previos sobre los procesos biofísicos involucrados. La Confederación Hidrográfica del Ebro ha utilizado estos estudios para establecer los caudales ambientales mínimos en los tramos de la cuenca.

El componente medioambiental se basa en esta representación del estado de salud y los beneficios medioambientales, y cubre los tramos principales de la cuenca hidrográfica. Esta es una mejora significativa con respecto a la literatura hidroeconómica previa, donde la representación medioambiental se limita a ciertas partes y localizaciones específicas de los ríos. La representación medioambiental captura la interacción espacial entre las asignaciones de agua para actividades económicas y para ecosistemas. El modelo hidroeconómico analiza las soluciones de compromiso entre beneficios privados y medioambientales que proporcionan las actividades económicas y los ecosistemas. El análisis de las alternativas de gestión del agua contribuye a identificar la asignación de agua adecuada para alcanzar un sistema de agua que sea sostenible.

El tercer estudio del Capítulo 4 supone una mejora del modelo hidroeconómico elaborado en el capítulo 2. El modelo hidroeconómico incluye la dimensión temporal, añadiendo aspectos dinámicos al modelo del Capítulo 2. También, la periodicidad del modelo ha pasado de anual a mensual. Se han incluido los principales embalses de la cuenca en el modelo, lo que permite simular y evaluar alternativas de gestión de agua a través de múltiples períodos de tiempo. En la representación de los embalses se incluye la capacidad de los embalses, las entradas de agua en el sistema, y el funcionamiento y evaporación de los embalses.

La escala temporal del modelo hidroeconómico es mensual, lo que permite analizar distintos períodos de sequía, desde varios meses hasta varios años. El modelo hidroeconómico compara la sostenibilidad del sistema hídrico bajo diferentes condiciones climáticas. Como consecuencia del cambio climático, en zonas áridas y semiáridas como la cuenca del Ebro, los eventos de sequía serán más intensos, frecuentes y de mayor duración. Por lo tanto, los impactos económicos y medioambientales de las sequías se agravarán en estas condiciones.

Las simulaciones de cambio climático se basan en datos históricos, proyecciones de cambio climático, y en un método avanzado de simulación de entradas de agua denominado Copulas. Este método ajusta la distribución conjunta de dos meses consecutivos para capturar su interdependencia. La ventaja de este procedimiento es que puede generar caudales que repliquen las condiciones climáticas históricas y las proyectadas con sequías más duraderas, frecuentes e intensas.

La incertidumbre y el riesgo relacionados con la sequía y el cambio climático se identifican mediante funciones de distribución de la disponibilidad de agua y las pérdidas de beneficios. El análisis revela la exposición del sistema del agua a las pérdidas, y posteriormente se consideran alternativas de gestión para reducir los impactos de las sequías y el cambio climático. A través de estas políticas de agua, se evalúa la fiabilidad, la resiliencia y la vulnerabilidad del sistema de agua para afrontar la escasez derivada del cambio climático.

Esta tesis presenta algunas innovaciones metodológicas y empíricas en relación a los estudios previos sobre escasez de agua. El análisis hidroeconómico realizado muestra la relevancia de la modelización integrada de los recursos hídricos para el desarrollo de la gestión sostenible a escala de cuenca. La gestión sostenible requiere disponer de información adecuada sobre los complejos procesos subyacentes al ciclo del agua, que pueden proporcionar una evaluación precisa de las soluciones de compromiso medioambientales y económicas. La representación de los beneficios medioambientales y del cambio climático emprendida en esta investigación contribuye al fortalecimiento de la metodología de modelización hidroeconómica. Empíricamente, los resultados muestran la superioridad de la cooperación institucional para la gestión sostenible del agua, en relación con otras políticas como los mercados del agua o las inversiones en eficiencia del riego. La tesis proporciona información sobre las consecuencias que las diferentes opciones de gestión del agua tienen sobre la reducción de los riesgos de impacto económico y medioambiental del cambio climático.

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Chapter 2

2. Tradeoffs between Water Uses and Environmental Flows: A Hydroeconomic Analysis in the Ebro Basin

Abstract

Addressing a more sustainable management of water resources involves new policies that require improved knowledge on water allocations and benefits from the economic and environmental uses of water. However, environmental uses have been mostly disregarded in traditional water management, and just recently the maintenance of environmental water flows is being considered as a key issue in water policies. The aim of this study is to analyze the spatial and sectoral allocation of water resources in the Ebro Basin (Spain), in order to inform the debate on the environmental flow in the Ebro mouth. The study analyzes in detail the irrigation districts using most of the water resources, and the environmental flow proposals for the river mouth. A hydro-economic model is developed to analyze the effects of different water allocation mechanisms under combinations of water availability and environmental flow scenarios. This is an important tool to explore the tradeoffs and political economy aspects from water reallocation. Results show that the petition of raising the environmental flow at the Ebro mouth during droughts by the downstream state (Cataluña) would be very costly for all irrigation districts in the basin. One alternative for the downstream state to gain the support of the rest of states for raising the environmental flow would be to compensate the losses of irrigation districts in upstream states.

Keyworks: Environmental flow Drought Water policy Hydro-economic modeling Ebro Basin

2.1. Introduction

Pressures on water resources have been mounting worldwide creating a widespread degradation of water resources in basins around the world. Global water extractions have climbed six fold during the last century (WWC 2000; Biemans et al., 2011). The scale of the global growing water scarcity indicates that water mismanagement is quite common, and that sustainable management of basins is a complex and difficult task. The upcoming water governance problem would be especially acute in arid and semiarid regions, where the combined effects of human-induced permanent water scarcity and climate change-induced water scarcity and droughts portend unprecedented levels of water resources degradation in the absence of remediating water reforms (WWAP 2006; Albiac 2017). Climate change is expected to become a major challenge for sustainable agricultural production, especially difficult to harness because global food demand will almost double by 2050 driven by the growth of world population and income (Alexandratos and Bruisma 2012). Water resources projections using coupled global hydrological and crop models indicate that crop losses from severe climate change impacts could be in the range of 20-30% by the end of the century (Elliott et al., 2014), with further losses occurring from water scarcity in some regions forcing the conversion of irrigated to rainfed cropland.

Most policies implemented to address water scarcity in water stressed basins frequently fail because the common pool characteristic of water resources are not taken into account and also because environmental externalities are ignored (Booker et al., 2012). The management of water resources requires collective action processes since pure competitive markets cannot account for the common pool and public good characteristics of water. Additionally, collective action is needed to account for the externalities linked to the use of water resources, such as, ecosystem damages or depletion of groundwater systems (Rausser et al. 2011). Lastly, the sustainable management of water requires accurate information on the economic and environmental costs and benefits of water allocations among sectors and spatial locations. Traditionally, environmental externalities have been not included in water management. But the severe degradation of basins across the world in recent decades is calling for implementing measures that specifically protect ecosystems. An example is the case of Europe, where water legislation emphasizes the objective of good ecological status for all water bodies by improving water quality. However, water allocation among sectors, locations and the environment is hardly addressed, despite the fact that this is the key issue in basins with acute water scarcity in Southern Europe.

Environmental flows sustain water dependent ecosystems, which provide many ecosystem goods and services to human societies. The water cycle of hydrological processes underlies the biodiversity, functionality and health of aquatic ecosystems. The alteration of environmental flows is the consequence of irrigation, urbanization and industrial activities that require growing streamflow diversions through reservoirs, water transfers and groundwater extraction schemes. There is a severe biodiversity decline of aquatic ecosystems that exceeds by far the decline of terrestrial and marine ecosystems (Arthington, 2012).

The choice of ecosystems to be preserved determines the regime of the required environmental flows, implying a trade-off among water allocations for human and for environmental uses (Acreman, 2016). The experience about this trade-off in basins around the world suggest that human uses have much higher priority over environmental uses, especially in arid and semi-arid regions. Furthermore, for maintaining healthy ecosystems not just environmental flows are required but also the maintenance of the natural seasonal flow patterns after human water withdrawals (Acreman et al. 2009). Water allocation in basins could be improved by considering both the economic and the environmental benefits provided by the different water allocation choices.

Hydro-economic modeling is a suitable methodology to analyze the economic and environmental impacts of different water allocation mechanisms between sectors and users, including water allocation for environmental purposes. This methodology is an advanced approach to support the design of policies at basin scale. This is because hydro-economic models integrate the spatially distributed water sources, water storage and conveyance infrastructures, water-based economic activities, and water-dependent ecosystems into a unified framework. The advantage of this approach is the formulation of interrelationships among hydrologic, economic, institutional and environmental components for a comprehensive assessment of the tradeoffs among water policy choices (Booker et al., 2005; Harou et al., 2009; Kahil et al., 2015; Almazán et al. 2018, 2021).

This paper aims to highlight the importance of considering both the environmental flow requirements and economic impacts when designing policies to allocate water resources in a water-scarce river basin. To meet this objective, we have developed a hydro-economic model of the Ebro basin of Spain, which integrates major water uses, sources, and infrastructure in the basin. This model has been used to analyze three different water allocation policies: upstream priority, proportional sharing, and water markets. These allocation policies can be implemented to maintain different environmental flow proposals under various water availability scenarios. An important contribution of the study relative to prior literature is to provide information on the socio-economic impacts sustained by human water uses, when ecosystems are protected by establishing different levels of environmental flows under various water scarcity conditions. The results highlight that the establishment of environmental flow requirements in water-scarce river basins is a key issue involving both human wellbeing and protection of water dependent ecosystems. However, the success of water allocation policies require the implementation of economically efficient and socially acceptable measures. The Ebro basin is an illustrative case for exploring the political tradeoffs when water is reallocated to the environment, and results could entail important lessons for other basin in arid and semiarid regions.

The paper is organized as follows. First, we briefly summarize the main issues with water management in the Ebro basin in section 2.2 Section 2.3 presents the development of the hydro-economic model of the Ebro basin. Section 2.4 describes the model application and the main results of the hydro-economic analysis. Finally, section 2.5 concludes with the summary and policy implications.

2.2. The Ebro River Basin

The Ebro basin is located in Northeastern Spain covering 85,000 km^2 and sustaining the economic activities of 3.2 million inhabitants (Figure 2.1). Available renewable water resources amount to 14,600 Mm^3 per year, and water withdrawals are 8,460 Mm^3 divided between 8,110 Mm^3 of surface diversions and 350 Mm^3 of groundwater extractions (CHE 2015). Water withdrawals for agriculture are around 7,680 Mm^3 covering 700,000 ha of irrigated crops. Withdrawals by water companies supplying urban centers are 630 Mm^3, and direct withdrawals by industries are 150 Mm^3. There are also non-consumptive withdrawals for the cooling of thermoelectric power plants (3,100 Mm^3) and for hydropower production (38,000 Mm^3). Water for agriculture represents 90% of the water demand and the main irrigated crops are alfalfa, corn, barley, wheat, rice and fruit trees.

The management of water is made by the Ebro Basin Authority (Confederación Hidrográfica del Ebro). The water authority is in charge of elaborating the Ebro River

Plan setting the medium term management strategies, where the objectives are to feed water demand, contribute to regional development, and protect ecosystems in the basin. Ecosystems protection is implemented by establishing minimum environmental flows in selected river reaches. The distinctive characteristic of this institutional approach is the key role played by stakeholders. Water stakeholders are inside the water authority and include water users, public administrations, and environmental groups. These stakeholders' representatives are in all governing and participation bodies at basin scale, and they run the watershed boards at local scale.

An important issue in the Ebro basin in recent decades is the conflict between the upstream states and the downstream state (Cataluña) because of the minimum environmental flow at the Ebro mouth. The Ebro and the Duero rivers are the only rivers in Spain with substantial minimum environmental flows at the river mouth, which are around 20% of natural stream flows compared with minimum flows around 0.1-4% in the rest of the basins.

Despite this significant minimum environmental flow threshold in the Ebro, Cataluña is asking for a steep increase in minimum environmental flow in normal years from the current 3,000 up to around 8,000-9,000 Mm^3/year, increasing the share over natural streamflow from 20% up to 50-65%. These extraordinary claims by the downstream Cataluña state are opposed by all upstream states in the basin, since their water related economic activities would be seriously threatened. The aim of this paper is to analyze the socio-economic impacts and costs of this large expansion in the Ebro basin environmental flows. Additionally, different alternative policies to distribute the costs among users and states along the basin are examined.

2.3. The hydro-economic model of the Ebro basin

A hydro-economic model of the Ebro basin is developed to analyze the current water allocation by sector and spatial location in the basin. The model integrates the hydrology, the economic activities, and the environmental flows of the basin. The hydrological component is a node-link network of supply nodes such as rivers and dams, and demand nodes such as irrigation districts, urban centers, and environmental flows. The regional economic component includes the irrigation activities and the urban and industrial activities, where a detailed farm-level optimization module represents irrigation districts, and urban centers maximize the social surplus derived from the supply and demand of urban water. The environmental use of water is represented by minimum environmental flow constraints, given the lack of information on the response of environmental benefits to the allocation of environmental flows (Momblanch et al. 2016). The full hydro-economic model framework showing the interactions among the model components is depicted in figure A2 in appendix.

2.3.1 Reduced form hydrological component

The reduced form hydrological component is built with information from the Ebro basin authority (CHE 2007; 2015), using data on stream flows and water allocations during normal climatic conditions. The hydrological component represents water flows among supply and demand nodes, using the basic hydrological concepts of mass balance and continuity of river flows (Figure A1 in appendix). The hydrological component is used to estimate the volume of available water for economic activities after fulfilling the restrictions on environmental flows. The mathematical formulation is the following:

$$W_{out_d} = W_{in_d} - W_{loss_d} - Div_d^{IR} - Div_d^{URB} \tag{2.1}$$

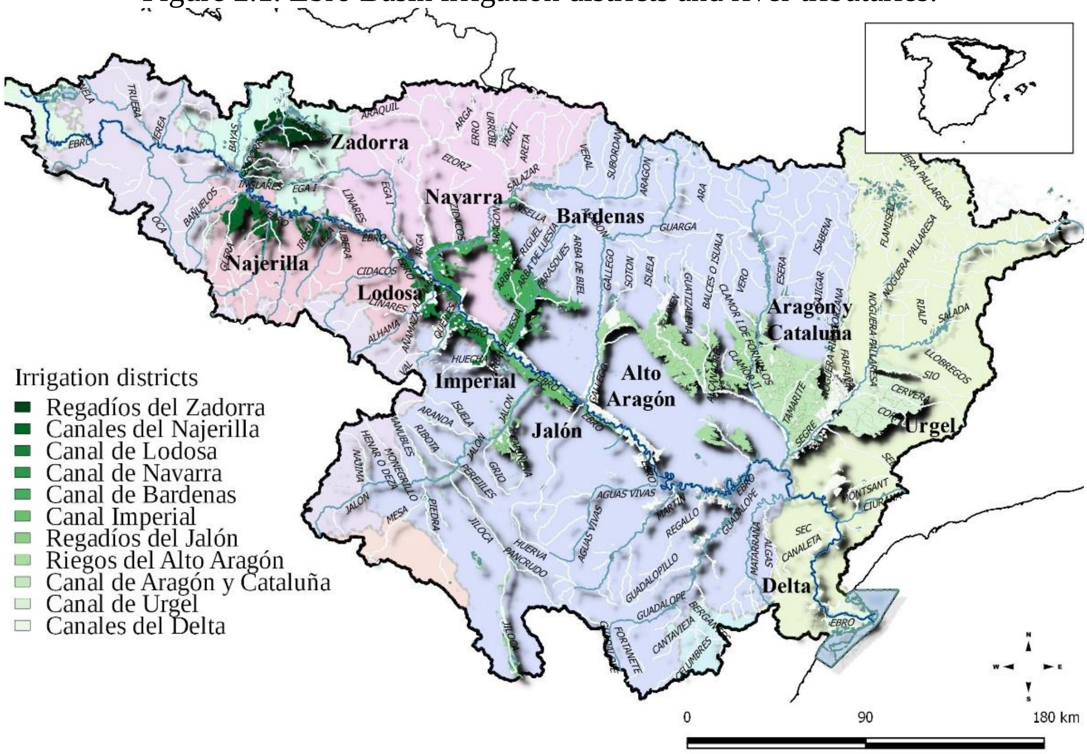
$$W_{in_{d+1}} = W_{out_d} + r_d^{IR} \cdot (Div_d^{IR}) + r_d^{URB} \cdot (Div_d^{URB}) + RO_{d+1} \tag{2.2}$$

$$W_{out_d} \geq E_d^{min} \tag{2.3}$$

where equation (2.1) is the mass balance equation, where water outflow W_{out_d} from a river reach d, is equal to water inflow W_{in_d} minus the loss of water W_{loss_d}, and minus the diversions for irrigation (Div_d^{IR}) and urban and industrial uses (Div_d^{URB}). Equation (2.2) is the continuity equation of river flow that indicates the water inflow to the next river reach $W_{in_{d+1}}$ is the sum of outflow from upstream river reach W_{out_d}, return flows from the upstream irrigation districts $[r_d^{IR} \cdot (Div_d^{IR})]$, return flows from urban centers $[r_d^{URB} \cdot (Div_d^{URB})]$, and runoff entering that river reach from tributaries RO_{d+1}. Equation (2.3) states that the water outflow W_{out_d} from a river reach d must be greater or equal to the minimum environmental flow requirements E_d^{min} in that river reach.

The calibration of the hydrologic component is made by adjusting the model parameters to reproduce the observed streamflows under baseline conditions. This calibration procedure involves introducing slack variables that represent unmeasured sources or uses of water, in order to balance supply and demand at each node. Headwater inflows, gauged streamflows and canal releases in the basin have been obtained from the Ebro Basin Authority and the Ministry of Agriculture for the period 2000-2014 (CHE

Figure 2.1. Ebro Basin irrigation districts and river tributaries.



Source: CHE (2017)

2009; CEDEX 2016). The water available in the system is 14,600 Mm^3, and the water allocated to irrigation districts and urban centers depends on the allocation rules of the Ebro Basin Authority.

2.3.2 Economic component

The economic component includes optimization models for each irrigation district, and an optimization procedure of social surplus for the provision of water to each urban center. The optimization model of agricultural activities represents the crop production of the main irrigation districts in the basin (Figure 2.1). This model maximizes the private benefits of farmers from crop production activities for each irrigation district, subject to various technical and resource constraints. For simplicity, it is assumed that yield functions are linear and decreasing, and input and output prices are constant. The problem formulation is the following:

$$Max(B_k^{IR}) = \sum_{ij} C'_{ijk} X_{ijk} \tag{2.4}$$

subject to

$$\sum_i X_{ijk} \leq Tland_{kj};\ j = surface, sprinkle, drip \tag{2.5}$$

$$\sum_{ij} W_{ijk}\, X_{ijk} \leq Twater_k \tag{2.6}$$

$$\sum_{ij} L_{ijk}\, X_{ijk} \leq Tlabor_k \tag{2.7}$$

$$X_{ijk} \geq 0 \quad (2.8)$$

where B_k^{IR} is private benefit in irrigation district k, and $C_{ijk}^{'}$ is net income per hectare of crop i under irrigation technology j. The decision variable in the problem is X_{ijk}, the area of crop i under irrigation technology j. Equation (2.5) is the land constraint representing the land $Tland_{kj}$ available in irrigation district k equipped with irrigation technology j. The water equation (2.6) represents the water available T_{water_k} in the irrigation district k, where W_{ijk} is gross water requirement per hectare of crop i under technology j. The water constraint level is the connecting variable between the optimization model of irrigation districts and the hydrological component. The labor constraint (2.7) represents labor available $Tlabor_k$ in irrigation district k, where L_{ijk} is the labor requirement per hectare of crop i under irrigation technology j. The irrigation systems for field crops are surface and sprinkle irrigation, and for fruit trees and vegetables are surface and drip irrigation.

The net income per hectare C'_{ijk} is the difference between revenue and costs, and is defined by the following equation:

$$C'_{ijk} = P_i Y_{ijk} - CP_i \quad (2.9)$$

where P_i is price of crop i, Y_{ijk} is yield of crop i under technology j in district k, and CP_i are the production costs of crop i. The model includes the Ricardian rent principle of decreasing yields when additional land enters production. The yield function is linear and decreasing in the area of crop i under technology j as follows:

$$\mathrm{Y_{ijk}} = \beta_{0_{\mathrm{ijk}}} + \beta_{1\mathrm{ijk}} \mathrm{X_{ijk}} \quad (2.10)$$

The optimization model is calibrated with the positive mathematical programming (PMP) method, using the procedure of (Dagnino and Ward, 2012). This procedure involves the estimation of the parameters of the linear yield function [Equation (2.10)], based on the first order conditions for profit maximization. The data on yields, prices, crop water requirements, production costs, availability of water, land and labor, together with the information on biophysical parameters, have been obtained from statistical databases and previous studies (MARM 2010b; MAGRAMA 2015; INE 2009; DGA 2009; GC 2009; GN 2009).

In urban use, the procedure is to maximize the economic surplus, adding the consumer and producer surpluses from the main urban centers in the basin. The optimization problem is the following:

$$Max\ B_u^{URB} = (a_{du}Q_{du} - ½\, b_{du}Q_{du}^2 - a_{su}Q_{su} - ½\, b_{su}Q_{su}^2) \quad (2.11)$$

subject to

$$Q_{du} - Q_{su} \leq 0 \quad (2.12)$$

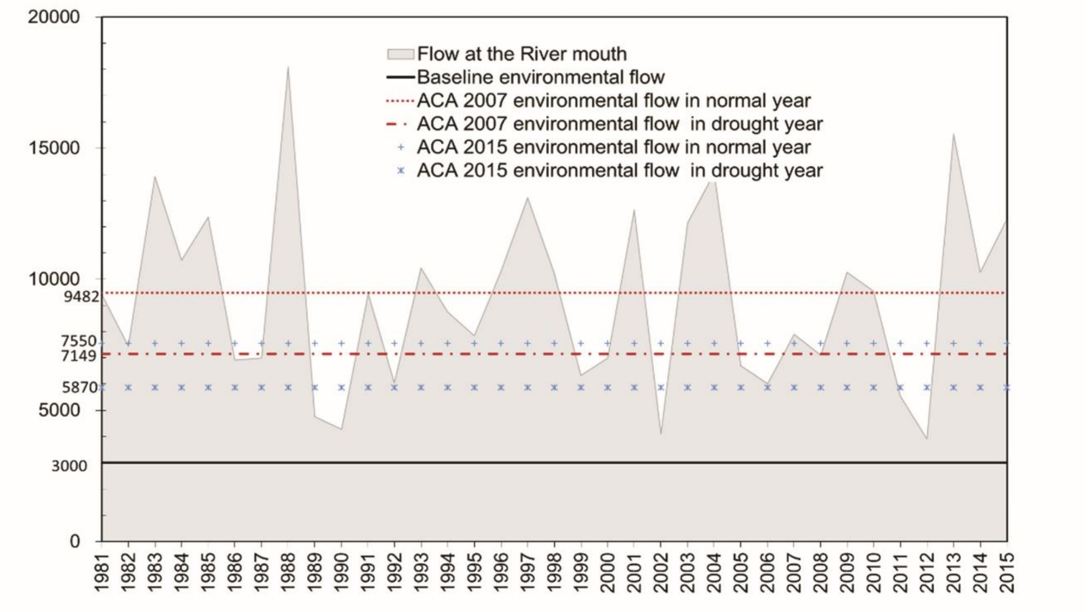
$$Q_{du};\ Q_{su} \geq 0 \quad (2.13)$$

where B_u^{URB} is the consumer and producer surplus of urban center u. Variables Q_{su} and Q_{du} are water supply and demand in urban center u. Parameters a_{du} and b_{du} are intercept and slope of the inverse demand function, and parameters a_{su} and b_{su} are the intercept and slope of the supply function. Equation (2.12) states that water supply must be greater of equal than demand. Water supply Q_{su} is the variable connecting the urban model with the hydrologic component. Water demand parameters for urban centers are based on the studies by Arbués et al. (2004) and Arbués et al. (2010).

2.3.3 Environmental component

Wetlands provide a diverse range of goods and services to society including food production, groundwater recharge, nutrients cycle, carbon capture, species habitat or recreation. Environmental benefits from ecosystems services can be represented by modeling the ecological response of these ecosystems and using available studies on the economic value of the different good and services they provide. However, to the best of our knowledge, the representation of environmental benefits in hydro-economic models is still quite limited. Some studies have included the water consumption of ecosystems in hydro-economic models (Ahmadi et al., 2012; Connor et al., 2013), but the insufficient knowledge on the ecosystems response to water and the lack of information on the economic benefits of ecosystems, prevents the inclusion of ecosystems in hydro-economic modeling. When the ecological response functions to water and the economic valuation studies are not available, a useful alternative is to represent the environmental uses of water by minimum environmental flow requirements (Girard et al., 2015; Jenkins and Lund, 2000). This is the approach taken in this study for the environmental component.

Figure 2.2. Ebro River flow and minimum environmental flow at the mouth (Mm^3).



Source: CHE (2016)

In the Ebro basin, the Water Plan establishes different environmental flows for the different river reaches in the basin. The most important environmental flow is in fact the one established for the Ebro mouth, because it affects the 'Delta del Ebro' which is the main ecosystems in the basin, and also all upstream water uses in the basin including ecosystems. To analyze the impact of the environmental flow at the mouth, a constraint of minimum mouth flow is added into our model. This constraint changes in the different scenarios that combine water availability in the basin and environmental flows at the mouth. The comparison of results is used to analyze the impacts on the whole basin of the different environmental flows at the river mouth, and to assess the implications for stakeholders of alternative water allocation policies.

In this study, the baseline environmental flow is the current level established in the Ebro Water Plan of 2015 setting a minimum flow of 3,000 Mm^3/year. Two other environmental flow levels are the two lobbied by the Agencia Catalana del Agua in 2007 [ACA (2007)] and in 2015 [ACA (2015)]. The ACA is the water agency in Cataluña, which is the downstream state in the Ebro basin. The ACA (2007) calls for a minimum flow of 9,482 Mm^3 in normal years and 7,149 Mm^3 during drought years. The ACA (2015) calls for a minimum flow of 7,550 Mm^3 in normal years and 5,870 Mm^3 in drought years (Figure 2.2). Each of these three environmental flow proposals (Water Plan, ACA 2007 and ACA 2015) is analyzed under two different water availability scenarios corresponding to normal and drought years. Finally, we analyze the alternative water allocation policies under water scarcity that could satisfy the three environmental flow proposals. The allocation policies considered are proportional shares, water markets, and priority of upstream regions. Figure 2.2 shows the historical Ebro river flows at the mouth, together with the environmental flow proposals.

It is important to mention that the proposal of the minimum environmental flow made by the Cataluña water agency in 2007 is incompatible with the hydrologic conditions of the Ebro basin. This is because the 9,482 Mm^3 minimum flow proposal in normal years is above 9.000 Mm^3, which is the average flow observed during the last thirty years. Such proposal will shut down a significant share of economic activities in all regions in the basin.

2.3.4 Policy analysis and environmental flows

The model optimizes the total basin benefits subject to the hydrological, technical and environmental constraints in every water sector and by spatial location. The optimization problem is given by the expression:

$$Max \sum_l B_l \quad \forall\, l = k, u \qquad (2.14)$$

subject to the constraints of equations (2.1)-(2.3), (2.5)-(2.8) and (2.11)-(2.12), where B_l are the benefits of each demand node l. The demand nodes in the hydro-economic model are the irrigation districts, urban centers and environmental flows, and the supply nodes are the rivers and dams. The regional economic component includes the irrigation districts and the urban centers in the basin (Figure A1 in appendix).

The hydro-economic model of the Ebro basin is used to analyze the impacts of the different levels of environmental flow at the river mouth. Additionally, we have included three water availability scenarios, of normal, moderate and severe drought conditions, to simulate the economic impacts from imposing different environmental flows under diverse hydroclimatic conditions. The inflows to the system under normal climate conditions are set at 14,600 Mm^3, which are the mean inflows for the period 2000-2014. These inflows are very close to the average inflow 14,700 Mm^3/year for the 1981-2006 period (CHE 2015). Under moderate and severe drought conditions, the basin inflows are reduced by 30% and 40% with respect to normal climate conditions, respectively. Three environmental flow scenarios are simulated following the environmental restrictions established by the Ebro Basin Plan and the two proposals of ACA (2007) and ACA (2015) being requested by the Cataluña state (see figure 2.2). The Basin Plan establishes an environmental flow of 3,000 Mm^3 at the mouth for normal and drought years, and this is the baseline scenario. In the case of droughts, the basin authority reduces water allocations proportionally for all irrigation uses in the basin, in order to satisfy the urban uses which have highest priority and the environmental flow constraint of 3,000 Mm^3.

Three water allocation policies are considered to analyze the ACA (2007) and ACA (2015) proposals of environmental flow when there is water scarcity because of drought: proportional share (which is the current allocation mechanism), water markets, and priority of water use by upstream regions. These alternative allocation policies result in very different benefit outcomes for stakeholders in downstream and upstream states. Since the downstream state (Cataluña) is asking for the huge increase of environmental flow in the mouth that is opposed by upstream states, the reasonable solution is that the bulk of the costs has to be borne by the downstream state. This solution correspond to the policy of upstream priority.

2.4. Results and policy implications

2.4.1 Baseline scenario of environmental flow and proportional allocation policy

The results of the water allocations and benefits under the baseline scenario of environmental flow (3,000 Mm^3) are presented in Table 2.1, showing the allocation of irrigation water by crop and irrigation technology. For normal climate conditions, the irrigation area is 528,000 ha divided between field crops (399,000 ha), fruit trees (104,000 ha), and vegetables (25.000 ha). By irrigation technology, 280,000 ha are under surface irrigation, 170,000 ha under sprinkle, and 78,000 ha under drip. The total water diversions are 5,400 Mm^3. Employment is 31,500 annual work units, and the net income generated is 635 million Euros.

As indicated, the main crops in the basin are field crops (75%), fruit trees (20%), and vegetables (5%), where Canal de Lodosa, Riegos del Jalón, Zadorra, Rioja and Canal de Navarra districts specialize in highly profitable vegetables and fruit trees. Riegos del Alto Aragón and Canal de Bardenas districts specialize in less profitable field crops. Other districts specializing in fruit trees are Canal de Aragón y Cataluña, Canal de Lodosa, Canal de Urgel and Riegos del Jalón.

During drought periods, the Basin Authority reduces the water allocated to irrigation districts proportionally, while allocation to urban centers is maintained. The provision of

Table 2.1. Outcomes from current and ACA 2015 flow scenarios with moderate drought.

	Normal year	**Moderate drought**			
Environmental flow	**3000**	**3000**	**5870 (ACA 2015)**		
Policy	**Baseline**	**Proportional**	**Proportional**	**Market**	**Priority**
Irrigated area (1.000 ha)	528	349	327	343	331
Cereals	399	235	215	227	219
Vegetables	25	21	20	21	21
Fruit trees	104	93	92	95	92
Labor (1.000 AWU)	31.5	26.1	25.5	26.1	25.4
Water use (Mm^3)	5,802	4,181	3,908	3,692	3,841
Agriculture water diversions	5,400	3,779	3,506	3,292	3,439
Urban water demand	402	402	402	402	402
Flow at the river mouth	8,890	5,710	5,870	5,870	5,870
Benefits (10^6 €)	2,492	2,341	2,321	2,337	2,325
Irrigation benefits	635	484	464	480	468
Urban benefits	1,857	1,857	1,857	1,857	1,857
Price of water (€/m^3)	0.04	0.09	0.16	0.15	0.15

water to urban centers has priority over any other use, including environmental flows. The urban use of water is maintained in all scenarios and the social surplus from urban use is almost 1,900 million Euros. Under moderate drought, water allocation to irrigation is reduced by 30%, down to 3,780 Mm^3. The effects of this reduction are smaller irrigated area (349,000 ha), net income (484 million €), and labor (26,100 AWU). The environmental flow at the river mouth is 5,710 Mm^3, well above the minimum environmental flow established at 3,000 Mm^3. Under a more extreme drought scenario, water allocation to irrigation is reduced by 40%, down to 3,530 Mm^3, with further reductions in irrigated area (304,000 ha), net income (444 million €), and labor (24,700 AWU). The production of field crops falls by half, because of their low profitability and high water requirements. The environmental flow at the river mouth is 4,650 Mm^3, which is also above the current minimum flow.

The results under moderate and severe drought scenarios show that in both cases the current 3,000 Mm^3 level of environmental flow are fulfilled. The proportional share policy distributes water shortages among all irrigation districts in the basin, and the drought costs are between 150-190 million Euro per year. These results suggest that the current water allocation regime in the Ebro basin is able to balance the economic activities with the environmental flow requirements of ecosystems, and this balance is maintained under different levels of water availability.

2.4.2 Environmental flow proposals ACA (2015) and ACA (2007) under different allocation policies

Under normal climate conditions, the environmental flow proposals are 9,480 Mm^3 by ACA (2007) and 7,550 Mm^3 by ACA (2015). These large increases over current minimum environmental flows (3,000 Mm^3) imply that more than half of the basin inflows have to be reserved for mouth streamflows in normal years. The ACA (2007) environmental flow is slightly above the 9,000 Mm^3 average flow in the river, so it would be almost feasible in normal years. The ACA (2015) environmental flow is below the average flow, so it is fully feasible in normal years. The ACA environmental flow scenarios are simulated only under moderate or severe drought, because in normal years environmental flows are above the requested thresholds.

The problem with the ACA claims appears clearly during drought years, because the flow at the mouth is only 5,710 Mm^3 under moderate drought and 4,650 Mm^3 under severe drought. Both ACA drought minimum flow requirements of 7,150 Mm^3 in ACA (2007) and 5,870 Mm^3 in ACA (2015) cannot be fulfilled even under moderate drought without curtailing the basin economic activities in order to reallocate water into the Ebro mouth. Since urban use has the highest priority, the shortfall during droughts to comply with the ACA claims requires the cutback of irrigation activities in the basin.

Three alternative water allocation policies are considered during droughts for water reallocation from irrigation into the Ebro streamflow in order to satisfy the ACA claims in the Ebro mouth: proportional sharing, water market, and priority of water use by upstream regions. The proportional sharing policy is the current policy enforced by the Ebro Water Authority during droughts. When there is water scarcity, water allocations in every basin location are reduced proportionally to the shortfall. The water market policy would allow water transfers between willing buyers and sellers, leading to private benefit gains. The policy of priority of water use by upstream regions is the following: if the downstream state (Cataluña) wants to increase the environmental flow at the mouth above 3,000 Mm^3 during periods of drought, the required water has to come first from curtailing downstream use of irrigation in the Cataluña region.

2.4.2.1. Water allocation policies under the ACA (2015) proposal and droughts

Proportional sharing: irrigation allocations are fixed shares of the available water in the basin, and they fall under drought scenarios. To satisfy the ACA environmental flow of

Table 2.2. Outcomes from current and ACA 2015 flow scenarios with severe drought.

	Normal year	**Severe drought**			
Environmental flow	**3000**	**3000**	**5870 (ACA 2015)**		
Policy	**Baseline**	**Proportional**	**Proportional**	**Market**	**Priority**
Irrigated area (1.000 ha)	528	304	139	153	141
Cereals	399	195	64	57	81
Vegetables	25	19	12	16	14
Fruit trees	104	90	63	80	46
Labor (1.000 AWU)	31,5	24.7	16.1	19.8	12.5
Water use (Mm^3)	5,802	3,635	1,704	1,413	1,491
Agriculture water diversions	5,400	3,533	1,302	1,211	1,089
Urban water demand	402	402	402	402	402
Flow at the river mouth	8,890	4,650	5,870	5,870	5,870
Benefits (10^6 €)	2,492	2,301	2,112	2,159	2,194
Irrigation benefits	635	444	255	302	237
Urban benefits	1,857	1,857	1,857	1,857	1,857
Price of water (€/m^3)	0.04	0.14	0.43	0.32	0.75

5,870 Mm^3 at the mouth during drought, the proportional sharing involves reducing irrigation water to 3,506 Mm^3 in moderate drought (-35% of baseline) and to 1,302 Mm^3 in severe drought (-76%) (Tables 2.1 and 2.2). The irrigated area falls sharply, mostly affecting low profitable field crops and less efficient surface irrigation technologies. Benefit losses of farmers are also strong from 171 million Euros in moderate drought (-27% of baseline) to 380 million Euro in severe drought (-60%). The losses sustained by farmers are evenly distributed among all irrigation districts in the basin.

Water market: the irrigation districts receive their allocation share, and then water trading between districts maximize their joint benefits. Irrigation water use is reduced to 3,292 Mm^3 under moderate drought (-39% of baseline) and to 1,211 Mm^3 under severe drought (-77%). The irrigated area with the water market policy is above the area cultivated with the proportional sharing policy. Benefit losses range between 155 million Euros in moderate drought (-25% of baseline) and 333 million in severe drought (-52%). Farmers would prefer water markets over proportional sharing allocation because of higher benefits with markets. The irrigation districts specializing in fruit trees and vegetables experience lower losses than districts specializing in field crops.

Priority of upstream regions: Cataluña is the downstream state asking for a steep increase in the environmental flow at the Ebro mouth. This policy places the burden of the water reallocation on the region requesting the reallocation of water from economic activities to the environmental, rather than on the upstream regions. The reallocation

Table 2.3. Upstream and downstream benefits under flow scenarios by climate (10^6 €).

Environmental flow/Policy	Climate					
	Moderate drought			Severe drought		
	Region			Region		
	Upstream	Downstream	Basin	Upstream	Downstream	Basin
Baseline (3,000 Mm^3)						
Proportional	357	127	484	328	116	444
ACA 2015 (5,870 Mm^3)						
Proportional	342	122	464	185	70	255
Market	359	121	480	229	73	302
Upstream priority	357	111	468	237	0	237
ACA 2007 (7,150 Mm^3)						
Proportional	202	75	277	Unfeasible[a]	Unfeasible	Unfeasible
Market	245	79	324	Unfeasible	Unfeasible	Unfeasible
Upstream priority	258	0	258	Unfeasible	Unfeasible	Unfeasible

[a]: "Unfeasible" indicates that there is no solution under severe drought because the environmental flow can not be reached even by cutting off all irrigation in the basin.

effort is made first by the irrigation districts located in the downstream region, and then any additional reallocation to meet the environmental flow at the mouth is made by the upstream regions. Under moderate drought, irrigation water in the basin falls to 3,439 Mm^3 (-36% of baseline), and the burden of the water reallocation is supported by the downstream region. In this region, the reduction of irrigation water with respect to the baseline is 45%, 30% because of the drought and 15% to cover the 5,870 Mm^3 environmental flow requirements. The reduction in upstream regions is 30% to cover the drought shortfall.

Under severe drought, the use of irrigation water at basin level is 1,089 Mm^3 feeding 103,000 ha of crop activities. All irrigation water in Catalonia is reallocated to the environmental flow of the Ebro mouth, while in upstream irrigation districts the use of water falls by 65% with respect to the baseline, compared to 76 percent under the proportional sharing policy. There is a full loss of benefits in Cataluña amounting to 167 million Euros with respect to the baseline. In the upstream regions the benefit loss is 233 million Euro. This loss is 50% of the baseline compared to 60% loss under the proportional sharing policy. The policy of priority of upstream regions during severe droughts is extremely costly to Cataluña for the 5,870 Mm^3 environmental flow requirement, but it is also very costly for upstream regions which are against raising the requirement. If Cataluña wants to raise the environmental flow from 3,000 Mm^3 up to 5,870 Mm^3 during severe drought years, the rest of regions could ask Cataluña for compensation of their losses. This compensation would amount to 91 million Euros, which is the benefit difference in upstream regions under severe drought between having the 3,000 Mm3 threshold (328 million €) and having the 5,870 Mm3 threshold (237 million €) (Table 2.3). Then under upstream priority and compensation to upstream states, the total costs for Cataluña of raising the environmental threshold would be 207 million Euros, the sum of the loss of 116 million from the upstream priority policy, plus the 91 million of compensation to upstream farmers.

2.4.2.2. Water allocation policies under the ACA (2007) proposal and droughts

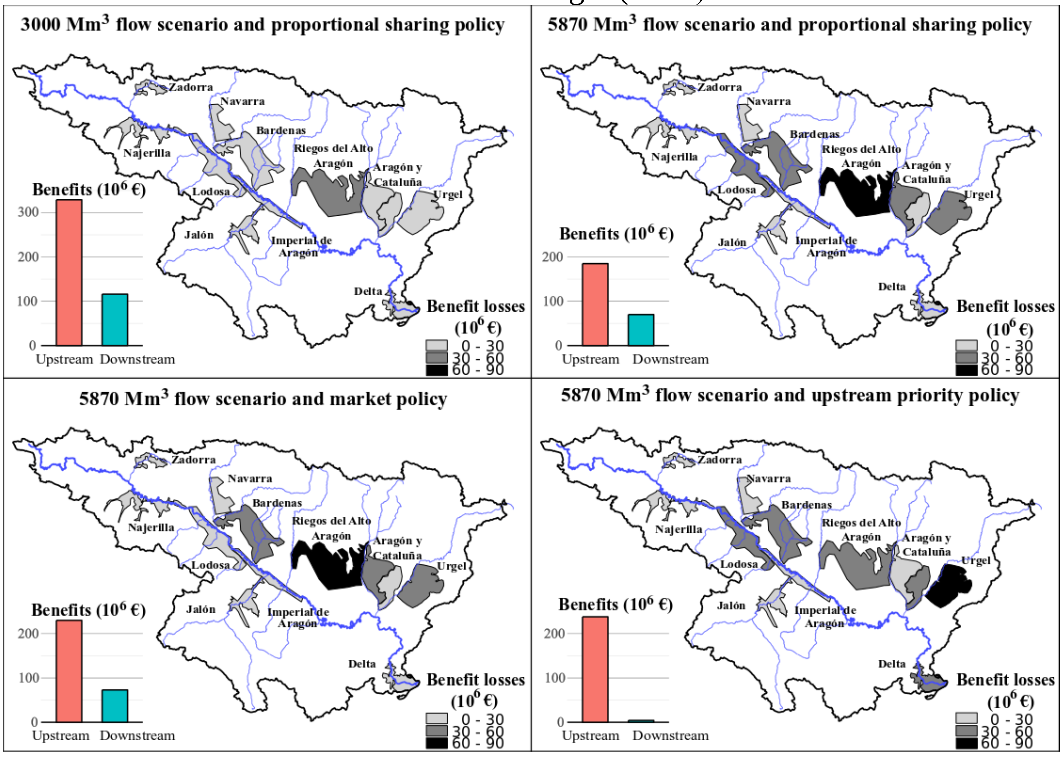
Under moderate drought, the ACA (2007) claim of increasing environmental flow from 3,000 up to 7,150 Mm^3 cuts the farmers benefits by more than half with respect to a normal year for the three allocation policies, falling from 635 to between 260 and 320 million Euros (Table A10 in appendix). By expanding the environmental flow from the current 3,000 to 7,150 Mm^3 during drought, the percentage of farmers losses doubles to more than 50% under any allocation policy.

Under severe drought, the ACA (2007) environmental flow claim is unfeasible, which means that the 7,150 Mm^3 of environmental flow can not be achieved even by cutting all irrigation use in the basin. These results indicate that the ACA (2007) proposal of environmental flow under drought is untenable. This is not only because this flow level is impossible to achieve under severe drought, but also because under moderate drought the massive losses to farmers would make this flow claim politically unfeasible.

Table 2.3 summarizes the results, by showing the benefits to upstream and downstream regions from the three water allocation policies under the environmental flow scenarios and climate conditions. Implementing the ACA (2015) proposal and the policy of upstream priority under moderate drought will maintain the benefits of upstream regions in relation to the baseline at 357 million Euros, but under severe drought the benefits of upstream regions fall by 91 million Euros with respect to the baseline. Implementing the ACA (2007) proposal and the policy of upstream priority under moderate drought will reduce the benefits of upstream regions by 99 million Euros, and this environmental flow proposal is unfeasible under severe drought.

Considering both the ACA (2015) and ACA (2007) proposals, the main outcomes from the three allocation policies are the following: i) raising the environmental flow of the Ebro mouth escalates the losses of benefits during droughts, and the losses become untenable in severe drought; ii) the water market policy is an alternative policy that could achieve higher benefits under both the moderate and severe droughts; iii) the bulk of the negative impact of raising the environmental flow requirements under droughts is

Figure 2.3. Benefits for the current (3,000) and ACA 2015 (5,870) flow scenarios, under severe drought (10^6 €)[a].



[a]: Benefit losses are calculated with respect to the baseline (normal year).

supported by the farmers of field crops; and iv) the proportional sharing policy distributes the benefit losses evenly among all basin regions, achieving higher total basin benefits compared to the upstream priority policy. However, the upstream regions could obtain higher benefits with the upstream priority policy than with the proportional sharing policy (Figure 2.3).

2.5. Conclusions

There is a growing concern in societies across the world regarding the escalating water scarcity in basins located in arid and semi-arid regions. Expanding human water demands are resulting in severe ecosystem degradation but also on serious threats to human activities. These emerging social demands call for securing minimum environmental flows for water-dependent ecosystems, which further increase the competition for already scarce water in basins exacerbated during drought periods.

This study contributes to the debate on water allocation in the Ebro basin of Spain. The paper analyzes the current disputes among states and the different basin stakeholders over the environmental flow at the Ebro mouth. We have developed a hydro-economic model of the Ebro basin which integrates various hydrological, economic and environmental components and includes the main irrigation districts and urban centers in the basin. The model is used to analyze three scenarios of environmental flow at the river mouth under normal and drought climate conditions. The environmental flow scenarios are the current flow of 3,000 Mm^3 established in the Ebro Water Plan, and the ACA 2007 and 2015 proposals of the downstream state (Cataluña) of raising the minimum environmental flow at the Ebro mouth between two and three times. Additionally, three allocation policies (upstream priority, proportional sharing, and water markets) have been simulated to analyze the different ways of sharing the costs imposed by raising the current environmental flow. The allocation policies are implemented in order to comply with the environmental flows proposals under different water stress scenarios.

Results show that under the current environmental flow requirement of 3,000 Mm^3, drought events already generate important losses of benefits to farmers. The adaptation of irrigation districts to drought consists in modifying both the crop pattern and the relative share of irrigation systems, concentrating production in the more profitable crops. The adjustment to water scarcity reduces the production of field crops cultivated in surface irrigation systems. The capability of response to drought conditions is higher in areas with profitable crops under advanced irrigation systems. The current minimum environmental flow requirement at the river mouth does not restrict the economic activities in the basin under any climate condition, and this flow level also facilitates a more flexible water management in the future.

Accepting the claims of Cataluña and raising the minimum environmental flow by two or three times at the Ebro mouth increase significantly the benefit losses sustained by farmers during droughts. These losses depend on the water allocation policy chosen. The policies considered are proportional sharing, water market, and priority of upstream regions. The comparison between these policies during droughts shows that the water market policy is a feasible alternative that achieves higher economic benefits in the basin. The policy of proportional sharing generates higher benefits than the policy of priority of upstream regions, and it is also more equitable by distributing the drought losses evenly among regions in the basin. This is because this policy favors the irrigation districts with low profitable crops and less advanced irrigation systems. The policy of upstream priority places the burden of adjusting to drought over the downstream region of Cataluña.

The reason behind the policy of upstream priority is that the downstream state of Cataluña is asking for a steep increase of the current environment flow requirement between two and three times, and upstream states will sustain heavy losses and are not willing to accept this proposal. The policy of upstream priority shifts therefore the costs of reaching the higher environmental flow towards the downstream region requesting it first, rather than spreading the costs evenly among all regions in the basin. So, the reallocation effort is made first by the irrigation districts downstream, and then any additional reallocation to meet the environmental flow threshold is made by the upstream regions. Our results indicate that the proposal by Cataluña of expanding environmental flows is very costly to farmers in other states of the basin. This negative impact could be reduced somehow by the policy of upstream priority, but benefit losses remain in some cases. One possibility to gain the support of these regions is by providing payments from the Cataluña downstream state to the upstream states to compensate for any remaining losses they could sustain because of the increase of environmental flow at the Ebro mouth. Policy tradeoffs and other political economy aspects for a more sustainable management have been examined in the Ebro basin. This is an illustrative case for exploring the political viability of reallocating water to the environment, which may entail important lessons for other basin in arid and semiarid regions.

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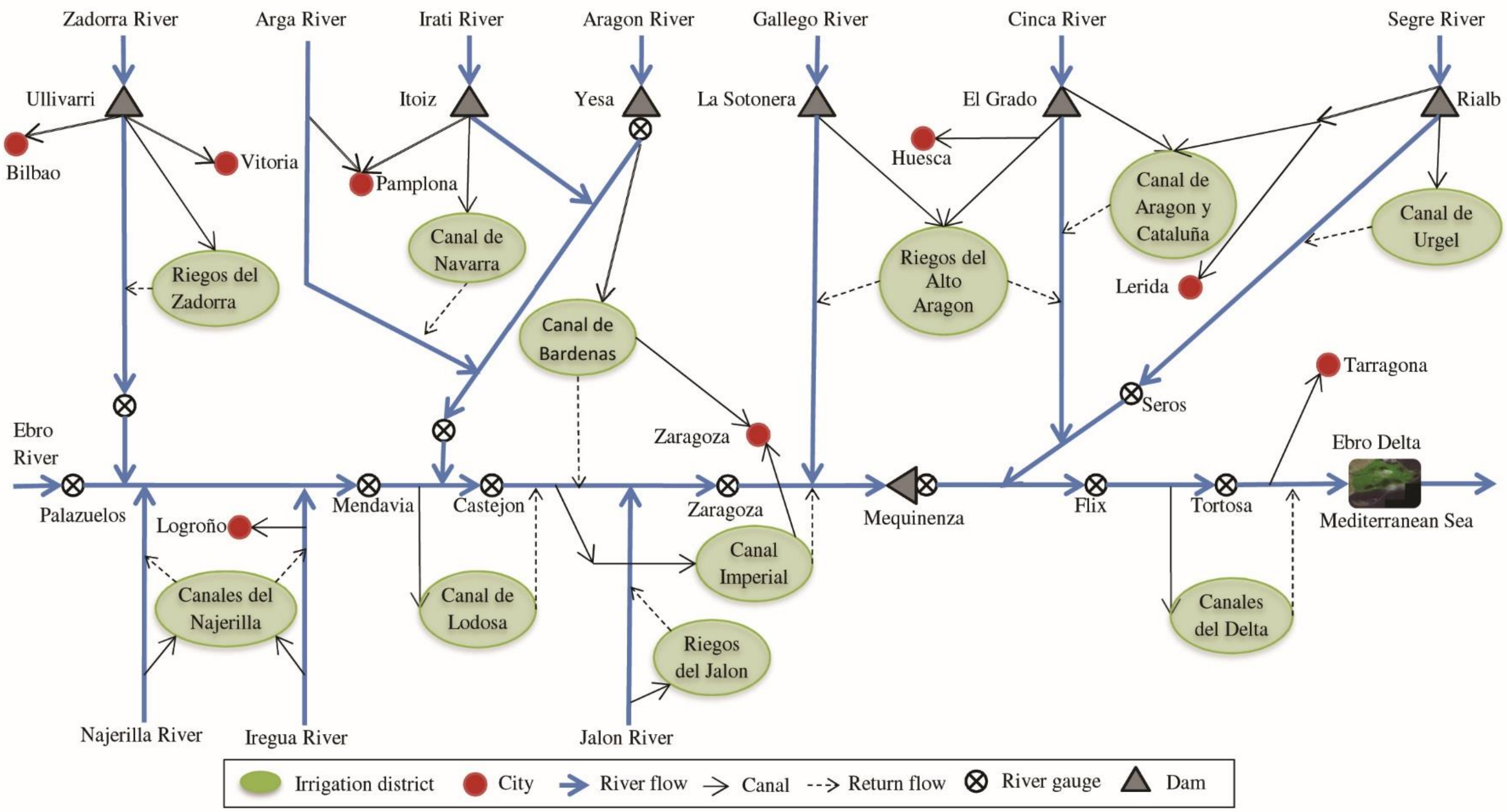
2.7. Appendix

2.7.1 Irrigation districts and urban centers and the Ebro Basin network

The irrigation districts considered are shown in figure A1 (upstream to downstream): Regadíos del Zadorra (ZA), Canales del Najerilla (CN), Canal de Lodosa (LO), Canal de Navarra (NA), Canal de Bárdenas (BA), Canal Imperial (IM), Regadíos del Jalón (JA), Riegos del Alto Aragón (RA), Canal de Aragón y Cataluña in Aragón (AA), Canal de Aragón y Cataluña in Cataluña (AC), Canal de Urgel (UR) y Canales del Delta (DE). The model of urban use includes the main towns of Vitoria, Logroño, Pamplona, Zaragoza, Huesca y Lérida, and the inter-basin water transfers to Bilbao and Tarragona.

Figure A1. Network of the Ebro River Basin.



2.7.2 Modelling framework, and Outcomes from current and ACA 2007 flow scenarios with moderate drought

Figure A2. Modelling framework.

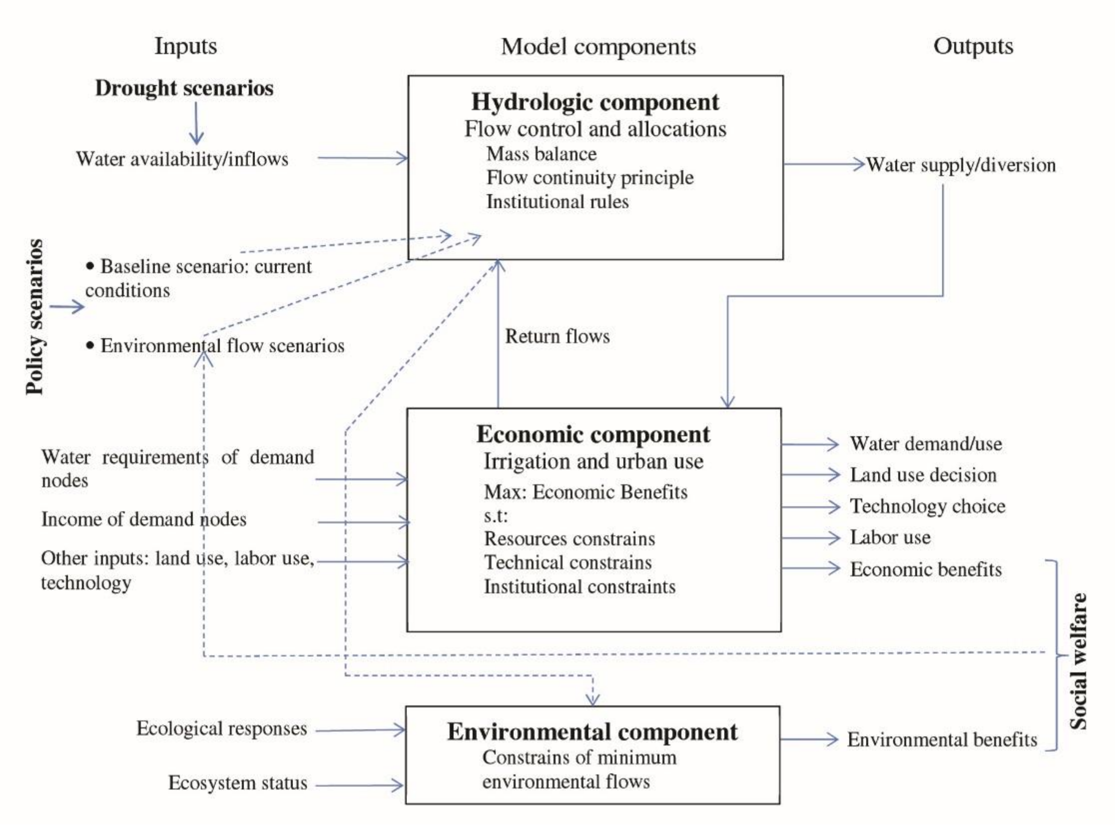


Table A2. Outcomes from current and ACA 2007 flow scenarios with moderate drought.

	Normal year	**Moderate drought**			
Environmental flow	**3000**	**3000**	**7150 (ACA 2007)**		
Policy	**Baseline**	**Proportional**	**Proportional**	**Market**	**Priority**
Irrigated area (1.000 ha)	528	349	154	172	158
Cereals	399	235	74	72	94
Vegetables	25	21	13	17	15
Fruit trees	104	93	67	83	49
Labor (1.000 AWU)	31.5	26.1	17.4	20.6	13.4
Water use (Mm^3)	5,802	4,181	1,872	1,784	1,653
Agriculture water diversions	5,400	3,779	1,470	1,382	1,251
Urban water demand	402	402	402	402	402
Flow at the river mouth	8,890	5,710	7,150	7,150	7,150
Benefits (10^6 €)	2,492	2,341	2,134	2,181	2,115
Irrigation benefits	635	484	277	324	258
Urban benefits	1,857	1,857	1,857	1,857	1,857
Price of water (€/m^3)	0.04	0.09	0.38	0.29	0.71

2.7.3 Disaggregated results by irrigation district

Table A3. Land use and labor under climate conditions an environmental flow scenario (1.000 ha y 1.000 AWU).

Climate: Normal

Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Irrigated área	6	22	56	23	78	27	21	110	49	34	72	31	528
Cereals	2	7	25	18	73	24	8	106	40	20	56	21	399
Vegetables	1	5	8	3	3	2	0	1	0	0	1	1	25
Fruit trees	3	10	22	2	2	2	13	3	9	14	15	9	104
Sprinkler	0	4	8	10	16	5	3	62	33	16	12	0	170
Drip	1	5	15	4	2	2	10	3	7	12	7	9	78
Surface	5	12	33	9	59	20	7	46	9	6	53	21	280
Labor	0.3	1.5	8.0	1.2	1.7	1.0	2.3	2.3	2.5	3.2	4.3	3.2	31.5
ACA 2015 environmental flow scenario proportional sharing													
Irrigated area	6	22	56	23	78	27	21	110	49	34	72	31	528
Cereals	2	7	25	18	73	24	8	106	40	20	56	21	399
Vegetables	1	5	8	3	3	2	0	1	0	0	1	1	25
Fruit trees	3	10	22	2	2	2	13	3	9	14	15	9	104
Sprinkler	0	4	8	10	16	5	3	62	33	16	12	0	170
Drip	1	5	15	4	2	2	10	3	7	12	7	9	78
Surface	5	12	33	9	59	20	7	46	9	6	53	21	280
Labor	0.3	1.5	8.0	1.2	1.7	1.0	2.3	2.3	2.5	3.2	4.3	3.2	31.5
ACA 2015 environmental flow scenario market													
Irrigated area	6	22	56	23	78	27	21	110	49	34	72	31	528
Cereals	2	7	25	18	73	24	8	106	40	20	56	21	399
Vegetables	1	5	8	3	3	2	0	1	0	0	1	1	25
Fruit trees	3	10	22	2	2	2	13	3	9	14	15	9	104
Sprinkler	0	4	8	10	16	5	3	62	33	16	12	0	170
Drip	1	5	15	4	2	2	10	3	7	12	7	9	78
Surface	5	12	33	9	59	20	7	46	9	6	53	21	280
Labor	0.3	1.5	8.0	1.2	1.7	1.0	2.3	2.3	2.5	3.2	4.3	3.2	31.5
ACA 2015 environmental flow scenario upstream priority													
Irrigated area	6	22	56	23	78	27	21	110	49	34	72	31	528
Cereals	2	7	25	18	73	24	8	106	40	20	56	21	399
Vegetables	1	5	8	3	3	2	0	1	0	0	1	1	25
Fruit trees	3	10	22	2	2	2	13	3	9	14	15	9	104
Sprinkler	0	4	8	10	16	5	3	62	33	16	12	0	170
Drip	1	5	15	4	2	2	10	3	7	12	7	9	78
Surface	5	12	33	9	59	20	7	46	9	6	53	21	280
Labor	0.3	1.5	8.0	1.2	1.7	1.0	2.3	2.3	2.5	3.2	4.3	3.2	31.5

Climate: Moderate drought

Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Irrigated área	4	13	39	15	51	17	14	74	32	22	46	21	349
Cereals	1	1	11	10	47	14	3	70	23	10	31	12	235
Vegetables	1	3	7	3	2	1	0	1	0	0	1	1	21
Fruit trees	3	9	20	2	2	2	11	3	8	12	13	8	93
Sprinkler	0	1	4	6	13	4	2	44	19	8	8	0	109
Drip	1	5	14	4	2	2	9	2	7	10	6	8	71
Surface	3	8	20	5	36	11	4	27	6	3	32	13	168
Labor	0.3	1.2	7.1	1.0	1.2	0.8	2.0	1.6	2.1	2.7	3.6	2.8	26.1
ACA 2015 environmental flow scenario proportional sharing													
Irrigated area	4	12	37	14	48	16	13	70	30	21	43	20	327
Cereals	1	1	10	9	44	13	2	66	21	8	29	11	215
Vegetables	1	3	7	3	2	1	0	1	0	0	1	1	20
Fruit trees	3	9	20	2	2	2	11	3	8	12	13	8	92
Sprinkler	0	1	4	6	12	3	1	42	18	7	8	0	102
Drip	1	5	14	4	2	2	9	2	7	10	6	8	70
Surface	3	7	19	4	33	10	3	27	5	3	29	12	154
Labor	0.3	1.1	7.0	0.9	1.1	0.8	1.9	1.5	2.0	2.7	3.5	2.7	25.5
ACA 2015 environmental flow scenario market													
Irrigated area	5	16	45	16	38	18	17	70	34	25	46	13	343
Cereals	1	3	16	12	34	15	5	66	25	12	32	4	227
Vegetables	1	4	8	3	2	1	0	1	0	0	1	1	21
Fruit trees	3	9	21	2	2	2	12	3	8	13	13	8	95
Sprinkler	0	2	5	7	10	4	2	41	20	10	8	0	109
Drip	1	5	14	4	2	2	9	2	7	11	6	8	71
Surface	3	10	25	6	26	13	6	27	6	4	32	5	163
Labor	0.3	1.3	7.4	1.0	1.0	0.8	2.1	1.5	2.1	2.8	3.5	2.4	26.1
ACA 2015 environmental flow scenario upstream priority													
Irrigated area	4	13	39	15	51	17	14	74	32	18	37	18	331
Cereals	1	1	11	10	47	14	3	70	23	6	24	9	219
Vegetables	1	3	7	3	2	1	0	1	0	0	1	1	21
Fruit trees	3	9	20	2	2	2	11	3	8	12	13	8	92
Sprinkler	0	1	4	6	13	4	2	44	19	5	7	0	105
Drip	1	5	14	4	2	2	9	2	7	10	6	8	70
Surface	3	8	20	5	36	11	4	27	6	3	24	10	156
Labor	0.3	1.2	7.1	1.0	1.2	0.8	2.0	1.6	2.1	2.5	3.6	2.6	25.4

Climate: Severe drought

Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Irrigated área	4	11	35	13	44	14	12	65	28	19	40	19	304
Cereals	1	1	8	8	40	11	1	61	19	7	27	10	195
Vegetables	1	2	7	3	2	1	0	1	0	0	1	1	19
Fruit trees	3	8	19	2	2	2	11	3	8	12	13	8	90
Sprinkler	0	0	4	5	12	3	1	40	16	5	7	0	95
Drip	1	4	14	4	2	2	9	2	7	10	6	8	69
Surface	3	6	17	4	30	9	3	23	5	3	27	11	140
Labor	0.2	1.1	6.8	0.9	1.1	0.8	1.8	1.4	2.0	2.6	3.4	2.7	24.7
ACA 2015 environmental flow scenario proportional sharing													
Irrigated area	2	5	16	6	21	6	4	30	12	8	17	11	139
Cereals	0	0	0	2	17	3	0	27	5	0	6	2	64
Vegetables	0	0	5	2	2	1	0	1	0	0	0	1	12
Fruit trees	2	5	11	2	2	2	4	3	7	8	11	8	63
Sprinkler	0	0	0	2	8	1	0	20	5	0	3	0	38
Drip	1	3	10	3	2	2	4	2	6	7	5	8	52
Surface	1	2	7	1	11	3	0	9	2	1	9	3	49
Labor	0.2	0.4	4.3	0.7	0.7	0.6	0.6	0.7	1.5	1.6	2.5	2.3	16.1
ACA 2015 environmental flow scenario market													
Irrigated area	3	11	30	9	7	6	12	22	15	14	17	7	153
Cereals	0	0	5	5	5	4	2	20	7	3	7	0	57
Vegetables	1	2	7	2	1	1	0	1	0	0	0	1	16
Fruit trees	2	8	18	2	1	1	11	2	7	11	10	6	80
Sprinkler	0	0	2	3	2	1	1	13	6	2	2	0	33
Drip	1	4	13	3	2	1	8	2	6	9	5	6	60
Surface	2	6	15	3	3	3	3	8	3	2	10	0	60
Labor	0.2	1.0	6.5	0.8	0.4	0.6	1.8	0.6	1.6	2.2	2.4	1.7	19.8
ACA 2015 environmental flow scenario upstream priority													
Irrigated area	3	7	23	8	28	8	7	41	17	0	0	0	141
Cereals	0	0	1	4	24	5	0	37	9	0	0	0	81
Vegetables	0	1	6	2	2	1	0	1	0	0	0	0	14
Fruit trees	2	6	16	2	2	2	7	3	8	0	0	0	46
Sprinkler	0	0	1	3	9	2	0	27	8	0	0	0	49
Drip	1	3	12	3	2	2	6	2	6	0	0	0	38
Surface	2	3	10	2	16	4	1	12	3	0	0	0	54
Labor	0.2	0.6	5.8	0.8	0.8	0.6	1.1	0.9	1.7	0.0	0.0	0.0	12.5

ZA: Regadios del Zadorra; CN: Canales del Najerilla; LO: Canal de Lodosa; NA: Canal de Navarra; BA: Canal de Bardenas; IM: Canal Imperial; JA: Regadios del Jalon; RA: Riegos del Alto Aragon; AA: Canal de Aragon y Cataluña in Aragon; AC: Canal de Aragon y Cataluña in Cataluña; UR: Canal de Urgel; DE: Canales del Delta.

Table A4. Land use and labor under climate conditions an environmental flow scenario (1.000 ha y 1.000 AWU).

Climate	Normal													Moderate drought													Severe drought												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario																																							
Irrigated area	6	22	56	23	78	27	21	110	49	34	72	31	528	4	13	39	15	51	17	14	74	32	22	46	21	349	4	11	35	13	44	14	12	65	28	19	40	19	304
Cereals	2	7	25	18	73	24	8	106	40	20	56	21	399	1	1	11	10	47	14	3	70	23	10	31	12	235	1	1	8	8	40	11	1	61	19	7	27	10	195
Vegetables	1	5	8	3	3	2	0	1	0	0	1	1	25	1	3	7	3	2	1	0	1	0	0	1	1	21	1	2	7	3	2	1	0	1	0	0	1	1	19
Fruit trees	3	10	22	2	2	2	13	3	9	14	15	9	104	3	9	20	2	2	2	11	3	8	12	13	8	93	3	8	19	2	2	2	11	3	8	12	13	8	90
Sprinkler	0	4	8	10	16	5	3	62	33	16	12	0	170	0	1	4	6	13	4	2	44	19	8	8	0	109	0	0	4	5	12	3	1	40	16	5	7	0	95
Drip	1	5	15	4	2	2	10	3	7	12	7	9	78	1	5	14	4	2	2	9	2	7	10	6	8	71	1	4	14	4	2	2	9	2	7	10	6	8	69
Surface	5	12	33	9	59	20	7	46	9	6	53	21	280	3	8	20	5	36	11	4	27	6	3	32	13	168	3	6	17	4	30	9	3	23	5	3	27	11	140
Labor	0.3	1.5	8.0	1.2	1.7	1.0	2.3	2.3	2.5	3.2	4.3	3.2	31.5	0.3	1.2	7.1	1.0	1.2	0.8	2.0	1.6	2.1	2.7	3.6	2.8	26.1	0.2	1.1	6.8	0.9	1.1	0.8	1.8	1.4	2.0	2.6	3.4	2.7	24.7
ACA 2007 [illegible]																																							
Irrigated area	5	18	48	20	66	23	18	94	42	29	60	26	449	2	5	18	7	23	7	5	34	14	9	20	11	154													
Cereals	2	4	19	14	62	19	5	90	33	15	46	17	326	0	0	0	3	19	4	0	30	6	0	8	3	74													
Vegetables	1	4	8	3	3	2	0	1	0	0	1	1	23	0	0	5	2	2	1	0	1	0	0	1	1	13													
Fruit trees	3	9	21	2	2	2	12	3	9	13	14	9	99	2	5	13	2	2	2	5	3	7	9	11	8	67													
Sprinkler	0	3	6	8	15	5	2	54	27	13	10	0	143	0	0	0	2	8	2	0	22	6	0	3	0	43													
Drip	1	5	15	4	2	2	10	3	7	11	7	9	75	1	3	11	3	2	2	4	2	6	8	5	8	55													
Surface	4	10	27	7	49	16	6	38	8	5	44	18	231	1	3	8	1	12	3	1	9	2	1	11	4	56													
Labor	0.3	1.3	7.6	1.1	1.5	0.9	2.1	2.0	2.3	3.0	4.0	3.0	29.2	0.2	0.5	1.9	0.7	0.7	0.6	0.8	0.8	1.6	1.9	2.6	2.3	17.4													
ACA 2007 environmental flow scenario market																																							
Irrigated area	6	20	51	21	61	24	19	95	43	30	61	24	454	3	11	32	10	10	7	13	27	16	15	21	7	172													
Cereals	2	6	22	15	57	20	7	90	34	17	47	15	331	0	1	6	6	7	5	2	24	9	4	9	0	72													
Vegetables	1	4	9	3	2	2	0	1	0	0	1	1	24	1	2	7	2	2	1	0	1	0	0	1	1	17													
Fruit trees	3	10	22	2	2	2	12	3	9	13	14	9	100	2	8	19	2	1	2	11	3	7	11	11	6	83													
Sprinkler	0	3	7	9	14	5	3	54	28	17	10	0	146	0	0	3	3	3	2	1	15	7	3	3	0	41													
Drip	1	5	15	4	2	2	10	3	7	11	7	9	75	1	4	13	3	2	2	8	2	6	9	5	6	62													
Surface	4	11	30	8	45	17	7	38	8	5	45	15	233	2	7	16	3	5	4	3	9	3	2	13	0	69													
Labor	0.3	1.4	7.8	1.1	1.4	0.9	2.2	2.0	2.4	3.1	4.0	2.9	29.4	0.2	1.1	6.6	0.8	0.5	0.6	1.8	0.7	1.6	2.3	2.6	1.8	20.6													
ACA 2007 environmental flow scenario upstream priority																																							
Irrigated area	6	22	56	23	78	27	21	110	49	17	35	17	461	3	8	25	9	31	9	8	46	19	0	0	0	158													
Cereals	2	7	25	18	73	24	8	106	40	6	22	9	338	0	0	2	5	27	7	0	42	11	0	0	0	94													
Vegetables	1	5	8	3	3	2	0	1	0	0	1	1	25	1	1	6	2	2	1	0	1	0	0	0	0	15													
Fruit trees	3	10	22	2	2	2	13	3	9	12	13	8	98	2	6	17	2	2	2	8	3	8	0	0	0	49													
Sprinkler	0	4	8	10	16	5	3	62	33	5	7	0	153	0	0	1	3	10	2	0	30	9	0	0	0	56													
Drip	1	5	15	4	2	2	10	3	7	10	6	8	75	1	4	13	3	2	2	7	2	6	0	0	0	40													
Surface	5	12	33	9	59	20	7	46	9	3	23	9	234	2	4	11	2	19	5	1	14	3	0	0	0	63													
Labor	0.3	1.5	8.0	1.2	1.7	1.0	2.3	2.3	2.5	2.5	3.2	2.6	29.1	0.2	0.7	6.1	0.8	0.8	0.6	1.3	1.0	1.7	0.0	0.0	0.0	13.4													

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Table A5. Agricultural and urban water use under climate conditions and environmental flow scenarios (Mm^3).

Climate	Normal													Moderate drought													Severe drought												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline																																							
Agriculture water diversions	53	124	331	156	792	202	123	998	366	243	791	1,203	5,382	37	85	229	109	554	162	85	698	255	168	550	847	3,779	32	72	195	94	475	139	72	598	218	143	470	725	3,233
Flow at the river mouth													8,890													5,710													4,650
Urban water demand													402													402													402
ACA 2015 environmental flow scenario and proportional sharing policy																																							
Agriculture water diversions	44	104	277	131	665	170	103	838	307	203	664	1,008	5,382	34	78	212	101	514	150	78	648	237	156	510	786	3,506	12	24	72	39	198	57	22	249	89	53	189	298	1,302
Flow at the river mouth													8,890													5,870													5,870
Urban water demand													402													402													402
ACA 2015 environmental flow scenario and market policy																																							
Agriculture water diversions	46	139	300	139	618	176	113	840	319	216	674	895	5,382	39	104	277	122	400	400	109	658	270	191	546	403	3,292	22	68	162	64	64	61	72	175	105	96	190	131	1,211
Flow at the river mouth													8,890													5,870													5,870
Urban water demand													402													402													402
ACA 2015 environmental flow scenario and upstream priority policy																																							
Agriculture water diversions	53	124	331	157	792	202	123	998	366	116	383	587	5,382	37	85	229	109	554	162	85	698	255	131	430	664	3,439	18	38	109	57	277	80	37	349	126	0	0	0	1,089
Flow at the river mouth													8,890													5,870													5,870
Urban water demand													402													402													402

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Table A6. Agricultural and urban water use under climate conditions and environmental flow scenarios (Mm^3).

Climate	Normal												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline													
Agriculture water diversions	53	124	331	156	792	202	123	998	366	243	791	1,203	5,382
Flow at the river mouth													8,890
Urban water demand													402
ACA 2007 environmental flow scenario and proportional sharing policy													
Agriculture water diversions	44	104	277	131	665	170	103	838	307	203	664	1,008	4,514
Flow at the river mouth													9,480
Urban water demanda													402
ACA 2007 environmental flow scenario and market policy													
Agriculture water diversions	46	139	300	139	618	176	113	840	319	216	674	895	4,446
Flow at the river mouth													9,480
Urban water demand													402
ACA 2007 environmental flow scenario and upstream priority policy													
Agriculture water diversions	53	124	331	157	792	202	123	998	366	116	383	587	4,233
Flow at the river mouth													9,480
Urban water demand													402

Climate	Moderate drought												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline													
Agriculture water diversions	37	85	229	109	554	162	85	698	255	168	550	847	3,779
Flow at the river mouth													5,710
Urban water demand													402
ACA 2007 environmental flow scenario and proportional sharing policy													
Agriculture water diversions	14	29	83	43	221	64	26	279	100	62	214	335	1,470
Flow at the river mouth													7,150
Urban water demanda													402
ACA 2007 environmental flow scenario and market policy													
Agriculture water diversions	23	74	174	72	91	73	76	209	118	104	229	139	1,382
Flow at the river mouth													7,150
Urban water demand													402
ACA 2007 environmental flow scenario and upstream priority policy													
Agriculture water diversions	21	45	127	62	316	92	44	399	145	0	0	0	1,251
Flow at the river mouth													7,150
Urban water demand													402

Climate	Severe drought												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline													
Agriculture water diversions	32	72	195	94	475	139	72	598	218	143	470	725	3,233
Flow at the river mouth													4,650
Urban water demand													402
ACA 2007 environmental flow scenario and proportional sharing policy													
Agriculture water diversions													
Flow at the river mouth													
Urban water demanda													
ACA 2007 environmental flow scenario and market policy													
Agriculture water diversions													
Flow at the river mouth													
Urban water demand													
ACA 2007 environmental flow scenario and upstream priority policy													
Agriculture water diversions													
Flow at the river mouth													
Urban water demand													

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Table A7. Agricultural and urban water use under climate conditions and environmental flow scenarios (Mm^3).

Climate	Normal												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline													
Agriculture water diversions	53	124	331	156	792	202	123	998	366	243	791	1,203	5,382
Flow at the river mouth													8,890
Urban water demand													402
ACA 2007 environmental flow scenario and proportional sharing policy													
Agriculture water diversions	44	104	277	131	665	170	103	838	307	203	664	1,008	4,514
Flow at the river mouth													9,480
Urban water demanda													402
ACA 2007 environmental flow scenario and market policy													
Agriculture water diversions	46	139	300	139	618	176	113	840	319	216	674	895	4,446
Flow at the river mouth													9,480
Urban water demand													402
ACA 2007 environmental flow scenario and upstream priority policy													
Agriculture water diversions	53	124	331	157	792	202	123	998	366	116	383	587	4,233
Flow at the river mouth													9,480
Urban water demand													402

Climate	Moderate drought												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline													
Agriculture water diversions	37	85	229	109	554	162	85	698	255	168	550	847	3,779
Flow at the river mouth													5,710
Urban water demand													402
ACA 2007 environmental flow scenario and proportional sharing policy													
Agriculture water diversions	14	29	83	43	221	64	26	279	100	62	214	335	1,470
Flow at the river mouth													7,150
Urban water demanda													402
ACA 2007 environmental flow scenario and market policy													
Agriculture water diversions	23	74	174	72	91	73	76	209	118	104	229	139	1,382
Flow at the river mouth													7,150
Urban water demand													402
ACA 2007 environmental flow scenario and upstream priority policy													
Agriculture water diversions	21	45	127	62	316	92	44	399	145	0	0	0	1,251
Flow at the river mouth													7,150
Urban water demand													402

Climate	Severe drought												
Irrigation districts and basin	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline													
Agriculture water diversions	32	72	195	94	475	139	72	598	218	143	470	725	3,233
Flow at the river mouth													4,650
Urban water demand													402
ACA 2007 environmental flow scenario and proportional sharing policy													
Agriculture water diversions													
Flow at the river mouth													
Urban water demanda													
ACA 2007 environmental flow scenario and market policy													
Agriculture water diversions													
Flow at the river mouth													
Urban water demand													
ACA 2007 environmental flow scenario and upstream priority policy													
Agriculture water diversions													
Flow at the river mouth													
Urban water demand													

ZA: Regadios del Zadorra; CN: Canales del Najerilla; LO: Canal de Lodosa; NA: Canal de Navarra; BA: Canal de Bardenas; IM: Canal Imperial; JA: Regadios del Jalon; RA: Riegos del Alto Aragon; AA: Canal de Aragon y Cataluña in Aragon; AC: Canal de Aragon y Cataluña in Cataluña; UR: Canal de Urgel; DE: Canales del Delta.

Table A8. Irrigation benefits and price of irrigation water under climate conditions and environmental flow scenarios (10^6 € y €/m^3).

Climate	Normal												
	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Benefit	15	44	96	30	64	30	37	97	54	47	88	32	635
Price of water	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
ACA 2015 environmental flow scenario and proportional sharing policy													
Benefit	15	44	96	30	64	30	37	97	54	47	88	32	635
Price of water	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
ACA 2015 environmental flow scenario and market policy													
Benefit	15	44	96	30	64	30	37	97	54	47	88	32	635
Price of water	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
ACA 2015 environmental flow scenario upstream priority policy													
Benefit	15	44	96	30	64	30	37	97	54	47	88	32	635
Price of water	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Climate	Moderate drought												
	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Benefit	12	36	80	23	47	21	31	68	39	36	67	24	484
Price of water	0.18	0.16	0.11	0.09	0.05	0.09	0.11	0.06	0.08	0.09	0.07	0.04	0.09
ACA 2015 environmental flow scenario and proportional sharing policy													
Benefit	12	35	78	22	44	20	30	64	38	35	64	23	464
Price of water	0.17	0.26	0.17	0.16	0.10	0.15	0.18	0.11	0.14	0.16	0.13	0.09	0.15
ACA 2015 environmental flow scenario and market policy													
Benefit	13	39	85	24	37	22	34	64	40	38	66	17	480
Price of water	0.18	0.18	0.14	0.14	0.16	0.16	0.13	0.14	0.14	0.14	0.15	0.12	0.15
ACA 2015 environmental flow scenario upstream priority policy													
Benefit	12	36	80	23	47	21	31	68	39	32	58	21	468
Price of water	0.16	0.22	0.16	0.14	0.10	0.14	0.16	0.11	0.13	0.18	0.15	0.10	0.15

Climate	Severe drought												
	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Benefit	12	34	75	21	42	19	29	61	36	33	61	22	444
Price of water	0.44	0.23	0.14	0.12	0.07	0.12	0.15	0.08	0.11	0.12	0.10	0.05	0.14
ACA 2015 environmental flow scenario and proportional sharing policy													
Benefit	7	16	47	14	25	10	12	32	22	19	36	15	255
Price of water	0.64	1.05	0.61	0.30	0.17	0.28	0.82	0.20	0.26	0.41	0.25	0.13	0.43
ACA 2015 environmental flow scenario and market policy													
Benefit	10	33	70	17	13	11	28	24	24	27	35	11	302
Price of water	0.41	0.41	0.30	0.30	0.34	0.34	0.26	0.29	0.29	0.29	0.32	0.25	0.32
ACA 2015 environmental flow scenario upstream priority policy													
Benefit	9	23	60	16	30	13	18	41	27	0	0	0	237
Price of water	0.45	0.68	0.35	0.26	0.15	0.23	0.56	0.17	0.21	1.97	1.97	1.94	0.75

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Table A9. Irrigation benefits and price of irrigation water under climate conditions and environmental flow scenarios (10^6 € y €/m^3).

Climate	Normal												
	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Benefit	15	44	96	30	64	30	37	97	54	47	88	32	635
Price of water	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
ACA 2007 environmental flow scenario and proportional sharing policy													
Benefit	14	41	89	27	56	26	35	84	47	42	80	28	568
Price of water	0.10	0.13	0.10	0.09	0.07	0.09	0.10	0.07	0.08	0.09	0.08	0.06	0.09
ACA 2007 environmental flow scenario and market policy													
Benefit	14	42	92	28	53	27	36	84	48	43	81	26	574
Price of water	0.10	0.10	0.09	0.09	0.09	0.09	0.08	0.07	0.08	0.08	0.09	0.07	0.09
ACA 2007 environmental flow scenario upstream priority policy													
Benefit	15	44	96	30	64	30	37	97	53	32	57	21	574
Price of water	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.20	0.17	0.11	0.07

Climate	Moderate drought												
	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Benefit	12	36	80	23	47	21	31	68	39	36	67	24	484
Price of water	0.18	0.16	0.11	0.09	0.05	0.09	0.11	0.06	0.08	0.09	0.07	0.04	0.09
ACA 2007 environmental flow scenario and proportional sharing policy													
Benefit	8	18	51	14	27	11	14	35	24	22	38	16	277
Price of water	0.58	0.92	0.50	0.29	0.17	0.26	0.73	0.19	0.24	0.35	0.24	0.13	0.38
ACA 2007 environmental flow scenario and market policy													
Benefit	11	34	72	18	16	12	29	28	26	28	39	11	324
Price of water	0.37	0.37	0.28	0.28	0.31	0.31	0.24	0.26	0.26	0.26	0.29	0.23	0.29
ACA 2007 environmental flow scenario upstream priority policy													
Benefit	10	25	64	17	33	14	21	45	29	0	0	0	258
Price of water	0.35	0.58	0.31	0.24	0.14	0.22	0.44	0.16	0.20	1.97	1.97	1.94	0.71

Climate	Severe drought												
	ZA	CN	LO	NA	BA	IM	JA	RA	AA	AC	UR	DE	Basin
Baseline environmental flow scenario													
Benefit	12	34	75	21	42	19	29	61	36	33	61	22	444
Price of water	0.44	0.23	0.14	0.12	0.07	0.12	0.15	0.08	0.11	0.12	0.10	0.05	0.14
ACA 2007 environmental flow scenario and proportional sharing policy													
Benefit													
Price of water													
ACA 2007 environmental flow scenario and market policy													
Benefit													
Price of water													
ACA 2007 environmental flow scenario upstream priority policy													
Benefit													
Price of water													

ZA: Regadios del Zadorra; CN: Canales del Najerilla; LO: Canal de Lodosa; NA: Canal de Navarra; BA: Canal de Bardenas; IM: Canal Imperial; JA: Regadios del Jalon; RA: Riegos del Alto Aragon; AA: Canal de Aragon y Cataluña in Aragon; AC: Canal de Aragon y Cataluña in Cataluña; UR: Canal de Urgel; DE: Canales del Delta.

Table A10. Benefits under climate conditions and Baseline and ACA 2007 environmental flow scenarios (10^6 €).

Climate	Normal			Moderate drought			Severe drought		
	Agriculture	*Urban*	*Total*	*Agriculture*	*Urban*	*Total*	*Agriculture*	*Urban*	*Total*
Baseline environmental flow scenario									
Benefits	635	1,857	2,492	484	1,857	2,341	444	1,857	2,301
ACA 2007 environmental flow scenario and proportional sharing policy									
Benefits	568	1,857	2,425	277	1,857	2,134			
ACA 2007 environmental flow scenario and market policy									
Benefits	574	1,857	2,431	324	1,857	2,181			
ACA 2007 environmental flow scenario and upstream priority policy									
Benefits	573	1,857	2,430	258	1,857	2,115			

Table A11. Benefits under climate conditions and Baseline and ACA 2015 environmental flow scenarios (10^6 €).

Climate	Normal			Moderate drought			Severe drought		
	Agriculture	*Urban*	*Total*	*Agriculture*	*Urban*	*Total*	*Agriculture*	*Urban*	*Total*
Baseline environmental flow scenario									
Benefits	635	1,857	2,492	484	1,857	2,341	444	1,857	2,301
ACA 2015 environmental flow scenario and proportional sharing policy									
Benefits	635	1,857	2,492	464	1,857	2,321	255	1,857	2,112
ACA 2015 environmental flow scenario and market policy									
Benefits	635	1,857	2,492	480	1,857	2,337	302	1,857	2,159
ACA 2015 environmental flow scenario and upstream priority policy									
Benefits	635	1,857	2,492	468	1,857	2,325	237	1,857	2,194

Chapter 3

3. Integrating ecosystem benefits for sustainable water allocation in hydroeconomic modeling

Abstract

The increasing concern about the degradation of water-dependent ecosystems calls for considering ecosystems benefits in water management decision-making. Sustainable water management requires adequate economic and biophysical information on water systems supporting both human activities and natural ecosystems. This information is essential for assessing the impact on social welfare of water allocation options. This paper evaluates various alternative water management policies by including the spatial and sectoral interrelationships between the economic and environmental uses of water. A hydroeconomic model is developed to analyze water management policies for adaptation to reduced water availability in the Ebro Basin of Spain. The originality in our contribution is the integration of environmental benefits across the basin, by using endemic biophysical information that relates stream flows and ecosystem status in the Ebro Basin. The results show the enhancement of social welfare that can be achieved by protecting environmental flows, and the tradeoffs between economic and environmental benefits under alternative adaptation strategies. The introduction of water markets is a policy that maximizes the private benefits of economic activities, but disregards environmental benefits. The results show that the current institutional policy where stakeholders cooperate inside the water authority, provides lower private benefits but higher environmental benefits compared to those obtained under water markets, especially under severe droughts. However, the water authority is not allocating enough environmental flows to optimize social welfare. This study informs strategies for protection of environmental flows in the Ebro Basin, which is a compelling decision under the imminent climate change impacts on water availability in coming decades.

Keywords: Freshwater ecosystems, Droughts, Hydroeconomic modeling, Climate change, Water resources management

3.1. Introduction

Ongoing water management and policies across the world deal with water scarcity by reallocating water to the most financially profitable activities or to priority uses (e.g., drinking water), with little or no consideration for the effects of reallocations on aquatic ecosystems (Vörösmarty et al., 2010). This inadequate recognition of the environmental services and related benefits in water allocation decisions has resulted in the degradation of many valuable ecosystems globally. In fact, biodiversity in inland aquatic ecosystems is the most threatened of all ecosystems (Environmental flows saving rivers in the third millennium, 2012; MEA, 2005). Overuse of water resources and ecosystem status deterioration have led to a decline in the environmental services provided by ecosystems (Dasgupta et al., 2020).

The growing concern about the environment fosters new methodologies for assessing environmental impacts of water degradation and improving policy decision making. Sustainable water management should account for the environmental externalities resulting from water allocation decisions, although the complex response of ecosystems to changes in environmental flows and imprecise environmental valuation make it difficult to identify optimal environmental flow requirements (Greve et al., 2018).

The expanding withdrawals by economic activities and the declining water availability as a result of droughts and the impending climate change are worsening water scarcity problems in arid and semi-arid regions (Kahil, 2019). Some striking examples are the disappearance of the Aral Sea, the fourth largest inland lake in the world, the desiccation of the Zayandeh Rud river in Isfahan (Iran), and the decades long deterioration of the Colorado river delta in Mexico. Environmental flows must remain at sufficient levels to protect ecosystem health, although this will reduce the water available for economic sectors. The sustainable management of water resources needs scientific knowledge and appropriate governance for enhancing the balance between human water withdrawals and environmental flows in basins (Harwood et al., 2018; Wineland et al., 2022). Understanding the interactions between humans and rivers is essential for the assessment and implementation of sustainable environmental flows (Anderson et al., 2019).

Freshwater ecosystems provide goods and services to society, which have characteristics of public good or common pool resources. Sustainable water allocation requires identifying and valuing the benefits of environmental services along with the private benefits of economic activities (Loomis, 1998). Current water policies mostly ignore the public good and common pool aspects of environmental flows. Aquifers are examples of common pool resources being overused, with massive global groundwater depletion [300 km^3 over 900 km^3 of extractions per year (Bierkens and Wada, 2019)], triggering very large ecosystem damages from the degradation of wetlands and the decline of stream flows in basins. Consequently, a more sustainable management must incorporate the external effects of human water withdrawals.

Hydroeconomic modeling is a valuable tool for identifying improved basin-level water management options, especially for adaptation to the impending climate change. This tool integrates several aspects such as the spatial distribution of water resources and the storage and transport infrastructures, water-based economic activities by sector and location, and water-dependent ecosystems. Selected notable works supported by hydroeconomic analysis can be found in Ward (Ward, 2021). The advantage of hydroeconomic modeling is the linkage between hydrology, economy, environment, and institutions in evaluating water allocation alternatives. The hydrology component represents the supply nodes of both surface and groundwater, and the demand nodes for irrigation, urban and industrial provision, and hydropower production.

Ecosystem protection in hydroeconomic models is usually represented by minimum environmental flows, because of the complexity of modeling the ecological response to streamflows. Some hydroeconomic models analyze environmental and also salinity damages in terms of water savings, replacement costs or crop production damages (Booker and Young, 1994; Booker, 1991; Brown et al., 1990; Cai et al., 2002; Divakar et al., 2011). Recreation benefits such as boating and fishing are sometimes included in relation to streamflow levels, and travel cost or contingent valuation techniques are used for valuation of the ecosystem services (Babel et al., 2005; Booker et al., 2005; Ringler et al., 2004; Ringler and Cai, 2006; Ward and Lynch, 1997; Ward and Pulido-Velazquez, 2012; Ward and Pulido-Velázquez, 2008).

Estimating environmental benefits or damages in riverine areas is difficult due to lack of information, so proxies are used, such as environmental drought cost (measured as an increasing and convex function of drought length) by Grafton et al. (2011b). A better option is to analyze the dependence between wet area and streamflow, and then select values for environmental services per unit of wet area from valuation studies (Bekchanov et al., 2016, 2015b, 2015a; Grossmann and Dietrich, 2012). However, these environmental benefit functions are not based on biophysical processes since the response of ecosystems to stream flows across river reaches is mostly unknown. Very few hydroeconomic studies specify ecological responses based on biophysical principles. Some examples are Yang and Cai (2011) that include fish diversity in a multiobjective optimization problem using the Shannon index, Bryan et al. (2013) that undertake a more extensive approach by considering the aggregated response of birds, vegetation and fish based on the biophysical information of inundation dynamics in floodplains.

The benefits of ecosystem services can be estimated by finding the response of ecosystems to water flows, and then valuating the services provided by these ecosystems. Information on environmental benefits in hydroeconomic models is quite limited because of the difficulties in identifying ecosystems and their services, and how these respond to changes in stream flows. Several studies include ecosystem water consumption in hydroeconomic modeling (Ahmadi et al., 2012; Connor et al., 2013), however the unspecified response of ecosystems to environmental flows and the scarcity of valuation estimates undermine the accuracy of results.

In any case there is a research gap, because the representation of environmental benefits in hydroeconomic modeling is patchy and limited. The reason is the insufficient knowledge on the relationships between physical, ecological, and valuation variables, and the uncertainty on critical environmental thresholds (Momblanch et al., 2016). The scope of environmental benefit estimations is usually limited to small areas like wetlands, lakes or river reaches, and the range of spatial interactions is narrow. In order to overcome these limitations, environmental benefits should be estimated on the basis of biophysical processes covering most river reaches at basin scale.

The aim of this paper is to analyze the economic and environmental impacts of droughts and water scarcity in the Ebro basin, and the social welfare that can be achieved under alternative water allocation policies. The main objective is to better understand the interactions between environmental and human water uses under water scarcity and drought conditions, by explicitly accounting for environmental benefits linked to river ecological status.

The contribution of this paper over previous literature is the inclusion of the benefits of environmental flows supporting ecosystems in decision making. This is an advance in hydroeconomic modeling that has not been fully developed in earlier studies, because of the difficulties in incorporating environmental components. The innovation over previous hydroeconomic modeling is the calculation of environmental benefits in river reaches, using biophysical information that relates stream flows and ecosystem status. Then, the environmental benefits of river reaches are integrated at basin scale in a framework that accounts for the spatial and sectorial tradeoffs of water allocation, including environmental flows.

The analysis in this study is based on the development of a hydroeconomic model with three components: a reduced-form hydrological component, a regional economy component, and an environmental component. The economy component includes the main urban and irrigation water uses, and the environmental component includes the ecosystem health and the associated environmental benefits. The novelty of this paper lies in the modeling of the environmental component, in which the ecological status response to stream flows is represented using information from biophysical studies relating the flow in river tracts with ecosystem health. The ecological status is an indicator of the potential of ecosystems to provide goods and services, and it proxies the environmental benefits received by society.

Selected water allocation policies have been evaluated to deal with water scarcity: i) the current institutional cooperation, based in proportional allocation between irrigation districts; ii) environmental institutional cooperation, where proportional allocation is coupled with increased environmental flows to maximize social welfare; iii) water markets, which maximize private benefits; and iv) environmental water markets, where users and the environment exchange water to maximize social welfare. This policy selection follows the approach suggested by (Kahil et al., 2015). Institutional cooperation is the current allocation mechanism based on collective action by stakeholders, rather than on administrative coercion or monetary incentives (e.g. pricing).

The paper is structured as follows. The next section describes the Ebro basin, and the following section explains the methodology, outlining the linkages between ecosystem status and environmental benefits, the response of ecosystems to stream flows, the hydroeconomic model framework, and the policy scenarios. Section four presents the results and discussion, and section five concludes with the main findings and policy implications.

3.2. The Ebro basin

The Ebro basin is located in the north-east part of the Iberian Peninsula. It covers an area of 85,600 km^2 and supports the economic activities of 3.2 million inhabitants. The Ebro basin is one of the main Mediterranean basins in Europe, containing almost 20 percent of the Spanish territory (Figure B1 in Appendix). The Ebro basin stream flows sustain 25 percent of both irrigated cropland and hydropower production in the country. Renewable water resources amount to 14,600 million cubic meters (Mm^3) per year. Water withdrawals amount to 8,460 Mm^3, of which 8,110 Mm^3 are surface water diversions and 350 Mm^3 groundwater extractions (CHE, 2015). Water withdrawals for agriculture are 7,680 Mm^3 covering 700,000 hectares of irrigated crops. Water abstractions in urban systems amount to 630 Mm^3 and direct industry abstractions are nearly 150 Mm^3. Non-consumptive water withdrawals are used for cooling thermal power plants (3,100 Mm^3) and for hydropower production (38,000 Mm^3). Water for agriculture represents 90% of consumptive water demand, and the main irrigated crops are corn, barley, alfalfa, wheat and fruit trees.

Red Natura 2000 spaces are special protection areas for habitat and species, covering 26,000 km^2 in the Ebro basin (CHE, 2015). Water management has been adapted to the environmental regulations governing these protected areas, and environmental flows are maintained even under exceptional conditions during droughts. Environmental flows are included in water planning to achieve good status in different water bodies.

The Confederación Hidrográfica del Ebro (CHE—the Ebro Water Authority) is the institution responsible for managing water in the basin. A special characteristic is the crucial role played by user groups, following the traditional culture of cooperation in the country. The water authority includes representatives from every sector (irrigation, urban, industrial and hydropower), central and state governments, municipalities, farmers' unions, environmental associations, business associations and workers unions.

The CHE is responsible for preparing the water plan of the Ebro, with the objectives of meeting water demand, contributing to regional development, and protecting ecosystems. Ecosystems are protected by setting minimum environmental flows in each river reach. In recent years, there has been a conflict between upstream and downstream states in the basin for the regulation of environmental flows at the Ebro mouth (Crespo et al., 2019).

Environmental flows are based on information from hydrological studies and habitat studies of fish species. Hydrological studies analyze aspects such as flow seasonality, and the rate of change or river continuity. Habitat studies are weighted usable area (WUA) studies relating the potential habitat for a species with the water flow, from which minimum environmental flows are selected. The Ebro Basin Authority has used a WUA study (MARM, 2010) covering 64 river reaches in order to define environmental flows for each river section.

The above cited WUA study has been used for the estimation of the environmental benefits of river reaches, together with the VANE study (MARM, 2010) which provides estimations of the value of environmental services in the Ebro basin (420 €/ha on average for the whole basin area). The benefits of economic activities are calculated for irrigated cropland and urban use. Data on crop yields, prices, crop water requirements, production costs, availability of water resources, land and labor, biophysical parameters, together with information on urban water use, have been obtained from statistical databases, reports, previous studies and expert consultation (MARM, 2010; MAGRAMA, 2015; INE, 2009; DGA, 2009; GC, 2009; GN, 2009.

3.3. Methods

Interactions between economic activities and the health of ecosystems are driven by multiple and complex biophysical processes, which determine the impacts of economic activities on nature (Momblanch et al., 2016). Harmful alterations of biophysical conditions diminish the services and benefits provided to humans (Potschin and Haines-Young, 2011). Both the ecological response to biophysical conditions and the valuation of ecosystem goods and services need to be determined for an adequate representation of environmental benefits (Horne, 2009).

Hydrological regime alterations are driven by the construction of dams for water withdrawals and flood control (Poff and Zimmerman, 2010), and these activities reduce stream flows and modify the river morphology (Acreman and Dunbar, 2004; Anderson et al., 2006; Andersson et al., 2000; Humphries and Lake, 2000). Indicators for analyzing biodiversity are used to show the consequences of alterations in the hydrological regime (Jørgensen et al., 2005). The ecological response can be studied at population, community, and ecosystem levels (Poff and Zimmerman, 2010), although population and community indicators are only partial and do not show the health status of the entire ecosystem (Arthington et al., 2006). The specification and estimation of the ecological response are challenging tasks (Rolls et al., 2018), and different techniques for the assessment of the ecosystem status are used (Davey and Kelly, 2007; Lamouroux et al., 2002; Laske et al., 2016; de Macedo-Soares et al., 2010; Poff et al., 2010; Arthington et al., 2012; Potschin-Young et al., 2017, 2017).

Ecosystem services are defined as the benefits provided by nature to humans (Boyd and Banzhaf, 2007), or else as the ecosystem functions that directly and indirectly benefit humans (TEEB, 2010). The classifications of ecosystem services are grouped into four categories: provision, regulation, habitat, and culture and recreation (Costanza et al., 1998; Haines-Young and Potschin, 2019; Millennium Ecosystem Assessment (Program) (Eds.) (MEA), 2005; TEEB, 2010). The valuation of ecosystems' goods and services is needed for calculating environmental benefits, although specific values of services by type and location remain an unsettled question. Economic valuations are mostly dependent on revealed or stated willingness to pay approaches, based on individual preferences. Valuation results are quite disparate and largely debated, however total economic valuation from use and no-use values is the approach broadly accepted to estimate the value of ecosystems (Costanza, 2020).

3.3.1 Response of ecosystems to stream flow levels

The approaches for establishing environmental flows are mostly based on hydrology, physical habitat simulation, or flow-ecology relationships (Anderson et al., 2019), and environmental flow methodologies are classified in hydrological, hydraulic rating, habitat simulation, and holistic methods (Arthington, 2012). Here we use the habitat simulation method, where habitat suitability is linked to habitat variables such as water velocity, river depth and riverbed composition. The suitability values are then assigned to the area of river reaches to determine the weighted usable area (WUA).

WUA is a measure of the habitat potential to host a specific species given the river streamflow. This methodology accounts for the hydrological, hydraulic (physical and mechanical properties), and biological relationships in order to evaluate environmental flow requirements (Cardwell et al., 1996; Sale et al., 1982; Tharme, 2003). Physical habitat simulation requires collecting data on the shape of the river channel, slope of the terrain and riverbed composition for modeling changes in water velocity and river depth with discharge. The habitat preference functions of species indicate the probability of use of a river area under certain conditions, usually water velocity, river depth or riverbed composition, but also water temperature. Preference curves have been modeled extensively for several species and there are numerous examples in the literature (e.g. (Grossman and Sostoa, 1994; Martínez Capel, 1999)

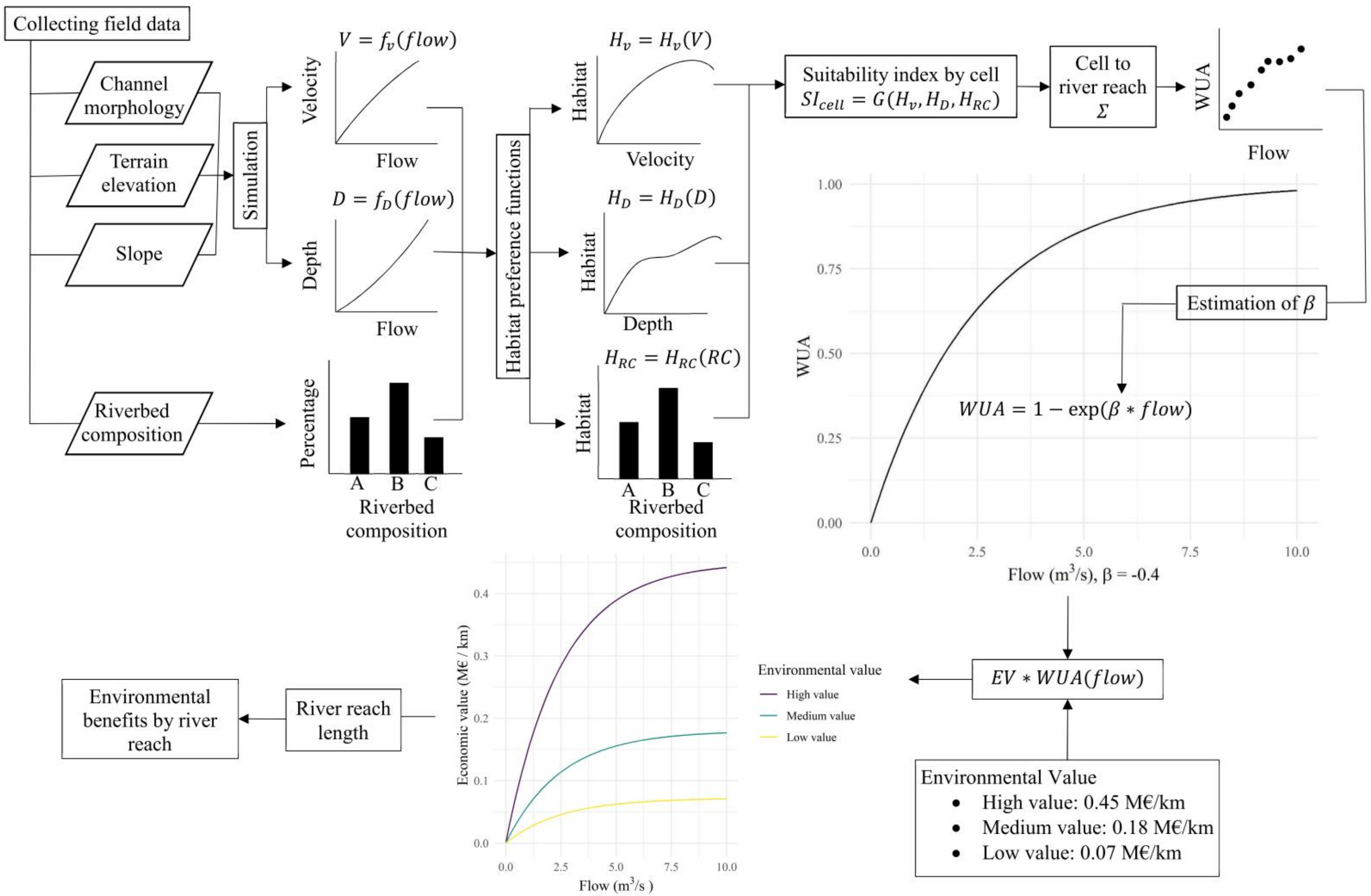
A river reach is divided in cells, where water velocity and river depth are simulated for levels of streamflow. The results of the simulations and riverbed composition by cell are evaluated with indexes in the habitat preference function, which relates streamflow and habitat adequacy. WUA is then the result of the sum of the suitability habitat index weighted by the size of the cell over the total area of the river reach (Figure 3.1). The WUA curves represent the habitat's potential to host some particular species, although they are not a predictor of the quantity of fish (Tharme, 2003).

Setting up environmental flows in river tracts is burdensome because of the difficulties to obtain habitat-flow relationships with costly field studies. This is solved by using methods that extrapolate available habitat-flow relationship from one part of the river to other parts of the river. These methods estimate the parameters from a functional approach that links WUA and flow. Many functional forms are used in these methods, for example quadratic functions and exponential functions (Lamouroux and Jowett, 2005; Wilding et al., 2014). Based on functions used in these studies, the functional form chosen to characterise ecosystem status is the following exponential form:

$$WUA_s(X_s) = 1 - e^{\beta_s X_i}$$

where WUA_s is the weighted usable area in river reach s, X_s is the flow in the reach, and β_s is the parameter characterizing the WUA response in reach s. This function provides an index of the health status of ecosystems. Parameter β must be negative and the function meets the following conditions: the values of the function range from zero to one; the function is strictly increasing; and *WUA* is zero when flow is zero and approaches one as flow rises.

Figure 3.1. Environmental benefit response using the Weighted Usable Area.



The procedure we followed in the Ebro basin has been to use ecosystem habitat as an indicator of ecosystem status, which is used to define the relationship between flow regime and ecosystem health. Then, we use the economic valuation of services provided by ecosystem health levels, in order to calculate environmental benefits in each river reach (Figure 3.1). We have used information from several institutions and projects that conduct studies on the valuation of ecosystem services related to water (MARM, 2010; TEEB, 2010; Troy and Bagstad, 2009; Troy and Wilson, 2006).

3.3.2 Modeling framework of the Ebro basin

The hydroeconomic model of the Ebro basin integrates hydrological, economic, environmental and institutional aspects. The model includes a reduced-form hydrological component, a regional economy component, and an environmental benefit component.

3.3.2.1. Reduced-form hydrological component

The hydrological component is represented by a "reduced-form" model, where the complex hydrological relationships are simplified using historical data and network topology from existing hydrologic models. This is a quick and credible procedure to build a reduced form hydrological model of the studied river basin (Cai et al., 2003). The hydrological component represents flows between supply and demand nodes using the hydrological principles of water mass balance and flow continuity. The hydrological component shows the spatial distribution of water flows used by economic sectors and environmental flows (Figure 3.2). The mathematical formulation is as follows:

$$W_{out_d} = W_{in_d} - W_{loss_d} - Div_d^{IR} - Div_d^{URB} \quad (3.1)$$

$$W_{in_{d+1}} = W_{out_d} + r_d^{RI} \cdot (Div_d^{IR}) + r_d^{URB} \cdot (Div_d^{URB}) + RO_{d+1} \quad (3.2)$$

$$W_{out_{mouth}} \geq E_{mouth}^{min} \quad (3.3)$$

Equation (3.1) is the mass balance equation, and it determines water outflow W_{out_d} in river reach d, which is equal to water inflow W_{in_d}, minus water losses W_{loss_d}, water abstraction for irrigation Div_d^{IR}, and abstraction for urban and industrial use Div_d^{URB}. Equation (3.2) guarantees river flow continuity, in which water inflow in the following river reach $W_{in_{d+1}}$ is the sum of the water outflow from the previous reach W_{out_d}, return flows from previous irrigation districts $[r_d^{RI} \cdot (Div_d^{IR})]$, urban return flows $[r_d^{URB} \cdot (Div_d^{URB})]$, and the flow entering this river reach from tributaries RO_{d+1}. Equation (3.3) states that water outflow at the mouth of the Ebro $W_{out_{mouth}}$ must be greater than or equal to the minimum environmental flow in the river reach.

The hydrological component has been calibrated adjusting the model parameters by introducing auxiliary variables for every river reach, in order to reproduce the observed system states of nature such as stream flows under baseline conditions. Calibration is used to close the mass balance equation, since there are water inflows and outflows in the system that cannot be observed (for example, underground flows, evaporation or some return flows). Calibration includes non-observed flows, which are the difference between flows estimated with the model and flows measured at gauging stations.

3.3.2.2. Regional economic component

The regional economic component includes agricultural irrigation and urban water use. There is a model for agricultural activities in every irrigation district, where farmers' private benefits from crop production are constrained by technical and resource restrictions. Crop yield functions are assumed linear and decreasing, and output and input prices are constant. These irrigation benefits enter into the objective function of the integrated model (equation 3.16), which is maximized. The formulation is the following:

$$B_k^{IR} = \sum_{ij} C'_{ijk} X_{ijk} \tag{3.4}$$

s.t.

$$\sum_i X_{ijk} \leq T_{land_{kj}};\ j = flood, sprinkler, drip \tag{3.5}$$

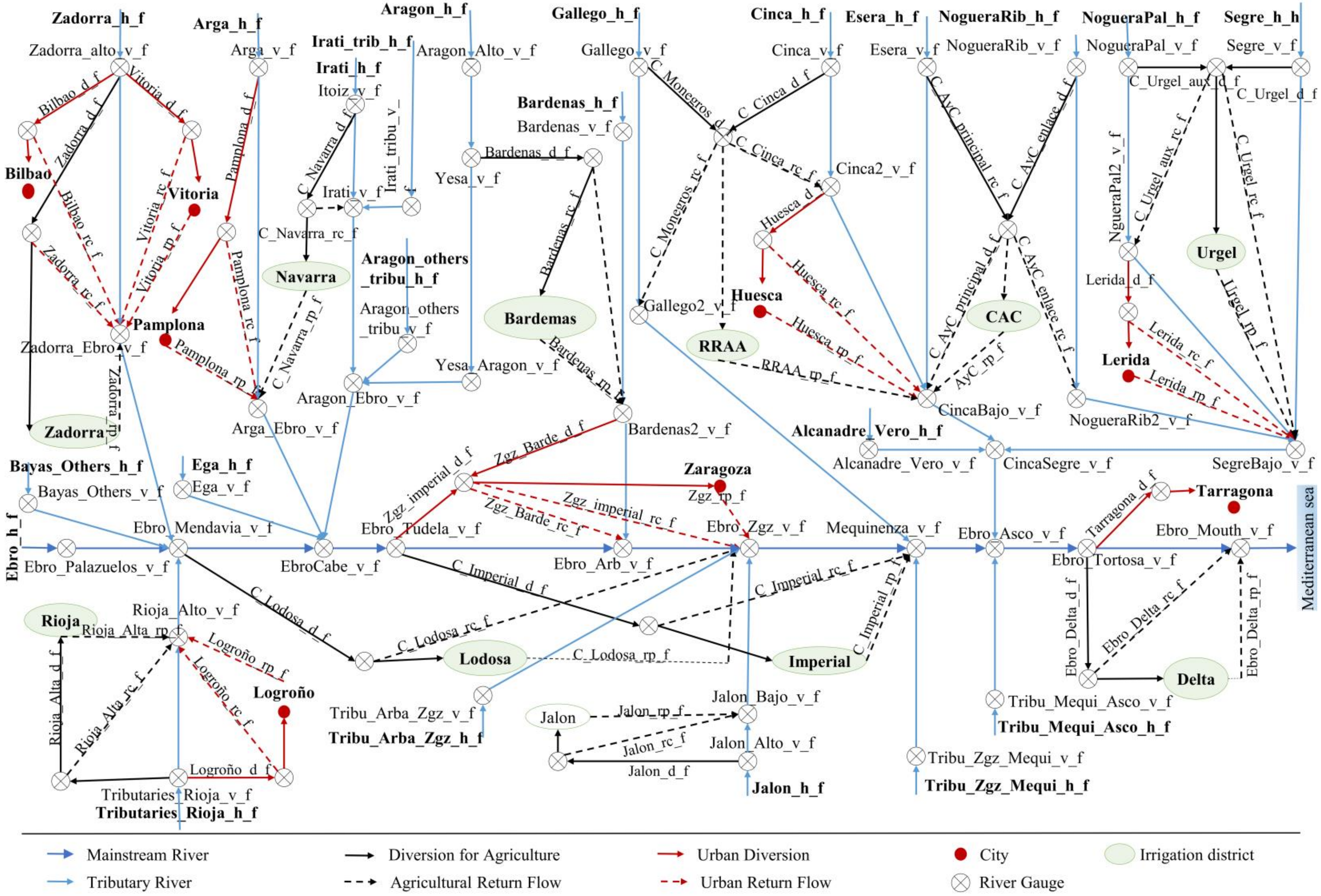
$$\sum_{ij} W_{ijk} X_{ijk} <= T_{water_k} \tag{3.6}$$

$$\sum_{ij} M_{ijk} X_{ijk} \leq T_{la_k} \tag{3.7}$$

$$X_{ijk} \geq 0 \tag{3.8}$$

where B_k^{IR} is private benefit in irrigation district k, and C'_{ijk} is net income of crop i using irrigation technology j. The decision variable of the problem is X_{ijk}, which is acreage of crop i under irrigation technology j. Equation (3.5) represents the restriction of available land $T_{land_{kj}}$ in irrigation district k equipped with irrigation system j. The water available T_{water_k} in irrigation district k is given by equation (3.6), where W_{ijk} is the water requirement of crop i with technology j. The water available T_{water_k} is the variable linking the optimization model of irrigation districts and the hydrological component. The labor constraint (3.7) represents labor availability T_{la_k} in irrigation district k, where M_{ijk} is the labor requirement of crop i with irrigation system j.

Figure 3.2. Hydrological network of the Ebro basin.



This irrigation model includes the major crops in every irrigation district. Irrigation systems for field crops are flood and sprinkler, and for fruit trees and vegetables are drip and flood. Net income per hectare C'_{ijk} is the difference between crop revenue and direct and indirect costs (including capital amortization) and it is expressed by $C'_{ijk} = P_i Y_{ijk} - CP_i$ where P_i is price of crop i, Y_{ijk} is yield of crop i under technology j in the irrigation district k, and CP_i are direct and indirect costs of crop i (including water costs).

The crop yield function is linear and represents a decreasing crop yield when additional land is assigned to crop production, based on the principle of Ricardian rent. The first lands in production have the highest yields, and yields fall off as less-suitable lands enter production. The crop function relates yields with acreage of crop i under irrigation technology j, and is defined as:

$$Y_{ijk} = \beta_{0_{ijk}} + \beta_{1ijk} X_{ijk} \quad (3.9)$$

The agricultural component is calibrated using Positive Mathematical Programming (PMP) to reproduce the observed land and water use under baseline conditions, and to address the problem of crop overspecialization (Howitt, 1995) . Calibration follows the PMP procedure by (Dagnino and Ward, 2012), where parameters are estimated for a linear yield function [Equation (3.9)] based on the first-order conditions of benefit maximization.

The modeling of urban water calculates economic surplus, the sum of consumer and producer surpluses in the basin's main cities. The urban economic surplus enters the objective function of the integrated model (equation 3.16), which is maximized. The formulation of the urban sector is expressed by:

$$B_u^{URB} = (a_{du} Q_{du} - ½\, b_{du} Q_{du}^2 - a_{su} Q_{su} - ½\, b_{su} Q_{su}^2) \quad (3.10)$$

s.t.

$$Q_{du} - Q_{su} \leq 0 \quad (3.11)$$

$$Q_{du};\ Q_{su} \geq 0 \quad (3.12)$$

where B_u^{URB} is the consumer and producer surplus in city u. The variables Q_{su} and Q_{du} are water supply and demand in city u, respectively. The parameters a_{du} and b_{du} are the constant term and the slope of the inverse demand function, and the parameters a_{su} and b_{su} are the constant term and the slope of the water supply function. Equation (3.11) states that the supply must be equal to or greater than the demand for water. The water supply

Q_{su} is the variable linking urban water with the hydrological component. The equation parameters have been obtained from the studies by Arbués et al. (2004) and Arbués et al. (2010)

3.3.2.3. Environmental component

The environmental benefits of aquatic ecosystem in the basin depend on the health status of ecosystems, where the relationship between the river's habitat status and stream flows is expressed by the WUA. A study of the WUA in the Ebro Basin provides data for these relationships for every section in the basin, based on their hydrological characteristics. The relationships are estimated by an exponential function calibrated to the data from the WUA study (CHE, 2015; TEEB, 2010; Troy and Bagstad, 2009; Troy and Wilson, 2006).

The WUA study covers 14 segments of the hydrology network of the Ebro Basin, characterizing the ecological status in every river reach. The benefits aquatic ecosystems generate are given by the following expressions:

$$WUA_s(W_s) = 1 - e^{\beta_s W_s} \tag{3.13}$$

$$EW_s^{eco} = WUA_s(W_s) \tag{3.14}$$

$$B_s^{eco} = VE \cdot l_s \cdot EW_s^{eco} \tag{3.15}$$

where WUA_s is the weighted usable area in river reach s, W_s is average flow in s, and EW_s^{eco} is the health status of ecosystem eco in s. The weighted usable area WUA_s depends on average flow W_s and the estimated parameter β_s, considering the months with less water availability. The parameter β_s has been estimated through non-linear regression for 14 of the 63 locations where information is available (Table 3.1).

WUA studies require collecting data of the river waterbed composition and undertaking a topographic study of the river reach. The information on the morphology and topology of the terrain enables the simulations of the hydraulic variables, water velocity and water depth, generated by a specific streamflow. This information is combined with habitat studies that describe fish preferences to water velocity, water depth and waterbed characteristics, in order to calculate the habitat potential. The WUA is the habitat potential weighted by the total area of the river reach. The studies of the Ebro basin authority includes 64 river reaches of the Ebro basin. For each river reach, a representative fish species is selected and the WUA is obtained for three different life-stages: fray, juvenile and adult. WUA for a fish species for the dry and wet seasons are produced combining life-stage WUA results and the mean flow at the river reach.

Table 3.1. Results of the WUA regression for 14 river reaches in the Ebro.

$$WUA_{river\ reach} = 1 - e^{\beta_{river\ reach} * flow_{river\ reach}}$$

River reach ID	n	β	Standard error	t	$Pr(>\|t\|)$	River reach ID	n	β	Standard error	t	$Pr(>\|t\|)$
202	33	-9.65	1.82	-5.31	< 0.01	**428**	34	-0.30	0.03	-12.01	< 0.01
264	32	-2.07	0.21	-9.84	< 0.01	**433**	44	-0.10	0.01	-12.05	< 0.01
274	24	-1.42	0.17	-8.52	< 0.01	**441**	46	-8.14	2.75	-2.96	< 0.01
406	41	-16.39	2.74	-5.98	< 0.01	**446**	20	-1.96	0.31	-6.44	< 0.01
418	39	-1.89	0.22	-8.74	< 0.01	**455**	26	-9.61	2.53	-3.79	< 0.01
421	41	-0.12	0.01	-13.54	< 0.01	**463**	30	-0.23	0.05	-4.39	< 0.01
426	24	-0.52	0.06	-7.95	< 0.01	**662**	40	-0.26	0.02	-14.60	< 0.01

This relationship and its corresponding parameter for each river reach determines the habitat size and the ecosystem potential to contain species given a specific flow. The benefit B_s^{eco} of ecosystems in reach s depends on the ecosystem health status EW_s^{eco} (from zero to one), the length l_s of the reach (km), and the economic value VE_s of ecosystem services (€/km) (equation 3.15).

The economic value of ecosystem services VE_s is derived from published studies in the literature. Values are usually given in euros per hectare of riverbed, which can be converted to euros per kilometer by knowing the surface area of the river reach covered by water and the length of the river reach. Valuation in the literature ranges from 2,000 to 40,000 €/ha of riverbed covered by water (TEEB, 2010; Troy and Bagstad, 2009; Troy and Wilson, 2006), and from this range we select an average value of 24,000 €/ha for ecosystems' services in the Ebro. The area covered by water in the rivers of the Ebro basin is 68,000 ha with a total length of 8,900 km, therefore the average value in euros per kilometer is 0.180 M€/km (24,000 €/ha•68,000 ha/8,900 km). However, ecosystems' values are spatially heterogeneous in the basin, with values higher for mountain rivers than for streams in the valley as estimated by MARM (2010a). Following the valuation ranges in the literature, three valuation levels are chosen: a low value (0.072 M€/km) for river sections with moderate environmental value in the main stem of the Ebro and in some right bank tributaries, a medium value (0.180 M€/km) for non-mountain Ebro tributaries, and a high value (0.450 M€/km) for mountain river reaches and also for the Ebro mouth where the Ebro Delta is located.

3.3.2.4. Modeling policy scenarios

The optimization model integrates the hydrologic, economic and environmental components. The model maximizes the basin's benefits subject to hydrological, technical, resource and institutional constraints in every economic sector and location. The optimization problem is defined by the expression:

$$Max \sum_k B_k^{ir} + \sum_u B_u^{urb} + \sum_s B_s^{eco} \quad (3.16)$$

subject to equations (1)– (15) and the constraints of water availability in the basin:

$$Div_d^l \leq W_{in_d} \quad \forall\ l,d \qquad \text{where } l = k,u \quad (3.17)$$

$$\sum_d Div_d^l \leq \bar{W} \quad \forall\, l = k,u \quad (3.18)$$

where B_k^{ri} are the benefits of each irrigation district, B_u^{urb} are the befits of each urban center, and B_s^{eco} are the environmental benefits of each river reach. Equations (3.17) and (3.18) allocate water among uses and locations. Equation (3.17) ensures that water extractions at each demand node are lower than or equal to net water inflows in river reaches. Equation (3.18) indicate that basin water withdrawals cannot exceed water availability $\bar{W}$ in the basin.

The model is used to analyze the impact of droughts on the basin economic activities and environment. Water inflows into the system under normal weather conditions are 14,600 hm^3, corresponding to the average inflows in the 1980–2014 period (CHE, 2015). Water inflows into the system are reduced by 40% under severe drought conditions. This reduction is chosen by considering the previous four severe droughts with a fall around 40% in basin inflows during the last 30 years (in years 1989, 2002, 2005 and 2012). Climate change will further reduce basin inflows by 12% at the end of this century (CEDEX, 2017). The model is also used to analyze the economic and environmental effects of drought management policies. The scenarios are a combination of the drought situation with the following four policies developed to deal with drought:

Institutional cooperation: Under drought conditions, the basin authority reduces water allocations for irrigation in proportion to drought intensity (fall in inflows). Consequently, the water shortfall is shared between irrigation districts, but it also reduces environmental flows. This is the policy currently applied in the Ebro basin. In the model, the water allocations to irrigation districts are reduced in proportion to the reduction in inflows due to drought.

Environmental institutional cooperation: Farmers receive the same allocations than under *institutional cooperation*, but then the basin authority purchases water from farmers for the environment in order to maximize social benefits, the sum of both private and environmental benefits. Water exchanges between irrigation districts are not allowed. In the model, the environmental benefits are included in the objective function, and the basin authority buys water to achieve the optimal solution found for stream flows.

Water markets: Farmers face the reduced water allocations of institutional cooperation, but then these water allocations can be exchanged among irrigation districts, maximizing the private benefits of water use. There is no direct exchange of water between selling and buying irrigation districts, but rather the selling district reduces withdrawals, and the buying district augments withdrawals in their respective river reaches. In the model, a restriction is introduced that limits the sum of reduced water allocations to districts (allowing trading), instead of limiting each district to its reduced water allocation.

Environmental water markets: Same water allocations as in institutional cooperation. Water can be exchanged between irrigation districts, and also the basin authority participates in the water market by acquiring water to protect environmental benefits in river reaches. This policy enhances both private and environmental gains, so it is an appealing policy to capture the private benefits of markets while protecting ecosystems. In the model, the environmental benefits are included in the objective function, and the water authority buys water from irrigation districts to achieve the optimal solution found for stream flows.

The baseline scenario assumes the policy currently applied under normal weather conditions. The minimum environmental streamflow at the mouth of the Ebro is set at 3,000 hm^3, and the urban water supply is guaranteed in all scenarios.

3.4. Results

In the *baseline scenario* with normal weather, the social benefits of water from economic activities and the environment are 3,442 M€, of which 629 M€ are from irrigation, 1,857 M€ from urban use, and 956 M€ from the environment. Water withdrawals are 5,380 Mm^3 in irrigation and 402 Mm^3 in urban use, while environmental flow at the mouth is 8,895 Mm^3. This environmental flow collects all water coming from stream flows across

Table 3.2. Policies under drought conditions: institutional cooperation, environmental institutional cooperation, water markets, and environmental water markets.

Weather scenario	Normal weather	Severe drought			
Policies	Baseline scenario	Institutional cooperation	Environmental institutional cooperation	Water markets	Environmental water markets
Water use (Mm^3)					
Water use	5,782	3,632	3,047	3,627	3,232
Irrigation	5,380	3,230	2,645	3,225	2,830
Urban	402	402	402	402	402
Water exchanges			585	235	780
Between irrigators				235	380
Between irrigators and environment			585		400
Environmental flow at mouth	8,895	5,350	5,540	5,345	5,435
Irrigation surface area (1,000 ha)					
Surface area	529	332	275	348	293
Field crops	400	219	165	229	182
Fruit trees	104	93	90	97	90
Vegetables	25	20	20	22	21
Private and environmental benefits (M€)					
Private benefits	2,486	2,321	2,332	2,340	2,346
Irrigation	629	464	475	483	489
Urban	1,857	1,857	1,857	1,857	1,857
Environmental benefits	956	761	834	719	826
Social benefits	3,442	3,082	3,105	3,059	3,118

the basin, sustaining aquatic ecosystems (Table 3.2 and Table B1 in appendix). Environmental benefits are displayed by local watershed, which is the water management unit in the basin (Figure 3.3 and Figure B2 in appendix).

The irrigated area under normal weather is 529,000 ha, distributed between field crops (75%), fruit trees (20%) and vegetables (5%). Fruit trees and vegetables generate half of farmers' benefits. The cropping pattern is quite different by irrigation district, with Riegos del Alto Aragón and Bardenas specializing in field crops, Riegos del Jalón specializing in fruit trees, and Canal de Lodosa specializing in vegetables.

Institutional cooperation. Water availability is reduced 40% under severe drought conditions. In the *institutional cooperation* policy, water allocations to irrigation are a share of water inflows into the basin, and they are reduced in proportion to drought intensity. Water withdrawals for urban centers are maintained because of the priority of urban supply over other uses, including the environment. The decrease in the availability of water causes losses in irrigation and environmental benefits, reducing social benefits. During drought periods and under the *institutional cooperation* policy, irrigation withdrawals fall to 3,230 Mm^3 (-40%). This reduction leads to less irrigated area (-37%) and private benefits (-26%), compared to the *baseline scenario*. The streamflow at the river mouth drops from 8,895 Mm^3 to 5,350 Mm^3 under drought (Table 3.2).

Environmental benefits decrease by 20% during drought, affecting the main stem and the left and right bank tributaries. The tributaries on the left bank provide most of the water in the Ebro, and pressures on environmental flows are mostly from irrigation withdrawals. Water scarcity in summer months determines the ecosystem sensitivity to drought. Under drought, urban benefits are maintained but irrigation and environmental benefits fall.

The *environmental institutional cooperation* policy reallocates water between irrigation and the environment to maximize social wellbeing. Social wellbeing is the sum of private and environmental benefits, minus the public expenses to buy irrigation water for the environment. Acquiring water for the environment improves ecosystem status, especially in areas with high potential for improvement, while maintaining irrigators' income. Under drought conditions the basin authority purchases 600 Mm^3 for €60 M. This reallocation increases environmental benefits by €70 M (9%) and irrigation benefits increase by nearly €9 M.

Water markets. Under the *water markets* policy, irrigation districts exchange water and maximize their private benefits, but environmental benefits are disregarded. Under drought, water withdrawals are 3,225 Mm^3 and cultivated area falls to 348,000 ha, with lower irrigation benefits. Flows at the river mouth are 5,345 Mm^3 under drought, well above the minimum environmental flow at 3,000 Mm^3. This minimum environmental flow is satisfied by all policy scenarios (Table 3.2, Figure 3.4). Irrigation districts exchange 235 Mm^3 under drought, where irrigation districts with low water efficiency and specialized in field crops sell water to irrigation districts with efficient irrigation systems and profitable crops. Water exchanges enable a larger cultivated area compared with the institutional cooperation policy. That is why crop water consumption (evapotranspiration) is higher under *water markets*, reducing basin stream flows and environmental benefits. The *water markets* policy generates higher private benefits and lower environmental benefits compared with *institutional cooperation*.

Figure 3.3. Environmental benefits of policies under normal and drought conditions.

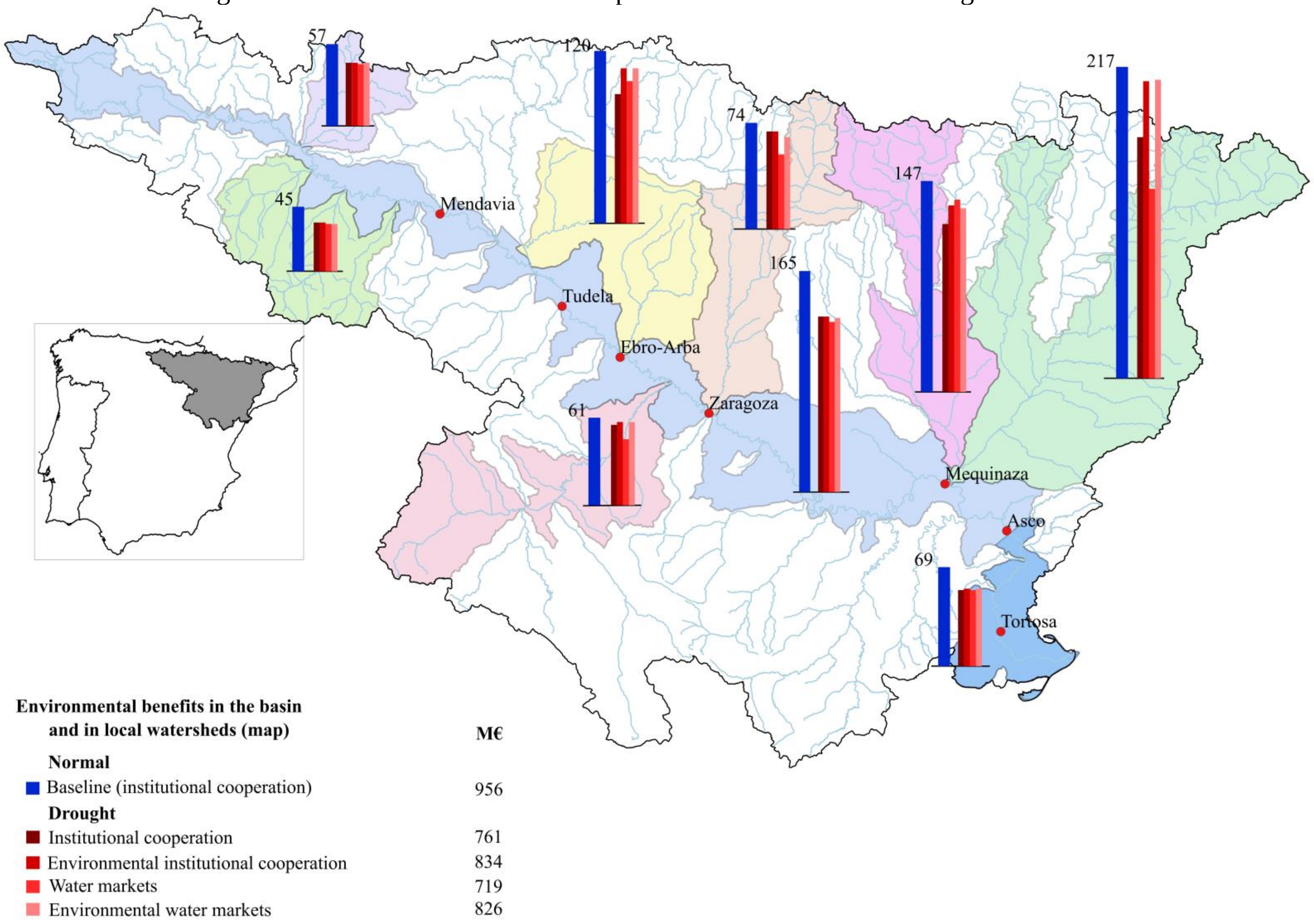
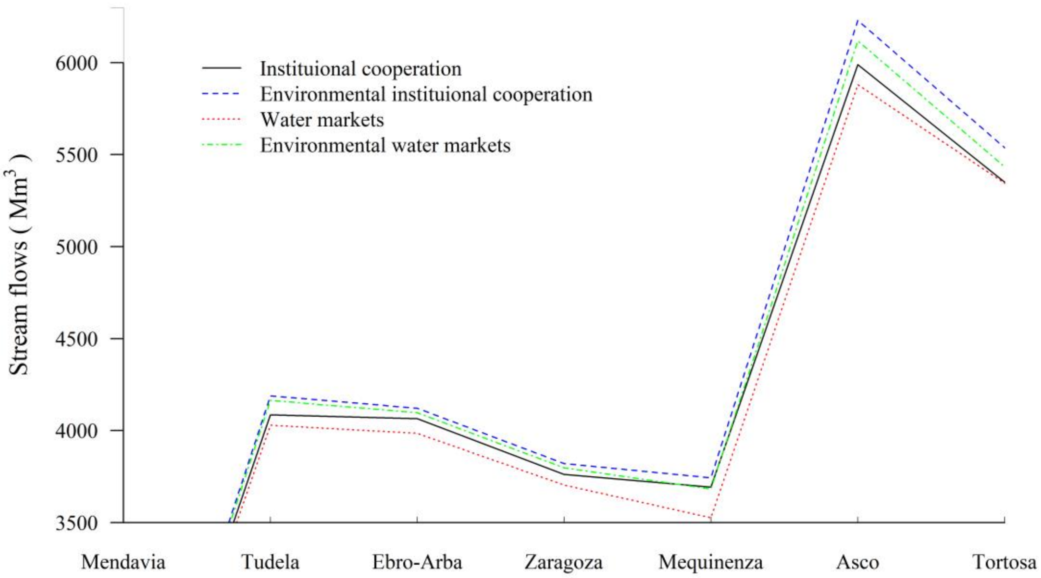


Figure 3.4. Stream flows along the Ebro for each policy under drought conditions (Mm^3/year).



Minimum annual environmental flows, regulated by the Ebro Basin Authority, are: 300 Mm^3 at Mendavia under normal and drought conditions; 945 Mm^3 at Zaragoza under normal conditions and 640 Mm^3 under drought conditions; and 3,000 Mm^3 in Tortosa under normal and drought conditions.

Irrigation districts buying water expand withdrawals and deplete water streams in their river reach, while the opposite takes place in selling districts. Consequently, water exchanges relieve environmental pressures in selling districts and aggravate pressures in buying districts. This can be observed in the Cinca watershed (Figure 3.3 in pink) where irrigation districts sell water and environmental benefits increase above any other policy, or in the Segre watershed (Figure 3.3 in green at right) where irrigation districts buy water and environmental benefits fall.

Environmental water markets. The purpose of this policy is to maximize social benefits by including both the private and public benefits of water, in order to internalize the external effects of water markets. The *environmental water markets* policy consists in water trading not only between irrigation districts but also with the environment, where the basin authority purchases water for the environment. Under drought conditions, water exchanges between irrigation districts are 380 Mm^3, and water exchanges between irrigation districts and the environment are 400 Mm^3. Irrigation withdrawals, irrigated area and crop production decrease compared with the *water markets* policy. The benefits of irrigation districts are obtained from crop production (393 M€) and from water trading with other districts (42 M€) and the environment (54 M€). The private benefits of irrigation under *environmental water markets* are above those of *water markets*, since crop production benefits and income from water sales are added in environmental water markets. The benefits of *environmental water markets* strictly dominate those from *water markets* in both private and environmental benefits.

3.5. Discussion

Environmental water markets and *environmental institutional cooperation* reduce water withdrawals, especially in river sections where environmental sensitivity is high. Water exchanges between irrigation and the environment increases environmental flows by reducing the cultivated area of field crops and fruit trees, while maintaining vegetables. The area of fruit trees decreases in irrigation districts withdrawing from river sections which are more environmentally sensitive, especially on the right bank.

Environmental institutional cooperation achieves a better ecosystem protection than *environmental water markets*, by acquiring almost 50% more water for the environment. Because there are no water exchanges among districts, farmers cannot take advantage of the private gains achieved under *environmental water markets*. Irrigation withdrawals under *environmental water markets* are around 200 Mm^3 larger than with *environmental institutional cooperation*, showing the trade-off between private and environmental benefits of these policies. *Environmental institutional cooperation* provides more environmental flows and better ecological status in all river reaches across the basin. In contrast, *environmental water markets* improve the ecological status in some river reaches at the expense of others reaches.

The spatial location of irrigation districts, the relationship between available water and water withdrawals, ecosystem sensitivity to water scarcity, crop patterns and irrigation technologies are the factors driving the impact caused by water scarcity on economic activities and the environment. Environmental and irrigation responses depend on spatial location, because water available and water withdrawal intensity are heterogeneous throughout the basin. Ecosystem sensitivity, the economic value of the ecosystem services, and alternative uses of water shape environmental flows. Under drought, each policy results in different distribution of losses between private and environmental benefits and the ensuing trade-offs.

During droughts, *institutional cooperation* distributes losses to irrigation districts and the environment in proportion to water allocations in normal years. *Environmental institutional cooperation* enhances social benefits providing additional protection to the environment. *Water markets* maximize private benefits of irrigation but disregards environmental benefits, and *environmental water markets* deliver both private and environmental gains, capturing the private benefits of markets while protecting ecosystems. Water exchanges from irrigation to the environment enhances environmental benefits in the river reach of the exchange, and also in downstream river reaches, thus boosting the exchange benefits.

Reponses to drought entail maintaining high profitable crops and efficient irrigation systems, and therefore water scarcity has greater negative impacts on cultivation of less technically-advanced irrigation districts specialized in field crops. These irrigation districts with field crops and low water efficiency sell water to efficient and profitable irrigation districts and also to the environment.

The water markets policy provides the lowest social benefits because environmental losses overcome irrigation gains. The environmental water markets policy accounts for the market shortcomings by internalizing the negative external effects of economic activities, enhancing social welfare. However, the ecological status with this "environmental" trading improves in some river reaches but worsens in others. Equity considerations are better addressed by the institutional cooperation policy, which distributes proportionally the drought water scarcity among all irrigation districts and aquatic ecosystems in the basin. This policy not only protects the environment but also contributes to a more equitable distribution of water and benefits. Environmental institutional cooperation further enhances social benefits by a full consideration of environmental benefits into water allocation decisions. The tradeoff between environmental and private benefits is obtained by comparing the outcomes of benefits under each policy. For example, there are gains in environmental benefits and losses in private benefits when environmental institutional cooperation is compared with water markets.

The range of the increase in environmental benefits between environmental institutional cooperation (high flow protection) and water markets (low flow protection) is quite close (115 M€ = 834-719, Table 3.1) to the environmental damages from water uses estimated by García de Jalón et al. (2017) in northern Spain. They estimate the environmental costs of streamflow variability induced by human extractions, applying the "polluter pays" principle. Their estimation of damages is 0.02 €/m^3, which in the case of the Ebro will amount to 107 M€ (0.02 €/$m^3 \cdot 5{,}345 \cdot 10^6$ m^3). This similarity in the estimation of environmental damages in the two studies, that use quite different methodologies, strengthen the reliability of the damages found in this study.

Previous studies on environmental benefits using hydroeconomic modeling are only partial and provide only rough estimations. Ringler and Cai (2006) use two functional forms for fisheries and wetlands in the Mekong River, however the authors acknowledge that their evaluation requires further improvement. The study by Grossmann and Dietrich (2012) only analyzes the Spreewald wetland in the mid-reaches of the Spree River, but not the environmental benefits in the whole basin. Bekchanov et al. (2016) analyze investments in irrigation technologies to improve irrigation, hydropower and ecosystem benefits in the Aral Sea Basin. They estimate ecosystem benefits only in the river delta, and ecosystem benefits are a simple linear function of flows at the mouth of the Amur Daria and Syr Daria rivers, recognizing that these benefits are only rough estimates.

The wider implications of the approach taken here are that: i) the importance for decision making of considering environmental benefits for whole river basins, rather than for partial locations that preclude finding the efficient allocation of water in the basin; ii) the advance of estimating environmental benefits using the weighted usable area, based on observed field data for every river reach along the hydrological basin network; iii) the assessment of drought policies in this study provide significant information on the trade-offs faced by decision makers in order to balance private benefits from economic activities and public benefits from ecosystem protection.

The modeling approach taken in our study present several limitations. One limitation is that the model is static, and the model can be converted to dynamic by including the reservoirs in the hydrological network of the basin. Also, more detailed findings can be obtained by changing the data step from yearly to monthly, because stream flows are predominantly threatened in summer months during droughts. Another aspect deserving improvement is the calculation of environmental benefits in river reaches. This requires a more precise valuation of the ecosystem services provided by river reaches with specific studies on local watersheds in the basin, and also better information on the response of ecosystem health status to stream flows, including more species and habitats in the weighted usable area technique for assessing environmental flows.

3.6. Conclusions and policy implications

This paper develops a hydroeconomic model that is used to analyze water allocation policies in the Ebro basin under water scarcity. The contribution made by this study is the inclusion of an environmental component linking stream flows with the status of aquatic ecosystems and their environmental benefits. Most hydroeconomic models consider environmental protection by setting minimum flow requirements, rather than representing the complex ecological responses to stream flows (Bekchanov et al., 2017; Momblanch et al., 2016).

The model is used to analyze water allocation policies in the Ebro basin, a basin with several semi-arid regions where droughts trigger water scarcity problems and significant impacts on irrigation and the environment. This problem is common to arid and semi-arid basins worldwide, and it is expected to worsen as a consequence of climate change and pressures from economic and population growth. The methodology and results of this policy analysis could be applied to other basins facing similar problems of mounting withdrawals and ecosystems degradation.

The hydroeconomic model includes the benefits from irrigated agriculture, urban use, and environmental flows. The purpose is to encompass both the spatial and sectoral interrelationships of water allocations in the basin, in order to find the economic and environmental impacts of drought and the social welfare that can be achieved under alternative water allocation policies.

The impacts of drought and the ensuing social welfare under the policies considered provide important information to support decision making. The *water markets* policy generates higher private benefits than the current *institutional cooperation* policy, but attains lower environmental benefits. The public good characteristics of environmental flows imply that ecosystem services are external to markets, and the market failure has to be corrected. One alternative is the *environmental water markets* policy, where the basin authority buys water for the river. This water sharing between economic sectors and the environment is based on the corresponding private and environmental benefits. Results from this “environmental” trading show that the policy of *water markets* is strictly dominated by *environmental water markets*, because the latter provides gains for both farmers and the environment, thus achieving higher social benefits. However, under this policy the ecosystem status improves in some river reaches but worsens in other reaches.

Environmental water markets require also stakeholders' cooperation as an essential ingredient to curtail losses from water scarcity, and achieve the "good ecological status" of water bodies promoted by European legislation (Ancev, 2015; Esteban and Albiac, 2011; Giuliani and Castelletti, 2013; Grafton et al., 2011b; Horne et al., 2018; Howitt et al., 2012; Kahil et al., 2016a; Kahil et al., 2016b). Well functioning *environmental water markets* would enhance social benefits (Ancev, 2015; Grafton et al., 2011a; Horne et al., 2018; Howitt et al., 2012), but this entails the support of strong institutions fostering collective action (Bekchanov et al., 2015a), which would prevent third party effects that mostly affect the environment.

In contrast, the *environmental institutional cooperation* policy achieves a more equitably distribution of drought shortfalls among irrigation districts, and attains the highest environmental protection. The water authority approach is based on stakeholders' cooperation in water management at local watershed and basin levels. This collaboration among water users, administrations and other stakeholders is essential for implementing sustainable water management.

The design and implementation of sustainable basin management requires information on the response of ecosystems to stream flows, and on the valuation of ecosystems services. This involves multidisciplinary research with considerable efforts in terms of resources and time, and this research is lacking at present in most basins around the world. Such information is also needed to gain the support of stakeholders in reversing the current global degradation of water resources.

The challenge for water management is balancing the effects of water allocations between economic activities and the environment in decision-making. Market policies overlook the externalities from private water usage, and public interventions are needed to deal with market failures. But even with institutional cooperation in the case of Spain, the situation in basins shows that basin stream flows have gradually decreased in recent decades, and more virtuous collective action outcomes are needed to prevent further deterioration of stream flows. In many basins around the world, the decline in environmental flows is damaging aquatic ecosystems, with private benefits increasing in the short run at the expense of environmental benefits. But in the long run the degradation of hydrological systems would become unsustainable, with strong negative impacts on both economic activities and ecosystems.

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3.8. Appendix

3.8.1 Figures and tables

Figure B1. Map of the Ebro basin.

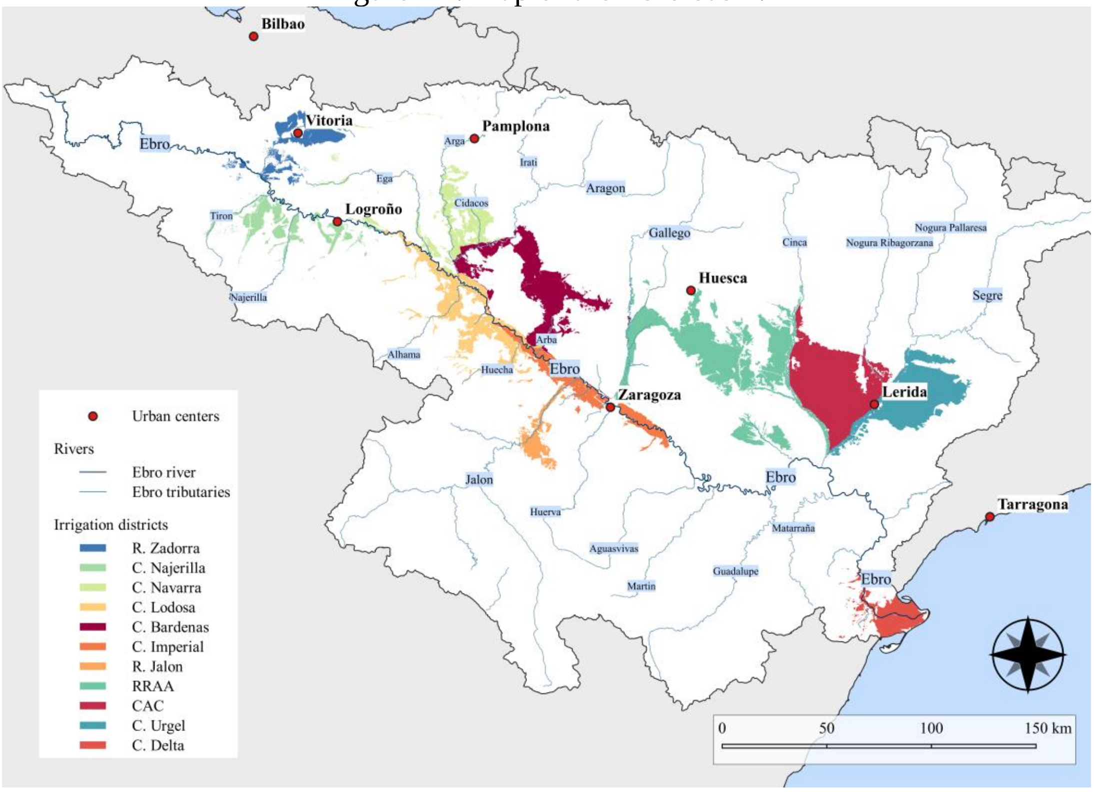
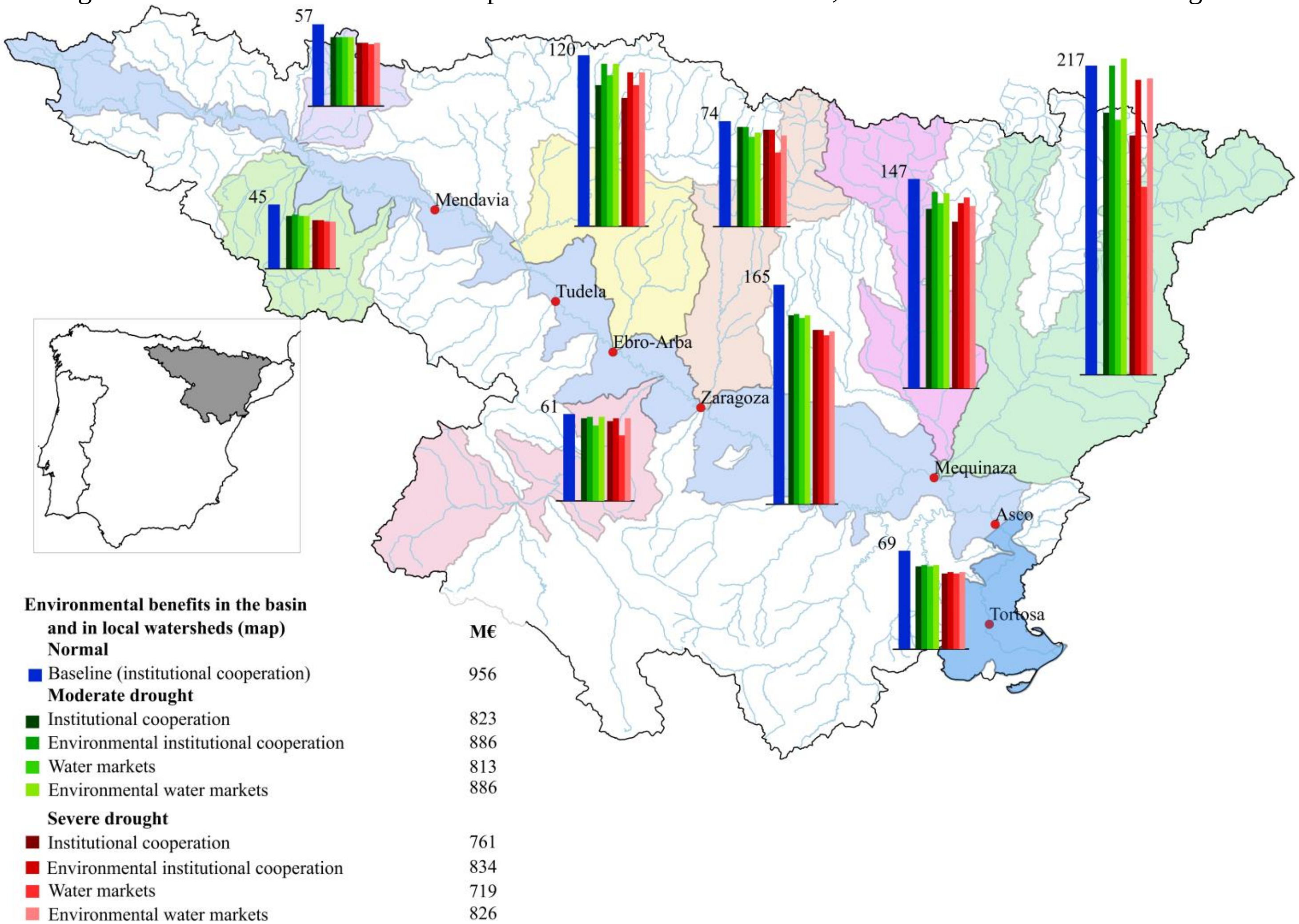


Figure B2. Environmental benefits of policies under normal weather, and moderate and severe drought[a].



[a] We present here additional results to the impacts of severe drought (-40% inflow reduction) considered in the main text of the study. These results correspond to a moderate drought scenario, where the reduction of inflows is lowered to 30% applying the same methodology

Table B1. Policies under drought conditions: institutional cooperation, environmental institutional cooperation, water markets, and environmental water markets.

Weather scenario	Normal	Moderate drought[a]				Severe drought[a]			
Policy type	Base scenario	Institutional cooperation	Environmental institutional cooperation	Water markets	Environmental water markets	Institutional cooperation	Environmental institutional cooperation	Water markets	Environmental water markets
				Water use (Mm^3)					
Water use	5,782	4,167	3,562	4,167	3,672	3,632	3,047	3,627	3,232
Irrigation	5,380	3,765	3,160	3,765	3,270	3,230	2,645	3,225	2,830
Urban	402	402	402	402	402	402	402	402	402
Water exchanges			605	435	820		585	235	780
Between irrigation				435	325			235	380
Between irrigation and environment			605		495		585		400
Environmental flow in mouth	8,895	6,230	6,440	6,220	6,370	5,350	5,540	5,345	5,435
				Irrigation surface area (1,000 ha)					
Surface area	529	377	317	393	331	332	275	348	293
Field crops	400	260	204	272	217	219	165	229	182
Fruit trees	104	96	92	99	92	93	90	97	90
Vegetables	25	21	21	22	22	20	20	22	21
				Private and environmental benefits (€ M)					
Private benefit	2,486	2,365	2,374	2,378	2,387	2,321	2,332	2,340	2,346
Irrigation	629	508	517	521	530	464	475	483	489
Urban	1,857	1,857	1,857	1857	1,857	1,857	1,857	1,857	1,857
Environmental benefit	956	823	886	813	886	761	834	719	826
Social benefits	3,442	3,188	3,199	3,191	3,211	3,082	3,105	3,059	3,118

[a] We present here additional results to the impacts of severe drought (-40% inflow reduction) considered in the main text of the article. These results correspond to a moderate drought scenario, where the reduction of inflows is lowered to 30% applying the same methodology.

Chapter 4

4. Hydroeconomic analysis of droughts in the Ebro basin using copulas for streamflow simulation

Abstract

Climate change intensifies water scarcity in arid and semi-arid regions where pressures on water resources are significant, further compromising the sustainability of water systems. Climate change triggers more frequent, longer and intense droughts that bring about serious challenges for management. Hydroeconomic analysis provides a modeling framework for policy design at basin scale, taking into consideration the spatial and temporal relationships between water sectors. In this study, an integrated hydroeconomic model of the Ebro basin is used to analyze the economic impacts of climate change under several water management alternatives. An innovative approach, the Copula procedure, is used to generate longer, and more intense and frequent drought events. Several policy scenarios are simulated by combining two water allocation rules, proportional share or water markets, with the possibility of investments in advanced irrigation systems. The sustainability of the Ebro water system is evaluated by looking at its reliability, resilience and vulnerability under each policy alternative. The risk assessment of the benefit losses informs on the water system exposure to extreme drought events, and the contribution of management options in reducing potential losses. The results highlight that climate change exacerbates the likelihood of substantial economic losses from droughts, which compromise the sustainability of the water system. Water markets and irrigation efficiency enhancements reduce uncertainty and losses from droughts, although there is a trade-off between irrigation benefits and damages to aquatic ecosystems. However, the effectiveness of this policy combination decreases for longer and intense droughts.
Keywords: Hydro-economic model; climate change; drought impacts; water management; copula; drought intensity, duration and frequency

4.1. Introduction

Droughts are a natural hazard that impair the capacity of water systems to support economic activities (Borgomeo et al., 2015). Agriculture, natural ecosystems, hydropower, and urban and industrial supply are substantially exposed to water scarcity and can sustain significant economic losses (Naumann et al., 2015). Droughts and water scarcity are already a serious problem in arid and semiarid regions across the world, with increasing pressures from the impending climate change. In Europe, the evidence during recent years indicates that the drought anomaly in Europe is unprecedented in the past 2,000 years (Büntgen et al., 2021).[1]

Conflicts among users often arise from water scarcity, compounded by unsustainable management policies and lack of cooperation (Iglesias et al., 2007; Quiroga et al., 2011). The management challenge is serious because climate change widens the uncertainty of water planning (Herman et al., 2020; Sandoval-Solis et al., 2011).

Costs of drought damages have been estimated at 9 billion € per year in the European Union (Cammalleri et al., 2020), and $8 billion per year in the United States (NOAA, 2021). These costs represent between 0.05% and 0.1% of the gross domestic product, although costs could be exceptionally higher some years. Kirby et al. (2014) estimate at 1% of GDP the costs of the 2009 drought in Australia, and Hernández et al. (2013) estimate the cost of the 2005 drought in the Ebro basin (Spain) at 0.5% of GDP.

The countries in Europe with large drought damages in billion € per year are Spain (1.5), Italy (1.4) and France (1.2), where drought planning efforts and climate adaptation actions are being developed. Most damages affect the agriculture (50%) and energy (35%) sectors, followed by the urban water supply sector (13%). Future damages would depend on the increase in the global warming temperature, with damages increasing up to five times for a +3°C scenario (Feyen et al., 2020).

Water management needs information to compare water system performance under a wide range of climate conditions in order to identify suitable governance alternatives. Sustainable water management faces the challenge of meeting human and environmental

[1] The anomaly seems to be driven by anthropogenic warming, which is changing the position of the summer jet stream.

water requirements while reducing the adverse impacts of droughts (Sandoval-Solis et al., 2011).

In Europe, drought frequency and intensity are highest in the Mediterranean area (Spinoni et al., 2015), with considerable damages sustained by Spain, France, Italy and Greece. Climate change will increase the frequency, intensity and duration of drought spells (IPCC, 2014). The effects would include reductions of crop and pasture production, higher risk of crop failures, livestock losses, land and ecosystems degradation, and negative impacts on hydropower and urban supply (Falloon and Betts, 2010; Li et al., 2009). Climate change will increase the vulnerability of water systems to droughts leading to critical failures, and the acute water scarcity will force adjustments in management to confront drought events (García-Ruiz et al., 2011; Vicente-Serrano et al., 2014).

The impact of droughts is driven by the intensity, duration and frequency of drought spells, and by the capacity of the system to endure these adverse events. River basin management policies should enhance the performance of the water system to confront disruptive events. Reliability, resilience and vulnerability are sustainability indicators that inform of the adequacy of management and policy alternatives.

Extreme droughts are climate events with low frequency, and they are rarely represented in climate projections (Rocheta et al., 2014). Water system vulnerabilities and management performance could be identified by generating synthetic stream flows that replicate historical and projected weather conditions.

Water management is challenging when drought spells entail large economic costs and environmental damages, especially in arid and semiarid regions. The difficulties of water management are compounded by economic growth, the increasing social concern for environmental protection, and climate change. This implies that water management becomes and adaptive process under constant revision based on updated information and knowledge. Hydroeconomic analysis (HEA) integrates biophysical, economic and ecosystem components in a framework that accounts for the temporal and spatial dimensions of water scarcity problems. Therefore, HEA is an important tool for evaluating water management adaptation to climate change (Ward, 2021).

This paper analyzes the economic impacts of drought and water scarcity in the Ebro basin under alternative water allocation policies, taking into account that climate change results in more frequent, intense and longer droughts. The reliability, resilience and vulnerability of the water system to droughts are analyzed under different water management policies using HEA. An important innovation in this hydroeconomic modeling study is that the inflows in the model are generated using a statistical method denominated copula. This procedure generates more accurate streamflow series, which replicate historical stream flows and projected weather conditions with longer and more intense droughts.

4.2. Modeling framework

There is a wide variety of procedures to calculate runoff and streamflow from climate and environment variables, such as temperature, radiation, precipitation and vegetation cover. Drought studies use this information together with climate change scenarios, for enhancing the estimation of the intensity, duration and frequency of droughts. The statistical models used to model droughts could be based on regression analysis, variations of the autoregressive integrated moving average (ARIMA) model, Markov chains, artificial neural networks (ANN) or probabilistic characterization using copulas, among others (Mishra and Singh, 2011).

The approach taken in this study to drought modeling is to develop a model that can inform water management at basin level, with the objective of enhancing long-term water security. This requires an overall risk analysis as part of the selection of measures to be taken in drought planning. This study does not focus on the biophysical drought processes, but rather on the human-water interactions in the basin by looking at impact linkages and finding accurate representations of the human-water interactions (Brunner et al., 2021). This is in line with the essence of water systems analysis, which is the prediction of the hydrologic, socioeconomic and environmental consequences of water management (Brown et al., 2015).

The human-water interactions are represented using hydroeconomic modeling, which is a spatially and temporally distributed mathematical model, where water demand and supply nodes are characterized hydrologically and economically. This HEA approach could address the challenges faced by stakeholders in the management of water systems, because of the systematic integration of the hydrologic, engineering, economic, environmental and institutional dimensions of basins in a unique framework. The HEA framework has clear advantages in evaluating management and policy strategies for adaptation to climate change, by providing efficient water allocations across water uses, spatial locations, and time periods (Ward, 2021).

The hydrological component of the model is represented by a simplified reduced form of the basin hydrology. Stream flows are stochastic, and therefore management decisions should be taken in a risk-based framework. Different risk metrics are used in water studies to compare the policy options for adaptation to climate change. Here we use the concepts of reliability (probability of failure), resiliency (recovery duration) and vulnerability (failure damages) for water system performance, which were proposed by Hashimoto et al. (1982).

Modeling the hydrology requires the consideration of the joint distribution of random variables, and we use the copula procedure to generate the headwaters entering the hydrological network. The advantage of the copula approach is that the dependence between the variables is independent from the choice of the marginal distributions of individual variables.

Generating synthetic stream flows overcomes the constraints imposed by the lack of long series of historical information. Streamflow generation is important in hydrology studies, and estimation methods cover a broad range of techniques. Representing extreme values using multivariate analysis is uncommon because of the limited number of multivariate distributions that represent extreme values. Distributions like bivariate Pareto and bivariate Gamma distributions could represent extreme values of two random variables. The problems with those distributions are that: the same distribution is needed for each marginal distribution; the estimation of parameter for these distributions could be difficult; and the extension to more than two variables are problematic.

The copula approach resolves these problems because the marginal distributions are fitted independently, parameters are estimated by maximum likelihood, and extensions to more than two variables are straightforward by regular and canonical copulas. The univariate marginal distributions and the multivariate dependence structure are separated, with the marginal distributions fitted independently and the dependence structure represented by a copula. Compared to other methods of streamflow simulation, copulas are flexible in the selection of marginal distributions, the dependence structure of variables, and the extension to multiple variables (Chen et al., 2015).

4.2.1 Streamflow simulation methodology

Duration, frequency and intensity are temporal variables that characterize droughts. Monthly stream flows are stochastic variables with temporal dependence, and the drought persistence is driven by this temporal dependence. Here the objective is to generate streamflow series matching the behavior of historic data but capable of including the climate change effects on droughts' intensity and duration. Several methods are used to simulate stream flows, such as autoregressive moving average, block bootstrapping, Markov chain processes, and copulas. The copula-based method is gaining traction to characterize the joint probability distributions of stream flows, and droughts with longer duration and larger intensity than previously observed can be generated by perturbing the copula parameter (Borgomeo et al., 2015; Salvadori and De Michele, 2004).

Monthly streamflow X_m in month m is a stochastic variable with a cumulative distribution function (cdf) $F(X_m)$. The probability integral transform states that $u_m = F(x_m) = P(X_m \leq x_m)$, where u_m has the standard uniform distribution. Two consecutive monthly stream flows are correlated and their dependence is represented by the joint cdf $H_{x_{m-1},x_m}(x_{m-1}, x_m) = P(X_{m-1} \leq x_{m-1}, X_m \leq x_m)$, where the marginal cumulative distributions of $H_{x_{m-1},x_m}(x_{m-1}, x_m)$ are $u_{m-1} = F_{m-1}(x_{m-1})$ and $u_m = F_m(x_m)$. Standard multivariate modeling is a complex task that may not yield the best fit for hydrological variables, and the copula-based method can overcome the difficulties in modeling multivariate distributions.

The copula is a function that links univariate cumulative distributions to create a multivariate distribution function. A copula is a joint distribution of two uniform random variables, and the Sklar's theorem states that the joint distribution function $H_{x_{m-1},x_m}(x_{m-1}, x_m)$ can be expressed in terms of their marginal distributions $F_{m-1}(x_{m-1})$ and $F_m(x_m)$, by defining a copula C as:

$$H_{x_{m-1},x_m}(x_{m-1}, x_m) = C\big(F_{m-1}(x_{m-1}), F_m(x_m)\big) = C(u_{m-1}, u_m)$$

where $C: [0,1]^2 \rightarrow [0,1]$ denotes the copula function, and $C(u_{m-1}, u_m) = Pr[U_{m-1} \leq u_{m-1}, U_m \leq u_m]$. The copula captures the dependence of two consecutive months. In order to generate random values of stream flows, the conditional distribution method was used in this study. The conditional probability of flow x_m given the flow at x_{m-1}, $Pr(X_m \leq x_m | X_{m-1} = x_{m-1})$, can be obtained from the copula as:

$$t = H_{x_{m-1},x_m}(x_m|x_{m-1}) = P(U_m \leq u_m|U_{m-1} = u_{m-1}) = C(u_m|u_{m-1}) = \frac{\partial C(u_{m-1}, u_m)}{\partial u_{m-1}}$$

This relationship feeds the simulations of the correlated random variables. If the flow at month $m-1$ is known, the value of u_{m-1} is given by evaluating $F_{m-1(x_{m-1})}$. Then, the value of u_m can be simulated from the inverse function $C^{-1}(u_m\,|u_{m-1})$ and a uniform random number t. The flow at month m is obtained from the inverse function or quantile function F_m^{-1} as $x_m = F_m^{-1}(u_m)$.

To simulate monthly stream flows, the distribution function of monthly stream flows and the copula have to be fitted. There are several distribution functions to model monthly streamflow, and the usual distribution functions are employed for characterizing hydrological variables. The Clayton copula is selected in this study for modeling droughts because it characterizes variables with low tail correlation, such as droughts.

The monthly streamflow is a random variable with unknown distribution function. The distribution functions tested to fit the marginals of the copulas were Gamma, Lognormal, Weibull, Pearson III and Generalized Extreme Values. The parameter of the distributions is estimated maximizing the likelihood function of the density function. The goodness of fit is computed by the Kolmogorov-Smirnov (KS), Anderson-Darling (AD) and Cramer-Von Mises (CVM) tests, which identify the distribution that better fits the observed data. Finally, the distribution is selected comparing the Bayesian and Akaike information criteria (BIC and AIC).

There are many types of copula structures C. The Archimedean copulas are a family of copulas commonly used to describe different correlation structures between variables. The copula considered in this study is the Clayton copula of the Archimedean copula family. The Archimedean copulas are defined as follows:

$$C(u_{m-1}, u_m) = \varphi^{-1}[\varphi(u_m) + \varphi(u_{m-1})]$$

where φ is the generator function that is a strictly decreasing function from $[0,1]$ onto $[0, \infty]$. The Clayton copula of two consecutive months is defined as:

$$C(u_{m-1}, u_m) = \left[u_{m-1}^{-\theta} + u_m^{-\theta} - 1\right]^{\left(\frac{-1}{\theta}\right)}$$

The conditional distribution of the Clayton copula is expressed as:

$$t = P(U_m \leq u_m | U_{m-1} = u_{m-1}) = \frac{\partial C(u_{m-1}, u_m)}{\partial u_{m-1}}$$
$$= u_{m-1}^{-(\theta+1)} \left(u_{m-1}^{-\theta} + u_m^{-\theta} - 1\right)^{-(\frac{1+\theta}{\theta})}$$

and the inverse function of the conditional distribution of the Clayton copula is:

$$u_m = \left[1 + u_{m-1}^{-\theta}\left(t^{\left(-\frac{\theta}{1+\theta}\right)} - 1\right)\right]^{\frac{-1}{\theta}}$$

Figure 4.1 shows the procedure followed for simulation. If the streamflow X_{m-1} at month $m-1$ is known, it is possible to simulate the streamflow at month m using the inverse function of the conditional distribution. The first step is to obtain the value of u_{m-1} using the cdf $F_{\mathrm{m}-1}(x_{m-1}) = u_{m-1}$, and then a uniform random number t between zero and one is generated. The second step is to find u_m using the inverse function of the conditional distribution of the copula. The value of the simulated flow x_m is obtained with the inverse function of the cdf $F_m(x_m)$.

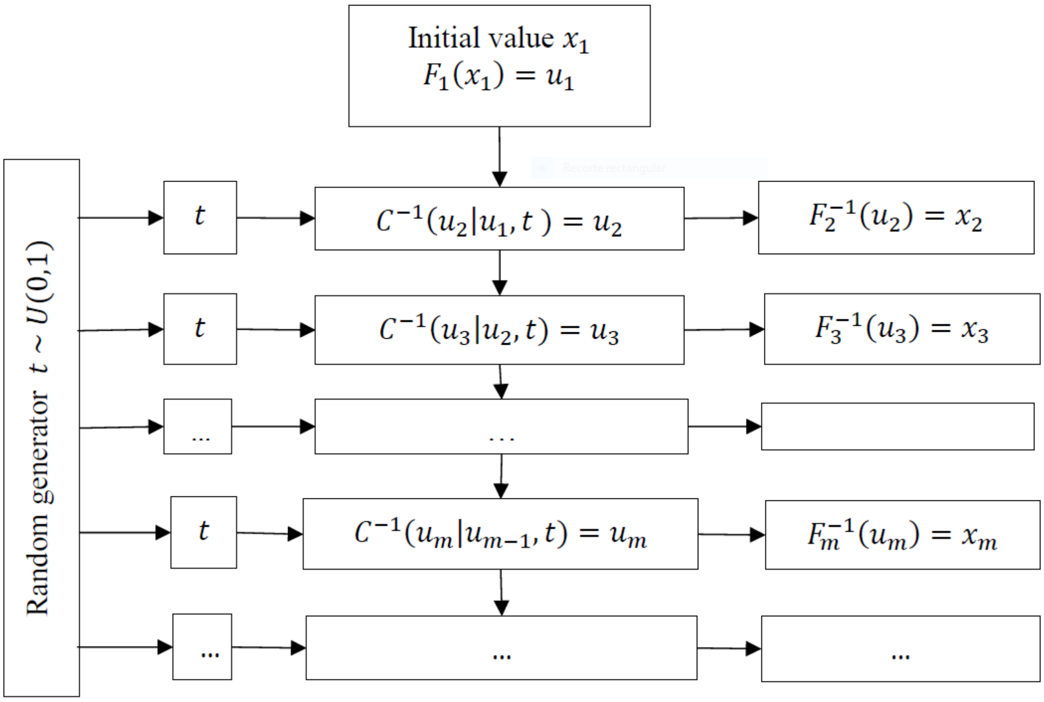
The simulation of the monthly stream flow using conditional copulas are summarized as follows

1) Fit the marginal distribution $F_m(x_m)$ for each month $m = 1,2, \ldots, 12$.
2) Fit the joint distribution using copulas for each pair of months and estimate their parameters θ_i where $i = 1,2, \ldots, 12$.

   $C\big(F_1(x_1), F_2(x_2)\big), \ldots, C\big(F_{m-1}(x_{m-1}), F_m(x_m)\big), \ldots, C\big(F_{12}(x_{12}), F_1(x_1)\big)$
3) Given the streamflow x_{m-1} in month $m-1$, u_{m-1} can be calculated with the marginal $u_{m-1} = F_{m-1}(x_{m-1})$. A uniform random variable t between zero and one is generated, and the value of u_m is obtained from the inverse conditional function.
4) The value of the streamflow at month m is calculated with the inverse distribution function $x_m = F_m^{-1}(u_m)$

The copula simulation procedure can be used to simulate longer droughts by multiplying the parameter of the copula θ_i by a factor β, where the values one, two, six and ten are selected for factor β. For each perturbation of β, 1.000 sequences were generated using the conditional method described before. The streamflow generation method has been used to generate 40 years of monthly stream flows.

Figure 4.1. Streamflow simulation procedure based on Copulas.



4.2.2 Model components and scenarios

The hydroeconomic model of the Ebro basin integrates hydrological, economic, environmental and institutional aspects. The model includes a reduced-form hydrological model, a regional economy component, and an environmental benefit component.

4.2.3 Reduced-form hydrological component

The hydrological component represents flows between supply and demand nodes, using the hydrological principles of water mass balance and flow continuity in the river. The hydrological component shows the spatial distribution of water flows used by economic sectors and environmental flows. The mathematical formulation is as follows:

$$W_{out_{d},m,y} = W_{in_{d},m,y} + W^{res}_{rel_{d},m,y} - W_{loss_{d,m,y}} - Div^{IR}_{d,m,y} - Div^{URB}_{d,m,y} \quad (4.1)$$

$$W_{in_{d+1},m,y} = W_{out_{d},m,y} + r^{RI}_{d} \cdot \left(Div^{IR}_{d,m,y}\right) + r^{URB}_{d} \cdot \left(Div^{URB}_{d,m,y}\right) + + RO_{d+1,m,y} \quad (4.2)$$

$$W_{out_{mouth},m,y} \geq E^{min}_{m} \quad (4.3)$$

Equation (4.1) is the mass balance equation, and it determines water outflow $W_{out_{d},m,y}$ in river reach d, in year y and month m, which is equal to water inflow $W_{in_{d},m,y}$, plus water release $W^{res}_{rel_{d},m,y}$ from reservoir res, minus water losses $W_{loss_{d},m,y}$, water abstraction for irrigation $Div^{IR}_{d,m,y}$, and abstraction for urban and industrial use $Div^{URB}_{d,m,y}$.

Equation (4.2) guarantees river flow continuity, in which water inflow in the following river reach $W_{in_{d+1},m,y}$ is the sum of the water outflow from the previous reach $W_{out_d,m,y}$, return flows from previous irrigation districts $\left[r_d^{RI} \cdot \left(Div_{d,m,y}^{IR}\right)\right]$, urban return flows $[r_{d,m,y}^{URB} \cdot \left(Div_{d,m,y}^{URB}\right)]$, and flows entering this river reach from tributaries $RO_{d+1,m,y}$. Equation (4.3) states that water outflow at the mouth of the Ebro $W_{out_{mouth},m,y}$ must be above the minimum environmental flow level.

The model dynamics is driven by the water storage in reservoirs. The formulation of the reservoirs' storage is as follows:

$$Z_{res,m,y} = Z_{res,m-1,y} - W_{rel_d,m,y}^{res} - W_{evp,m,y}^{res} \quad (4.4)$$

$$Z_{res,0} = B_{res,0} \quad (4.5)$$

$$Z_{res,t} \leq C_{res}^{max} \quad (4.6)$$

$$Z_{res,t} \geq C_{res}^{min} \quad (4.7)$$

$$W_{evp,m,y}^{res} = Evp_{res}\, S_{res,m,y} \quad (4.8)$$

$$S_{res,m,y} = \alpha_{res} + \beta_{res}\, Z_{res,m,y} \quad (4.9)$$

Equation (4.4) states that the reservoir stored water $Z_{res,m,y}$ is equal to the stock in the previous period, $Z_{res,m-1,y}$, minus both net release (outflow minus inflow), $W_{rel_d,m,y}^{res}$, and evaporation, $W_{evp,m,y}^{res}$. Equation (4.5) is the initial reservoir water stock at $m = 12$ and $y = 0$, $B_{res,0}$. Equations (4.6) and (4.7) are upper and lower bounds on reservoir storage, given by maximum capacity, C_{res}^{max}, and dead storage C_{res}^{min}. Equation (4.8) states that reservoir evaporation, $W_{evp,m,y}^{res}$, is proportional to the reservoir surface area, $S_{res,m,y}$. The parameter Evp_{res} is the water evaporation per hectare of reservoir surface area (Mm^3/ha). Equation (4.9) states the linear relationship between reservoir surface area and stored water, where parameters α_{res} and β_{res} are the intercept and the linear coefficients of the surface-storage equation. This equation gives a good approximation because storage variations are limited between the upper and lower bounds.

The hydrological component has been calibrated introducing auxiliary variables for river reaches, so that so that the predicted gauged flows are broadly consistent with observed flows at each river gauge where measurement data are available. Calibration is used to close the mass balance equation, since there are water inflows and outflows in the system that cannot be observed (for example, underground flows, evaporation, or some return flows). Calibration includes non-observed flows, which are the difference between flows estimated with the model and flows measured at gauging stations. The parameters of the surface-storage equation are obtained using the database in (Yigzaw et al., 2018).

4.2.4 Regional economic component

The regional economic component includes agricultural irrigation and urban water use. There is an optimization model for agricultural activities in every irrigation district, which maximizes farmers' private benefits from crop production subject to technical and resource constraints. Crop yield functions are assumed linear and decreasing in cropland acreage, and output and input prices are constant. The optimization problem is formulated as follows:

$$Max\left(B_{k,y}^{IR}\right) = \sum_{ij} C'_{i,j,k} \cdot X_{i,j,k,y} \tag{4.10}$$

s.t.

$$\sum_{i} X_{i,j,y} \leq T_{land_{k,j}};\ j = flood, sprinkler, drip \tag{4.11}$$

$$\sum_{ij} W_{i,j,k,m} \cdot X_{i,j,k,y} <= T_{water_{k,m,y}} \tag{4.12}$$

$$\sum_{ij} M_{i,j,k} \cdot X_{i,j,k,y} \leq T_{la_k} \tag{4.13}$$

$$X_{per,j,k,y} \leq X_{per,j,k,y-1} \tag{4.14}$$

$$X_{i,j,k,y} \geq 0 \tag{4.15}$$

where $B_{k,y}^{IR}$ is private benefit in irrigation district k and year y, and $C_{i,j,k,y}^{'}$ is net income of crop i using irrigation technology j. The decision variable of the optimization problem is $X_{i,j,k,y}$, which is acreage of crop i under irrigation technology j, in year y. Equation (4.11) represents the restriction of available land $T_{land_{k,j}}$ in irrigation district k equipped with irrigation system j. Equation (4.12) states that water applied in an irrigation district k, in year y and month m, is restricted to water availability $T_{water_{k,m,y}}$, where $W_{i,j,k,m}$ is the water requirement of crop i with technology j, in month m. The water available $T_{water_{k,m,y}}$ in irrigation district in year at month m is the variable linking the optimization model of irrigation districts and the hydrological component. The labor constraint (4.13) represents labor availability T_{la_k} in irrigation district k, where M_{ijk} is the labor requirement of crop i with irrigation system j. Equation (4.14) states that fruit trees for each irrigation district, at year y, cannot exceed the fruit trees irrigated the previous year, $y - 1$. This constraint represent future loss of capital investment in fruit trees if farmers decide not to irrigate in the current time period.

This optimization model includes the major crops in every irrigation district. Irrigation systems for field crops are flood and sprinkler, and for fruit trees and vegetables the irrigation systems are drip and flood. Net income per hectare C'_{ijk} is the difference between crop revenue and direct and indirect costs (including capital amortization) and it is expressed by $C'_{ijk} = P_i Y_{ijk} - CP_i$ where P_i is price of crop i, Y_{ijk} is yield of crop i under technology j in the irrigation district k, and CP_i are direct and indirect costs of crop i (including water costs).

The crop yield function is linear and represents decreasing crop yields when additional land is assigned to crop production, based on the principle of Ricardian rent. The first lands in production have the highest yields, and yields fall off as less-suitable lands enter production. The crop function relates yields with acreage of crop i under irrigation technology j, and is defined as:

$$Y_{ijk} = \beta_{0_{ijk}} + \beta_{1ijk} X_{ijk} \quad (4.16)$$

The agricultural component is calibrated using the Positive mathematical programming (PMP) to reproduce the observed land and water use under baseline conditions, and to address the problem of crop overspecialization (Howitt, 1995). Calibration follows the PMP procedure by (Dagnino and Ward, 2012), where parameters are estimated for a linear yield function [Equation (4.16)] based on the first-order conditions of benefit maximization. Data on yields, prices, crop water requirements, production costs, availability of water resources, land and labor, together with information on biophysical parameters have been obtained from statistical databases, reports, previous studies and expert consultation (MARM, 2010; MAGRAMA, 2015; INE, 2009; DGA, 2009; GC, 2009; GN, 2009).

The modeling of urban water maximizes economic surplus, the sum of consumer and producer surpluses in the basin's main cities. The optimization problem of the urban sector is expressed by:

$$Max B_{u,y}^{URB} = \left(a_{du} Q_{du,y} - ½\, b_{du} Q_{du,y}^2 - a_{su} Q_{su,y} - ½\, b_{su} Q_{su,y}^2 \right) \quad (4.17)$$

s.t.

$$Q_{du,y} - Q_{su,y} \leq 0 \quad (4.18)$$

$$Q_{du,y};\ Q_{su,y} \geq 0 \quad (4.19)$$

where B_u^{URB} is the consumer and producer surplus in city u. The variables $Q_{su,y}$ and $Q_{du,y}$ are water supply and demand in city u, respectively. The parameters a_{du} and b_{du} are the constant term and the slope of the inverse demand function, and the parameters a_{su} and b_{su} are the constant term and the slope of the water supply function. Equation (4.17) states that the supply must be equal to or greater than the demand for water. The water supply $Q_{su,y}$ is the variable linking urban water with the hydrological component. The equation parameters have been obtained from the studies by Arbués et al. (2004) and Arbués et al. (2010) (all unit prices are expressed in euros at 2009).

4.2.5 Model optimization, scenarios and sustainability outcomes

The net present value (NPV) of the benefits of economic sectors is maximized over the planning horizon, where NPV is the sum of present benefits from agricultural irrigation and urban water use. The model optimizes the objective function:

$$Max\ NPV\ = \sum_{k,y} \frac{B_{k,y}^{IR}}{(1+r\ )^{y}}\ + \sum_{u,y} \frac{B_{u,y}^{URB}}{(1+r\ )^{y}} \tag{4.20}$$

subject to the basin's hydrological, land use, institutional, and environmental constrains stated in equations (4.1) to (4.19).

The performance of the Ebro water system will be threatened by climate change and the increasing frequency, duration and intensity of droughts. Several indicators such as reliability, resilience or vulnerability are used to assess water system performance to disruptive events like droughts. Reliability is the probability that water supply could meet water demand during the simulation period, where reliability is simply one minus the risk of system failure. Resiliency describes the capacity of the system to recover after a system failure, and vulnerability can be measured by the economic losses of drought spells.

Sustainability and risk-based indicators contribute to the assessment of the likelihood and impact of disruptive events on water systems. A comprehensive sustainability index can be built by combining reliability, resilience and vulnerability indicators in a general sustainability index. This sustainability index is used in the Ebro to compare the performance of the water system under different management and policy strategies for climate change adaptation.

The analysis of the impact of water scarcity on the sustainability of the water system is undertaken under several scenarios, which combine climate change conditions, water allocation policies, and investments in advanced irrigation systems.

The assumptions for climate change in the Ebro for the next 40 years simulation period are the following: the mean inflows in the basin decline progressively up to 12%, and higher temperatures increase crop evapotranspiration and dam evaporation by 5.7% and 6%, respectively. Climate change will also increase drought persistence, with longer droughts spells. The copula procedure is used to account for the longer duration of droughts. Eleven inflow series of forty-year each have been simulated by the copula for a given value of parameter θ, which regulates drought duration. The duration of historical droughts are represented by parameter θ, and then the parameter is increased to 2θ, 6θ and 10θ to represent longer drought durations.

There are three climate scenarios: 1) current climate, which replicates historical inflows, temperature, and drought duration; 2) future climate with decreasing inflows, increasing temperature, and historical drought duration; and 3) future climate with decreasing inflows, increasing temperature, and longer drought duration. Scenarios 2 and 3 compare future climate with historical or with longer drought duration, and the reason is to discern the effects of drought duration and intensity.

The water allocation policies analyzed are institutional cooperation and water markets. Institutional cooperation is the current policy applied by the water authority in the Ebro basin. Under drought conditions, the basin authority reduces water allocations for irrigation in relation to drought intensity, assigning the fall of inflows by proportional share. Under the water markets policy, farmers receive the water allocations of institutional cooperation, but then these water allocations can be exchanged among irrigation districts, maximizing the private benefits of water use. There is no direct exchange of water between selling and buying irrigation districts, but rather the selling district reduces withdrawals and the buying district augments withdrawals in their respective river reaches.

The investments in advanced irrigation systems is the preferred solution by decision makers to confront water scarcity in most arid and semiarid basins around the world. These investments improve the water conveyance systems and the irrigation equipment in parcels, with gains in water efficiency at irrigation district level and higher crop yields. However, Grafton et al. (2018) indicate that these investments tend to reduce stream flows in basins, and call it “the paradox of irrigation efficiency”. Channel efficiency in the Ebro range between 70% and 90% at present, and investments improve all channels up to 90% efficiency. Current parcel irrigation technologies include flood, sprinkle and drip

Table 4.1. Climate change, water allocation and efficiency investment scenarios.

Climate change conditions		Water allocation policy	Efficiency investments
No climate change		*Proportional share*	*No efficiency enhancements*
Inflows			
Parameter θ does not change. Inflows and drought spells replicate historical behavior. Mean inflows are the observed levels	Crop evapotranspiration and dam evaporation do not change	Under drought, water allocations for irrigation are reduced in proportion to drought intensity	Irrigation technology does not change, with channel efficiency between 70% and 90%
Climate change		*Water markets*	*Efficiency enhancements*
Inflows			
Drought duration is prolonged by increasing the copula parameter θ. Stream flows are simulated for 2θ, 6θ and 10θ. Inflows fall steadily up to 12% in 2040	Crop evapotranspiration and dam evaporation increase up to 5.7 and 6% in 2040, respectively.	Water is exchanged among irrigation districts	More efficient irrigation technologies. Irrigation systems change to sprinkle for field crops (except rice), and drip for fruit trees and vegetables. Channel efficiency is also increased

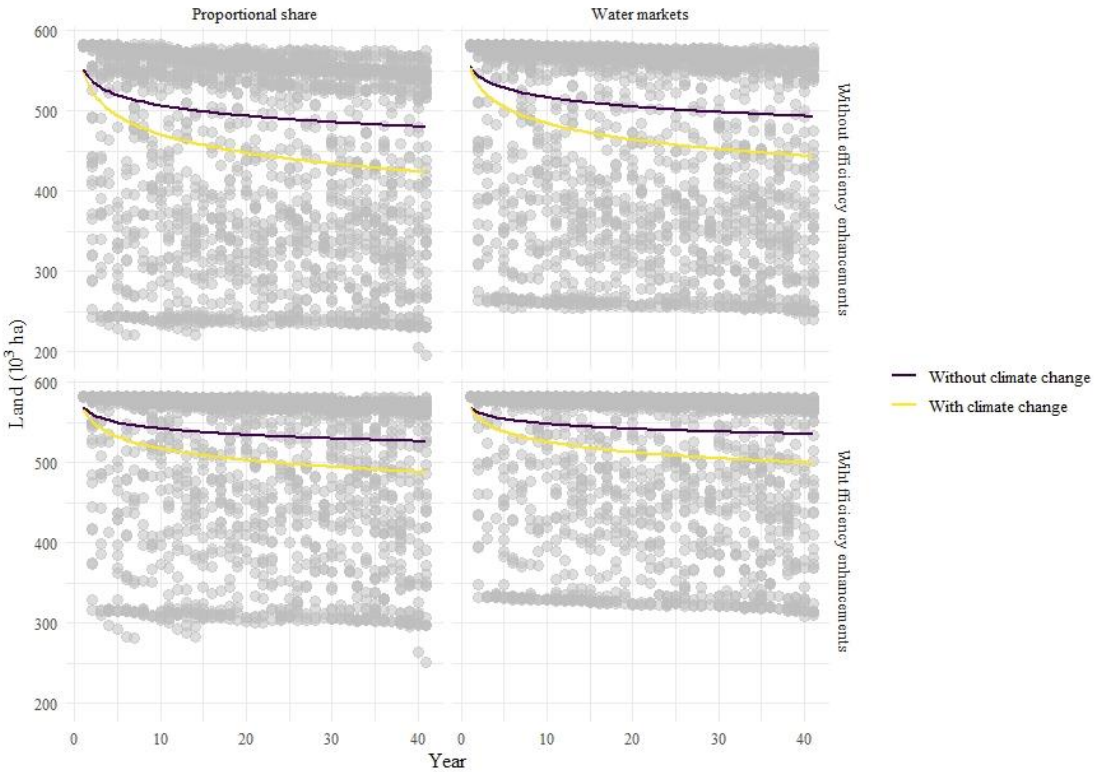
irrigation, and investments will expand in the basin sprinkle irrigation to all field crops (except rice), and drip irrigation to all vegetable and fruit crops.[2] Table 4.1 summarizes the main aspects of the simulated scenarios.

4.3. Results

The results correspond to each combination of climate change and policy scenarios, by performing eleven series of forty-year length simulations. These simulations are replicated with the data on water inflows that are generated for the different values of the factor β in the copula procedure (β=1, 2, 6 and 10), which regulate drought duration. Then, the outcomes from each combination of policies are calculated. The results show the impacts of droughts on irrigated cropland, water extractions and irrigation benefits. The analysis in irrigation districts shows the adaption strategies in cropland distribution undertaken by districts. Simulations provide monthly information on water withdrawals, environmental stream flows, water scarcity, and water system stress. The information is used to estimate reliability, resilience, vulnerability and sustainability indicators, which reveal the system performance.

[2] The investment costs of these advanced irrigation technologies are included in the benefits of crops.

Figure 4.2. Expected irrigation area under climate and policy scenario (10^3 ha).

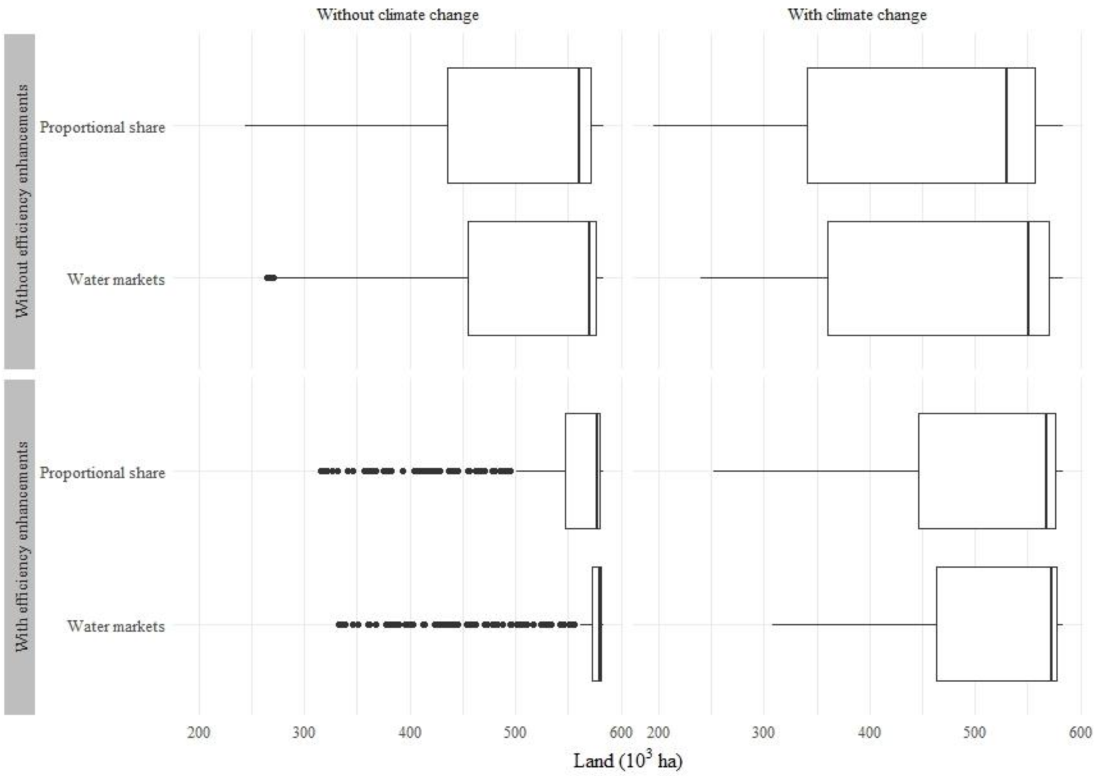


4.3.1 Sustainability of the water systems for irrigation

Drought intensity and duration generate benefit losses, which indicate the system sensibility to drought events. The performance of the different policies is compared, in order to identify which are the tradeoffs between policies. In figure 4.2, the grey points display the irrigated area by year for climate change and policy scenarios. The lines are smoothed trends, assuming a logarithmic relationship between irrigated area and time. The top panels show the irrigated area with and without climate change, for water markets (top-left) and proportional share (top-right) policies under current irrigation technologies. The bottom panels show the irrigated area for improved irrigation technologies. The irrigated area declines in the future because of the recurrent drought events and the growing trend in water scarcity from climate change.

Annual cropland, water diversions and benefits under climate and policy scenarios, are presented in figures 4.3, 4.4 and 4.5, respectively. The size of boxplots range between the first and third quartiles of the distribution, providing information on dispersion and uncertainty. The first quantile indicates the 25% of worst cases or the 75% of best cases.

Figure 4.3. Annual cropland distribution under climate and policy scenarios (10^3 ha).

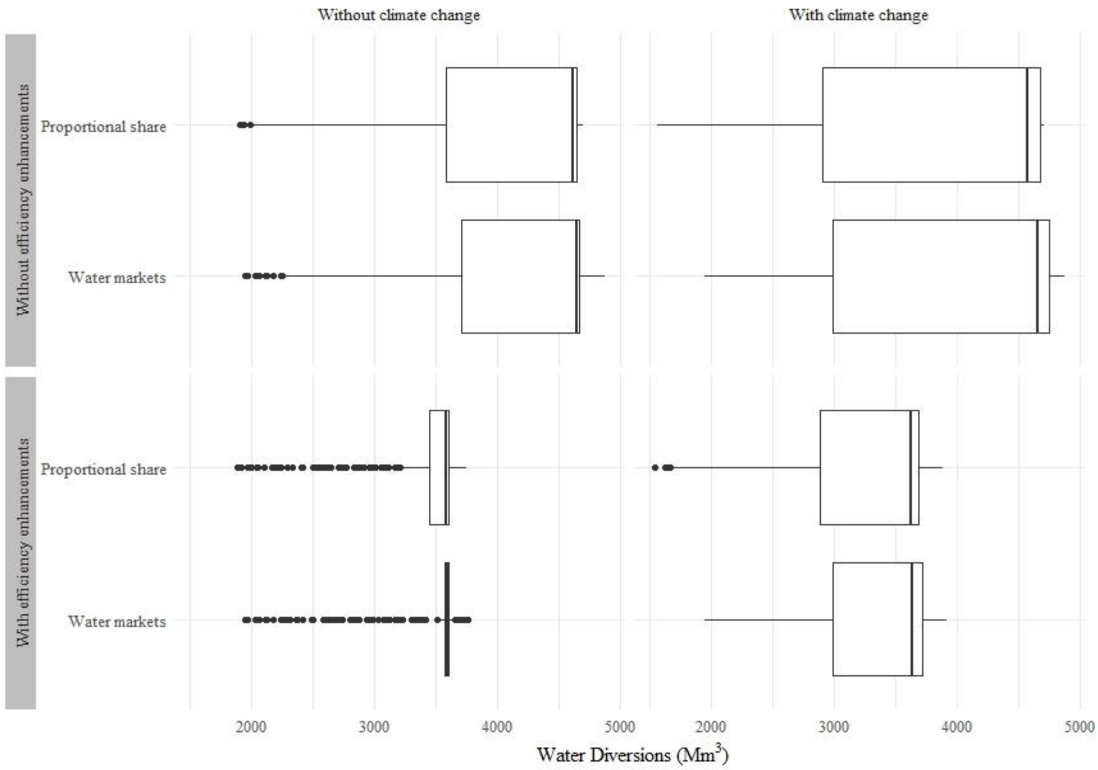


Climate change exacerbates water scarcity problems, worsening the drought impacts. Enhancements in the efficiency of parcel irrigation systems and conveyance channels contributes to moderate the fall in irrigated cropland. The efficiency enhancements contribute to meet the water consumed by crops, especially under climate change when crop water requirements increase. The water market policy slows down cropland reductions, compared with the proportional share policy. The combination of water markets and efficiency enhancements maintains more cropland in production, but also shrinks environmental flows. Under climate change, the first quartile of irrigated area is around 100.000 ha lower for all policy scenarios.

The vertical line dividing the boxplots is the median of the cropland distribution ranging between 525,000 and 580,000 ha for all scenarios (figure 4.3), with the median close to the baseline irrigated area (580,000 ha). Normal or wet weather conditions occur in half of the time periods, during which the baseline crop production and water extractions are maintained.

The impact of droughts is determinate by several factors like water stored in dams, monthly inflows and policy. The relationship between irrigated area reductions and annual water inflows is estimated by a Beta regression (see table C1 in the appendix for

Figure 4.4. Annual water diversions distribution by climate and scenarios (Mm^3).



details). Regression parameters are used to estimate the expected land reduction under alternative policies. For example, investments in efficiency enhancement cut by half land reductions, compared with maintaining current irrigation efficiency (Table C1).

The drought scenarios are moderate drought where water inflows fall by 15% and extreme drought where water inflows fall by 50%. Table 4.2 presents the policy results from the beta regression predictions. The percentages indicate the expected land reductions under moderate and extreme drought conditions, for the first and last periods of simulation. Results show that under the same policy and climate condition, the fall in irrigated area doubles between the first and last periods. Climate change increases land reduction between one and two percentage points. The mitigation capacity of the combined policies declines with drought severity, climate change and time. The market policy cuts the reduction in cropland by 20%, compared with the proportional policy, while investments in irrigation efficiency cut cropland reductions by 55% compared with no investments (Figure C4 and table C1 in the appendix).

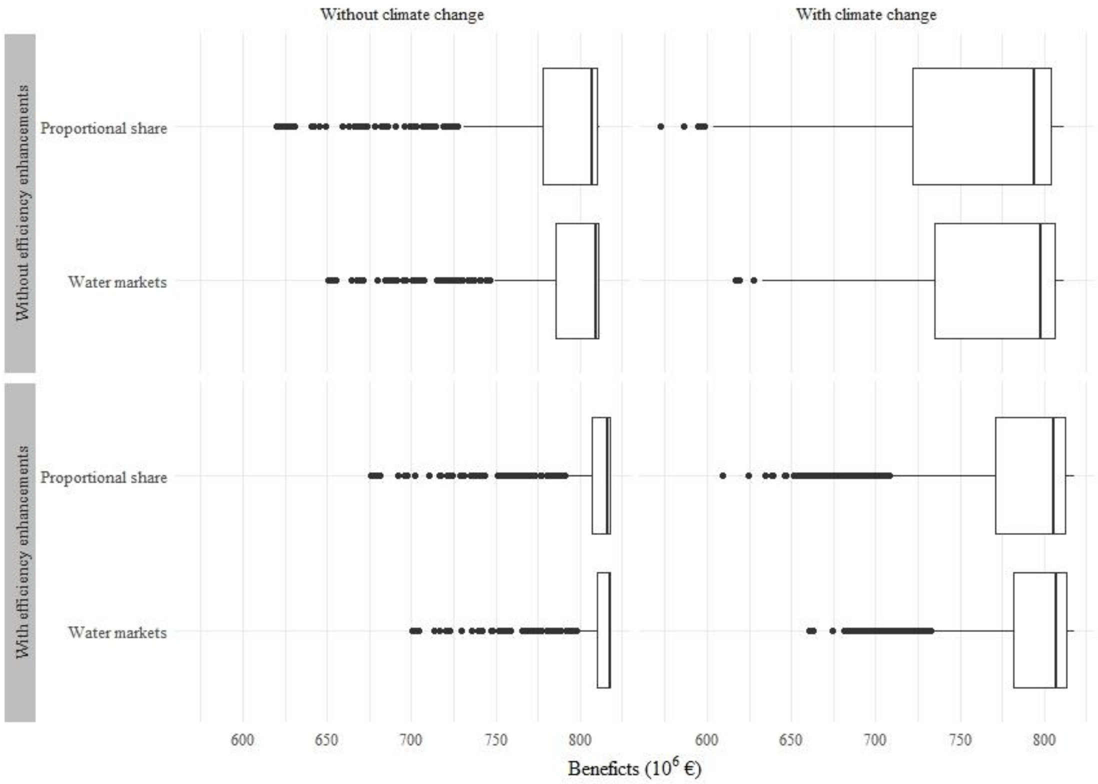
Table 4.2. Percentage cropland reduction over the baseline, under climate change and policy.

		First period of the simulation		*Last period of the simulatio*	
		Moderate drought (-15%)	Extreme drought (-50%)	Moderate drought (-15%)	Extreme drought (-50%
Without climate change	*Without efficiency enhancements*				
	Proportional share	8.40%	33.40%	19.10%	56.20%
	Water markets	6.90%	28.60%	15.90%	50.70%
	With efficiency enhancements				
	Proportional share	4.00%	18.60%	9.70%	36.80%
	Water markets	3.30%	15.50%	7.90%	31.80%
With climate change	*Without efficiency enhancements*				
	Proportional share	9.10%	35.20%	20.40%	58.10%
	Water markets	7.40%	30.30%	17.00%	52.70%
	With efficiency enhancements				
	Proportional share	4.40%	19.80%	10.40%	38.70%
	Water markets	3.50%	16.50%	8.50%	33.60%

The response of farmers to drought is reducing field crops and maintaining fruit trees and vegetables. Corn represents around 18% of total crop mix and remains constant under drought conditions, while the other field crops fall. Wheat and rice acreage diminish progressively until they get out of production. Fruit trees and vegetables share of crop mix grow, in particular vineyard and peach. Five crops account for 75% of the irrigated area in the baseline, but under drought the cropping pattern is more diversified and minority crops gain importance (Figure C5 and figure C6 in appendix). Adaptation to drought involves the retirement of crops with high water consumption and low profitability.

Water scarcity takes place during droughts, and their impact depends on the policy mix that combines proportional share or water markets, with current or enhanced water efficiency. Stream flows lower than the median correspond to 50% of the worst cropland reductions, and the ensuing likelihood and size of benefit losses. Water extractions are driven by climate conditions and policies. The enhancement of irrigation systems reduces water extractions from 4,500 Mm^3 to 3,500 Mm^3 under normal weather, where basin inflows are around the historic mean (Figure 4.4).

Figure 4.5. Annual benefits distribution under climate and policy scenarios (10^6 €).



Climate change increases water diversions because of the rising temperatures and evaporation, even under normal and wet weather conditions. Also, the likelihood of water scarcity and droughts increases under climate change, which shrinks mean inflows and enlarges the duration of drought spells. Under climate change, the first quartile of water diversions is around 3,000 Mm^3 for all policy scenarios, which shows the fall of water in the basin when droughts are severe.

The index of water stress is the proportion of water diversions over water inflows, so the water deficit is the gap between water diversions and water inflows. Water scarcity and water stress are especially intense in summer, when crop water requirements are large and water inflows small, demonstrating the importance of dams to meet water demand. Water stress is more likely from June to September when water extractions double basin inflows, and the water system could be in stress (Figure C7 in appendix). However, water stress and water scarcity can be underestimated because environmental flows are not included in the supply-demand balance.

Larger irrigated cropland involves more water extractions and consumption (evapotranspiration), reducing stream flows in the basin. Under drought, investments in irrigation efficiency increase water extractions by 25% to 30% in comparison with

Table 4.3. Min, 1st quartile, mean, median, 3rd quartile and max of annual benefits under drought by policy-mix.

	Min	1st Quartile	Mean	Median	3rd Quartile	Max
Without efficiency enhancements						
Proportional share	573	729	762	797	806	812
Water markets	617	741	769	800	808	812
With efficiency enhancements						
Proportional share	609	776	785	808	814	818
Water markets	660	786	791	809	815	818

maintaining current irrigation efficiency (Figure C8). The consequence is lower stream flows at the river mouth, with an average fall around 200 Mm^3 (Figure C9).

The annual benefits for policy and climate scenarios are presented in Figure 4.5. The median benefits are close to baseline benefits (820 M€), and range between 790 and 820 M€. To assess the effects of climate change on the distribution of benefits, we have pooled the data of benefits from all policy scenarios, Climate change displaces the distribution of benefits, since without climate change the benefits exceed 775 M€ in 75% of the cases, but with climate change the benefits exceed only 725 M€ in 75% of the cases.

Weather conditions are stochastic, and therefore the impacts of drought are also stochastic. These impacts are measured by the benefits obtained under each combination of policies. Then, the benefit outcomes from each combination of policies are compared. The first quartile of the distribution of benefit contains the worst benefit outcomes from drought events. Also, climate change amplifies the dispersion of benefits, while increasing both the uncertainty and likelihood of the fall in benefits.

Table 4.3 shows the minimum, first quartile, mean, median, third quartile and maximum of the annual benefits by policy mix, which combines proportional share or water markets, and current or enhanced water efficiency. Benefits are higher for water markets compared to proportional share, and benefits are also higher for efficiency enhancements compared to current efficiency. The mean benefits fall from 820 M€ of the baseline scenario to between 760 and 790 M€, depending of the policy combination.

The likelihood and size of benefit losses from drought impacts reveal the degree of exposure of the water system to adverse events. Risk is measured by the probability (likelihood) of withstanding a certain level of benefit damages (size), and risk management plays an important role in decision making. Value at risk (VaR) is a standard risk measure that calculates the benefit level that is not exceeded for a given probability or confidence interval. VaR can also be calculated in terms of benefit losses by the exceedance of probability, which is the probability of exceeding a certain benefit loss. Therefore, in terms of benefits losses, VaR is the benefit loss that is exceeded for a given probability or confidence interval (see section 3 of the appendix for details). The VaR for a 5% probability is widely used for risk assessment, and the combination of water markets and efficiency enhancements reduce in 70 M€ the benefit loss level of the VaR at 5%, compared with proportional share and current irrigation efficiency. This reduction in benefit losses represent around 8% of baseline benefits (Figure C10). Figure 4.6 shows the results by irrigation district of the mean percentage reductions from the baseline scenario of variables benefits, water diversions, labor, cropland, and cultivated areas of field trees, field crops, and vegetables. Under the water markets policy, Canal de Bardenas (CB), Canal Imperial (CI), Delta, and Zadorra sell water to other irrigation districts under drought conditions. These water selling districts reduce field crops, while buying districts have higher crop profitability and irrigation efficiency and could maintain fruit trees, vegetables, and even field crops. Investments in efficiency enhancement retain more cropland under production, and when combined with the market policy the water exchanges go down because of lower water scarcity and a more uniform efficiency among districts. The Jalon irrigation district is heavily damaged by drought because water is quite scarce in the left bank of the Ebro, with considerably reductions of field crops for all policy combinations.

Labor reductions depend on crop patterns, with large declines in districts specializing in vegetables and fruit trees that use labor intensively. Labor losses are up to 20% in Jalon and Riegos del Alto Aragon districts. The combination of market and efficiency enhancement policies maintains labor, although losses are important in water selling districts.

Figure 4.6. Reductions from the baseline scenario of benefits, labor, water diverted, land (field crops, fruit trees, vegetables) in irrigation districts by combinations of market, proportional and efficiency enhancement policies.

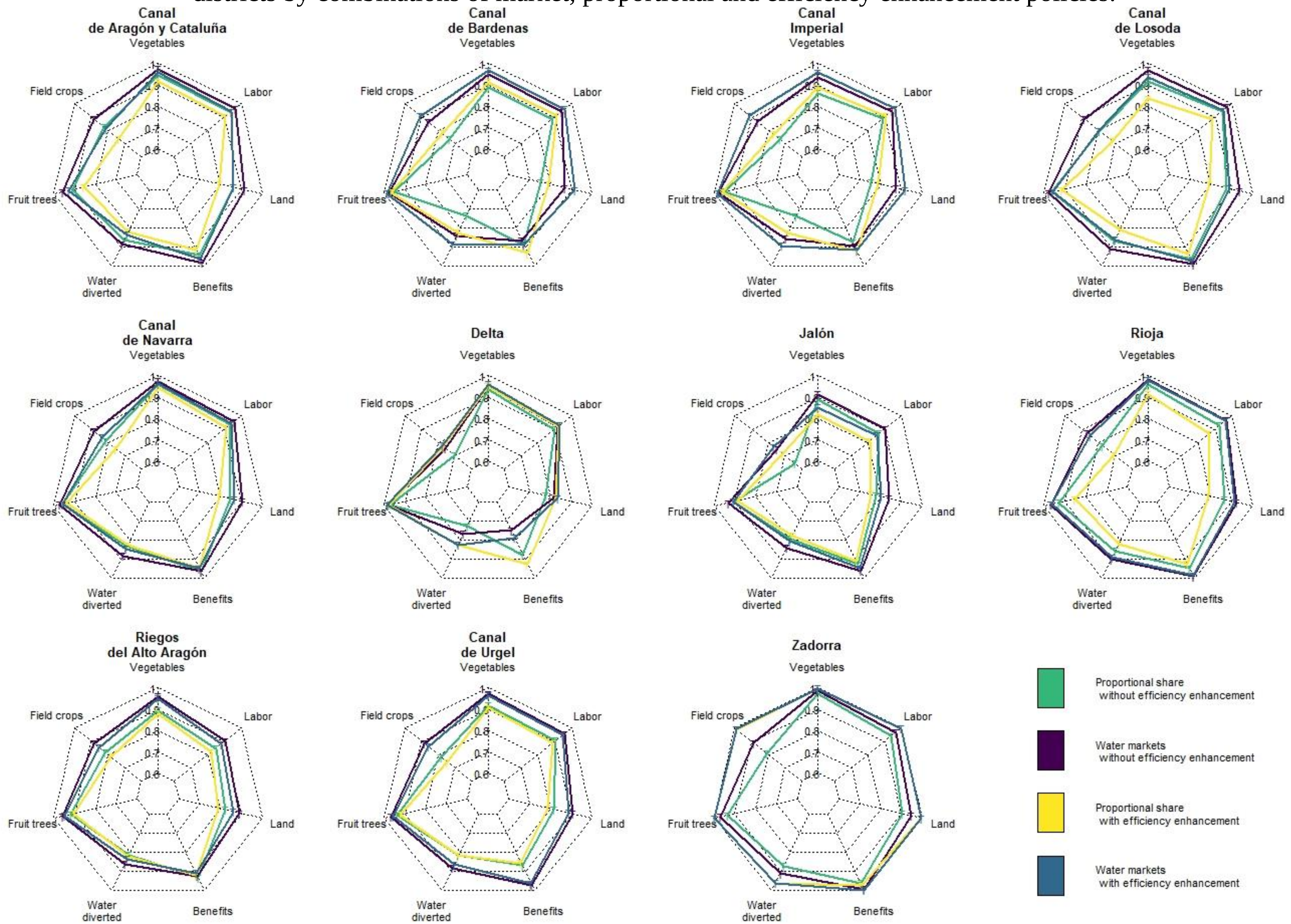


Table 4.4. Reliability, resilience, vulnerability and sustainability index by climate and policy scenarios.

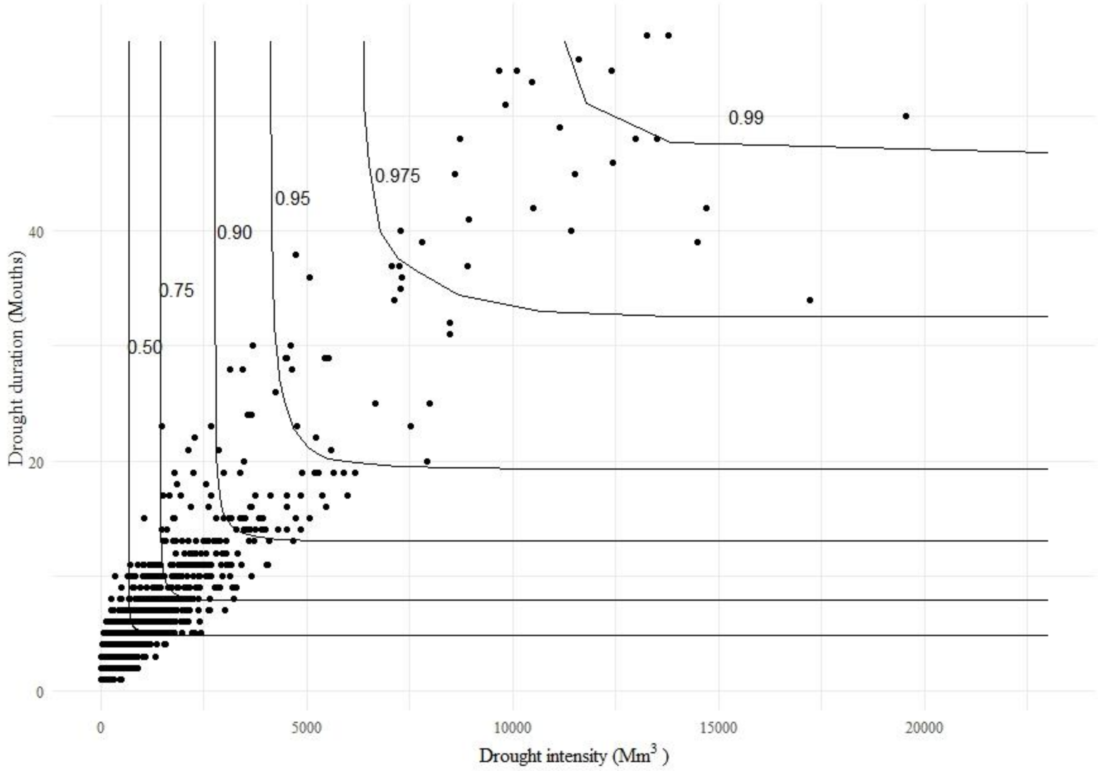
	Reliability	Resiliency	Vulnerability	Sustainability
Without climate change				
Without efficiency enhancements				
Proportional share	0.76	0.73	0.78	0.43
Water markets	0.78	0.76	0.81	0.48
With efficiency enhancements				
Proportional share	0.85	0.83	0.83	0.58
Water markets	0.86	0.83	0.86	0.62
With climate change				
Without efficiency enhancements				
Proportional share	0.63	0.45	0.77	0.22
Water markets	0.64	0.46	0.80	0.24
With efficiency enhancements				
Proportional share	0.79	0.57	0.82	0.37
Water markets	0.80	0.59	0.85	0.40

Reliability is measured by the proportion of time periods in which baseline cropland water demand is met by the water system, resilience is measured by the recovery duration after the water system fails, and vulnerability is measured by the benefits losses from water system failure (index decreases for more vulnerability). Then, the sustainability index is defined as the product of reliability, resilience and vulnerability (see details in section 4.6.2. of the appendix).

The indexes for reliability, resilience, vulnerability and sustainability by policy combination are shown in Table 4.4. Climate change raises the likelihood of system failure with longer recovery periods and lower benefits. These reduced reliability and resilience and increased vulnerability, make the system less sustainable. The sustainability of the system improves by combining water markets and efficiency enhancements, with gains in reliability, resilience and vulnerability.

Figure 4.7 shows the joint distribution of drought duration and drought intensity. Drought events are identified by falling basin inflows below a threshold, defined at 75 percent of baseline monthly inflows. The drought period starts when inflows fall below the threshold and finishes when inflows recuperate, with the duration being the number of months under drought. The monthly deficit is the gap between the drought observed inflows and the drought threshold, and drought intensity is the sum of monthly deficits over the drought spell. Around 90 percent of drought spells are shorter than 12 months

Figure 4.7. Joint distribution of drought duration (months) and drought intensity (Mm^3).



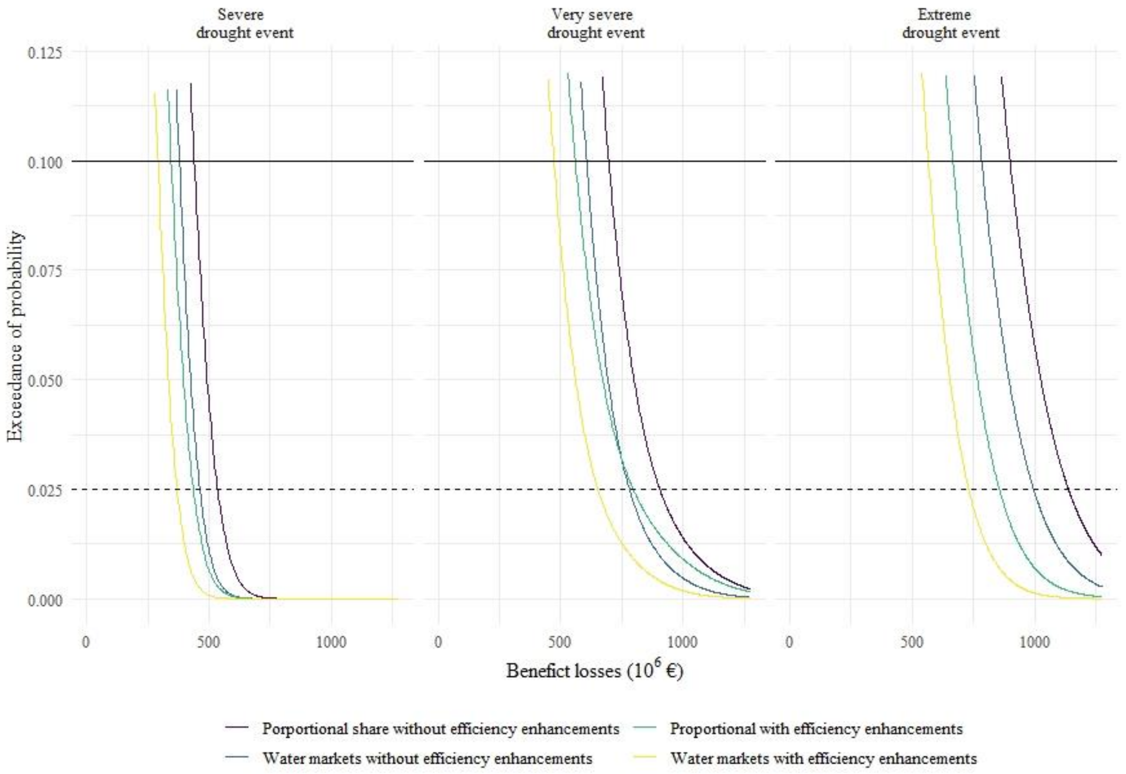
with water deficit below 2,500 Mm^3. Drought spells longer than two years with water deficits above 5,000 Mm^3 have a 5 percent probability. In extreme cases, the drought duration reaches 60 months with deficits above 20,000 Mm^3.

Figure 4.8 shows the conditional exceedance of probability of benefit losses under severe, very severe, and extreme droughts.[3] The figure is zoomed to the area where the exceedance of probability is lower than 0.125 (12.5%). The continuous line marks the exceedance of probability at 0.10 (10%), and the dotted line at 0.025 (2.5%). Figure C11 in the appendix shows the full range of the figure.

Under a severe drought spell (19 months duration and 4.128 Mm^3 deficit), the probability of accumulated benefit losses exceeding 250 M€, range between 12.5% and 37.5% for the different policy combinations. Combining water markets and efficiency enhancements divides by three the probability that benefit losses exceed 250 M€ under

[3] The duration and water deficit for severe, very severe and extreme droughts are the following: 19 months and 4,128 Mm^3 deficit for severe drought, 33 months and 6,355 Mm^3 deficit for very severe drought, and 47 months and 11,146 Mm^3 deficit for extreme drought. These values are the empirical quantiles at 0.95, 0.97 and 0.99 of drought duration and drought intensity. The conditional probability is estimated by nonparametric methods (Li and Racine, 2008 and Li et al. 2013)

Figure 4.8. Conditional exceedance of probability of benefit losses for increasing drought severity.

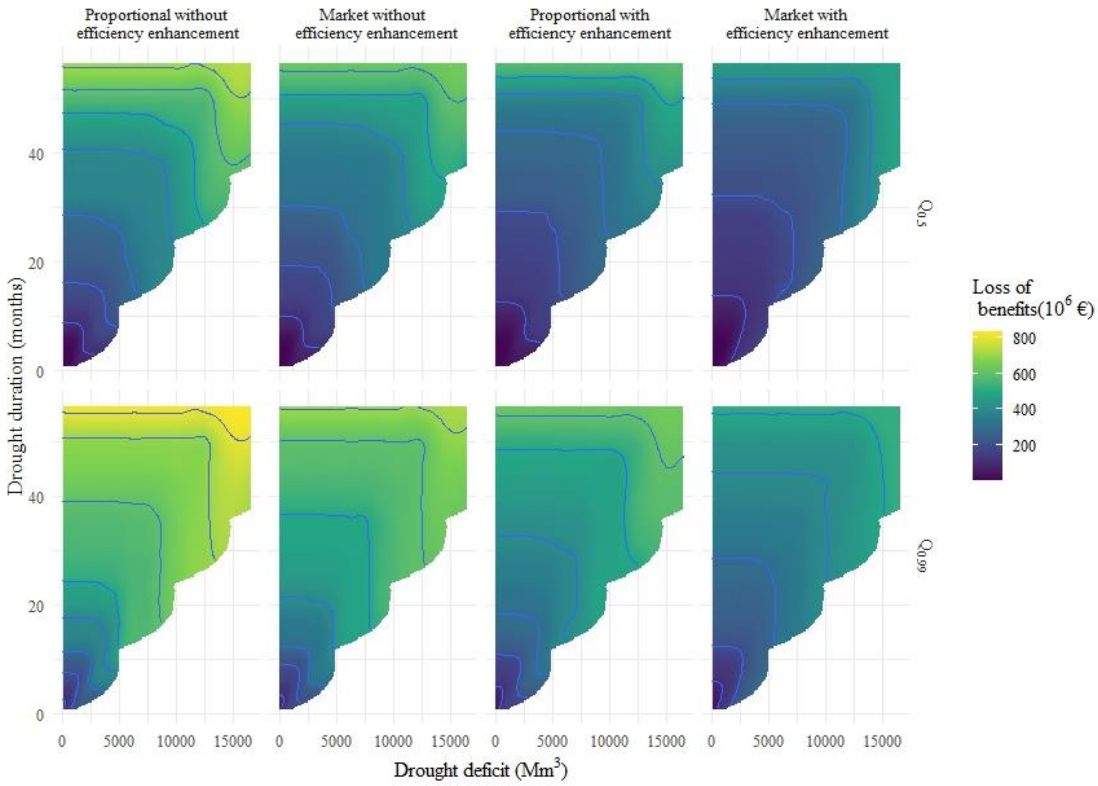


severe drought. The probability than benefit losses exceed 500 M€ is close to 5% in a severe drought spell for proportional share without efficiency enhancements, but the probability decreases below 1.5% for all other policy combinations.

Extreme droughts (47 months and a deficit of 11,146 Mm^3) trigger benefit losses that exceed 500 M€ in half of the cases for the proportional share policy, and 250 M€ with the combination of water markets and efficiency enhancements (Figure C11). For the 5% of worst cases, benefits losses exceed 1,000 M€ under proportional share without efficiency enhancements, and 650 M€ under water markets and efficiency enhancements (Figure 8).

Figure 9 shows how conditional benefit losses depend on the duration and intensity of drought, by policy combination. Benefit losses correspond to quantiles 0.5 (50%) and 0.99 (99%), and contour lines show additional benefit losses of 100 M€. The benefit losses in the first and second columns are for proportional share and water market, without efficiency enhancements, while the third and fourth columns are for combinations with

Figure 4.9. Contour lines of benefit losses (10^6 €), by policy at quantiles 0.5 and 0.99.



efficiency enhancements. The rows show the conditional quantile benefit losses at 0.5 and 0.99 probabilities.[4]

The combination of water markets and efficiency enhancements reduces benefit losses by almost half (probability 0.5), and by one third in extreme cases (probability 0.99). However, this policy combination also shrinks environmental flows, further degrading water dependent ecosystems.

The more frequent droughts are shorter than 12 months with water deficits under 2,500 Mm^3, and their benefit losses are below 100 M€ with a probability of 50% for all policies. In extreme cases (probability 0.99), the droughts up to 12 months have benefit losses around 300 M€ for proportional share, shrinking to 200 M€ when combining water markets and efficiency enhancements. This indicates that droughts of short duration and low intensity could involve substantial benefit losses, and that the gap in policy performance is greater in adverse cases.

[4] This information is extend to quantiles 0.5, 0.9, 0.95 and 0.99 in figure A12 of the appendix.

For longer and more intense droughts (between 12 and 24 months and between 2,500 and 5000 Mm^3), there is a sharp increase in benefit losses. In extreme cases (probability of 0.99), benefit losses rise to 500 M€ for proportional share, but only to 300 M€ for the combination of water markets and efficiency enhancements. The join probability of having a drought longer than 4 years and with deficits greater than 12,500 Mm^3 is lower than one percent. In these extreme drought events, the combination of water markets and efficiency enhancement reduces benefits losses by 300 M€ compared to proportional share and current irrigation efficiency. The sequence of annual droughts is usually a mix of moderate, severe and extreme drought events, and extreme droughts lasting consecutive years are very rare. For prolonged droughts, the system cannot longer relieve water scarcity because water storage in dams is depleted. Once the dam storage is exhausted, the only response to drought is sharing the remaining water with adjustments in crop patterns.

4.3.2 Sustainability of the water systems for irrigation and the environment

Ecosystems in the Ebro basin are protected by minimum environmental flows in river reaches across the basin, which are set-up by the Ebro Basin Authority in the basin plan. These environmental flows are minimum levels of stream flows that maintain the status of water-dependent ecosystem. The environmental flows are gauged in 15 river reaches in the basin.

The percentage of the flow gap between non-complying and minimum environmental flows provide information on expected environmental damages. Table 4.5 shows the average percentage of the flow gap between non-complying and minimum environmental flows during drought periods. The percentages indicate the size of the flow gap for each policy combination, and the ensuing impairment of ecosystems. Efficiency enhancements and water market policies, together with climate change, aggravate non-compliance, especially the policy of efficiency enhancements that maintains crop production at the expense of ecosystems' degradation.

The environmental sustainability is measured by the average proportion of minimum environmental flows covered by each policy combination during droughts (Table 4.6). This environmental sustainability index is highest for proportional share water allocation without efficiency enhancements, and lowest for water markets with efficiency enhancements. Water allocation by the current proportional share policy promotes

Table 4.5. Percentage of flow gaps between non-complying and minimum environmental flows by policy combination*.

	Without climate change	*With climate change*
Without efficiency enhancements		
Proportional share	8.9%	11.9%
Water markets	9.9%	13.7%
With efficiency enhancements		
Proportional share	11.6%	14.6%
Water markets	12.3%	16.2%

* These are the average percentages during drought periods.

environmental sustainability, while water markets promote irrigation sustainability. However, the differences in environmental sustainability by policy combination are small compared with the differences in irrigation sustainability.

The entire water system sustainability is assessed by multiplying the irrigation sustainability and the environmental sustainability indexes (Table 4.6). The combination of water markets and efficiency enhancements provide the highest ranking for the water system, and the combination of proportional share without efficiency enhancements the lowest. Decision makers have to decide the policy mix to be chosen by considering the tradeoff between irrigation benefits and environmental protection. The tradeoff indicates that small increases in environmental protection require incurring in large losses in irrigation benefits.

However, the environmental damages can be underestimated for irrigation efficiency investments, as a consequence of the "paradox of irrigation efficiency" (Grafton et al. 2018). The paradox states that higher efficiency rarely reduces water consumption (evapotranspiration) by crops for the same water withdrawals, and the consequence is a fall in irrigation returns that reduce basin stream flows. To confront the paradox, investments in efficiency gains must be coupled with virtuous collective action outcomes capable of preventing the expansion of water consumption by crops.

The result of higher benefits from water markets compared with proportional share, highlighted in this study, is consistent with the findings in the hydroeconomic analysis literature (e.g. Crespo et al., 2019; Escriva-Bou et al., 2017; Salman et al., 2017). Many studies find that gains in irrigation efficiency reduce the impacts of drought, water scarcity and climate change (Bekchanov et al., 2016; Sánchez Chóliz and Sarasa, 2019). However, the "paradox of irrigation efficiency" mentioned above will undermine this finding, unless the expansion of water consumption by efficiency gains is prevented.

Table 4.6. Sustainability indexes for irrigation, environment and the whole system by climate and policy scenario.

	Irrigation sustainability	Environmental sustainability	Water system sustainability
Without climate change			
Without efficiency enhancements			
Proportional share	0.43	0.91	0.39
Water markets	0.48	0.90	0.43
With efficiency enhancements			
Proportional share	0.58	0.88	0.51
Water markets	0.62	0.87	0.54
With climate change			
Without efficiency enhancements			
Proportional share	0.22	0.88	0.19
Water markets	0.24	0.86	0.21
With efficiency enhancements			
Proportional share	0.37	0.85	0.31
Water markets	0.40	0.83	0.33

Connor and Kaczan (2013) describe this downside of water markets for in-stream flows in the Murray-Darling basin in Australia, indicating that Australia has chosen trading on water extractions instead of trading in water consumption, in order to reduce the transactions costs of water markets.

Climate change modifies the reliability, resilience and vulnerability of water systems, because of the shift in both water supply and demand. Despite considerable water management efforts, the sustainability of water systems can be threatened by the conflicting goals of maintaining irrigation and protecting the environment. Folke et al. (2004) recommend a secure range of water allocations for ecosystems, given the uncertainty in ecological responses involving irreversible regime shifts and tipping points.

The present study could be further expanded for a better assessment of the Ebro water system. Possible improvements include modeling the environmental benefits linked to the response of ecosystems to stream flows, and adding the hydropower sector to the economic activities in the basin. Other possible enhancement is to consider the spatial variability of water inflows in stream flows simulations, given the local heterogeneity of climate change impacts across sub-basins.

4.4. Conclusion

This study analyzes the economic impacts of drought and water scarcity in the Ebro basin, under current and future climate conditions. Climate change projections point toward more frequent, intense and longer drought spells. Reliability, resilience, and vulnerability of the water system to droughts are examined under several water management alternatives. The evaluated policies are the combinations of proportional share or water markets, with current or enhanced irrigation water efficiencies. The assessment of risk provides information on the water system exposure to extreme events, which is important for water management.

Hydroeconomic analysis is conducted with a model that integrates hydrological, economic, and environmental components into a framework that emphasizes the temporal and spatial relationships between water usages. Water inflows are generated using the copula approach, in order to represent both historical stream flows and projected stream flows under weather conditions with longer and more intense droughts. This study is innovative in the assessment of water scarcity impacts, by taking into account that the duration, intensity, and frequency of droughts are changing in the coming decades. The results are examined in terms of probability given the intrinsic uncertainty of drought events and climate change.

Growing crop water requirements, reductions in water inflows, and longer and more intense drought events are expected outcomes from climate change in the Ebro basin. Droughts under historical and climate change conditions entail cutbacks in water extractions, triggering substantial benefit losses in irrigation. Climate change increases the likelihood of longer and more intense droughts and their negative impacts, and impairs the resilience of the water system exposed to longer recovery periods. The frequency of extreme weather conditions will be also higher, boosting the risk of severe benefit losses. The climate stress will reduce the reliability of the water system to meet both human water security and environmental flows.

The impacts of droughts and climate change can be reduced by combining water markets with investments in irrigation efficiency. This policy mix expands cropland in production, water extractions and irrigation benefits, while lowering their dispersion and uncertainty. The impacts of extreme droughts are reduced somewhat, although the policy effectiveness decreases when droughts are more intense. The combination of water markets and efficiency enhancements improves the system sustainability because vulnerability is reduced, and reliability and resilience are reinforced. However, the gains in efficiency increase water consumption, reducing the basin in-stream flows. Consequently, this policy hinders the compliance with environmental flows and jeopardizes the status of aquatic ecosystem. Therefore, irrigation benefits are maintained at the expense of the environment.

The duration of most droughts is less than one year, and the likelihood of longer droughts shrinks because the probability of consecutive years of drought declines with duration. However, ten percent of droughts are longer than one year, and the ensuing benefit losses over several years can be important. The capacity of the water system to avoid cutbacks during droughts depends on the water storage available in dams. Once the capability of dams to offset water scarcity is exceeded, the reactions to droughts are limited to adjustments in crop patters and water trading. Water markets and efficiency enhancements are good interventions to maintain irrigation activities, at the cost of degrading aquatic ecosystems, and the trade-off has to be settled by decision makers.

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4.6. Appendix

4.6.1 Beta regression for modelling proportions and bounded data

The performance of each policy alternative under different climate conditions is analyzed, by regression, comparing the percentage of cropland reductions over the baseline. OLS estimation is the simplest method, but is not appropriate since the irrigation area and the percentage of cropland reductions are bounded variables.

Sinusoidal regression or logit regression analyze bounded data, like rates and proportions, but they are difficult to interpret and do not treat heteroskedastic problems. In addition, the distribution of proportions could be asymmetric and Gaussian approximations are not appropriate. Beta regression overcome these difficulties assuming that the response variable is beta distributed.

Following the model proposed by Ferrari and Cribari-Nato (2004), the response variable is Beta distributed, $y \sim \mathcal{B}(\mu, \phi)$, and its density function $f(y; \mu, \phi)$ is defined by two parameters μ and ϕ, and takes the expression:

$$f(y; \mu, \phi) = \frac{\Gamma(\phi)}{\Gamma(\mu\phi)\Gamma\big((1-\mu)\phi\big)} y^{\mu\phi-1}(1-y)^{(1-\mu)\phi-1}, \qquad 0 < \mathrm{y} < 1$$

where μ and ϕ are the precision and dispersion parameters, respectively, and satisfy that $0 < \mu < 1$ and $\phi > 0$. The mean and variance of the beta distribution are expressed with the precision and dispersion parameters as:

$$E(y) = \mu \text{ and } VAR(y) = \mu(1-\mu)/(1+\phi)$$

As in generalized linear models (GLM), the precision parameter is linked to the covariates, x, by a link function, $g_1(\mu)$, and a linear predictor, $x'\beta_\mu$; and the dispersion parameter is linked to another set of covariates, z, by a second link function, $g_2(\phi)$, and a linear predictor, $z'\beta_\phi$.

$$g_1(\mu) = x'\beta_\mu$$
$$g_2(\phi) = z'\beta_\phi$$

The coefficient sets β_μ and β_ϕ are estimated by Maximum Likelihood (ML). The logit, probit or loglog are functions commonly used as link functions. A comprehensive explanation of the model can be found at Cribari-Neto and Zeileis (2010).

The assumptions in the model are:

1) The percentage of cropland reductions over the baseline is beta distributed.
2) The precision and dispersion parameters are fitted by the percentage of the annual inflows over the baseline inflows, year, climate change and policy combination.
3) The logit link function and log link function connect the precision parameter and dispersion parameter, respectively, with the covariate sets.

The logit link function has been selected because the coefficients estimated indicate odds ratios, and the log link function ensures that dispersion parameter is greater than zero. Table C1 in the appendix shows the results of the estimation. The percentage crop reduction under different drought intensity, climate change, year, and policy showed in table 4.2 are computed with the results of the beta regression.

Table C1. Beta regression estimation results (standard deviation in brackets).

	Dependent variable:	
	Percentage of cropland reductions over the baseline	
	M.1	M.2
Precision (μ) model with logit link		
Year	0.023***	0.023***
	(0.001)	(0.001)
Proportional share	0.226***	0.221***
	(0.019)	(0.016)
Climate Change	0.081***	0.081**
	(0.028)	(0.028)
Enhancement of efficiency	-0.787***	-0.787***
	(0.019)	(0.019)
Inflows	-4.232***	-4.230***
	(0.035)	(0.035)
Intercept	-0.516***	-0.513***
	(0.040)	(0.040)
Dispersion (ϕ) model with log link		
Year	0.010***	0.008***
	(0.001)	(0.001)
Proportional share	-0.018	
	(0.030)	
Climate Change	0.470***	0.470***
	(0.040)	(0.040)
Enhancement of efficiency	0.277***	0.277***
	(0.030)	(0.030)
Inflows	2.314***	2.310***
	(0.053)	(0.053)
Intercept	0.817***	0.809***
	(0.058)	(0.056)
Observations	9,020	9,020
R^2	0.650	0.650
Log Likelihood	15,536	15,535
Note:		***p<0.001; **p<0.01

4.6.2 Reliability, resilience, vulnerability and sustainability index

Water management seeks to maintain the water system in a satisfactory state. The threshold for determining system failure is settled as the 75 percent of the baseline cropland water demand, and therefore the water system is in a satisfactory state if the 75 percent of the water demand at the baseline is meet. Reliability (Rel) measures the capacity of the water system to maintain a satisfactory state, and it is the number of the years over the total number of years (n) in which water system operates satisfactorily (S_i). In terms of probability, reliability is the probability of the water system to satisfy the 75 percent of the irrigation water demand.

$$S_i = \begin{cases} S_i = 1 \; if \; Div > 0.75 * Div_{baseline} \\ S_i = 0 \; if \; Div < 0.75 * Div_{baseline} \end{cases} \qquad Rel = \frac{\sum S_i}{n} = P(S_i = 1)$$

System resilience (Res) measures the recovery capacity of the system after a system failure. Then, resilience is the frequency with which the system recovers from failure

$$Res = P(S_{i+1} = 1 \mid S_i = 0) = \frac{P(S_i = 0 \cap S_{i+1} = 1)}{P(S_i = 0)}$$

Vulnerability (Vul) of the water system is measured by the benefit losses in the water system. Vulnerability is defined by the mean value of irrigation benefits (π_i) over irrigation benefits in the baseline ($\pi_{baseline}$), when the system is in an unsatisfactory state:

$$Vul = \frac{1}{\sum_i^n (1 - S_i)} \cdot \sum_i^n (1 - S_i) \cdot \frac{\Pi_i}{\pi_{baseline}}$$

Sustainability Sus is measured as the product of the reliability, resilience and vulnerability

$$Sus = Rel * Res * Vul$$

4.6.3 Probably, exceedance of probability and conditional probability

Probability is an important concept in this study that is used in several indicators used in the analysis of the results. In order to clarify concepts as exceedance of probability or Value at Risk, the concept of probability is briefly explained. Probability is a measure of the likelihood of an event happening. For a continuous random variable X, the probability that X takes a value lower than x is expressed as $P(X \leq x)$; and the probability that the variable exceeds a certain value is named exceedance of probability, that is $P(X > x) = 1 - P(X \leq x)$.

The cumulative distribution function (c.d.f.) $F_X(x)$ is defined as $F_x(x) = P(X \leq x)$; and the complementary cumulative distribution function (c.c.d.f.) (tail distribution or exceedance of probability function) is a function that account the probability that X is equal or greater than x, and it is expressed as:

$$\widetilde{F_X}(x) = P(X > x) = P(X \geq x) = 1 - P(X \leq x) = 1 - F_X(x)$$

The inverse function of c.d.f. is the quantile function $q(\alpha)$, and is the minimum value of the amongst x that the c.d.f. excess the value α:

$$q(\alpha) = F_X^{-1}(x) = \inf\{x \mid F_X(x) = P(X \leq x) \geq \alpha\}$$

Value at Risk (VaR) is a risk metric that indicates the maximum benefit losses given a probability level, and is obtain with the quantile function. Benefits losses can be accounted with a positive value or with a negative value. In case that benefit losses X are expressed as a negative value, $X < 0$, the VaR is the lower α- quantile of the random variable X and is defined as

$$VaR_\alpha(x) = \inf\{\, x \mid P(X \leq x = VaR) \geq \alpha\}$$

and when benefit losses are greater than zero, $X > 0$, the VaR is obtained by the exceedance of probability:

$$VaR_\alpha(x) = \inf\{\, x \mid P(X \geq x = VaR) \geq 1 - \alpha\}$$

VaR provides information about uncertainty and risk, and it is appropriate to compare water management alternatives.

The economic impact of a drought spell is the accumulated annual benefit losses in relation to the baseline throughout the episode, and depends on its duration and intensity. The conditional probability of benefit losses given certain duration and intensity of a drought spell indicates the exposure of the system to that drought event, since it measures the probability of an event given the occurrence of another events. The conditional probability of the random variable Y given X_1 and X_2 is expressed as

$$F_{Y|X=x}(y) = P(Y \leq y \mid X_1 = x_1, X_2 = x_2)$$

and the conditional quantile is given by the expression

$$F_{Y|X=x}^{-1}(\alpha) = \inf\{y \in \mathbb{R} \mid F_{Y|X=x}(y) \geq \alpha\}$$

Its definition is straightforward from quantile definition: the minimum value of y from amongst all those values of whose c.d.f. value excess the value α given the events $X_1 = x_1$ and $X_2 = x_2$. A different way to express the conditional quantile function is

$$F_{Y|X=x}(y) = P(Y \leq y \,|X_1 = x_1, X_2 = x_2) = \alpha$$

The maximum benefit losses at a certain level of probability α given a drought duration and a drought intensity is obtain from the quantile that satisfices

$$P(L \leq \ l|\ D = d, I = i) = \alpha$$

where L is benefit losses in M€, D is drought duration in months and I is drought intensity in Mm^3. The VaR of irrigation benefits given a drought spell with certain duration and intensity is obtain from the conditional probability and the conditional quantile.

Non-parametric estimators and copulas approach estimate the conditional probability and the quantile required to compute the VaR. Non parametric estimators are computationally demanding and copula approach could be preferred when the number of estimations is large. The non-parametric method proposed by Li et al. (2013) estimates the conditional quantile function $q_\alpha(x_1, \dots, x_n)$ by numerically inverting the estimated conditional distribution function $\hat{F}(y|x_1, \dots, x_n)$ and solving:

$$\hat{q}_\alpha(x_1, \dots, x_n) = \underset{x}{\operatorname{argmin}} |\alpha - \ \hat{F}(q|x_1, \dots, x_n)|$$

The conditional distribution function and the conditional quantile function are estimated in R with the package np developed by Hayfield and Racine (2008). The exceedance of probability at figure 8 and figure A11 are estimated by the non-parametric method.

The conditional quantile based on copulas is an alternative method to non-parametric (Kraus and Czado, 2016). The joint distribution $F(x_1, x_2, x_3)$ of a multivariate random vector is expressed in terms of a copula $C\big(F(x_1), F(x_2), F(x_3)\big)$. Then, the density function $f(x_1, x_2, x_3)$ can be expressed as

$$f(x_1, x_2, x_3) = f_1(x_1) \cdot f_2(x_2) \cdot f_3(x_3) \cdot c_{12}\{F_1(x_1), F_2(x_2)\} \cdot c_{23}\{F_2(x_2), F_3(x_3)\} \cdot c_{13|2}\{F(x_1|x_2), F(x_3|x_2)\}$$

where $c(\cdot,\cdot)$ is the copula density (Aas et al., 2009) and the estimation of the conditional quantile function is obtained following Kraus and Czado (2016).

Table C2. Copula and parameters of the join function of benefits losses (L), drought duration (D) and drought intensity (I).

Scenario	Copula	Type	θ_1	θ_2	τ
Without efficiency enhancements					
Proportional share					
	C_{ID}	Gumbel	3.62	-	0.72
	C_{LD}	Survival Clayton	2.37	-	0.54
	$C_{LI\|D}$	BB8	1.42	0.99	0.18
Water markets					
	C_{ID}	Gumbel	3.62	-	0.72
	C_{LD}	Survival Clayton	2.37	-	0.54
	$C_{LI\|D}$	BB8	1.40	0.99	0.18
With efficiency enhancements					
Proportional share					
	C_{ID}	Gumbel	3.62	-	0.72
	C_{LD}	Survival Clayton	2.09	-	0.72
	$C_{LI\|D}$	BB8	1.43	0.99	0.19
Water markets					
	C_{ID}	Gumbel	3.62	-	0.72
	C_{LD}	Survival Clayton	2.04	-	0.51
	$C_{LI\|D}$	BB8	1.41	1.00	0.18

The conditional quantile in figure 9 and figure A12 is estimated by the copula method, since the non-parametric approach is impracticable due to the number of estimations needed for the grid. The join function distribution of benefit losses, drought duration and drought intensity is estimated with a C-Vine copula that combine bivariate copulas. Tabla A2 shows the structure of the C-Vine and parameter estimations.

4.6.4 The join probability of drought duration and drought intensity

Gumbel copula describes asymmetry dependence and it is used to capture strong upper tail dependence and weak lower tail dependence. The joint distribution of drought duration and drought intensity is obtained from a Gumbel Copula and it takes the form:

$$C(u,v) = \exp\left[-\left((-\ln(u))^{\theta} + (-\ln(v))^{\theta}\right)^{\frac{1}{\theta}}\right]$$

The marginal distributions of the copula are the empirical distributions and the parameter of the copula is estimated by maximum likelihood.

4.6.5 Figures

Figure C1. Boxplot of the mean (top) and standard deviation (bottom) of 1.000 realizations of monthly streamflow generated with copula parameter θ

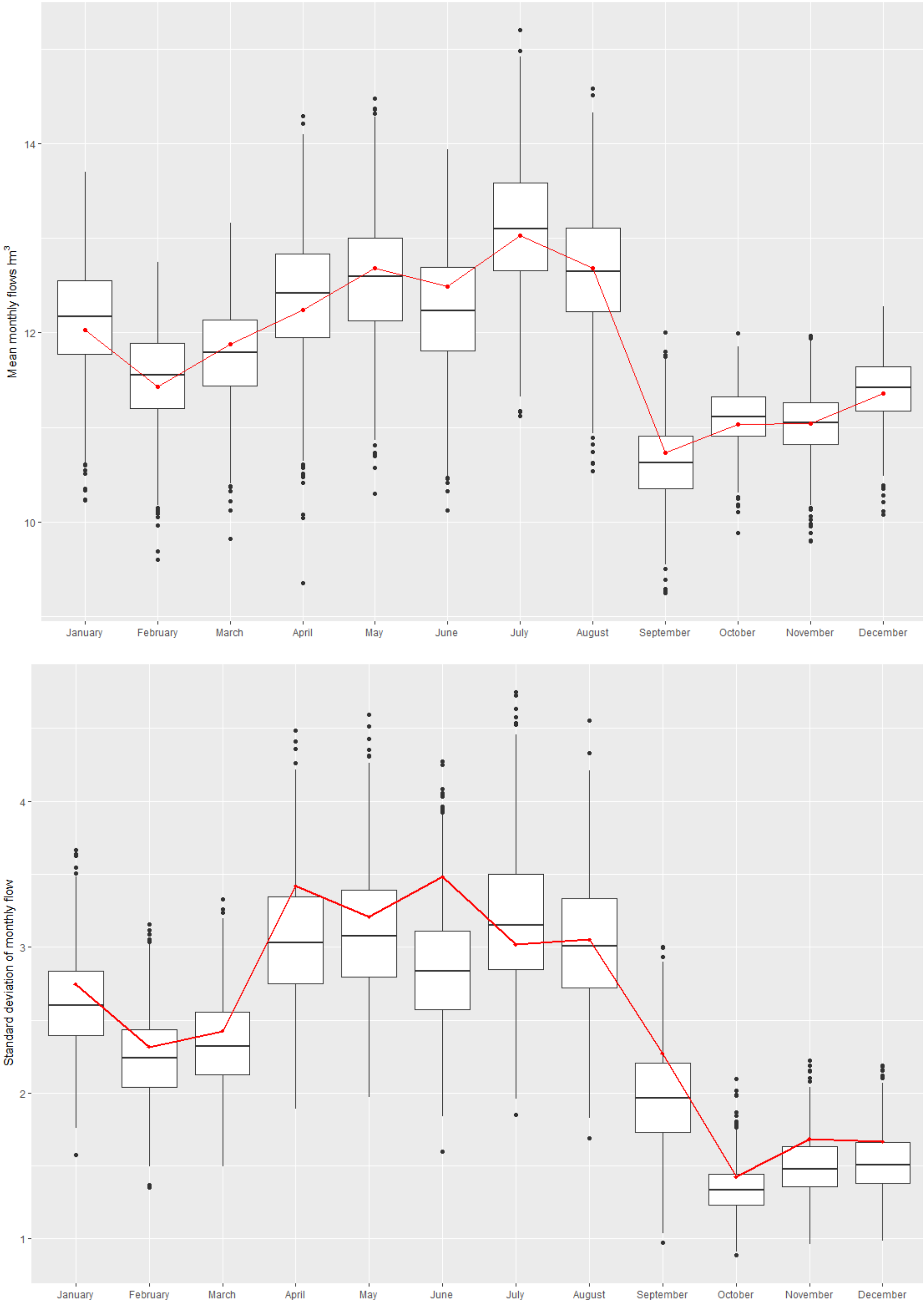


Figure C3. Boxplot of the autorrelation function of 1.000 realizations of monthly streamflow generated with copula parameter θ (top) and 2θ (bottom).

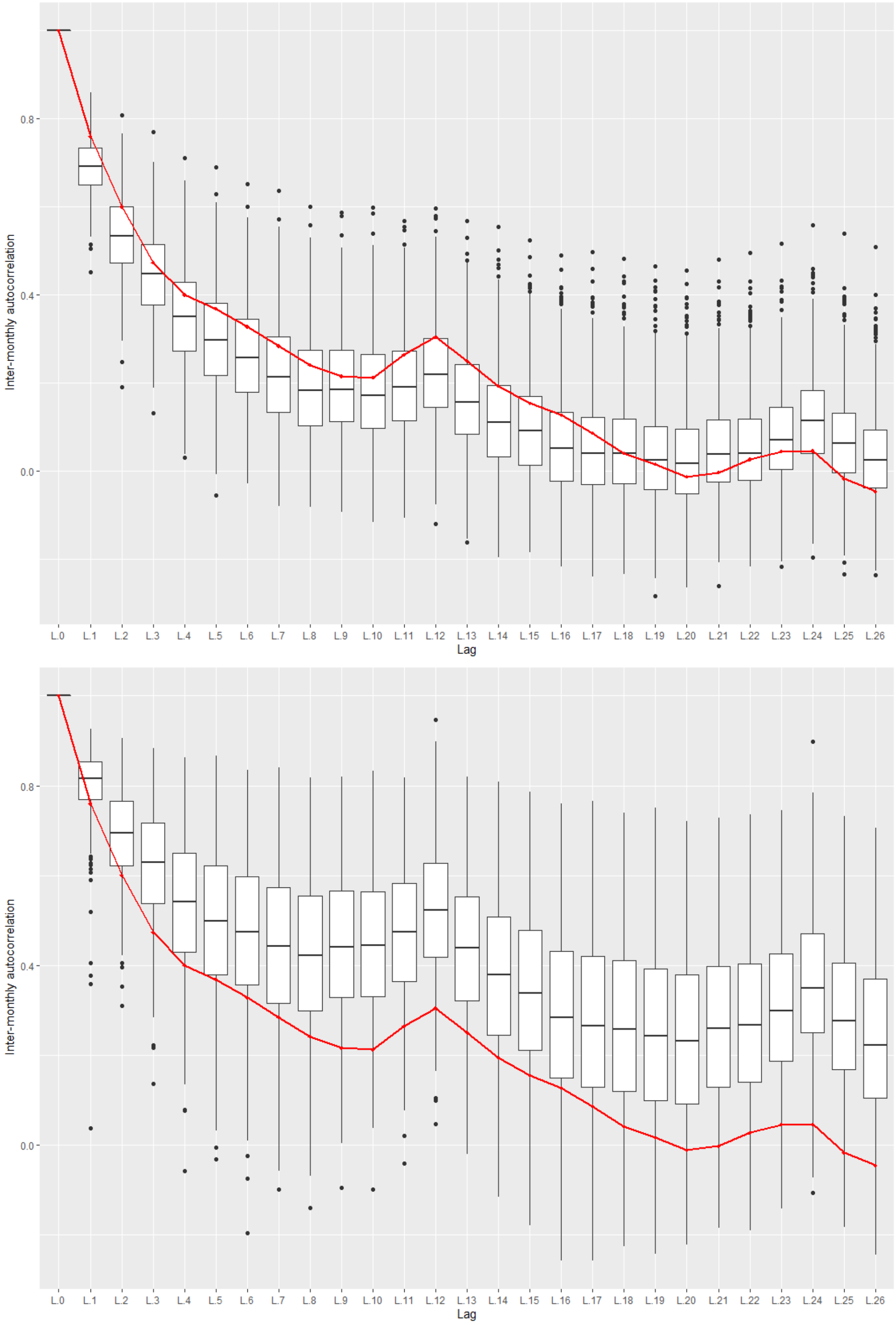
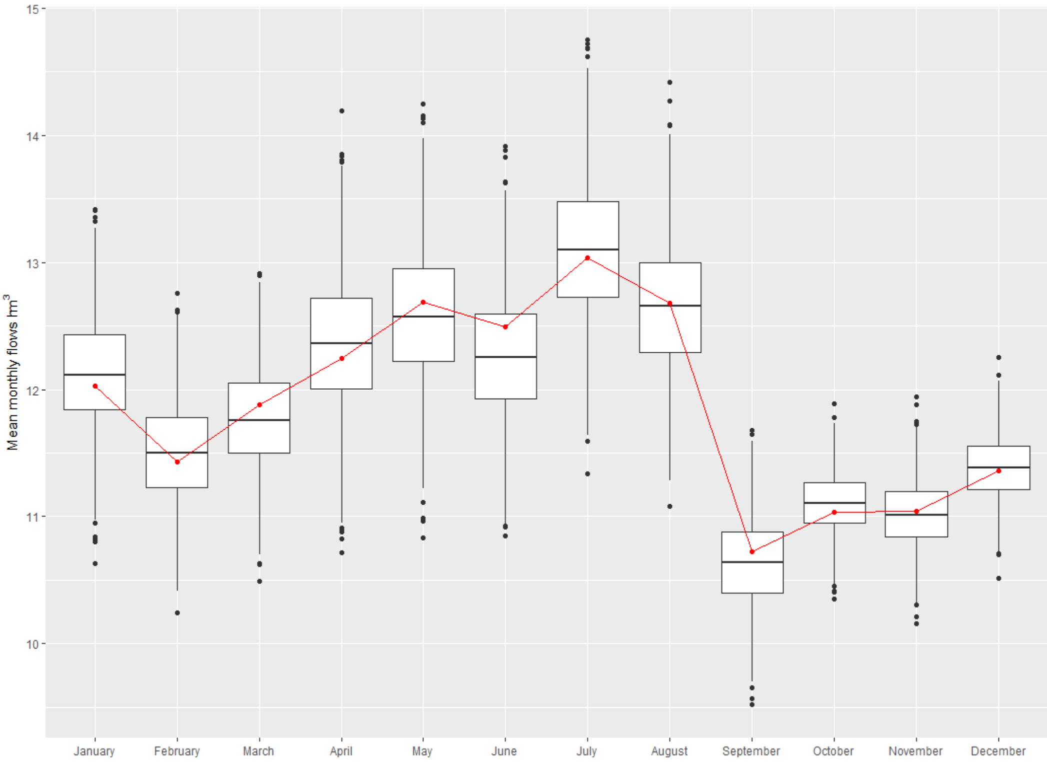


Figure C2. Boxplot of the mean (left) and standard deviation (right) of 1.000 realizations of monthly streamflow generated with copula parameter 2θ.



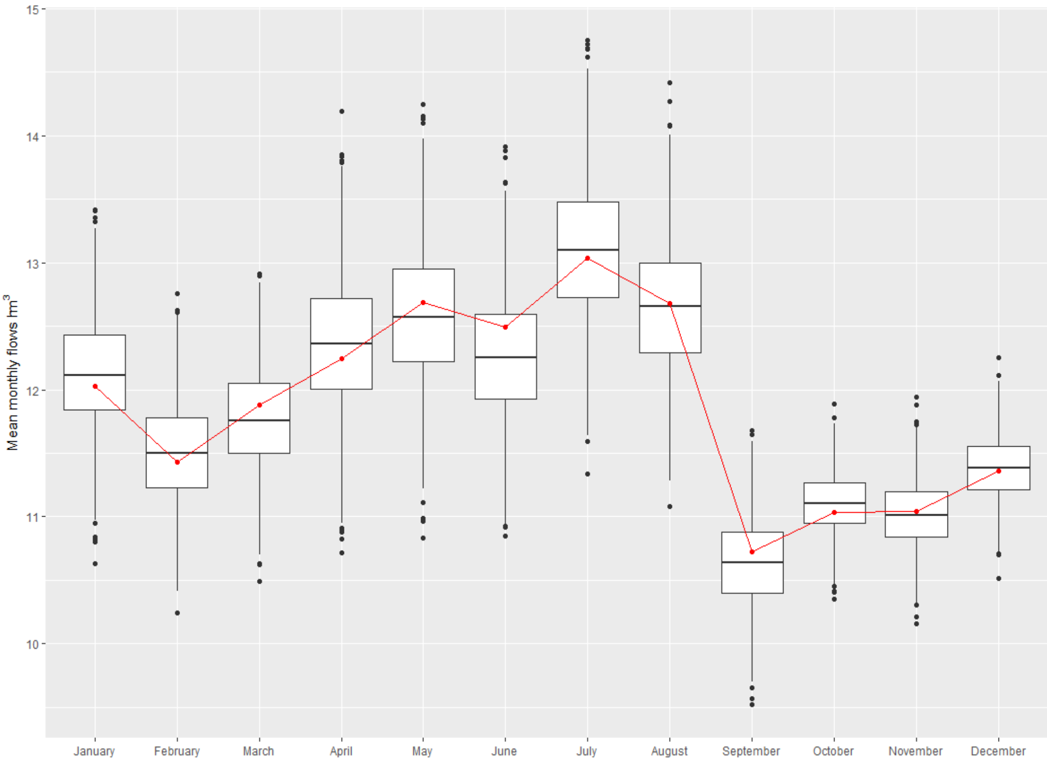
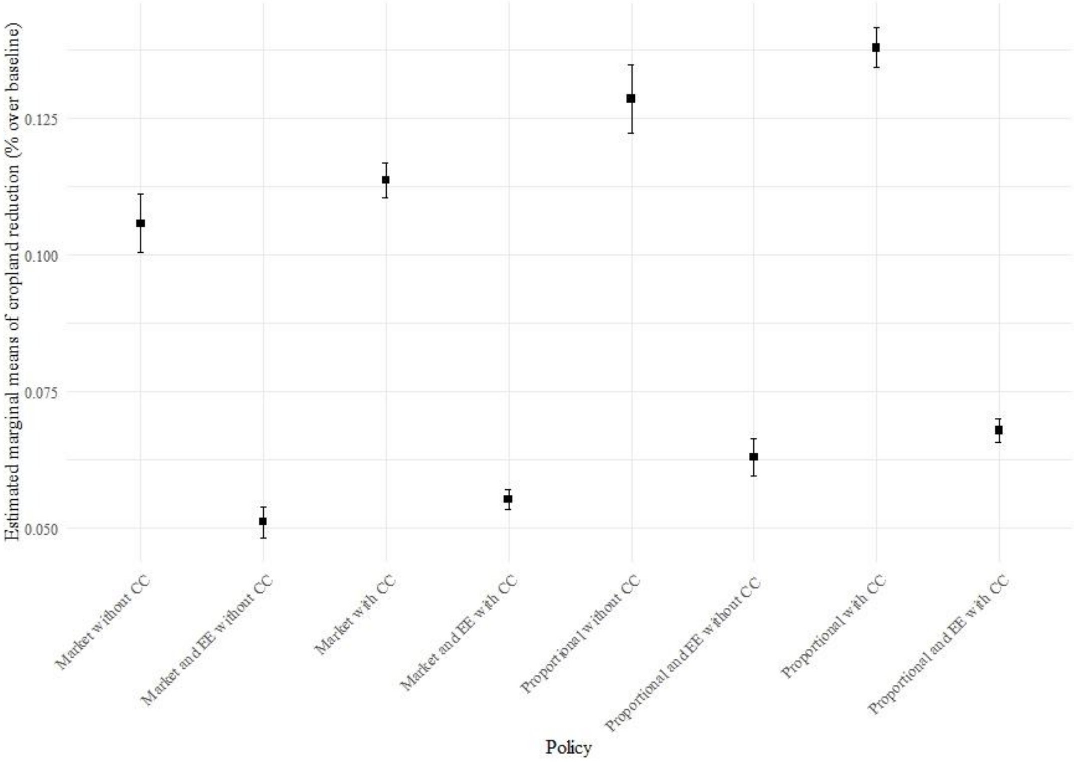


Figure C4. Estimated marginal means of cropland reduction over the baseline scenario by policy and climate change scenario. Confidence interval at 95%.



EE means Enhance of efficiency and CC is climate change

Figure C5. Cropland distribution under irrigation land reduction.

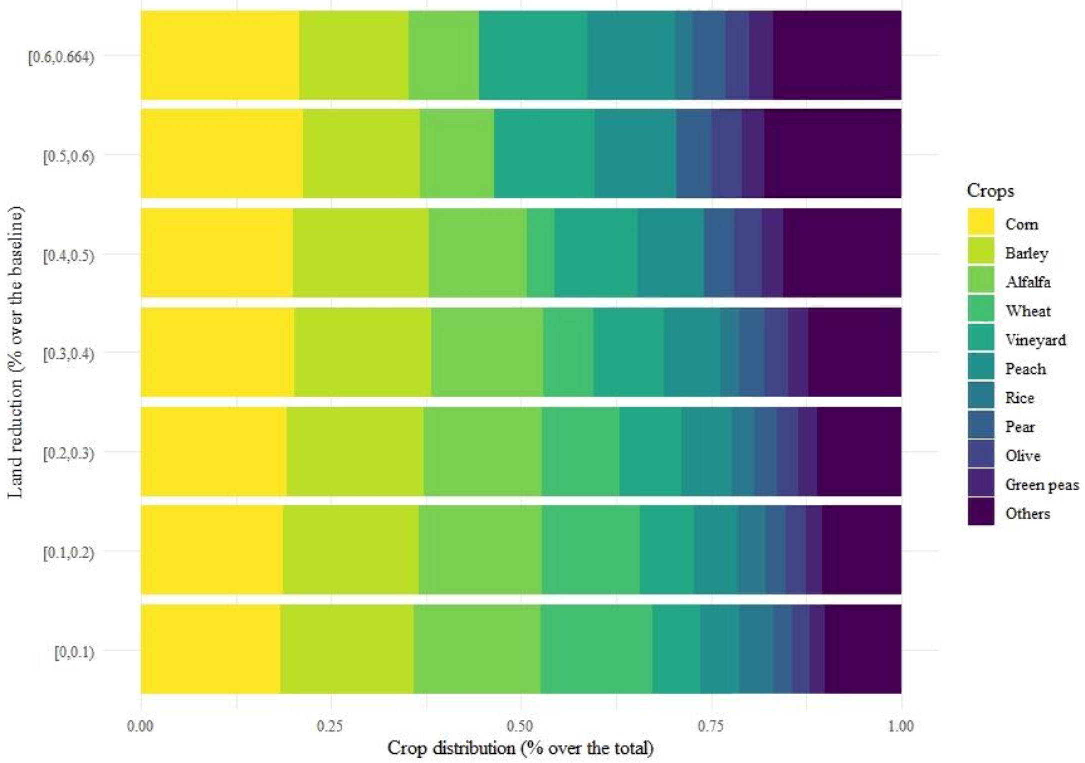
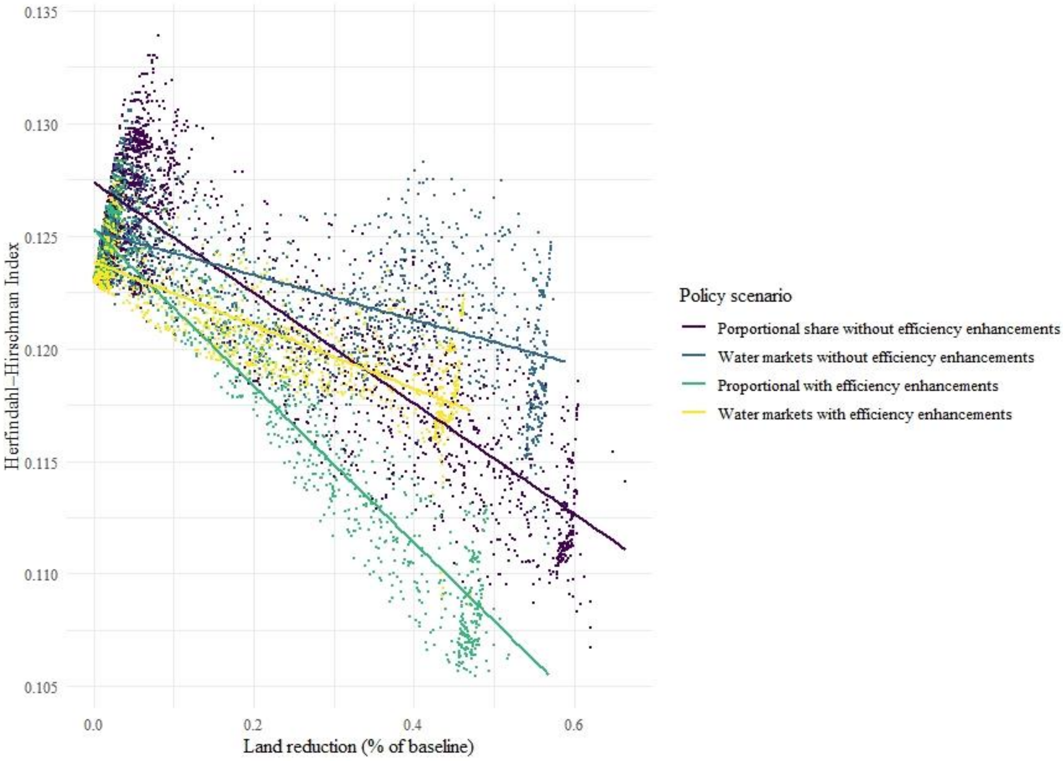


Figure C6. Concentration index under policy scenario.



The figure A6 shows the Herfindahl-Hirschman concentration index under policy scenario and it is defined as:

$$H = \sum_{i=1}^{N} s_i^2$$

where s_i is the share of the crop i over the total land and N is the number of crops. The index measures the production concentration, specialization, and sharing. Higher values of H means higher concentration.

Figure C7. Monthly water deficit (Mm^3) and water scarcity index.

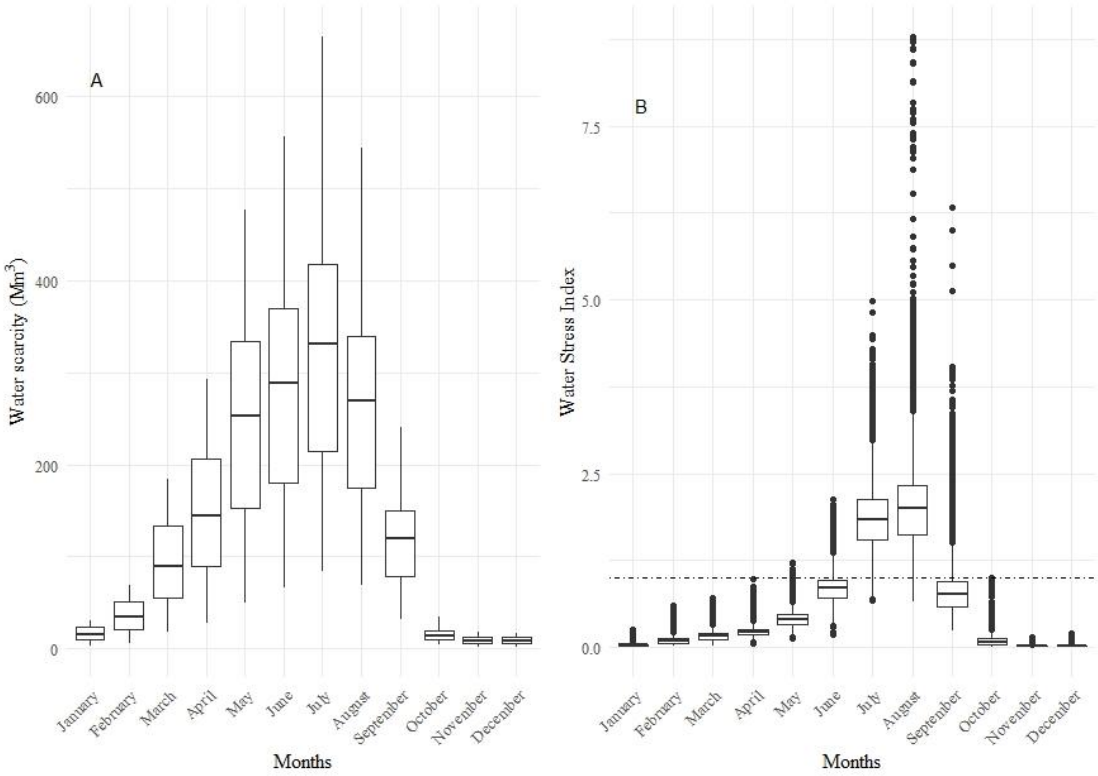


Figure C8. Comparison of water use by policy with and without efficiency enhancements under the same climate conditions.

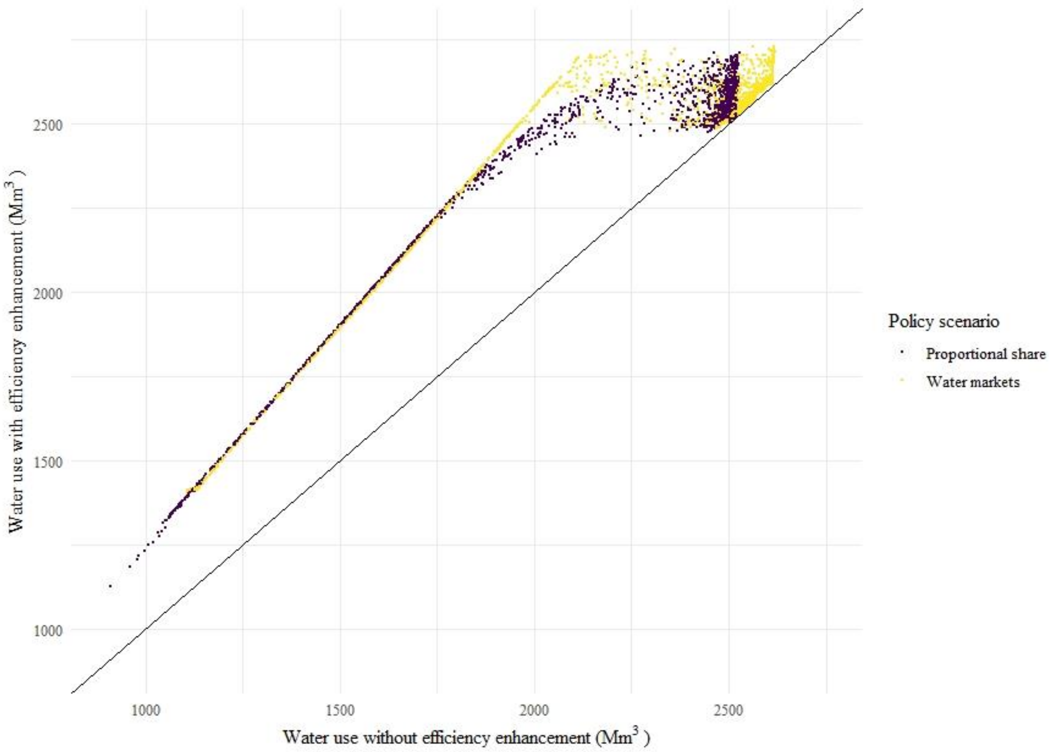


Figure C9. Distribution of the fall in streamflow at the river mouth from investments in efficiency enhancements (Mm^3).

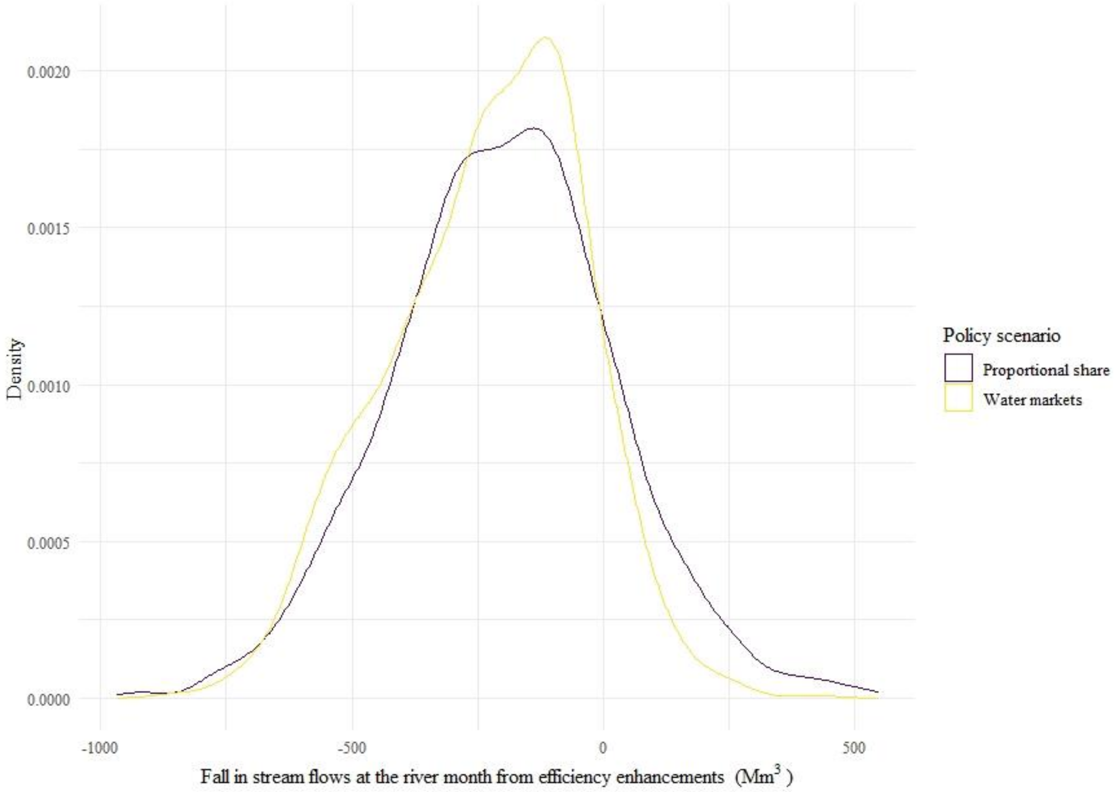


Figure C10 shows the cumulative probability of the annual irrigation benefits and the exceedance of probability of losses under market and proportional policies with and without efficiency enhancement.

Figure C10. Probability of annual benefits and exceedance of probability of annual benefit losses (10^6 €).

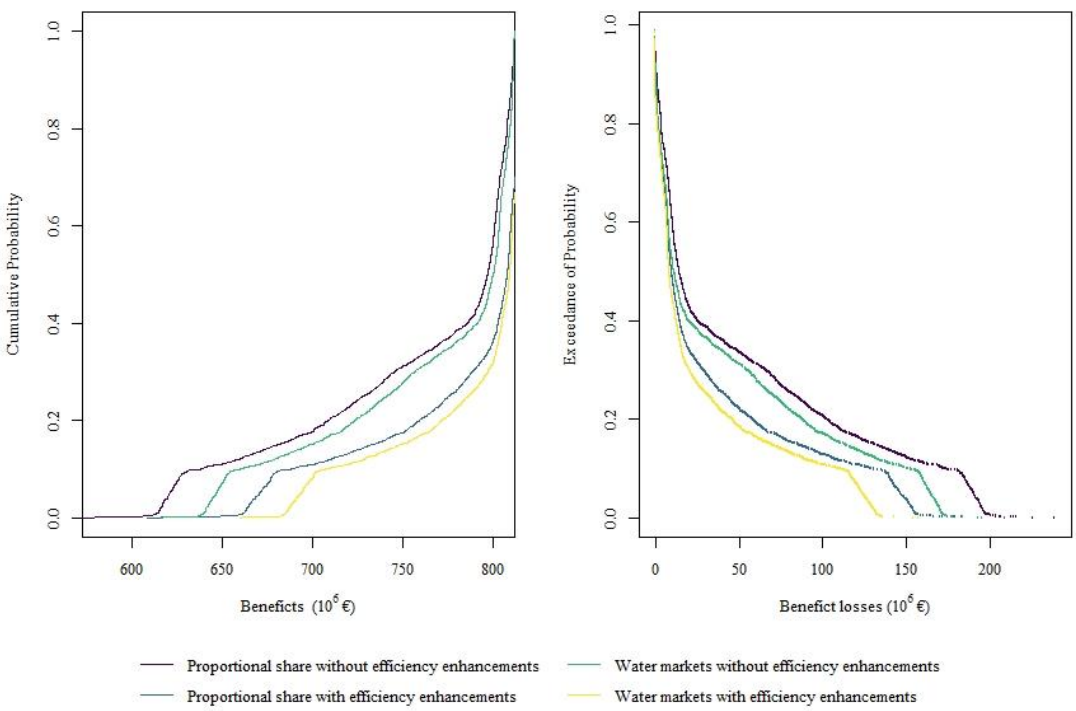


Figure C11. Conditional exceedance of probability of benefit losses under different drought spells.

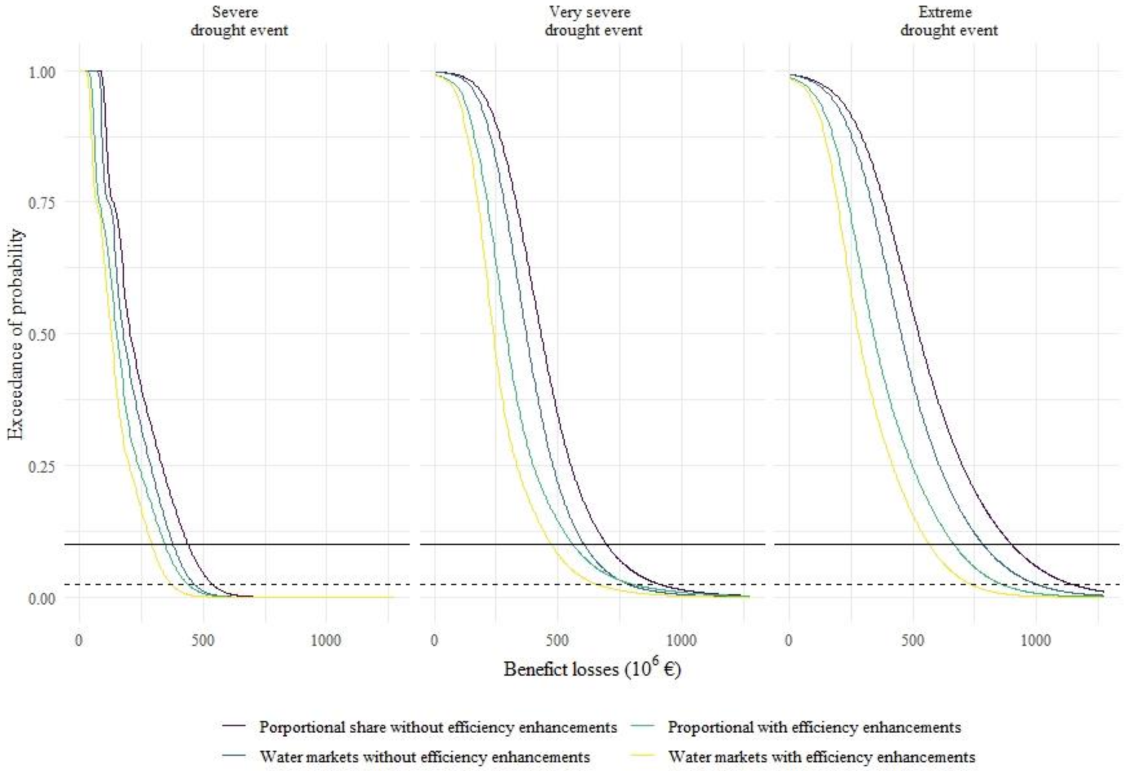
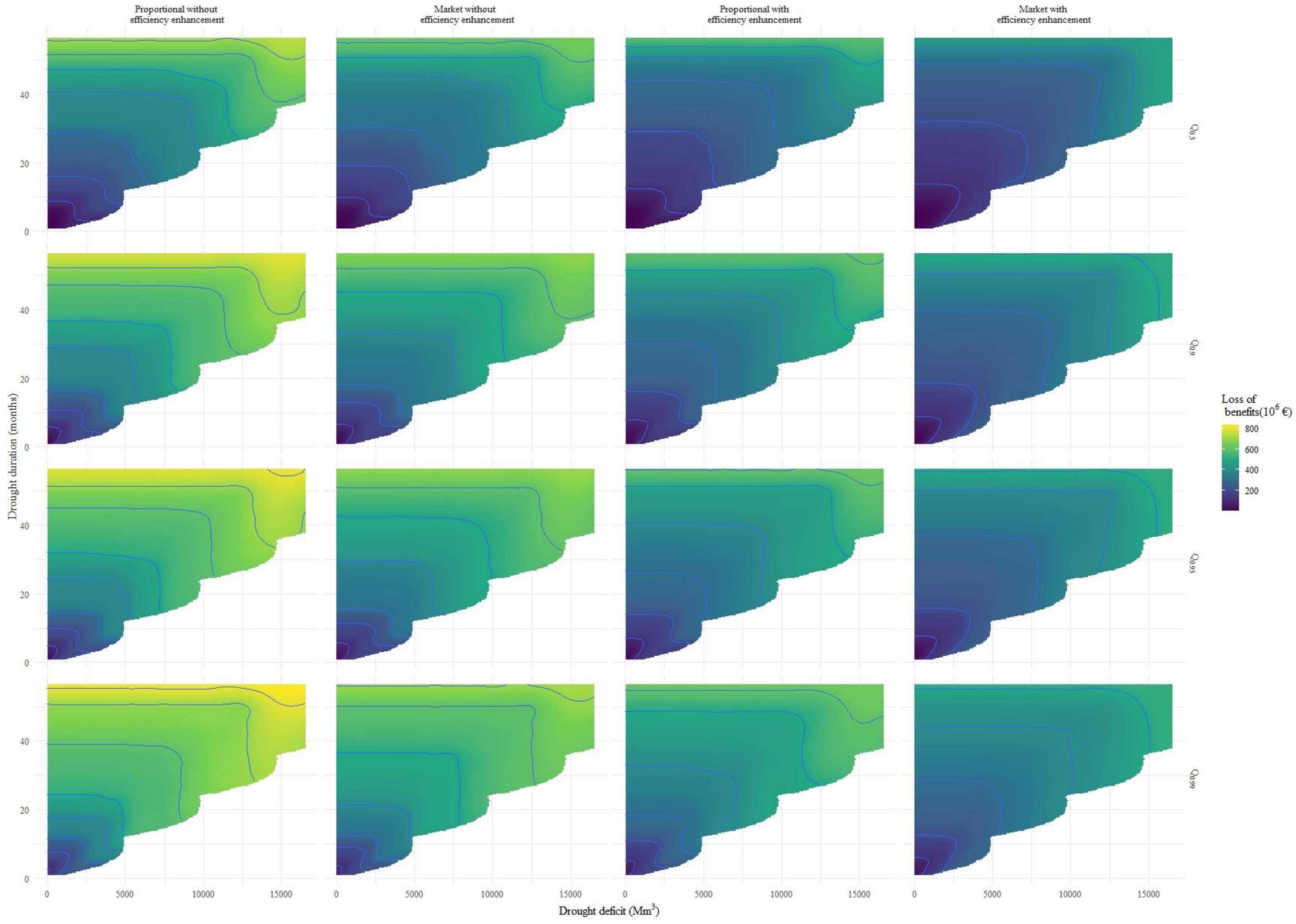


Figure C12. Conditional loss of benefits (10^6 €) by policy at quantiles 0.5, 0.9, 0.95 and 0.99.



4.6.6 References

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Chapter 5

5. Summary and Conclusions

Water management faces water scarcity problems in a context of growing demand for water and shrinking water availability, which further aggravate the unsustainable operation of water systems in many basins. Population expansion, changing consumption patterns, and economic growth are pushing the strong escalation of water demand in recent decades, a trend that will continue in the future. The impending effects of climate change are going to worsen with further reductions in precipitations, higher temperatures, and longer and more intense drought periods. Current water scarcity problems will become wicked challenges for management in many basins, given the growing unbalance between demand and available resources.

Environmental protection is becoming a decisive issue because of the degradation of water dependent ecosystems and their functions that support life. Preserving aquatic ecosystems entails the containment of water withdrawals for economic activities, further increasing the current competition for already scarce water resources. Disputes among water users arise in periods of strong water scarcity, resulting in conflicts between economic sectors and locations, and critical depletion of environmental flows. Sustainable water management seeks to conciliate water users' interests in order to achieve efficient water use, social equity and environmental protection. Climate change brings about quite overwhelming management challenges, adding further uncertainty to water planning.

Hydroeconomic analysis is becoming a valuable tool for the design of sustainable water management policies, providing insights for adaptation to climate change. These insights are based on the evaluation of impacts resulting from water allocations under alternative management policies, but also from the tradeoffs between maintaining economic activities or protecting environmental flows. Despite the advances in hydroeconomic modeling, several methodological and empirical issues require further enhancements. This thesis suggests some answers to several unsettled questions in hydroeconomic analysis regarding the sharing of costs from water scarcity, the incorporation of environmental benefits for advancing sustainable management, and the appropriate treatment of basin inflows under climate change. In addition, the findings in this thesis indicate the combination of water management policies that could improve the reliability, resilience, and vulnerability of water systems.

5.1. Summary

The first study of the thesis (Chapter 2) “Tradeoffs between Water Uses and Environmental Flows: A Hydroeconomic Analysis in the Ebro Basin”, presents the development and application of an integrated hydro-economic model for the Ebro basin. The hydroeconomic model integrates a reduced form hydrological component, a regional economic component and an environmental component.

The reduced form hydrological component represents water flows among supply and demand nodes in the Ebro basin. The advantage of this simplified hydrology representation is that comprehensive hydrology involves highly disaggregated and detailed hydrology that may not be available, and in addition hydrologic and economic models usually have different resolution techniques and spatial and temporal scales, which complicate their linkage. The reduced form hydrological component is calibrated by the observed flows in the river and slack variables that represent unobserved water inflows and outflows.

The regional economic component includes the agricultural and urban benefits of water use, which are spatially distributed throughout the basin. The calibration of crop production is undertaken with Positive Mathematical Programming, by using observed data of cropland production and water use from local statistics and production reports. Calibration of urban water use involves knowing water price, water quantity, and elasticity in urban centers. The environmental component is represented by a minimum environmental flow constraint.

The model has been used to evaluate the tradeoffs and political implications of allocating water among sectors and environmental flows under water scarcity conditions. The water policies include management instruments such as upstream priority, proportional water sharing, and water markets, in order to meet several environmental flows in the river mouth under water scarcity conditions. The economic impacts of droughts are substantial, even under the least minimum environmental flow. Raising the minimum environmental flow increases the benefit losses sustained by farmers during droughts, especially farmers of field crops. The water allocation policy determines the range of benefit losses and their distribution between water users and regions. Under drought conditions, water markets deliver higher benefits compared to proportional water sharing. The upstream priority policy brings about the largest benefit losses for downstream irrigation districts. Proportional water sharing results in the most equitable policy, by evenly distributing the drought losses among regions in the basin. Cooperation between stakeholders, which characterizes the proportional sharing policy, balances water use efficiency, equity and environmental protection.

The second study of the thesis (Chapter 3) “Integrating benefits for sustainable water allocation in hydroeconomic”, develops the environmental component of the hydroeconomic model by explicitly including environmental benefits in the objective function. The novelty of this chapter with respect to previous hydroeconomic modeling is that environmental benefits are represented at basin level, using biophysical information that relates stream flows and ecosystem status. A satisfactory environmental status is essential to maintain the flow of goods and services provided by ecosystems, which contribute to social wellbeing but are external to markets because of their public good characteristics. Environmental benefits are estimated by linking the stream flows, the status of aquatic ecosystems, and their environmental benefits. The relationship between stream flows and the status of ecosystems is modeled and calibrated using the biophysical studies undertaken by the Ebro Basin Authority. The economic value of ecosystem services has been taken from valuation studies and related literature, covering basins in Spain and other countries.

The hydroeconomic model is used to analyze the economic and environmental tradeoffs of various water policies under drought conditions. Institutional cooperation and water markets are combined with recognizing the benefits of environmental flows. Four water allocation alternatives are examined, in order to identify the outcomes regarding the objectives of efficiency, equity and environmental protection. Under drought conditions, water markets maintain higher private benefits than institutional cooperation. However, the environmental benefits are disregarded undermining social benefits, and leading to market failure given the public good characteristics of environmental flows. Internalizing the externalities generated by the private use of water involves taking into account environmental benefits in water allocation. Environmental institutional cooperation and environmental water markets policies incorporate environmental benefits in decision making. These two policies entail that the basin authority acquires water for the river from farmers in order to maximize social benefits, the sum of both private and environmental benefits. Water exchanges between irrigation and the environment increase environmental flows and environmental benefits. Environmental institutional cooperation achieves a better environmental protection, but social benefits are higher when irrigation districts and the environment exchange water under the environmental water market policy. Private benefits could increase in the short run in detriment of public environmental benefits, but in the long run degradation of hydrological systems would be unsustainable, with strong negative impacts on both economic activities and ecosystems

The third study (Chapter 4) “Hydroeconomic analysis of droughts in the Ebro basin using copulas for streamflow simulation” incorporates dynamics in the model presented in Chapter 2, by adding the main dams of the Ebro basin. The main contribution in this chapter over previous hydroeconomic modeling is that the analysis of longer, more intense, and more frequent drought events as a result of climate change. Water inflows are generated by the Copula procedure, which simulates historical and projected climatic conditions with more frequent, intense and longer drought spells. The model analyzes the economic impacts of drought under current and future climate conditions. Reliability, resilience, and vulnerability indicators are used to assess the sustainability of the water system during droughts, which is evaluated under several water policies. The combinations of proportional water share or water markets policies, with current or enhanced irrigation water efficiency are the set of combined policies that are evaluated. Water system exposure to extreme drought events has been assessed in terms of risk, providing information about policy performance. Results are evaluated from a probability perspective, given the inherent uncertainty of droughts and climate change.

The results of this chapter indicate that climate change will increase the probability of significant economic losses under drought conditions. Furthermore, climate change is likely to impair the sustainability of the water system. Water markets and improvements in irrigation efficiency are found to reduce uncertainty and losses from droughts. This policy combination reinforces reliability and resilience, while reducing vulnerability in the water system. However, the preservation of irrigation benefits jeopardizes the status of aquatic ecosystems. In prolonged and intense droughts spells, the effectiveness of this policy combination decreases.

5.2. Conclusion and future research

This thesis provides answers to some outstanding problems for water management in arid and semi-arid regions. Water conflicts, environmental protection, and impacts of climate change are examined by hydroeconomic analysis. In the three main chapters, a hydroeconomic model of the Ebro basin is developed to capture the interactions and interdependences of water uses. The hydrological reduced form component, the economic regional component and the environmental component are linked spatially and temporally, in order to reveal which are the water policies that could achieve the objectives of efficiency, equity and environmental protection. The methodology developed in this thesis could be a valuable tool for conducting hydroeconomic analysis in other water systems. The results are important not only locally, but also for other arid regions, especially in Mediterranean basins, where similar climate change impacts are expected.

This thesis provides information to improve the sustainability of water systems and water policies. Advances in hydroeconomic analysis which are developed in this thesis include enhancements in environmental benefits modeling, the simulation of climate change impacts on stream flows, and the analysis of water conflicts. A limited number of studies jointly address the problem of modeling and water policy implementation. The results show the potential of hydroeconomic modeling for the design and evaluation of management policies that mitigate the effects of drought, water scarcity, and climate change. The environmental component combines biophysical and economic aspects, which are essential for advancing sustainable water management.

The results of this thesis highlight the growing challenges from drought, water scarcity, and climate change that water management must confront. Sustainability of the water system is a long-run problem that requires robust and resilient water systems. Risk and uncertainty are concerns that must be considered in the policy design of sustainable water management, that could confront water scarcity while taking into account the goals of society. Water markets, water sharing, water conservation, and enhancement of the efficiency are instruments that contribute to water management objectives. However, the rivalry between water efficiency, equity and environmental protection objectives could compromise the success of policies. To avoid policy failure, it is important to identify the tradeoffs of water allocation.

For instance, the results show that cooperation among water users contributes to reducing water conflicts, ensuring equity and ecosystem protection. The offset is the loss of efficiency that leads to higher economic losses during drought spells. Water markets and improvements in irrigation efficiency reduce economic losses from water scarcity and reduce risk and uncertainty, but this policy increases the risks of environmental damages and undermines social benefits. The implementation of water policies requires institutions where stakeholders are represented. Even with water markets, strong institutions are indispensable for appropriate water management. The successful implementation of water policies entails institutions where stakeholders' interests are represented, so they will support the introduction of measures and the subsequent enforcement.

Despite the progress presented in this thesis, some challenges remain to be addressed in future research. For example, ecosystems health depends on both the quantity and quality of water. Then, identifying the tradeoffs between economic activities and water pollution could improve the analysis. Another issue is that climate change impacts on stream flows would fluctuate through time and spatial location. Since some regions will be impacted more than others, the analysis of the spatial dependence has to be addressed for finding optimal water allocations. Hydropower is an important economic sector that depends on water availability, and therefore the analysis of the nexus between water, energy, food, and ecosystems is essential for adaptation to climate change. In addition, more work is needed not only to enhance the knowledge on the biophysical responses of ecosystems, but also on better valuation estimates of the goods and services provided by ecosystems. All these improvements will advance the accuracy of the results, converting hydroeconomic analysis in a powerful tool to support the decision making process.

5.3. Resumen y conclusiones

La gestión del agua se enfrenta a problemas de escasez de agua en un contexto de expansión en la demanda de agua y reducción de la disponibilidad de agua, que agravan aún más el funcionamiento insostenible de los sistemas de agua en muchas cuencas. La expansión de la población, los cambios en los patrones de consumo y el crecimiento económico están impulsando un fuerte aumento en la demanda de agua en las últimas décadas, y esta tendencia continuará en el futuro. Los incipientes efectos del cambio climático van a empeorar la situación con reducciones en las precipitaciones, temperaturas más altas y períodos de sequía más largos e intensos. Los actuales problemas de escasez de agua se convertirán en desafíos considerables para la gestión en muchas cuencas, debido al creciente desequilibrio entre la demanda y los recursos disponibles.

La protección del medio ambiente se está convirtiendo en un tema decisivo por la degradación de los ecosistemas dependientes del agua y sus funciones que sustentan la vida. La preservación de los ecosistemas acuáticos implica limitar las extracciones de agua para las actividades económicas, acrecentando aún más la actual rivalidad por los recursos hídricos cada vez más escasos. Las disputas entre los usuarios del agua surgen en períodos de fuerte escasez de agua, que pueden dar lugar a conflictos entre sectores económicos y regiones y al agotamiento de los caudales medioambientales hasta niveles críticos. La gestión sostenible del agua busca conciliar los intereses de los usuarios del agua para alcanzar un uso eficiente y equitativo que proteja el medio ambiente. El cambio climático plantea desafíos de gestión muy complicados , añadiendo gran incertidumbre a la planificación de los recursos hídricos.

El análisis hidroeconómico se está convirtiendo en una herramienta valiosa para el diseño de políticas de gestión del agua sostenibles, proporcionando información para la adaptación al cambio climático. Esta información se basa en la evaluación de los impactos que resultan de la asignación del agua bajo diferentes alternativas de gestión, y asimismo del equilibrio de asignaciones entre el mantenimiento de las actividades económicas y la protección de los caudales medioambientes. A pesar de los avances en modelizacion hidroeconómica, varias cuestiones metodológicas y empíricas requieren mejoras adicionales. Esta tesis sugiere algunas respuestas a varias preguntas no resueltas en el análisis hidroeconómico; sobre la distribución de los costes originados por la escasez de agua, la asunción de los beneficios medioambientales en el desarrollo de la gestión sostenible, y el tratamiento adecuado de las entradas de agua en las cuencas en condiciones de cambio climático. Además, los resultados de esta tesis muestran combinaciones de políticas de gestión del agua que podrían mejorar la fiabilidad, la resiliencia y la vulnerabilidad de los sistemas de agua.

5.4. Resumen

El primer estudio de la tesis (Capítulo 2) "Tradeoffs between Water Uses and Environmental Flows: A Hydroeconomic Analysis in the Ebro Basin", presenta el desarrollo y aplicación de un modelo hidroeconómico integrado en la cuenca del Ebro. El modelo hidroeconómico integra un componente hidrológico en forma reducida, un componente económico regional y un componente medioambiental.

El componente hidrológico en forma reducida representa los flujos de agua entre los nodos de oferta y demanda de la cuenca del Ebro. La ventaja de esta representación hidrológica simplificada es que una representación hidrológica completa requiere una hidrología altamente desagregada y detallada que podría no estar disponible; además los modelos hidrológicos y económicos suelen tener técnicas de resolución distintas y escalas espaciales y temporales diferentes, lo que dificulta su integración. El componente hidrológico en forma reducida está calibrado con los caudales observados en el río y variables de holgura que representan las entradas y salidas de agua no observadas.

El componente económico regional incluye los beneficios del uso del agua en la agricultura y los centros urbanos, que se distribuyen espacialmente en toda la cuenca. La calibración de la producción de cultivos se lleva a cabo con Programación Matemática Positiva, mediante el uso de datos observados de la producción de tierras de cultivo y el uso del agua, obtenidos de estadísticas locales e informes de producción. La calibración del uso del agua en los centros urbanos requiere conocer el precio del agua, la cantidad de agua y la elasticidad de uso del agua. El componente medioambiental está representado por una restricción de caudal mínimo medioambiental.

El modelo se ha utilizado para evaluar los intercambios e implicaciones políticas de la asignación de agua entre los sectores económicos y los caudales medioambientales en condiciones de escasez de agua. Las políticas de asignación de agua incluyen instrumentos de gestión de prioridad de uso aguas arriba, reparto proporcional del agua y mercados de agua, con el fin de satisfacer varios caudales ambientales en la desembocadura del río en condiciones de escasez de agua. Los impactos económicos de las sequías son sustanciales, incluso con el caudal medioambiental menos restrictivo. Incrementar el caudal medioambiental mínimo aumenta las pérdidas de beneficios que sufren los agricultores durante las sequías, especialmente los agricultores de cultivos herbáceos. La política de asignación de agua determina el rango de las pérdidas de beneficios y su distribución entre usuarios del agua y regiones. En condiciones de sequía, los mercados de agua ofrecen mayores beneficios en comparación al reparto proporcional del agua. La política de prioridad de uso aguas arriba genera mayores pérdidas de beneficios para los polígonos de riego localizados aguas abajo. El reparto proporcional del agua es la política más equitativa, distribuyendo equitativamente entre las regiones de la cuenca las pérdidas por sequía. La cooperación entre los usuarios del agua, que caracteriza la política de reparto proporcional, equilibra la eficiencia del uso del agua, la equidad y la protección del medio ambiente.

En el segundo estudio de la tesis (Capítulo 3), “Integrating ecosystem benefits for sustainable water allocation in hydroeconomic modeling”, se desarrolla el componente medioambiental del modelo hidroeconómico incluyendo explícitamente los beneficios medioambientales en la función objetivo. La novedad de este capítulo, con respecto a la modelización hidroeconómica anterior, es que los beneficios medioambientales se representan a nivel de cuenca, utilizando información biofísica que relaciona los caudales en tramo de los ríos y el estado de los ecosistemas. Un estado satisfactorio del medio ambiente es esencial para mantener el flujo de bienes y servicios proporcionados por los ecosistemas, que contribuyen al bienestar social, pero son externos a los mercados por sus características de bien público. Los beneficios medioambientales se estiman relacionando los caudales en los tramos de los ríos, el estado de los ecosistemas acuáticos y los beneficios medioambientales. La relación entre los caudales en los tramos de los ríos y el estado de los ecosistemas se modeliza y calibra a partir de los estudios biofísicos realizados por la Confederación Hidrográfica del Ebro. El valor económico de los servicios ecosistémicos se ha tomado de estudios de valoración y literatura relacionada, que comprende cuencas en España y otros países.

El modelo hidroeconómico se utiliza para analizar los efectos económicos y medioambientales de varias políticas de gestión del agua en condiciones de sequía. La cooperación institucional y los mercados del agua se combinan con el reconociendo de los beneficios que proporciona los caudales medioambientales. Se han examinado cuatro alternativas de asignación de agua, para identificar sus implicaciones respecto a los objetivos de eficiencia, equidad y protección del medio ambiente. En condiciones de sequía, los mercados del agua mantienen mayores beneficios privados que la cooperación institucional. Sin embargo, los beneficios medioambientales no se tienen en cuenta, lo que socava los beneficios sociales y conduce a fallos de mercado, como resultado de las características de bien público que tienen los caudales medioambientales. Internalizar las externalidades generadas por el uso privado del agua implica reconocer los beneficios medioambientales en la asignación de agua. La cooperación institucional medioambiental y las políticas medioambientales de mercados de agua incorporan los beneficios medioambientales en la toma de decisiones. Estas dos políticas consisten en que la autoridad de cuenca adquiere agua de los agricultores para aumentar el caudal del río y maximizar los beneficios sociales, la suma de los beneficios privados y medioambientales. Los intercambios de agua entre el regadío y el medio ambiente aumentan los caudales y beneficios medioambientales. La cooperación institucional medioambiental alcanza una mejor protección del medio ambiente, pero los beneficios sociales son mayores cuando los distritos de riego y el medio ambiente intercambian agua con la política medioambiental de mercados de agua. Los beneficios privados podrían aumentar a corto plazo en detrimento de los beneficios públicos medioambientales, pero a largo plazo la degradación de los sistemas hídrico sería insostenible, con fuertes impactos negativos tanto en las actividades económicas como en los ecosistemas.

El tercer estudio (Capítulo 4) "Hydroeconomic analysis of droughts in the Ebro basin using copulas for streamflow simulation" incorpora la dinámica en el modelo presentado en el Capítulo 2, incluyendo las principales presas de la cuenca del Ebro. La contribución principal en este capítulo respecto a la modelización hidroeconómica anterior está en el análisis de períodos de sequía más largos, más intensos y más frecuentes como consecuencia del cambio climático. Las entradas de agua en el sistema se generan mediante el procedimiento denominado Copula, que simula las condiciones climáticas históricas y proyectadas con períodos de sequía más frecuentes, intensos y duraderos. El modelo analiza los impactos económicos de la sequía en las condiciones climáticas actuales y futuras. Los indicadores de fiabilidad, resiliencia y vulnerabilidad se utilizan para evaluar la sostenibilidad del sistema de agua durante las sequías, bajo varias políticas de gestión del agua. Las combinaciones de reparto proporcional del agua o de la política de mercados del agua, con la eficiencia actual o con la mejorada de la eficiencia de riego son las combinaciones de políticas que se evalúan. La exposición del sistema de agua a eventos de sequía extrema se ha evaluado desde el punto de vista del riesgo, lo que proporciona información sobre el desempeño de las políticas. Los resultados se valoran en términos probabilísticos, dada la incertidumbre inherente de las sequías y el cambio climático.

Los resultados de este capítulo indican que el cambio climático aumentará la probabilidad de experimentar importantes pérdidas económicas en condiciones de sequía. Además, es probable que el cambio climático socave la sostenibilidad del sistema de agua. El análisis muestra que los mercados de agua y las mejoras en la eficiencia de los sistemas de riego reducen la incertidumbre y las pérdidas causadas por las sequías. Esta combinación de políticas refuerza la fiabilidad y la resiliencia, al tiempo que reduce la vulnerabilidad del sistema de agua. Sin embargo, el mantenimiento de los beneficios del regadío pone en peligro el estado de los ecosistemas acuáticos. En períodos prolongados e intensos de sequía, la eficacia de esta combinación de políticas disminuye.

5.5. Conclusión e investigación futura

Esta tesis proporciona respuestas a algunos problemas pendientes para la gestión del agua en regiones áridas y semiáridas. Los conflictos relacionados con el agua, la protección del medio ambiente y los impactos del cambio climático se examinan mediante el análisis hidroeconómico. En los tres capítulos principales se desarrolla un modelo hidroeconómico de la cuenca del Ebro para captar las interacciones e interdependencias de los usos del agua. El componente hidrológico en forma reducida, el componente económico regional y el componente medioambiental están relacionados espacial y temporalmente, con el fin de revelar cuáles son las políticas hídricas que podrían alcanzar los objetivos de eficiencia, equidad y protección medioambiental. La metodología desarrollada en esta tesis podría ser una herramienta valiosa para realizar análisis hidroeconómicos en otros sistemas de agua. Los resultados son importantes no solo a nivel local, sino también para otras regiones áridas, especialmente en las cuencas mediterráneas, donde se esperan impactos similares del cambio climático.

Esta tesis proporciona información para mejorar la sostenibilidad de los sistemas de agua y las políticas del agua. Los avances en el análisis hidroeconómico que se desarrollan en esta tesis abarcan mejoras en la modelización de beneficios medioambientales, la simulación de los impactos del cambio climático en los caudales de los ríos y el análisis de los conflictos hídricos. Un número limitado de estudios abordan conjuntamente el problema de la modelización y la aplicación de la política de agua. Los resultados muestran el potencial de la modelización hidroeconómica en el diseño y evaluación de políticas de gestión que mitiguen los efectos de la sequía, la escasez de agua y el cambio climático. El componente medioambiental combina aspectos biofísicos y económicos, que son esenciales para avanzar en la gestión sostenible del agua.

Los resultados de esta tesis destacan los crecientes desafíos de la sequía, la escasez de agua y el cambio climático, que la gestión del agua debe afrontar. La sostenibilidad del sistema de agua es un problema a largo plazo que requiere sistemas de agua robustos y resistentes. El riesgo y la incertidumbre son preocupaciones que deben considerarse en el diseño de políticas de gestión sostenible del agua, para afrontar la escasez de agua en relación a los objetivos de la sociedad. Los mercados del agua, el intercambio de agua, la conservación del agua y la mejora de la eficiencia son instrumentos que contribuyen a los objetivos de gestión del agua. Sin embargo, la rivalidad entre la eficiencia del uso del agua, la equidad y los objetivos de protección del medio ambiente podría comprometer el éxito de las políticas. Para evitar el fracaso de las políticas, es importante identificar los compromisos en la asignación de agua.

Por ejemplo, los resultados muestran que la cooperación entre los usuarios del agua contribuye a reducir los conflictos relacionados con el agua, garantizando la equidad y la protección de los ecosistemas. La contrapartida es la pérdida de eficiencia que conduce a mayores pérdidas económicas durante los períodos de sequía. Los mercados del agua y las mejoras en la eficiencia del sistema riego reducen las pérdidas económicas por la escasez de agua y reducen el riesgo y la incertidumbre, pero esta política acrecienta el riesgo de daños medioambientales y socava los beneficios sociales. La implementación de políticas de agua requiere instituciones donde las partes interesadas estén representadas. Incluso con mercados del agua, es indispensabel un fuerte marco institucional para lograr una gestión adecuada del agua. La implementación exitosa de las políticas de agua implica instituciones donde los intereses de los usuarios del agua estén representados, ya que éstos tienen que apoyar la introducción de medidas y su posterior cumplimiento.

A pesar de los avances presentados en esta tesis, quedan algunos retos por abordar en futuras investigaciones. Por ejemplo, la salud de los ecosistemas depende tanto de la cantidad como de la calidad del agua. Por lo tatno, identificar las soluciones de compromiso entre las actividades económicas y la contaminación del agua podría mejorar el análisis. Otro problema es que los impactos del cambio climático en los caudales del río serán heterogéneos temporal y espacialmente. Dado que unas regiones se verán más afectadas que otras, la dependencia espacial debe incorporarse al análisis para encontrar asignaciones óptimas de agua. La energía hidroeléctrica es un sector económico importante que depende de la disponibilidad de agua y, por lo tanto, el análisis del nexo entre el agua, la energía, los alimentos y los ecosistemas es esencial para la adaptación al cambio climático. Además, se necesita más trabajo no sólo para mejorar el conocimiento sobre las respuestas biofísicas de los ecosistemas, sino también para mejorar las estimaciones de valoración de los bienes y servicios proporcionados por los ecosistemas.

Todas estas mejoras harán avanzar la precisión de los resultados, convirtiendo el análisis hidroeconómico en una poderosa herramienta para apoyar el proceso de toma de decisiones.