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TESIS DOCTORAL

HYDROECONOMIC MODELING FOR SUSTAINABLE WATER MANAGEMENT OF MULTIPLE USES AND THEIR ADAPTATION TO CLIMATE UNCERTAINTY

Presentada por

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En satisfacción de los requisitos necesarios
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“Only those who will risk going
TOO FAR
can possibly find out
How FAR
one can go.”

(Thomas Stearns Eliot, 2015)

A mes très chers parents,

Qu'ils trouvent dans chaque ligne de ce travail l'expression de mon respect,
mon profond amour et éternelle reconnaissance.

Et que dieu leur procure bonne santé et longue vie.

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Contents

List of Tables

List of Figures

Abstract

Water stress and water quality degradation are major problems in river basins worldwide, challenging the goal of achieving water, food, and energy security and environmental protection. Water scarcity, economic growth, population expansion, and changing water use patterns between competing and vulnerable sectors have led to a sharp increase in water demands. Climate change projections anticipate higher variability of water supply, increased temperatures, and reductions of water resource availability, especially in arid and semiarid basins. These are major risks that emphasize the need for taking immediate action to deal with climate change effects. A specific challenge along these lines is the development of management strategies to effectively allocate water among competing sectors, improve water quality, and enhance climate resilience and adaptation in coming decades. The contribution of this research is to support the design of efficient and equitable water planning in the Ebro basin (Spain), which can be useful for other basins with similar climate conditions.

Hydroeconomic modeling offers considerable potential to support decision making. This information is essential for the design, implementation and enforcement of sustainable water management and climate adaptation plans. A number of studies use hydroeconomic modeling to investigate water allocation problems, analyzing sectoral and spatial interactions in catchment areas. Despite the widespread advances in integrated hydroeconomic modeling over recent decades, several gaps are not yet settled in the literature, and much more progress is expected. Facing these gaps, this thesis presents the development and application of selected integrated hydroeconomic modeling approaches for multi-sector analysis, using nonlinear and stochastic optimization techniques. The four main chapters of this thesis present specific methodological approaches and evaluate combinations of water management strategies for improving water supply reliability, water quality, and adaptation of water systems.

Agricultural nonpoint pollution is a major sources of water quality degradation and air pollution, arising from excessive use of crop nutrients and intensive livestock farming. Thus, the first article of the thesis “**Chapter 2:** *Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain*”, analyzes water scarcity and the interactions between water quantity and water quality. These results are used to evaluate the cost-efficiency of a series of mitigation and adaptation measures for the abatement of water and air pollution, under both normal and drought conditions. The study is based on an integrated hydroeconomic model developed and applied for the Ebro basin. The model integrates hydrological, biophysical, economic and water quality aspects,

capturing the main spatial and sectoral interactions in the basin. The model is validated using two calibration procedures: hydrological calibration based on observed stream flows, and economic calibration using Positive Mathematical Programming (PMP). The inclusion of water quality is a topic of growing relevance, although there are few hydroeconomic modeling studies analyzing water quality. The key messages from this study are: (1) drought conditions reduce water availability and increase nitrate concentrations in river reaches and the Ebro mouth, highlighting the tradeoffs between water quantity and water quality; (2) selected mitigation and adaptation policies have large potential for decreasing climate change impacts, improving water quality, reducing GHG emissions, and lowering environmental damages; (3) the most cost-effective policies are optimizing nitrogen application by reducing excessive fertilization, substituting synthetic fertilization by manure, and irrigation modernization. Those policies would facilitate the achievement of sustainable water management goals.

Improving the efficiency of water allocation to confront future climate stress conditions is a strong challenge in many regions in the world, especially in arid and semi-arid areas. The second article "**Chapter 3**: *Climate Adaptation Guidance: New Roles for Hydroeconomic Analysis*" develops an innovative model framework that integrates hydrology, economics, climate stress, and institutional water sharing arrangements. The model design illustrates how flexible sharing alternatives during water shortages can play an important informing role in adaptation to climate stress. This study discovers the potential of different water sharing policies in providing efficient water allocations across sectors and spatial locations, and in reducing economic losses incurred from the impacts of climate change. Selected policy alternatives are identified for adaptation to climate stress and protection of sustainable use of water resources in the future. Findings highlight that the accomplishments under unrestricted water trading or under proportional sharing of shortages provide significant grounds for optimism, made more pronounced in light of the economic value of additional water. This offers critical information for decisions makers in the assessment of the performance and efficiency of policies. Those values provide a clearer understanding of the costs and benefits of policies, giving the economic attractiveness of climate water stress adaptation patterns. Implementing economically efficient water sharing policies in the face of high water stress uncertainty will have a growing interest in sustaining water resources, and can be viewed as a practical way to adapt to the impact of climate stress.

A cross-sectoral WEFE nexus dialogue is presented in the third article "**Chapter 4**: *Ecosystems in WEFE nexus planning enhance water security and biodiversity for climate resilience*". An integrated optimization framework is developed addressing future climate risks, with the purpose of identifying affordable climate adaptation strategies. The model is used to find synergies and trade-offs among sectors (agriculture, urban, energy, and ecosystems) and spatial locations, for a series of water management strategies under climate change scenarios (CC-2070, CC-2100), giving insights into the extent of gains and losses among sectors and locations. The research offers information on water reallocations not only between economic activities but also with the environment, as well as the associated benefits and costs of policies across sectors. The results of this chapter demonstrate the capabilities of integrated hydroeconomic models to accurately assess a wide range of sectors, climate water stress scenarios, and water management policy choices. This integrated management provides a detailed information on: (1) the spatiotemporal impact of future climate change on the hydrology, land and energy production, environmental flows, and economic outcomes; (2) the sectoral vulnerabilities and hydrological and economic loses; and (3) the potential of selected strategies in achieving water, food, and energy and environmental security, and in promoting sustainable development. This critical information could be useful for the design of sustainable climate change adaptation policies.

Addressing future climate vulnerability in water sectors is a topic of growing interest, which is critical in drought risk research and for designing and implementing mitigation strategies. The last article "**Chapter 5**: *Probabilistic cross-sectoral trade-offs assessments under climate stress for sustainable and equitable water planning*" developpes an integrated hydroeconomic model for optimal water allocation decisions under future climate stress. The model assesses the probabilistic trade-offs between competing and vulnerable water users and spatial locations under different water priority policies and climate scenarios. The model methodology is stochastic dual dynamic programming (SDDP), which has been successfully employed to solve optimization problems with stochastic inflows. The stochastic programming formulation enables the assessment of hydrologic and economic risks, and reveals the future hydrologic uncertainties linked to each allocation policy. The extent of gains and losses from policy interventions is measured across spatial locations of irrigation districts, urban centers, and hydropower plants to characterize suitable mechanisms for equitable water and benefit-sharing arrangements. Findings indicate that the option of agricultural priority promotes food security but increases the vulnerability of downstream energy production, where the main hydropower plants are located. In contrast, the energy priority option advances energy security, but increases the vulnerability of upstream irrigated agriculture. The probabilistic trade-off analysis contributes to the design of water management strategies capable of handling the challenges of larger water vulnerability. It also contributes to implementing appropriate benefit-sharing schemes that could reach win-win outcomes and deliver acceptable levels of food, energy and human water security in large river basins.

Resumen

El estrés hídrico y la degradación de la calidad del agua son problemas importantes en las cuencas fluviales de todo el mundo, lo que supone un desafío para alcanzar los objetivos de seguridad hídrica, alimentaria y energética, y de protección medioambiental. La escasez de agua, el crecimiento económico, el aumento de la población y los cambios en los patrones de uso del agua entre sectores con fuerte competencia y vulnerabilidad, han llevado a un enorme aumento de demanda de agua en las cuencas. Las proyecciones de cambio climático anticipan mayor variabilidad en el suministro de agua, aumento de temperaturas, y reducción de la disponibilidad de recursos hídricos, especialmente en cuencas áridas y semiáridas. Estos riesgos son importantes por lo que es necesario empezar a tomar medidas que hagan frente a los efectos del cambio climático. Un desafío específico es la elaboración de estrategias de gestión que asignen agua de manera eficiente entre sectores competitivos, que mejoren la calidad del agua, y que promuevan la resiliencia y adaptación climática en las próximas décadas. La contribución de esta investigación consiste en contribuir al diseño de una planificación hidráulica eficiente y equitativa en la cuenca del Ebro (España), que también pueda ser útil en otras cuencas con condiciones climáticas similares.

La modelización hidroeconómica tiene un considerable potencial de apoyo a la toma de decisiones. La información que proporciona es esencial para el diseño, implementación y cumplimiento de planes de gestión de agua sostenibles y adaptados al cambio climático. Distintos estudios utilizan modelos hidroeconómicos para investigar problemas de asignación de agua, analizando las interacciones sectoriales y espaciales en las cuencas. Aunque ha habido avances generalizados en modelización hidroeconómica integrada en las últimas décadas, aún quedan por resolver distintas cuestiones en la literatura que deben abordarse. Frente a estas cuestiones pendientes, esta tesis pretende abordar algunos de estos desafíos mediante el desarrollo y aplicación de enfoques seleccionados de modelización hidroeconómica integrada incorporando análisis multisectoriales, y utilizando técnicas de optimización no lineal y estocástica. Los cuatro capítulos principales de esta tesis desarrollan enfoques metodológicos específicos para evaluar distintas estrategias de gestión de agua. El objetivo es mejorar la seguridad del suministro, recuperar la calidad del agua, y adaptar los sistemas de agua al cambio climático.

La contaminación difusa de la agricultura es una fuente principal de degradación de la calidad del agua y de la contaminación de la atmósfera, como consecuencia del uso excesivo de fertilizantes en los cultivos y de las emisiones de la ganadería intensiva. Así, el primer artículo de la tesis “**Capítulo 2**: *Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the*

Ebro River Basin, Spain", analiza la escasez de agua y las interacciones entre la cantidad y la calidad del agua. Estos resultados se han utilizado para evaluar la eficiencia de una serie de medidas de adaptación de los recursos hídricos, y de mitigación de la carga de contaminación del agua y de la atmósfera, tanto en condiciones climáticas normales como de sequía. El estudio se basa en un modelo hidroeconómico integrado que se ha desarrollado y aplicado en la cuenca del Ebro. El modelo integra aspectos hidrológicos, biofísicos, económicos y de calidad del agua, capturando las principales interacciones espaciales y sectoriales en la cuenca. El modelo se ha validado mediante dos procedimientos de calibración: calibración hidrológica basada en los caudales observados, y calibración económica mediante programación matemática positiva (PMP). La inclusión de la calidad del agua es un tema de relevancia creciente, y solo existen unos pocos estudios de modelización hidroeconómica que analizan la calidad del agua. Los mensajes clave de este estudio son los siguientes: (1) las condiciones de sequía reducen la disponibilidad de agua y aumentan la concentración de nitratos en los tramos de los ríos de la cuenca y en la desembocadura del Ebro, lo que pone de relieve el balance entre la cantidad y la calidad del agua; (2) las políticas de mitigación y adaptación seleccionadas tienen un gran potencial para disminuir los impactos del cambio climático, mejorar la calidad del agua, reducir las emisiones de GEI y reducir los daños ambientales; (3) las políticas más eficientes son la optimización de la aplicación de nitrógeno reduciendo la fertilización excesiva, la sustitución de fertilizantes sintéticos por estiércoles, y la modernización del regadío. Esas políticas facilitan el logro de los objetivos de gestión sostenible del agua.

La mejora de la eficiencia en la asignación de agua para enfrentar futuras condiciones de estrés climático es un gran desafío en muchas regiones del mundo, especialmente en áreas áridas y semiáridas. El segundo artículo, "**Capítulo 3**: *Climate Adaptation Guidance: New Roles for Hydroeconomic Analysis*", desarrolla un marco de modelización innovador que integra la hidrología, la economía, el estrés climático y los compromisos institucionales para compartir el agua. Los resultados del modelo ilustran cómo las alternativas flexibles para compartir agua durante periodos de escasez pueden desempeñar una función informativa importante entre los grupos de interés para poder adaptarse al estrés climático. Este estudio muestra el potencial de diferentes políticas de distribución de agua para poder proporcionar asignaciones de agua eficientes en todos los sectores y ubicaciones espaciales, y así reducir las pérdidas económicas provocadas por los impactos del cambio climático. Se han identificado distintas políticas alternativas para la adaptación al estrés climático que facilite un uso sostenible de los recursos hídricos en el futuro. Los resultados muestran que los logros tanto de la política de mercados de agua sin restricciones, como de la política de distribución proporcional de la escasez suponen una motivación significativa de optimismo, que se hace más pronunciado al considerar el valor económico del agua adicional. Estos resultados ofrecen una información crítica para los responsables de la toma de decisiones, en relación a la evaluación del rendimiento y la eficiencia de las políticas. Esos valores económicos facilitan una comprensión más clara de los costes y beneficios de las políticas, proporcionando una valoración económica a los distintos patrones de intervención disponibles para la adaptación al estrés hídrico del cambio climático. La implementación de políticas económicamente eficientes para compartir agua, para poder hacer frente a la elevadaincertidumbre del estrés hídrico, va a tener un interés creciente en la protección de los recursos hídricos, y puede considerarsecomo una forma práctica de adaptación al impacto del estrés climático.

En el tercer artículo, "**Capítulo 4**: *Ecosystems in WEFE nexus planning enhance water security and biodiversity for climate resilience*", se presenta un análisis intersectorial del nexo WEFE. El trabajo desarrolla un marco de optimización integrado para abordar los riesgos climáticos futuros, con el fin de identificar estrategias de adaptación climática que sean asequibles. En el modelo se examinan los compromisos y sinergias entre sectores (agricultura, urbano, energía y ecosistemas) y ubicaciones espaciales, que se obtienen de las distintas estrategias de gestión bajo escenarios de cambio climático (CC-2070, CC-2100). Estos resultados proporcionan información sobre el alcance de las ganancias y pérdidas entre sectores y ubicaciones que generan las estrategias alternativas. La investigación ofrece información sobre las reasignaciones de agua no solo entre actividades económicas sino también sobre los caudales medioambientales, así como sobre los beneficios y costes de cada política en los sectores económicos y medioambiental. Los resultados de este capítulo muestran la capacidad de los modelos hidroeconómicos integrados para poder evaluar con precisión una amplia gama de sectores, escenarios de estrés hídrico climático, y opciones de políticas de gestión del agua. Esta evaluación integrada proporciona información detallada sobre: (1) el impacto espacio-temporal del cambio climático futuro en la hidrología, la producción agrícola y de energía, el consumo urbano, los caudales ambientales, y los resultados económicos; (2) las vulnerabilidades sectoriales y las pérdidas hidrológicas y económicas; y (3) el potencial de las estrategias seleccionadas para lograr la seguridad hídrica, alimentaria, energética y medioambiental, a la vez que se promueve un desarrollo sostenible. Esta información es crítica para poder diseñar políticas de adaptación al cambio climático que sean sostenibles.

Abordar la vulnerabilidad climática futura en los sectores del agua es un tema que tiene un interés creciente en la investigación de los riesgos de sequía, y que permite diseñar e implementar estrategias de adaptación. En el último artículo, "**Capítulo 5**: *Probabilistic cross-sectoral trade-offs assessments under climate stress for sustainable and equitable water planning*", se desarrolla un modelo hidroeconómico integrado para conseguir decisiones óptimas de asignación de agua bajo estrés climático futuro. El modelo

evalúa los compromisos (trade-offs) probabilísticos entre usuarios de agua que compiten y son vulnerables a la escasez, así como entre las ubicaciones espaciales. La evaluación se realiza bajo diferentes políticas prioritarias de agua y distintos escenarios climáticos. En el modelo se utiliza la metodología de la programación dinámica dual estocástico (SDDP), que se ha empleado con éxito para resolver problemas de optimización con caudales estocásticos. La formulación de la programación estocástica permite evaluar los riesgos hidrológicos y económicos, y muestra las incertidumbres hidrológicas futuras vinculadas a cada política de asignación. El alcance de las ganancias y pérdidas de las intervenciones de política se mide en relación a las ubicaciones espaciales de los distritos de riego, los centros urbanos y las plantas hidroeléctricas. Esta información sirve para poder caracterizar mecanismos adecuados para lograr acuerdos equitativos de agua y de distribución de beneficios. Los resultados indican que la opción de prioridad agrícola promueve la seguridad alimentaria, pero aumenta la vulnerabilidad de la producción de energía en la cuenca baja, donde se ubican las principales centrales hidroeléctricas. Por el contrario, la opción de prioridad energética promueve la seguridad energética, pero aumenta la vulnerabilidad de la agricultura de regadío en la cuenca alta. El análisis de compromisos probabilísticos contribuye al diseño de estrategias de gestión del agua capaces de manejar los desafíos de una mayor vulnerabilidad del acceso al agua. También contribuye a implementar esquemas apropiados de distribución equitativa de beneficios, para lograr resultados que beneficien a todos los grupos de interés, y que aseguren niveles aceptables de seguridad alimentaria, energética y urbana en grandes cuencas fluviales.

CHAPTER 1

GENERAL INTRODUCTION

Chapter 1 General introduction

1.1 Background

Water scarcity and the lack of clean water are global concerns in many river basins resulting from increased population, income growth, changing water use patterns, and climate stress. Climate change is affecting water systems by altering weather patterns, leading to more severe droughts and floods, and to uneven water availability and demand. Global water demand has increased in the last century by a factor of seven and projections show that demand will rise by about 30% by 2050 (AQUASTAT, 2010; Boretti and Rosa, 2019). Managing water resources efficiently has become more critical than ever, especially in arid and semi-arid regions with increasing water demand and shrinking water availability. Erratic and uncertain water supply and the absence of effective water policies amplify scarcity, shortages, and unjust water access. Water scarcity becomes a major impending impact of climate change, involving large economic, social and environmental damages. According to the World Bank (2016), water scarcity in some regions of the Middle East and the Sahel in Africa could cost up to 6% of their GDP by 2050.

The potential impacts of water-related climate risks include reduced access to sufficient water quantity, water quality degradation, and increased competition between sectors and locations. Water resources competition for dwindling supplies could lead to production disruptions, assets decay and human water insecurity, which can multiply the risks of conflicts between local communities in water scarce basins. Insufficient water to simultaneously cover production activities, human settlements, and ecosystems, are threatening water, food, energy, and environmental security (IPCC, 2023). Stronger and successful water management policies and reforms are required for water secure and climate resilient economies that could cope with escalating climate stresses. The IPCC (2021) affirms the need for immediate global action to halt climate change and deal with its challenging impacts and risks. The main specific challenges are the difficulties of fostering effective cooperation between interest agents and stakeholders in the face of potential conflict in water scarce basins, and the complexities of developing water management strategies to improve climate adaptation and resilience. Future water shortages and increased water supply unreliability will exacerbate these challenges.

1.2 Climate change, water scarcity and security

Climate change and the associated increase in the frequency and intensity of extreme weather events (heat waves, droughts, floods, and storms) are regarded as the most serious security risks (UNEP, 2021).

The impacts affect people's lives and livelihoods in all corners of the globe, collapsing food production, freshwater access, biodiversity, and ocean food chains. Climate change effects on water resources are quite large, even for small increases in temperature (Schewe et al., 2014). Jiménez et al. (2014) indicate that for each degree of global warming, approximately 7% of the global population is expected to face a 20% decrease in renewable water resources. Changes in precipitation patterns can challenge the use of water for energy production, sanitation systems, drainage, reservoirs storage, threatening the security of many sectors. Furthermore, the variability of the timing and duration of temperature and rainfall patterns affects crops and livestock growth, endangering food security (USAID, 2014).

Water scarcity and insecurity are rising worldwide, increasing competition between users, and resulting in conflicts and instability in communities, countries and regions. IPCC (2022) indicates that roughly half of the world's population is experiencing severe water scarcity for at least one month of the year. The weak institutional capacity to constructively adapt to water scarcity and variability, and respond to extreme climate events, would further aggravate climate risks. Water distribution inequality is particularly visible in developing countries, with weak institutional arrangements to govern water security (Hepworth et al., 2013). Climate water stress is affecting the way people live in those countries, because the lack of adaptation and development of coping mechanisms by communities and institutions (USAID, 2014). More equitable water distribution could reduce the burden on deprived people and the risks of water conflicts (Gunasekara et al., 2014). Successful and sustainable water strategies need to balance the interests of sectors and spatial locations (upstream, downstream), while protecting the environment (Munia et al., 2016).

1.3 Agricultural nonpoint pollution

Pollution from crop and livestock production, in the form of nutrient loads and greenhouse gas emissions, degrade water and atmosphere quality. Water quality deterioration causes considerable damage to ecosystems in watersheds, places water supplies at risk, jeopardizes food quality (crops and freshwater fisheries), and damages economically lucrative ecotourism (USAID, 2014). About 2 billion of worldwide population don't have access to clean and safe drinking water (UN, 2022). Nutrient pollution is one of the main sources of water quality degradation from excessive use of fertilizers in crops and from livestock manure. The overloading with nutrients of river basins and coastal waters promotes adverse effects such as eutrophication.

Several actions and regulations have been taken to reduce nonpoint pollution from agriculture and induce better management practices, such as the Nitrates Directive in Europe, and the USDA conservation programs (Conservation Reserve and Environmental Quality Programs, with US$5 billion funding per year) in the United States. However, the efficiency of those pollution abatement policies remains to be seen in both Europe and the USA. The Nitrates Directive seems to have failed in reducing pollution loads in the last 30 years, with pollution loads doubling in the Seine River since 1991 (Romero et al., 2016), or no abatement in the Po or Thames rivers (Howden et al., 2011; Musacchio et al., 2020). The only country showing abatement of agricultural nitrogen loads is Denmark, achieved with a mix of command and control (fines) and institutional instruments started with the Action Plans in the 1980s (Dalgaard et al., 2014). In the USA, despite the large public funding in agricultural non-point pollution policies, there is no clear general improvement of water quality in basins (Ribaudo, 2015). The preoccupation of the European Union with the environment has increased in recent years, leading to the adoption of the EU action plan ”Towards zero pollution for air, water and soil for 2050” (EC, 2021).

Several studies assess water quality deterioration and propose cost-effective practices to mitigate the climate change effects. Pena-Haro et al. (2009) address water quality deterioration using hydroeconomic modeling, with the purpose of finding effective and economically beneficial measures to control nitrate groundwater pollution. Ward and Pulido-Velazquez (2008a) develop a basin scale optimization framework to identify the hydrologic and economic impacts of water pricing alternatives that protect water quality and comply with environmental regulations. Ward (2021) emphasizes the growing relevance of including water quality aspects in hydroeconomic modeling and assess new emerging contaminants from agriculture, urban, and industrial sources.

1.4 Water management strategies for climate adaptation and resilience

Resilient and sustainable water systems that advance socio-economic and environmental goals are required to deal with increasing climate stress and future uncertainties. Successful water management strategies for climate adaptation are essential to sustain water supply reliability, efficient water distribution among sectors, environmental biodiversity, and food systems. Poff et al. (2016) consider that sustainable water management should meet human water demands while maintaining ecosystems biodiversity crucial to support the long-term provision of environmental goods and services.

Designing and enacting water management strategies are challenging, especially in arid and semiarid regions where climate stress and water scarcity involve high economic costs and environmental damages. Numerous potential options are available for enhancing the performance of water systems and developing the capacity for climate risk adaptation. Ward (2022) reviews several measures that improve the capacity of irrigated agriculture for climate resilience, such as water conservation, water treatment, and reservoir and aquifer recharge management. Expanding reservoir storage capacity is an interesting management option for dealing with periods of water scarcity during droughts. Gohar et al. (2013) indicate that increasing reservoir storage offers considerable opportunities for boosting economic growth and for increasing farm income and food security. This water management strategy buffers against water supply fluctuations and builds capacity for climate adaptation, with releases covering economic and environmental demands in a controlled manner that dampen down the effects of droughts and floods.

Increased water supply fluctuations, water demand, population growth, and awareness of the need for water management for food, water, energy, and environmental security, and for climate resilience, have led many farmers, business and social organizations, and governments to promote water use efficiency in irrigated agriculture. Investments in irrigation modernization convert traditional flood irrigation to modern and efficient irrigation technologies (drip, sprinkler), which are believed to conserve water. However, Perez-Blanco et al. (2021) and Ward and Pulido-Velazquez (2008b) find that the strategy of water conservation technologies could increase water consumption because of increases in water evapotranspiration associated with more water demanding crops, double crops, and irrigated land expansion. This could result in the fall of basin stream flows, an issue known as the “paradox of irrigation efficiency” (Grafton et al., 2018).

Institutional water markets encourage more economically efficient water use patterns and provide significant grounds of optimism to confront water scarcity. Markets facilitate water reallocation from low- to high valued uses and improve private benefits (Brewer et al., 2008; Olmstead, 2014; Wheeler et al., 2014). Water trading and moving water to high profitable uses depend on differences in the water marginal values across users, that create incentives for water reallocation (Schwabe et al., 2020). The economic value of additional water offers critical information for decisions makers in the assessment of the performance and efficiency of policies. The shadow price of water provides a clearer understanding of the costs and benefits of policies, highlighting the economic attractiveness of alternative strategies for climate water stress adaptation. 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). However, the available experience with fully developed water markets in Australia and Chile shows that the protection of environmental flows is not evident, either with public buying of water for the river in Australia (Colloff et al., 2020; Grafton, 2019) , or with limitations of withdrawals in Chile (Macpherson and Salazar, 2020).

Considerable and growing interest by policymakers in finding ways to enhance climate resilience and reduce economic and environmental damages require scientific support, such as cost-efficiency information on management strategies to deal with predicted dwindling water supplies and future climate stress. This information on the cost and benefits of management options could be a valuable resource to limit financial exposure and economic losses in guiding policy debate.

1.5 Review of modeling approaches for water policy analysis

The complexity of water resources and climate change impacts are challenging the understanding of stakeholders and policymakers about the severity of future climate water stress and its impacts. Several modeling approaches have been developed, contributing to many achievements in recent decades. Integrated and dynamic hydroeconomic modeling has been used to solve different water management problems for a given time frame. This models account for hydrological, economic, institutional, food security, or cultural constraints (Ward, 2021), and advance the sustainable management of water resources (Booker et al., 2012). Some examples of hydroeconomic models' application are studies that assess hydrologic uncertainty: analysis of water allocation policies that reduce hydrologic risks (Goor et al., 2010); integration of several sectors' demand and supply components (Booker et al., 2012); evaluation of flood risks management (Zhao et al., 2014); assessment of hydropower capacity development in the Koshi river basin (Amjath-Babu et al., 2019); or integration of environmental benefits across the Ebro basin (Crespo et al., 2022).

Despite the important achievement of previous studies, several gaps are not yet closed in the development of hydroeconomic models. Booker et al. (2012) indicate that hydroeconomic modeling requires further advances in representing the interdependence between model components, and in including dynamic and stochastic dimensions. Ward (2021) points out that a good hydroeconomic model needs to be based on solid hydrological specification, including crop evapotranspiration, ecosystem water use, and stream aquifer interactions, both at present and in the future. Most existing hydroeconomic models have been developed to find best responses to climate stress in river basins. However, less attention has been paid to the importance of including water quality or integrating climate, water, food, energy, and environment. These aspects are needed for the design of cost-effective interventions under future climate conditions, and for their uptake by stakeholders. The joint management of water along with other scarce resources such as energy, food, and ecosystems, is being recognized in decision making. This effort requires further development in hydroeconomic modeling at appropriate temporal, sectoral, and spatial scales. Such advances are needed to address the challenges of the growing population and income under climate stress, in order to guide climate adaptation policies.

1.6 Thesis objectives and methodology

The main objective of this research is develop and apply integrated and dynamic hydroeconomic modeling, that could provide cost-effective water policy interventions for climate adaptation at basin scale. These models are used to examine the impacts of droughts and water scarcity from climate stress on cross-sectoral water use in the Ebro River basin, and then assess the scope of different management strategies in bringing about the sustainability of the water system. The empirical results of this thesis could support the design of efficient and equitable water planning, and serve as a guide for other basins in arid and semiarid regions.

The thesis includes four articles (chapters 2 to 5) that present various hydroeconomic modeling approaches for addressing several water management policies under future climate water stress scenarios. The following specific objectives were established in order to achieve this goal:

The inclusion of water and air quality in hydroeconomic modeling for the assessment of climate change mitigation and adaptation policies. The analysis deals with both water scarcity and agricultural nonpoint pollution (Chapter 2)

To meet this objective, an integrated hydroeconomic modeling is developed that integrates hydrological, biophysical, economic, water quality (nutrients) and GHG emissions. The inclusion of water quality is a topic of growing relevance, even though few published studies use hydroeconomic modeling to examine water quality. The interactions among model components provide a better assessment of water allocation options among sectors and spatial locations, showing the large negative impacts of droughts on the system.

The model is validated using two calibration procedures:

<u>*Hydrologic calibration*</u>: The reduced form hydrological component is calibrated by including slack variables to close the mass balance between estimated and observed stream flows.

<u>*Economic calibration*</u>: The economic regional component is calibrated with positive mathematical programming (PMP), reproducing the observed water and land use under baseline conditions.

Assessment of institutional water sharing arrangements to guide farm and urban economic benefits optimization for successful climate adaptation (Chapter 3)

In this chapter, we develop a novel model framework that integrates hydrology, economics, climate stress, and institutional water sharing arrangements. The purpose is to address climate water stress variability and identify opportunities for water sharing policies adapted to climate change, which could deliver sustainable water resources in the future. The model uses innovative calibration methods for ensuring that optimization outcomes from the model match historically observed data on water use and economic welfare. The calibrated model enables the discovery of efficient water allocation plans, and provide insights into marginal behavioral responses to climate water stress and water policies.

Integrating ecosystem benefits in the Water Nexus enhances human water security and biodiversity, and increases climate resilience (Chapter 4)

A hydroeconomic model that includes the hydrology, the main economic sectors (agriculture, urban, energy), but also the ecosystem services is developed to spur more comprehensive cross-sectoral nexus dialogue among stakeholders. The cross-sectoral integration will be used to find synergies and trade-offs among sectors and spatial locations, giving insights into the extent of gains and losses among sectors and locations from policy interventions. This model assesses the potential of water management strategies in achieving water, food, and energy security and ecosystem protection, under climate change scenarios for periods 2040-2070 (CC-2070) and 2070-2100 (CC-2100). Results identify affordable measures that could limit sector vulnerability, minimize the risks of water stress, and improve climate resilience. For future climate scenarios, the basin headwater series are generated using the statistical delta change downscaling method (Escriva-Bou et al., 2017; Fowler et al., 2007).

A stochastic optimization framework to assess probabilistic trade-offs is developed. Trade-offs between competing and vulnerable water users and spatial locations (upstream-downstream) are estimated combining water priority policies and climate scenarios (Chapter 5)

This chapter presents an integrated hydroeconomic model using a stochastic optimization procedure for optimal water allocation decisions under future climate stress. The model is solved with the SDDP algorithm that could deal with complex multi-stage and stochastic problems, applying the Bellman's principle of optimality. The model integrates the economic activities and the hydrologic system, and it is used to analyze water priority allocation policies for water sector withdrawals and reservoir releases. This model focuses on assessing the spatial distribution of water uses' risks and vulnerabilities, as well as the corresponding trade-offs in heavily committed river basins.

References

Amjath-Babu TS, Sharma B, Brouwer R, Rasul G, Wahid SM, Neupane N, et al. Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. Applied Energy 2019; 239: 494-503.

AQUASTAT. Global Water Withdrawal. AQUASTAT website. Food and Agriculture Organization of the United Nations, Rome. 2010.

Booker JF, Howitt RE, Michelsen AM, Young RA. ECONOMICS AND THE MODELING OF WATER RESOURCES AND POLICIES. Natural Resource Modeling 2012; 25: 168-218.

Boretti A, Rosa L. Reassessing the projections of the World Water Development Report. Npj Clean Water 2019; 2: 6.

Brewer J, Glennon R, Ker A, Libecap G. 2006 Presidential Address - Water markets in the West: Prices, trading, and contractual forms. Economic Inquiry 2008; 46: 91-112.

Colloff M, Rocheta E, Hillman T, al. Assessment of river flows in the Murray-Darling Basin: Observed versus expected flows under the Basin Plan 2012-2019. Wentworth Group of Concerned Scientists. Sydney. https://wentworthgroup.org/wp-content/uploads/2020/08/MDB-flows.pdf. . 2020.

Crespo D, Albiac J, Dinar A, Esteban E, Kahil T. Integrating ecosystem benefits for sustainable water allocation in hydroeconomic modeling. Plos One 2022; 17: 23.

Dalgaard T, Hansen B, Hasler B, Hertel O, Hutchings NJ, Jacobsen BH, et al. Policies for agricultural nitrogen management-trends, challenges and prospects for improved efficiency in Denmark. Environmental Research Letters 2014; 9: 16.

EC. (EUROPEAN COMMISSION), EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil'. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0400&qid=1623311742827. 2021.

Escriva-Bou A, Pulido-Velazquez M, Pulido-Velazquez D. Economic Value of Climate Change Adaptation Strategies for Water Management in Spain's Jucar Basin. Journal of Water Resources Planning and Management 2017; 143: 13.

Fowler HJ, Blenkinsop S, Tebaldi C. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. International Journal of Climatology 2007; 27: 1547-1578.

Gohar AA, Ward FA, Amer SA. Economic performance of water storage capacity expansion for food security. Journal of Hydrology 2013; 484: 16-25.

Goor Q, Halleux C, Mohamed Y, Tilmant A. Optimal operation of a multipurpose multireservoir system in the Eastern Nile River Basin. Hydrology and Earth System Sciences 2010; 14: 1895-1908.

Grafton RQ. Policy review of water reform in the Murray-Darling Basin, Australia: the "do's" and "do'nots". Australian Journal of Agricultural and Resource Economics 2019; 63: 116-141.

Grafton RQ, Williams J, Perry CJ, Molle F, Ringler C, Steduto P, et al. The paradox of irrigation efficiency. Science 2018; 361: 748-750.

Gunasekara N, Kazama S, Yamazaki D, Oki T. Water Conflict Risk due to Water Resource Availability and Unequal Distribution. Water Resources Management 2014; 28: 169-184.

Hepworth N, Hooper V, Hellebrandt D, Lankford B. What Factors Determine the Performance of Institutional Mechanisms for Water Resources Management in Developing Countries in Delivering Pro-poor Outcomes and Supporting Sustainable Economic Growth? CEE review 11-006. Collaboration for Environmental Evidence. Available online at: www.environmentalevidence.org/SR11006.html . 2013.

Howden NJK, Burt TP, Worrall F, Mathias S, Whelan MJ. Nitrate pollution in intensively farmed regions: What are the prospects for sustaining high-quality groundwater? Water Resources Research 2011; 47: 13.

IPCC. (Intergovernmental Panel on Climate Change), AR6 Climate Change 2021: the Physical Science Basis. Irmak, S., Haman, D.Z., Bastug, R., 2000. Determination of crop water stress index for irrigation timing and yield estimation of corn. Agron. J. 92, 1221–1227. 2021.

IPCC. (Intergovernmental Panel on Climate Change), Climate Change 2022: Impacts, Adaptation and Vulnerability. The Working Group II contribution to the IPCC Sixth Assessment Report. https://www.ipcc.ch/report/ar6/wg2/downloads/outreach/IPCC_AR6_WGII_FactSheet_FoodAndWater.pdf 2022.

IPCC. (Intergovernmental Panel on Climate Change), Synthesis Report of the IPCC Sixth Assessment Report (AR6) en la seccion 2.1 página 6 del longer report. IPCC. Geneva. 2023.

Jiménez C, T BE, N O, A NW, et al. Freshwater resources. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269. . 2014.

Macpherson EJ, Salazar PW. Towards a Holistic Environmental Flow Regime in Chile: Providing for Ecosystem Health and Indigenous Rights. Transnational Environmental Law 2020; 9: 481-519.

Munia H, Guillaume JHA, Mirumachi N, Porkka M, Wada Y, Kummu M. Water stress in global transboundary river basins: significance of upstream water use on downstream stress. Environmental Research Letters 2016; 11: 13.

Musacchio A, Re V, Mas-Pla J, Sacchi E. EU Nitrates Directive, from theory to practice: Environmental effectiveness and influence of regional governance on its performance. Ambio 2020; 49: 504-516.

Olmstead SM. Climate change adaptation and water resource management: A review of the literature. Energy Economics 2014; 46: 500-509.

Pena-Haro S, Pulido-Velazquez M, Sahuquillo A. A hydro-economic modelling framework for optimal management of groundwater nitrate pollution from agriculture. Journal of Hydrology 2009; 373: 193-203.

Perez-Blanco CD, Loch A, Ward F, Perry C, Adamson D. Agricultural water saving through technologies: a zombie idea. Environmental Research Letters 2021; 16: 10.

Poff NL, Brown CM, Grantham T, Matthews JH, Palmer MA, Spence CM, et al. Sustainable water management under future uncertainty with eco-engineering decision scaling. Nature Climate Change 2016; 6: 25-34.

Ribaudo M. The limits of voluntary conservation programs. Choices 30(2): 1-5. 2015.

Romero E, Le Gendre R, Garnier J, Billen G, Fisson C, Silvestre M, et al. Long-term water quality in the lower Seine: Lessons learned over 4 decades of monitoring. Environmental Science & Policy 2016; 58: 141-154.

Schewe J, Heinke J, Gerten D, Haddeland I, Arnell NW, Clark DB, et al. Multimodel assessment of water scarcity under climate change. Proceedings of the National Academy of Sciences of the United States of America 2014; 111: 3245-3250.

Schwabe K, Nemati M, Landry C, Zimmerman G. Water Markets in the Western United States: Trends and Opportunities. Water 2020; 12: 15.

UN. (United Nations), SDG report, SDG 6 Clean water and sanitation: Ensure availability and sustainable management of water and sanitation for all. Department of Economic and Social Affairs, United Nations Statistics Division. 2022.

UNEP. (United Nations Environment programme), Climate action: Climate change, water scarcity, and security. 2021.

USAID. (United States Agency International Development). Water and Conflict. A toolkit for programming. 2014.

Ward FA. Hydroeconomic Analysis to Guide Climate Adaptation Plans. Frontiers in Water 2021; 3: 26.

Ward FA. Enhancing climate resilience of irrigated agriculture: A review. Journal of Environmental Management 2022; 302: 15.

Ward FA, Pulido-Velazquez M. Efficiency, equity, and sustainability in a water quantity-quality optimization model in the Rio Grande basin. Ecological Economics 2008a; 66: 23-37.

Ward FA, Pulido-Velazquez M. Water conservation in irrigation can increase water use. Proceedings of the National Academy of Sciences of the United States of America 2008b; 105: 18215-18220.

Wheeler S, Loch A, Zuo A, Bjornlund H. Reviewing the adoption and impact of water markets in the Murray-Darling Basin, Australia. Journal of Hydrology 2014; 518: 28-41.

World Bank. High and Dry: Climate Change, Water, and the Economy. World Bank, Washington, DC. License: Creative Commons Attribution CC-BY 3.0 IGO. 2016.

Xu JP, Lv CL, Yao LM, Hou SH. Intergenerational equity based optimal water allocation for sustainable development: A case study on the upper reaches of Minjiang River, China. Journal of Hydrology 2019; 568: 835-848.

Zhao TTG, Zhao JS, Lund JR, Yang DW. Optimal Hedging Rules for Reservoir Flood Operation from Forecast Uncertainties. Journal of Water Resources Planning and Management 2014; 140: 11.

CHAPTER 2

HYDROECONOMIC MODELING FOR ASSESSING WATER SCARCITY AND AGRICULTURAL POLLUTION ABATEMENT POLICIES IN THE EBRO RIVER BASIN, SPAIN

Chapter 2 Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain

Abstract

Water scarcity and water quality degradation are major problems in many basins across the world, especially in arid and semiarid regions. The severe pressures on basins are the consequence of the intensification of food production systems and the unrelenting growth of population and income. Agriculture is a major factor in the depletion and degradation of water resources, and contributes to the emissions of greenhouse gases (GHG). Our study analyzes water allocation and agricultural pollution into watercourses and the atmosphere, with the purpose of identifying cost-effective policies for sustainable water management in the Ebro River Basin (Spain). The study develops an hydroeconomic model that integrates hydrological, economic and water quality aspects, capturing the main spatial and sectoral interactions in the basin. The model is used to analyze water scarcity and agricultural pollution under normal and droughts conditions, providing information for evaluating mitigation and adaptation policies. Results indicate that drought events increase nitrate concentration by up to 63% and decrease water availability by 42% at the mouth of Ebro River, highlighting the tradeoffs between water quantity and quality. All mitigation and adaptation policies reduce the effects of climate change, improving water quality and reducing GHGs' emissions, thus lowering environmental damages and enhancing social well-being. Manure fertilization and optimizing the use of synthetic fertilizers are important cost-effective policies increasing social benefits in a range between 50 and 160 million Euro. Results show that irrigation modernization increases the efficient use of nitrogen and water, augmenting social benefits by up to 90 million Euro, and enlarging stream flows at the river mouth. In contrast, manure treatment plants reduce private and social benefits even though they achieve the lowest nitrate concentrations. Our study provides insights on the synergies and tradeoffs between environmental and economic objectives. Another finding is that drought conditions decrease the effectiveness of policies, and increase the tradeoffs between water availability and nitrate pollution. The results contribute to the discussion of designing cost-effective policies for the abatement of agricultural polluting emissions into water and the atmosphere.

Keywords: hydroeconomic modeling, nonpoint pollution, droughts, water quality, abatement policies, climate change.

2.1 Introduction

Water resources are vitally important for both human livelihoods and natural ecosystems. Water withdrawals have risen sharply in the last century, placing massive pressures on water resources and causing severe water scarcity and degradation problems in most river basins worldwide, especially in arid and semiarid regions (Greve et al., 2018, Dasgupta, 2021). These negative impacts are linked to the strong growth in population and income. Climate change is altering precipitation patterns and making extreme weather events more frequent and intense. Drought is one of the most devastating natural disasters, with serious effects like the shortage of freshwater to meet societal requirements (Ahmadi et al., 2019). Water scarcity and water quality degradation are serious global problems. The challenge is to ensure good quality water to fulfill human, environmental, social, and economic demands in order to support sustainable development (UNESCO, 2021; Berthet et al., 2021). Addressing water scarcity and quality is one important topic of the eighth phase of the Intergovernment Hydrological Programme (IHP-VIII), which focuses on "Water Security: Responses to Local, Regional and Global Challenges (2014–2021)". There are critical connections between water availability and water quality (Jury and Vaux, 2005), and both have been associated with human health (Myers and Patz, 2009), food security (Rockström et al., 2009; Simelton et al., 2012) and sustaining natural ecosystems (Poff et al., 1997). This means that water availability and quality should be assessed in a consistent manner to account for the relationships between water availability and quality.

Nonpoint pollution is responsible for 38% of pressures affecting water bodies in Europe, mainly due to agricultural sources such as nitrates and pesticides (European Environment Agency, 2018). Agriculture is a major source of water quality deterioration and GHG emissions to the atmosphere. Both water pollution by nutrients and GHG loads are complex problems arising from excessive use of fertilizers and intensive livestock farming (Bluemling and Wang, 2018). Nitrous oxide (N_2O) and methane (CH_4) are potent GHGs that contribute to the planet global warming (IPCC, 2007; Kanter et al., 2017). Rivers receive large quantities of nutrients, which cause water eutrophication and create large hypoxic dead zones in some regions (Breitburg et al., 2018). Parris (2011) highlights that agricultural water quality is a major environmental issue in OECD countries, and it is a relevant matter for policy consideration in all OECD countries.

Protecting water resources and natural ecosystems requires robust institutions, coupled with compelling and enforceable water policies. Sustainable river basin management is a quite challenging task, considering the current scale of global water degradation in basins. The methodologies needed to address this challenge call for a better understanding of water management problems in order to deploy effective and politically viable measures dealing with water scarcity, droughts, climate change and pollution. Sustainable management of water resources for different uses will not only depend on water quantity withdrawals, but also on nutrient loads, organic matter, salinity, water temperature, and other pollutants (Van Vliet et al., 2017; Barbieri et al., 2019).

The use of hydroeconomic modeling is increasing, driven by the advances of integrating hydrology, environment, and socio-economics in the analysis of water resources management. Several studies investigate the problem of water allocation among sectors using hydroeconomic modeling to assess water policies (Ringler et al., 2006; Kahil et al., 2015; 2016a; Escriva et al., 2018). Other studies emphasize sectoral and spatial interactions in catchment areas (Bekchanov et al., 2015; Kahil et al., 2016b; 2018; Dogan et al., 2018; Crespo et al., 2019). Despite the widespread use of hydroeconomic modeling in assessing water allocation, the inclusion of the policy analysis for the abatement of water pollution is limited.

The inclusion of water quality is a topic of growing relevance, although there are few studies analyzing water quality by using hydroeconomic modeling. Some examples are salinity pollution (Cai et al., 2003; Aein and Alizadeh, 2021), arsenic in drinking water (Ward and Pulido, 2008), organic matter loads (Moraes et al., 2010), biochemical oxygen demand (Gunawardena et al., 2018), nitrate pollution (Carolus et al., 2020), and environmental and salinity damages in terms of water savings, replacement costs or crop production damages (Booker and Young, 1991; 1994; 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 stream flows evaluation, and travel cost or contingent valuation techniques are used for valuation of the ecosystem services (Ringler et al., 2004; Babel et al., 2005; Booker et al., 2005; Ringler and Cai, 2006; Ward and Pulido, 2008; 2012). In Spain, there are only a couple of previous studies on water pollution abatement using hydroeconomic modeling, where the modelling framework was applied to a hypothetical groundwater system (Peña-Haro, 2009; 2011).

Some studies assess the tradeoff between water quantity and quality using a simulation model (Yang et al., 2015). However, the tradeoffs between water scarcity and water quality degradation using an optimization model remain unsettled in the literature. The advantage of using an optimization model is in the capacity of the model to maximize the economic benefits under water scarcity and agricultural nonpoint pollution simultaneously, which involves a more realistic approach. This integrated hydroeconomic model is designed to find the most cost-effective management policies (Heinz et al., 2007) and to make socially optimal policy decisions (Gunawardena et al., 2018). The assessment of the relationship between water quantity and quality is important to strengthen hydroeconomic modeling, in order to understand and realize its full power to inform critical policy debates.

In this paper, an integrated hydroeconomic model is developed addressing both water allocation and agricultural nonpoint pollution, with the purpose of looking at the tradeoffs between water quantity and water quality under normal and drought conditions. The model estimates agricultural pollution impacts on both the watercourses (nitrates) and the atmosphere (nitrous oxide and methane). The integration of hydrological, economic and environmental components captures the interactions among components. This provides a better assessment of water allocation options among sectors and spatial locations, showing the large negative impacts of droughts on the system.[1]

Selected climate change mitigation and adaptation policies are evaluated under normal climate and severe drought conditions in order to identify the effectiveness and robustness of policies. These policies could boost the efficient use of nitrogen and water in agricultural activities, reduce pollution loads and improve water and air quality, or protect environmental flows. The hydroeconomic model is developed to analyze the Ebro River Basin in northeastern Spain. Nearly all basins in Spain are under mounting scarcity pressures and water quality problems that require effective policy intervention (Lassaletta et al., 2009). Climate change and agricultural nonpoint pollution problems have to be tackled locally, with practical alternatives addressing water depletion and pollution.

This study contributes to the literature performing a detailed concurrent assessment of water allocation and pollution abatement solutions at river basin level, using hydroeconomic modeling. The study analyzes how to achieve a more sustainable management of the Ebro Basin, but also contributes to the scientific debate on sustainable policies and measures for water management worldwide. The results of this paper highlight the strong links between water quality and water quantity in the basin, and show that drought conditions reduce water availability and dilution processes, increasing nitrate concentration in water media. Our results indicate also that mitigation and adaptation policies have a double effect by

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[1] Costs of drought damages have been estimated at $8 billion per year in the United States (NOAA, 2021), and around €9 billion per year in the European Union (Cammalleri et al., 2020). Hernandez et al. (2013) estimate the cost of the 2005 drought in the Ebro basin at 0.5% of GDP. The evidence during recent years indicates that the drought anomaly in Europe is unprecedented (Büntgen et al., 2021).

abating pollution into the atmosphere and in watercourses, thus reducing environmental damages and enhancing social welfare.

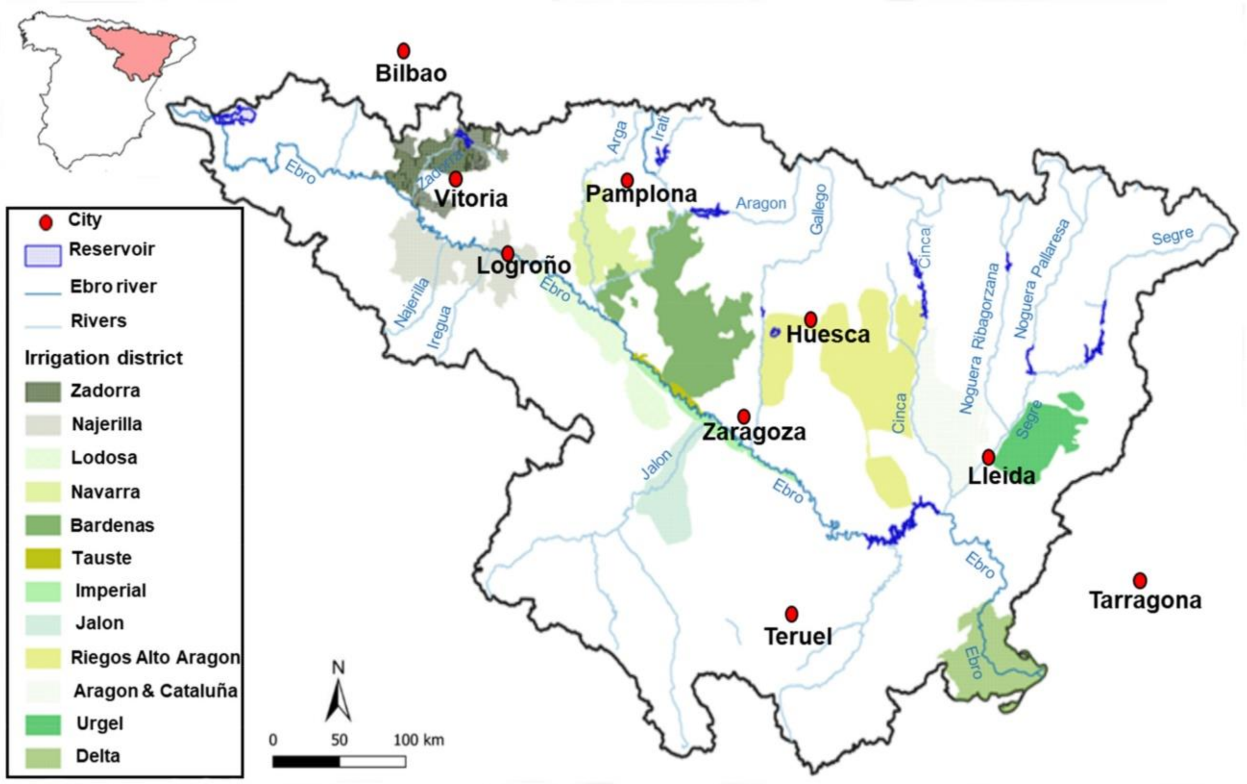
2.2 The Ebro River Basin: Backround information

The Ebro Basin, located northeast of the Iberian Peninsula, is one of the main European Mediterranean basins. It covers an area of 85,600 km^2, a fifth of the Spanish territory, and its streamflow is one of the largest in the country. Natural ecosystems of great value cover 30% of the basin area. Precipitation occurs mainly in the Pyrenees, where it exceeds 1000 mm/year, while it does not exceed 350 mm/year in the central part of the basin, where conditions are semi-arid (CHE, 2015). The most important tributaries (Zadorra, Aragon, Gallego, Cinca and Segre) supply the canals of the main irrigation districts and also the most important urban areas in the basin (Figure 2.1).

The renewable resources of the Ebro basin are estimated at 14,600 Mm^3, and withdrawals amount to 8,460 Mm^3, of which 8,110 Mm^3 are surface diversions and 350 Mm^3 are groundwater extractions (CHE, 2015). Water use in agricultural activities is estimated at 7,680 Mm^3 and urban extractions amounts to 357 Mm^3 supplying three million inhabitants, including households and industries connected to urban networks. The irrigated crops in the Ebro Basin are field crops, fruit trees and vegetables covering an area of 750,000 ha, distributed under surface, sprinkle and drip irrigation technologies (CHE, 2016). The Ebro River is one of Spain's rivers with substantial minimum environmental flows at river mouth. The Ebro water plan of 2015 established the current level of this environmental flow at 3,000 Mm^3/year.

The Ebro Basin Authority is responsible for water management, water allocation, water quality, and water planning and control. The special characteristic of this institutional approach is the key role played by stakeholders, which are involved at all decision making in the basin governing bodies and in local watershed boards. The Ebro Basin Authority or Confederación Hidrográfica del Ebro (CHE, 2020) indicates that nonpoint pollution represents one of the main pressures on the Ebro coming from agricultural and livestock activities. Almost half surface waters in the basin are being significantly affected, particularly in its middle and lower reaches (Ollero, 2007; Vericat and Batalla, 2006). The mean annual streamflow has decreased 40% in the last 50 years because of the expansion of irrigation, decreasing rainfall and revegetation (Buendia et al., 2016). The ecological condition of water bodies is threatened by these hydrological alterations and nonpoint pollution loads, impairing the dilution capacity. Herrero et al. (2018) highlight that changes in land use, rainfall, water temperature, and nitrate concentration could lead to a general decrease in the ecosystem quality of water bodies within the basin. Overall, water quality

Figure 2. 1. Map of the Ebro River Basin.



pressures from agricultural nonpoint pollution are degrading the status of water bodies in the Ebro, and require the active intervention of state and federal public authorities together with all water stakeholders.

2.3 Hydroeconomic model for the Ebro Basin

Water is an essential component of sustainable development, underpinning almost all types of economic activities, human water security, and ecosystems services. Challenges to water management such as water scarcity, pollution loads, and the impacts of climate change are threatening human wellbeing and biodiversity. Hydroeconomic analysis is one type of water- economy modeling, which is based on the hydrologic network of river basins. The hydroeconomic approach has clear advantages in evaluating management and policy strategies for adaptation to climate change, by providing efficient water allocations and pollution abatement across water uses and spatial locations. Hydroeconomic models have achieved greater sophistication by integrating agronomic, hydrologic, and economic components (Cai et al. 2003; Harou et al., 2009; Booker et al. 2012; Ward 2021). This involves a more realistic approach to water allocation and water quality trade-offs across space and sector, and less reliance on temporally and spatially integrated demand functions used by economywide models (Bekchanov et al. 2017).

The hydroeconomic model is used to analyze water allocation among sectors and spatial locations, nonpoint pollution loads across the basin, and also to evaluate drought scenarios and climate change mitigation and adaptation measures. The policy analysis deals with both water allocation adjustments under droughts and climate change, and pollution abatement of nutrient loads and GHG emissions. The model includes the main water uses in the basin: irrigation, livestock, and urban and industrial. Dryland crops are also included in the assessment of pollution emissions. The model integrates three components: (1) the hydrological component, (2) the regional economic component, and (3) the environmental component (Figure 2.2).

2.3.1 The hydrological component

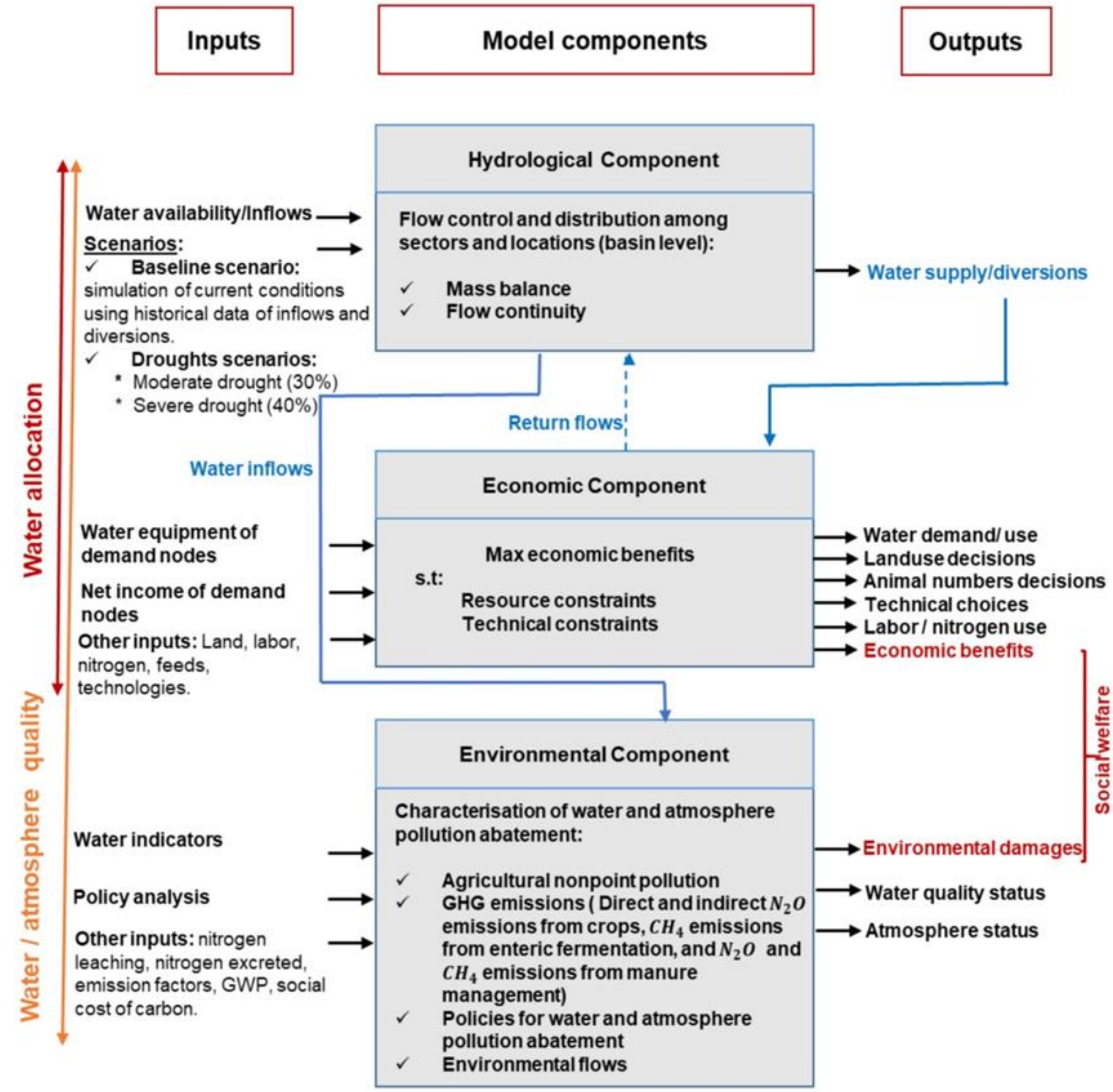
The hydrological component is a reduced form hydrological model of the Ebro basin, calibrated with observed stream flows. The reduced form hydrological model is a node-link network, in which nodes represent physical units impacting the stream system, and links represent the connection between these units. The nodes are classified into supply nodes such as rivers, and demand nodes such as irrigation districts, livestock, households and industries. The links could be rivers or canals, and stream flows between supply and demand nodes are characterized by simplified equations using the hydrological concepts of mass balance and continuity of river flows (Kahil et al., 2015). The representation of the interactions among nodes is based on detailed information on each node's spatial location and physical characteristics. The component incorporates information on inflows, withdrawals, return flows and losses, and water metering at selected measurement stations in the basin. The model can simulate the flows at each node and the distribution of water availability between sectors and spatial locations. The hydrologic component is developed using the databases of CHE (2016), and it is calibrated with the observed historical allocations in selected stations of the basin (Figure A2.1). The mathematical formulation is given by the following equations:

$$\mathrm{Wout_d} = \mathrm{Win_d} - \mathrm{Wloss}_{\mathrm{d}} - Div_d^{IR} - Div_d^{URB} - Div_d^{LIV} \tag{2.1}$$

$$Win_{d+1} = Wout_d + r_d^{IR} \cdot \left(Div_d^{IR}\right) + r_d^{URB} \cdot \left(Div_d^{URB}\right) + r_d^{LIV} \cdot \left(Div_d^{LIV}\right) + RO_{d+1} \tag{2.2}$$

$$Wout_d \geq E_d^{min} \tag{2.3}$$

Figure 2. 2. Modeling framework.



The first equation shows the mass balance and determines the water outflow $Wout_d$ in river reach *d,* which is equal to the inflow Win_d minus water losses $Wloss_d$, and minus the diversions for irrigation Div_d^{IR}, urban use Div_d^{URB} and livestock use Div_d^{LIV}. The second equation guarantees flow continuity in the basin. Win_{d+1} is the water inflow into the following river reach *d+1* as the sum of the outflow from the upstream water reach $Wout_d$, the return flows from upstream irrigation districts $[r_d^{IR} \cdot (Div_d^{IR})]$, urban return flows $[r_d^{URB} \cdot (Div_d^{URB})]$, livestock return flows $[r_d^{LIV} \cdot (Div_d^{LIV})]$, and the runoff entering the river reach from tributaries RO_{d+1}. The third equation specifies that the water outflow in river reach *d* must be greater than or equal to the minimum environmental flow imposed on that river reach.

The hydrologic component is calibrated by introducing slack variables in every river reach to balance supply and demand at every node. These variables represent unmeasured water sources or uses. This calibration procedure reproduces the water flows observed in the reference conditions. Water inflows, outflows and characteristics of flow rates in rivers and channels have been taken from databases and reports by CHE (2016) and CEDEX (2020).

2.3.2 The regional economic component

The regional economic component consists of optimization models for irrigation districts, for livestock and dryland crops, and for urban economic surplus. For irrigation, the component is set at irrigation district scale to maximize the benefits of crops subject to a set of technical and resource constraints. Yield functions are linear and decreasing in cropland area, with constant input and output prices. The optimization problem is as follows:

$$Max\ B_k^{IR} = \sum_{ij} C_{ijk}^{\prime(IR)} \cdot X_{ijk}^{IR} \tag{2.4}$$

subject to

$$\sum_{i} X_{ijk}^{IR} \leq Tland_{kj}; \qquad i: crop;\ j: flood, sprinkler, drip;\ k: irrigation\ district \tag{2.5}$$

$$\sum_{ij} W_{ijk} \cdot X_{ijk}^{IR} \leq Twater_k \tag{2.6}$$

$$\sum_{ij} L_{ijk} \cdot X_{ijk}^{IR} \leq Tlabor_k \tag{2.7}$$

$$\sum_{ij} N_{ijk} \cdot X_{ijk}^{IR} \leq Tnitrogen_k \tag{2.8}$$

$$X_{ijk}^{IR} \geq 0 \tag{2.9}$$

where B_k^{IR} is the private benefit in each irrigation district *k* and $C_{ijk}^{\prime(IR)}$ is net income per hectare of crop *i* using irrigation technology *j*. The decision variable of the optimization problem is X_{ijk}^{IR}, the area of crop *i* with irrigation system *j*. Irrigated crops are grouped into field crops, vegetables and fruit trees, using surface, sprinkler and drip irrigation systems. Field crops are irrigated by surface and sprinkler irrigation, while vegetables and fruit trees are irrigated by surface and drip irrigation.

Equation (2.5) is the land constraint, and it represents the land available in each irrigation district *k* equipped with irrigation system *j*, $Tland_{kj}$. Equation (2.6) is the water constraint, and it represents the water available in each irrigation district *k*, $Twater_k$, where W_{ijk} is the requirement for water per hectare and per crop *i* with irrigation system *j*. The level of available water, $Twater_k$, is the variable linking the optimization model of the irrigation districts and the hydrological component. Equation (2.7) is the labor constraint, and it represents the labor available in each irrigation district *k*, $Tlabor_k$. L_{ijk} is the requirement for labor per hectare of crop *i* with irrigation system *j*. Equation (2.8) is the nitrogen constraint and it represents the nitrogen available in each irrigation district *k*, $Tnitrogen_k$. N_{ijk} is the nitrogen applied per hectare of crop *i* with irrigation system *j*. Equation (2.9) is the non-negativity constraint of the crop surface area. Net income per hectare $C'^{(IR)}_{ijk}$ is the difference between revenues and costs and it is defined as:

$$C'^{(IR)}_{ijk} = P_i Y_{ijk} - CP_i \tag{2.10}$$

where P_i is the price of crop *i*, Y_{ijk} is the yield of crop *i* under irrigation system *j* in irrigation district *k*, and CP_i represents the direct and indirect costs of crop *i*.

The Ricardian rent principle is used in the yield function by assuming that yield decreases as the scale of production increases. The yield function is linear and decreasing in the area of crop *i* under irrigation system *j* and it is expressed by:

$$Y_{ijk} = \beta 0_{ijk} + \beta 1_{ijk} X^{IR}_{ijk} \tag{2.11}$$

Positive mathematical programming (PMP) is used to calibrate irrigated crop production following the approach of Dagnino and Ward (2012) in order to solve the aggregation and over-specialization problems. The procedure estimates the linear yield function parameters $\beta 0_{ijk}$ and $\beta 1_{ijk}$. Those parameters are calculated based on "first order necessary conditions" for optimal resource use.

The optimization model for dryland cultivation maximizes farmers' private benefits in each watershed board, subject to technical and resource constraints. A constant yield production function for crops and constant input and output prices are used. The optimization problem is as follows:

$$Max B^{DRY}_e = \sum_{i_{dr}} C'^{(DRY)}_{ei_{dr}} \cdot X^{DRY}_{ei_{dr}} \tag{2.12}$$

subject to

$$\sum_{i_{dr}} X^{DRY}_{ei_{dr}} \leq Tland^{DRY}_e; \tag{2.13}$$

$$\sum_{i_{dr}} L_{ei_{dr}} \cdot X_{ei_{dr}}^{DRY} \leq Tlabor_{e}^{DRY} \tag{2.14}$$

$$\sum_{i_{dr}} N_{ei_{dr}} \cdot X_{ei_{dr}}^{DRY} \leq Tnitrogen_{e}^{DRY} \tag{2.15}$$

$$X_{ei_{dr}}^{DRY} \geq 0 \tag{2.16}$$

where B_{e}^{DRY} is the private benefit in each watershed board *e* and $C_{ei_{dr}}^{\prime(DRY)}$ is the net income per hectare of crop i_{dr}. The decision variable of the optimization problem is $X_{ei_{dr}}^{DRY}$, the area of each crop i_{dr} in watershed board *e*. The main dryland crops in the basin are barley, wheat, alfalfa, almond trees, olive trees and vineyards.

The dryland model constraints are equations (2.13), (2.14), (2.15) and (2.16). Equation (2.13) is the land constraint, which is the land available in each watershed board *e*, $Tland_{e}^{DRY}$. Equation (2.14) is the labor constraint, and it represents the availability of labor in each watershed board *e*, $Tlabor_{e}^{DRY}$. Equation (2.15) is the nitrogen constraint, and it represents the availability of nitrogen in each watershed board *e*, $Tnitrogen_{e}^{DRY}$. $N_{ei_{dr}}$ is nitrogen fertilization per hectare of crop i_{dr}. Equation (2.16) is the non-negativity constraint.

Net income per hectare $C_{ei_{dr}}^{\prime(DRY)}$ is the difference between revenue and costs. The net income of each crop is constant, and it is calculated as follows:

$$C_{ei_{dr}}^{\prime(DRY)} = P_{idr}^{DRY} \cdot Y_{ei_{dr}}^{DRY} - CP_{i_{dr}}^{DRY} \tag{2.17}$$

where P_{idr}^{DRY} is the price of dryland crop i_{dr}, $Y_{ei_{dr}}^{DRY}$ is the yield of crop i_{dr} in watershed board *e* and $CP_{i_{dr}}^{DRY}$ is the production cost of crop i_{dr}. The yields of dryland crops are reduced by 20% and 30% under moderate and severe droughts, respectively.

The livestock optimization model represents livestock production in each watershed board. This model maximizes private benefits from livestock, and the optimization problem is defined as follows:

$$MaxB_{e}^{LIV} = \sum_{a} C_{ea}^{\prime\,LIV} \cdot A_{ea} \tag{2.18}$$

subject to

$$\sum_{a} F_{ea} \cdot A_{ea} \leq Tfeed_{e} \tag{2.19}$$

$$\sum_{a} L_{ea} \cdot A_{ea} \leq \ Tlabor_{e}^{LIV} \tag{2.20}$$

$$A_{ea} \qquad\qquad \geq \ 0 \tag{2.21}$$

where $\mathrm{B}_{\mathrm{e}}^{\mathrm{LIV}}$ is livestock farmers' private benefit in each watershed board *e*, which is the sum of net income $C_{ea}'^{\,LIV}$ per type of animal *a* multiplied by the number of heads A_{ea}. The decision variable is A_{ea}, which is the number of animals of each type of livestock *a* in each watershed board *e*. Equation (2.19) is the livestock feed constraint and it represents the availability of feed in each watershed board *e*. L_{ea} is labor per type of animal *a* and per watershed board *e*. The most important livestock species in the basin are pigs, sheep and cattle.

The economic benefits of urban water use are determined using a social surplus model, by maximizing the consumer and producer surpluses for the main urban centers in the basin, subject to the water supply and demand balance constraint. The optimization problem is expressed as follows:

$$MaxB_{u}^{URB} = \left(a_{du} \cdot Q_{du} - \frac{1}{2} \cdot b_{du} \cdot Q_{du}^{2} - a_{su} \cdot Q_{su} - \frac{1}{2} \cdot b_{su} \cdot Q_{su}^{2}\right) \tag{2.22}$$

subject to

$$Q_{du} - Q_{su} \ \leq \ 0 \tag{2.23}$$

$$Q_{du} \ ; \ Q_{su} \quad \geq \ 0 \tag{2.24}$$

where B_{u}^{URB} is the sum of the consumer and producer surpluses in urban center *u*. The variables Q_{du} and Q_{su} are water supply and demand in urban center *u*, respectively. The parameters a_{du} and b_{du} are the intercept and the slope of the inverse demand function, $P_{du} = a_{du} - b_{du} \,.\, Q_{du}$. The parameters a_{su} and b_{su} are the intercept and the slope of the inverse water supply function, $P_{su} = a_{su} + b_{su} \,.\, Q_{su}$. Equation (2.23) indicates that water supply is greater than or equal to demand. The variable Q_{su} is the quantity of water supplied and it is the variable linking the urban model with the hydrological component. The water demand parameters have been obtained from the estimates by Arbués et al. (2004) and Arbués et al. (2010).

2.3.3 The environmental component: water and atmosphere pollution

Agricultural nonpoint pollution is analyzed in the environmental component, assessing the environmental damage derived from agricultural activities in the Ebro Basin. The impact of nonpoint pollution is assessed by estimating the nitrate loads into watercourses and GHG emissions from irrigated and dryland crops, and from livestock. GHG emissions from cropland include direct and indirect nitrous oxide (N_2O), while livestock emissions include methane (CH_4) from enteric fermentation and nitrous oxide and methane from manure management. The environmental component includes the minimum environmental flows at each section of the basin. The estimation of the social costs of agricultural nonpoint pollution is a complex task that requires a detailed analysis of the biophysical processes generating source emissions and transport and fate processes, the damages from water and atmosphere pollution, and the costs of these damages.

The nitrogen pollution is estimated from leaching and runoff from crops, and from the nitrogen excreted by livestock. The biophysical information for each crop and irrigation system are taken from literature reviews and fertilization practices in Spain published by the Spanish Ministry of Agriculture. The nitrogen pollution from crops by leaching and runoff is a consequence of excessive nitrogen fertilization, coupled with inefficient irrigation practices. Also, the nitrogen excreted by livestock could be used to substitute synthetic fertilizers, and therefore reduce the entry of nitrogen in soils. The nitrogen loads entering soils are given by the following equations:

$$Tleach_k^{IR} = \sum\nolimits_{ij} L_{ijk} \cdot X_{ijk}^{IR} \tag{2.25}$$

$$Tleach_e^{DRY} = \sum\nolimits_{i_{dr}} L_{ei_{dr}} \cdot X_{ei_{dr}}^{DRY} \tag{2.26}$$

$$TNex_e = \sum\nolimits_{a} Nex_{ea} \cdot A_{ea} \tag{2.27}$$

Equation (2.25) represents nitrogen leaching from crops in irrigation district *k*, $Tleach_k^{IR}$, where L_{ijk} is the leached fraction of nitrogen per hectare of crop *i* with irrigation system *j* in irrigation district *k*, and X_{ijk}^{IR} is area of crop *i*. Equation (2.26) represents nitrogen leaching from dryland crops in watershed board *e*. $L_{ei_{dr}}$ is the leached fraction of nitrogen from crop i_{dr} in watershed board *e*, and $X_{ei_{dr}}^{DRY}$ is area of crop i_{dr}. Equation (2.27) addresses the quantity of nitrogen excreted, where Nex_{ea} is the nitrogen excreted per head of each type of animal *a*, and A_{ea} is the number of heads of animals *a* in watershed board *e*.

In this study, the methodology applied to estimate GHG emissions from agriculture is the Tier 1 method of the IPCC (2019a; 2019b). GHG emissions are estimated using the following equations:

$$\mathrm{D}N_2\mathrm{OE}_k^{IR} = \sum\nolimits_{i} (N_{ijk} \cdot X_{ijk}^{IR} . EF_1 \cdot \frac{44}{28} \cdot GWP_{N_2\mathrm{O}}) /1000 \tag{2.28}$$

$$\mathrm{D}N_2\mathrm{OE}_e^{DRY} = \sum\nolimits_{i_{dr}} (N_{ei_{dr}} \cdot X_{ei_{dr}}^{DRY} \cdot EF_1 \cdot \frac{44}{28} \cdot GWP_{N_2\mathrm{O}}) /1000 \tag{2.29}$$

$$\mathrm{ID}N_2\mathrm{OE}_k^{IR} \quad = \sum\nolimits_i (L_{ijk} \cdot X_{ijk}^{IR} \cdot EF_2 \cdot \frac{44}{28} \cdot GWP_{N_2\mathrm{O}}) \,/1000 \qquad (2.30)$$

$$IDN_2OE_e^{DRY} \quad = \sum\nolimits_{i_{dr}} (L_{ei_{dr}} \cdot \; X_{ei_{dr}}^{DRY} \cdot EF_2 \,.\, \frac{44}{28} \cdot GWP_{N_2O}) \,/1000 \qquad (2.31)$$

$$CH_4EFE_e^{LIV} \quad = \sum\nolimits_a (A_{ea} \cdot EF_{3_a} \cdot GWP_{CH_4})/1000 \qquad (2.32)$$

$$N_2O\; MME_e^{LIV} \; = \sum\nolimits_{as} (A_{ea} \cdot Nex_{ea} \cdot EF_{4_s} \cdot \frac{44}{28} \cdot GWP_{N_2O}) \,/1000 \qquad (2.33)$$

$$CH_4MME_e^{LIV} \quad = \sum\nolimits_a (A_{ea} \cdot EF_{5_a} \cdot GWP_{CH_4})/1000 \qquad (2.34)$$

Nitrous oxide emissions from crops derive from nitrification and denitrification processes, which are related to the entry of nitrogen in soils. The emissions are divided into direct emissions from applied fertilizers and indirect emissions from nitrogen losses from leaching and runoff. Equations (2.28) and (2.29) represent direct N_2O emissions from irrigated and dryland crops, respectively, where N_{ijk} and $N_{ei_{dr}}$ are the nitrogen fertilization applied to irrigated crops i in irrigation district k, and to dryland crops idr in watershed board e. Equations (2.30) and (2.31) represent indirect N_2O emissions from irrigated and dryland crops, respectively. L_{ijk} and $L_{ei_{dr}}$ are the leaching fractions for irrigated crop i and dryland crop idr, and X_{ijk}^{IR} and $X_{ei_{dr}}^{DRY}$ are the irrigated and dryland crops areas. The N_2O emission factors of crops are 0.010 kg of N_2O-N per kilogram of nitrogen applied for direct emissions EF1, and 0.011 kg of N_2O-N per kilogram of nitrogen leached for indirect emissions EF2 (IPCC, 2019a). The coefficients GWP_{N2O} and GWP_{CH4} define the global warming potential of greenhouse effect for nitrous oxide (265) and methane (28). Coefficient $\frac{44}{28}$ is the molecular weight ratio between N_2O and N.

Equation (2.32) represents methane emissions from enteric fermentation of ruminants (sheep and cattle), where A_{ea} is the number of heads of type of animal a in watershed board e, and EF_{3_a} is the emission factor for type of animal a. Equation (2.33) describes the nitrous oxide emissions from manure management, where Nex_{ea} is the nitrogen excreted by type of animal a in watershed board e. EF_{4_s} is the N_2O emission factor of manure management, which depends on the manure management systems. Methane emissions from manure management are equal to the number of heads A_{ea} (type of animal a in watershed board e) multiplied by the associated emission factor EF_{5_a} (IPCC, 2019b).

The environmental damage of agricultural activities is the sum of the cost of GHG emissions and the cost of nitrogen pollution into watercourses. The damage of GHG emissions is determined by the volume of GHG emissions and the social cost of carbon set at 40 Euro/tCO_2e, which is taken from OECD estimates (Smith and Braathen, 2015) and is close to current US EPA regulation (\$51/tCO_2e). We assume also that the NO_3-N loads reaching watercourses are 40% of all nitrogen loads at the source of pollution, and the NO_3-N loads reaching the Ebro River mouth represent only 10% of all nitrogen loads at the source of pollution. This is based on the results of Lassaletta et al. (2012), which indicate a high level of retention in the basin (90%). The environmental damage from nitrates is calculated multiplying the volume of nitrate loads from crops and livestock, by the cost to removing nitrate from water at 1.3 Euro/kg NO_3-N (Martínez and Albiac, 2006). The environmental damages are given by the following equations:

$$\mathrm{ED}_{\mathrm{k}}^{\mathrm{IR}} = (\mathrm{D}N_2\mathrm{OE}_k^{IR} + \mathrm{ID}N_2\mathrm{OE}_k^{IR}) \cdot \mathrm{SC} + 0.4 \cdot Tleach_k^{IR} \cdot \mathrm{NC} \tag{2.35}$$

$$\mathrm{ED}_{\mathrm{e}}^{\mathrm{DRY}} = (\mathrm{D}N_2\mathrm{OE}_e^{DRY} + \mathrm{ID}N_2\mathrm{OE}_e^{DRY}) \cdot \mathrm{SC} + 0.4 * Tleach_e^{DRY} \cdot \mathrm{NC} \tag{2.36}$$

$$\mathrm{ED}_{\mathrm{e}}^{\mathrm{LIV}} = (CH_4EFE_e^{LIV} + N_2\mathrm{O}\ \mathrm{MME}_e^{LIV} + CH_4MME_e^{LIV}) \cdot \mathrm{SC} + 0.4 \cdot TNex_e \cdot \mathrm{NC} \tag{2.37}$$

where the first component is GHG damages (social cost of carbon SC multiplied by crops or livestock emissions), and the second component is nitrate damages (nitrate cost NC multiplied by nitrate loads). $\mathrm{Tleach}_{\mathrm{k}}^{\mathrm{IR}}$ and $\mathrm{Tleach}_{\mathrm{e}}^{\mathrm{DRY}}$ are nitrogen leaching from irrigated and dryland crops and $\mathrm{TNex}_{\mathrm{e}}$ is the nitrogen excreted from livestock.

2.3.4 Ebro optimization model and model application

The optimization model of the Ebro Basin integrates the three components described above, and the objective function represents social benefits, the sum of private benefits minus environmental damages. The maximization of social benefits covers all water sectors and spatial locations. The optimization problem is given by:

$$Max\ (B - ED) = Max\ \ \sum_{l=k,e,u} (B_l - ED_l) \tag{2.38}$$

subject to all hydrological, technical, economic and environmental constraints of irrigated, dryland, and livestock activities, where B_l are private benefits and ED_l are environmental damages from crops in irrigation district *k*, from dryland crops and livestock in watershed board *e*, and from urban centers *u*. The mathematical programing GAMS package has been used for the Ebro model. The model has been solved using a nonlinear programming algorithm (CONOPT4). Ward (2021) indicates that GAMS might be an effective tool for implementing linear, non-linear, and integer optimization. It can solve large systems of non-linear equations simultaneously. The system is flexible, open, and self-documenting, with obvious connections between model formulation and solution.

The hydroeconomic model is used to analyze the interdependence between water quantity and water quality, under normal water inflows and drought scenarios. Drought scenarios are used to understand future drought severity levels, and the ensuing impacts of water scarcity and pollution on social benefits in the basin. Moderate and severe drought scenarios assume reductions of 30% and 40% in water inflows, respectively, relative to the flows under normal climate conditions. Then, the model is used to assess selected mitigation and adaptation policies under normal climate and severe drought conditions.

This assessment highlights the role that policies could play in the abatement of nonpoint pollution in watercourses and the atmosphere, and also in identifying the tradeoffs between water quality and water scarcity. The analysis shows the effectiveness of policies under extreme droughts and the impacts on water use, pollution loads and their environmental damages, and social benefit outcomes. The selected policies are P1: Optimization of nitrogen fertilization (by reducing fertilization to crop requirements); P2: Substitution of synthetic fertilization by organic fertilization; P3: Irrigation modernization; P4: Manure treatment plants, (Table 2.1).

2.4 Results

2.4.1 Water allocation, and nonpoint pollution under normal and drought scenarios

The results of water allocation, environmental damages and social benefits under the baseline and drought scenarios are presented in Table 2.2. Under normal climate conditions, the social benefits are €3,375 million and the total water use reaches 3,874 Mm^3. The irrigated land covers 557,000 ha of field crops, fruit trees and vegetables. Dryland covers 1,194,000 ha and livestock herds amount to 2,769 Livestock Units (LSU). Employment in the basin is 37,000 Annual Work Units (AWU) for irrigated crops, 21,500 AWU for dryland crops, and 34,000 AWU for livestock rearing. Results show that nitrogen emissions at the source are 236,000 tNO_3-N and GHG emissions are 7.15 $MtCO_2e$ from agricultural activities, which concentrate in Canal de Urgel, Canal de Bardenas, and the lower sections of the Segre and Gallego tributaries, given the large irrigated cropland and swine herds in these areas (Figure 2.2a; Figure 2.3). Nitrogen loads entering watercourses in the Ebro are around 94,000 tNO_3-N, and the nitrate concentration at the river mouth is estimated at 11.3 mg/l NO_3^- under normal climate (Figure 2.2b). The environmental damages from water pollution and GHG emissions are €409 million, which are subtracted from the farming private benefits in order to calculate social benefits.

Table 2. 1. Description of policies.

Policies	Description	Source
P1	Efficient use of nitrogen fertilization at crop requirements without impacts on yields. The nitrogen price used is equal to 1,037 Euro/kg.	(Kahil et al., 2011)
P2	Substitution of synthetic by organic fertilization up to 60% share (from current 27%). The cost of manure application amounts to 3.7 Euro/m^3 for a distance of 10 km, which includes transport and specialized equipment costs.	(Daudén et al., 2011)
P3	Replacing surface irrigation by more efficient irrigation technologies.	Guardia et al. (2010).
P4	Use of manure treatment technologies to reduce nitrogen emissions. This study considers plants of 50,000 m^3/year capacity with nitrification and denitrification processes, with total cost at 7 Euro/m^3 of manure	(Flotats et al., 2011)

Under drought conditions, water allocation to irrigation districts is reduced proportionally to their regular allocation, while water allocation to urban areas and livestock is maintained. Urban areas take priority over any other water use, followed by livestock. In normal weather conditions, animals only use 1% of water withdrawals, and during droughts water is not a limiting factor for livestock. Under moderate drought, water diversions for irrigation are reduced by 30% with private benefits dropping to €739 million. Moderate drought reduces irrigated acreage by 35%, especially for less efficient irrigation system. GHG emissions and nitrogen pollution at the source are reduced, while the nitrate concentration at the Ebro River mouth increases by 40% due to the reduction of river flows. Under severe drought conditions, water withdrawals for irrigation are reduced proportionally by 40%. Irrigated cropland generates €686 million in private benefits using 2,098 Mm^3 of water. The irrigated acreage falls almost by half and nitrogen pollution at the source decreases. However, the nitrate concentration at the mouth of river increases by 63%.

The results show that droughts reduce crops with low profitability and high water requirements, and the cropland acreage under less efficient irrigation technologies (Figure A2.2). The drought scenarios illustrate what are the more efficient water and land management options for adaptation to water scarcity, which vary between irrigation districts and respond to factors such as crop diversification, the level of modernization of irrigation systems, and the access to water resources (Figure A2.3). In addition, results highlight the tradeoff between nitrate concentrations and water availability. Nitrate concentrations increase under drought conditions, as the dilution processes worsen driven by water scarcity.

2.4.2 Policy analysis under normal and drought conditions

P1. Optimization of nitrogen fertilization

The efficient use of nitrogen fertilization in irrigated and dryland crops in the Ebro Basin is an interesting policy that can reduce nonpoint pollution into the atmosphere and watercourses. This policy increases the profit of crops by €45 million while reducing environmental damages by €12 million, achieving higher social benefits. The increase in private benefits results from the drop of nitrogen fertilization (-39,000 tN) which reduces nitrogen leaching (-7,000 tN) and crops N_2O emissions (-196,000 tCO_2e). Cultivated area and water withdrawals increase, reducing the streamflow at the Ebro mouth. Nitrate loads at the source in the basin are reduced to 229,000 tNO_3-N, declining nitrate concentrations at the river mouth by 0.3 mg/l NO_3^-.

Under drought conditions, despite the reduction of streamflow at the mouth to 5,341 Mm^3, this policy still improves water and atmosphere quality by reducing nitrate concentration to 18.2 mg/l NO_3^- and GHG emissions to 6.79 $MtCO_2e$, compared to drought conditions without policies. The results point out also that the policy under drought reduces nitrate loads at the source to 220,000 tNO_3-N but increases water withdrawals to 2,566 Mm^3. Compared with the policy in normal flow, nitrate concentration at the mouth rises 65%, and the reason is drought decreases water availability and impairs the dilution processes. In both cases, normal and drought conditions, this policy is efficient in mitigating agricultural pollution into the atmosphere and watercourses (although reductions are moderate), and in enhancing private profits. The policy benefits both farmers and the environment generating synergies between environmental and economic outcomes (Table 2.3). However, its implementation requires the training and willingness to cooperate of farmers.

P2. Substitution of synthetic fertilization by organic fertilization

Substituting synthetic fertilization by organic fertilization is also an interesting policy for reducing nonpoint pollution to the atmosphere and water streams, and avoid the high abatement costs of manure treatment plants. Increasing the circular use of manure as fertilizer from the current 27% up to 60% would promote a more sustainable agriculture by reusing nutrients in the soil and preventing pollution. This study assumes that the cost of manure application amounts to 3.7 Euro/m^3 for a distance of 10 km, which includes transport and specialized equipment costs (Daudén et al., 2011). Results show that manure fertilization increases irrigated land to 584,000 ha and water withdrawals to 4,031 Mm^3, reducing streamflow at the river mouth by 112 Mm^3.

Table 2. 2. Agricultural use of resources, pollution and benefits under drought scenarios.

Climate conditions	**Normal flow**	**Moderate drought**	**Severe drought**
Land (1,000 ha)			
Irrigated land	**557**	**362**	**315**
Field crops	399	225	184
Vegetables	36	30	28
Fruit trees	122	107	103
Dryland	**1,194**	**1,194**	**1,194**
Field crops	900	900	900
Fruit trees	294	294	294
Livestock (1,000 head)			
Swine	12,913	12,913	12,913
Ovine	2,380	2,380	2,380
Beef cattle	724	724	724
Dairy cattle	74	74	74
Water use (Mm^3)	**3,874**	**2,825**	**2,475**
Irrigated land	3,497	2,448	2,098
Livestock	55	55	55
Urban	322	322	322
Irrigation system (1,000 ha)			
Flood	292	158	129
Sprinkler	174	120	104
Drip	91	84	82
Streamflow at the river mouth (Mm^3)	**9,272**	**6,366**	**5,406**
Nitrogen emissions (1000 tNO_3-N)			
At the source	236	227	225
Entering water bodies	94	91	90
Nitrate concentration at Ebro mouth (mg/l)	11.3	15.8	18.4
GHG emissions ($MtCO_2e$)	**7.15**	**6.97**	**6,93**
N_2O from crops	0.76	0.58	0.54
CH_4 from Enteric Fermentation	1.92	1.92	1.92
N_2O from Manure Management	0.85	0.85	0.85
CH_4 from Manure Management	3.62	3.62	3.62
Private benefits (million Euro)	**3,784**	**3,650**	**3,586**
Irrigated land	813	739	705
Dryland	301	241	211
Livestock	811	811	811
Urban	1,859	1,859	1,859
Environmental damages (million Euro)	**409**	**397**	**394**
Irrigated land	34	22	19
Dryland	14	14	14
Livestock	361	361	361
Social benefits (million Euro)	**3,375**	**3,253**	**3,192**
Irrigated land	779	717	686
Dryland	287	227	197
Livestock	450	450	450
Urban	1,859	1,859	1,859

This policy increases organic fertilization up to 153,000 tN, while synthetic fertilization declines, achieving a reduction of 300,000 tCO_2e in GHG emissions and 28,000 tNO_3-N in nitrate loads into watercourses, which decreases nitrate concentration at the Ebro mouth by 32% to 7.7 mg/l NO_3^-. Environmental damages decrease by €109 million and private benefits increase by €12 million because of the cost savings of organic fertilization, augmenting social benefits up to €3,496 million.

Under drought conditions, the policy abates nitrate loads at the source to 189,000 tNO_3-N and GHG emissions to 6.81 $MtCO_2e$, while water withdrawals amount to 2,564 Mm^3. However, nitrate concentration increases at the river mouth by 39% to 15.7 mg/l NO_3^- because of the drought lower streamflow. Compared with drought conditions without any policy, manure fertilization improves water and air pollution, lowering environmental damages (- €82 million) and increasing social benefits (+ €119 million). This policy entails synergies in reducing both atmosphere and water pollution, and synergies between economic and environmental outcomes under normal and drought conditions. It shows also an acceptable tradeoff between water quantity (streamflow at the mouth) and quality (pollution abatement) (Table 2.3).

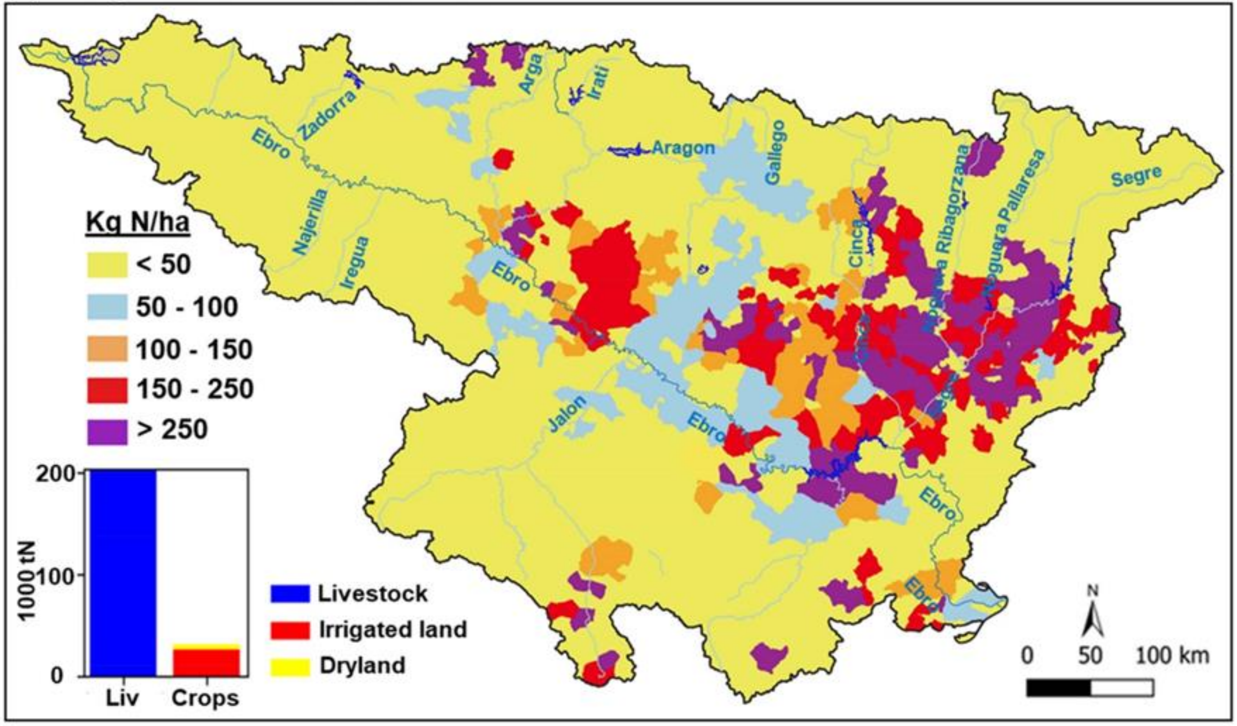
P3. Irrigation modernization

Modernization investments involve upgrading irrigation technologies, which enhance the efficiency of water use and reduce nitrate and GHG emissions. Modernization increases cultivated land to 566,000 ha after substituting surface irrigation by sprinkler and drip systems. However, advanced irrigation systems reduce water withdrawals to 3,173 Mm^3 and nitrogen fertilization to 85,000 tN, increasing the efficiency of water and nitrogen use. Therefore, nitrate loads at the source and nitrate concentration at the Ebro mouth are reduced, while the streamflow at the mouth increases. N_2O emissions also decrease to 0.72 $MtCO_2e$. This shows that modernization generates suitable tradeoffs between streamflow, nitrate concentrations and GHG emissions. Advanced irrigation technologies increase yields and farmers' benefits, but modernization costs are very high. As a consequence, the private benefits of irrigation decrease but they are still advantageous compared with the baseline.

Under drought, modernization reduces water use, nitrogen leached, and GHG emissions, increasing social benefits by €35 million compared to drought without policies. Although modernization increases streamflow at the mouth, the abatement of nitrate concentration is very small, which shows the tradeoff of this policy between water quantity and quality (Table 2.3).

Figure 2. 2. Nitrogen emissions at the source and in water bodies at municipal level.

(a) Nitrogen emissions at the source



(b) Nitrogen emissions entering water bodies

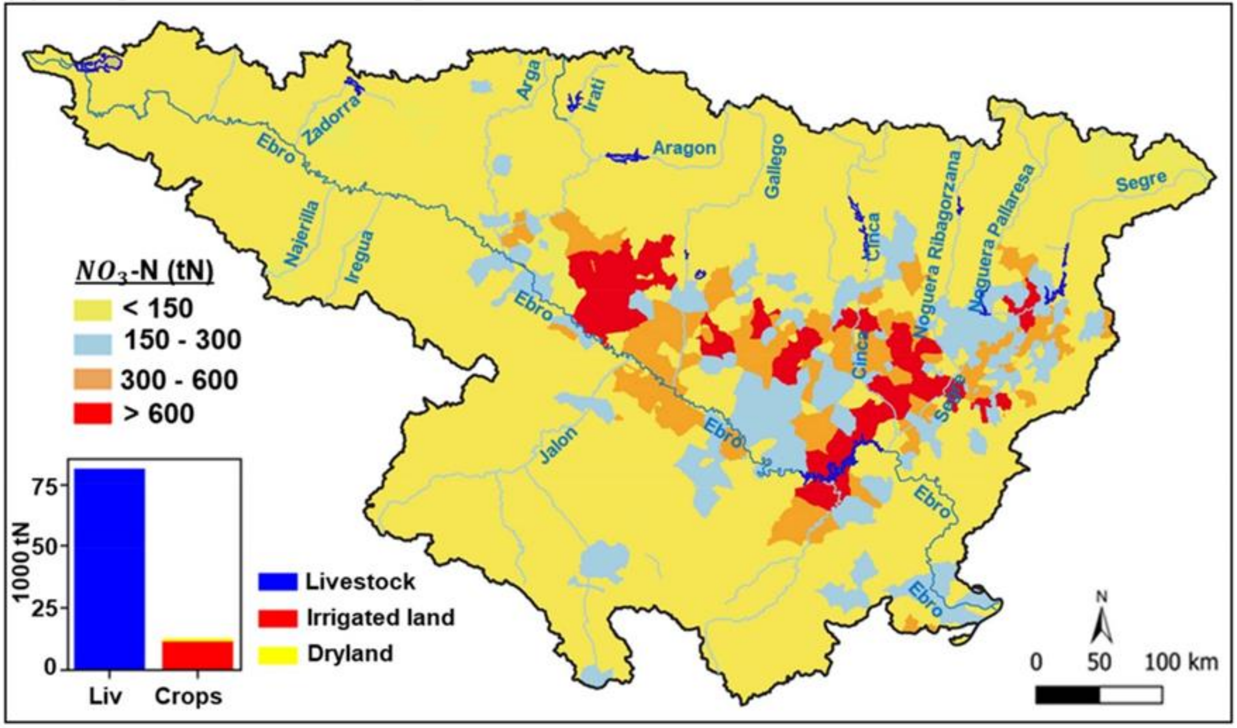


Figure 2. 3. Agricultural GHG emissions in the Ebro Basin at municipal level.

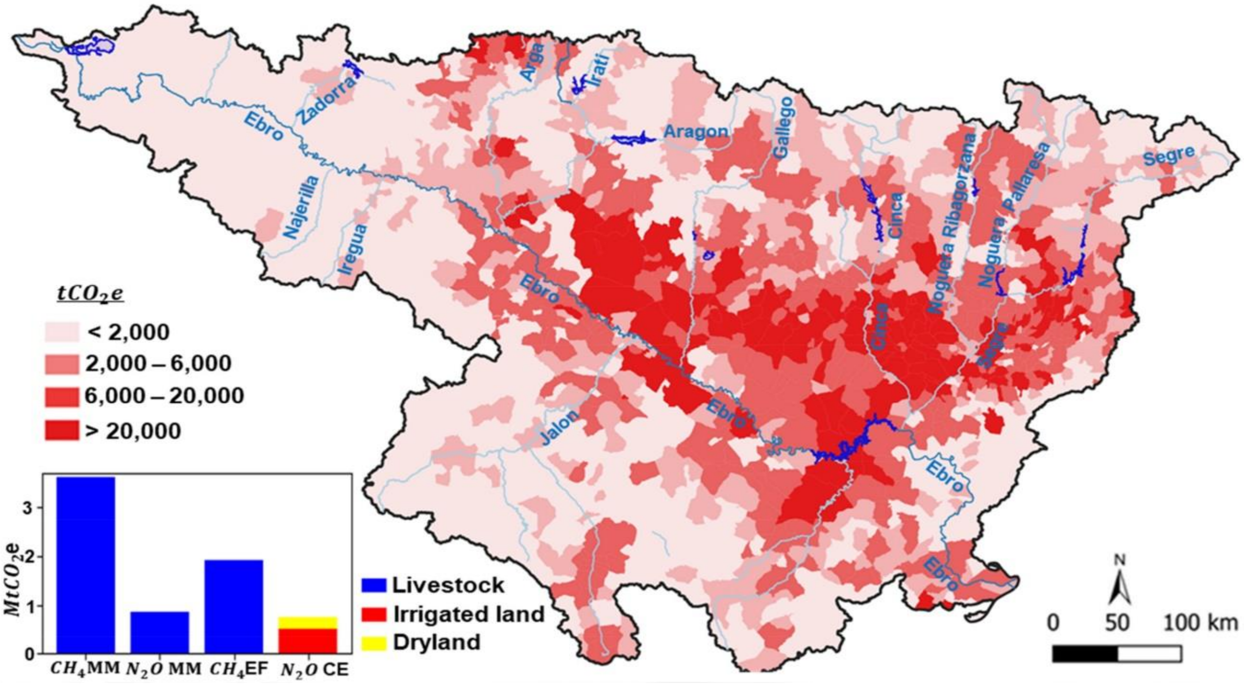


Figure shows N_2O emissions from crops (N_2O CE), the CH_4 emissions from enteric fermentation (CH_4 EF), and the N_2O (N_2O MM) and CH_4 (CH_4 MM) emissions from manure management.

Table 2. 3. Use of resources, pollution and benefits for each policy under normal and drought conditions.

	Normal flow					Severe drought				
Policies	**Without policies**	**P1**	**P2**	**P3**	**P4**	**Without policies**	**P1**	**P2**	**P3**	**P4**
Land (1,000 ha)										
Irrigated land	557	584	584	566	557	315	330	347	328	315
Dryland	1,194	1,194	1,194	1,194	1,194	1194	1,194	1,194	1,194	1,194
Animals (LSU)	2,769	2,769	2,769	2,769	2,769	2,769	2,769	2,769	2,769	2,769
Water use (Mm³)	**3,874**	**4,031**	**4,031**	**3,549**	**3,874**	**2,475**	**2,566**	**2,564**	**2,280**	**2,475**
Agriculture	3,552	3,709	3,709	3,227	3,552	2,176	2,244	2242	1,958	2,176
Urban	322	322	322	322	322	322	322	322	322	322
Streamflow at Ebro mouth	**9,272**	**9,160**	**9,160**	**9,290**	**9,272**	**5,406**	**5,341**	**5,342**	**5,416**	**5,406**
Nitrogen emissions (1000 tNO$_3$-N), Nitrate concentration NC (mg/l), and GHG emissions (MtCO$_2$e)										
At the source	236	229	160	234	115	225	220	189	224	105
Entering watercourse	94	91	66	93	46	89	87	73	89	42
NC at Ebro mouth	11.3	11.0	7.7	11.1	5.5	18.4	18.2	15.7	18.3	8.6
GHG emissions	7.15	6.96	6.85	7.11	6.65	6.93	6.79	6.81	6.92	6.43
Private benefits (M€)	**3.784**	**3,829**	**3,796**	**3,796**	**3.501**	**3,586**	**3,623**	**3,623**	**3,620**	**3,303**
Agriculture	1,925	1,970	1,937	1,937	1,642	1,727	1,764	1,772	1,761	1,444
Urban	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859
Env. damages (M€)	**409**	**397**	**300**	**406**	**326**	**394**	**386**	**312**	**393**	**312**
Social benefits (M€)	**3,375**	**3,432**	**3,496**	**3,390**	**3,175**	**3,192**	**3,237**	**3,311**	**3,227**	**2,991**
Agriculture	1,516	1,573	1,672	1,531	1,316	1,333	1,378	1,452	1,418	1,133
Urban	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859

P4. Manure treatment plants

Manure treatment plants reduce direct and indirect nitrogen loads into watercourses and nitrous oxide emissions into the atmosphere from manure management. These abatement technologies involve high investment, operation and maintenance costs. This study considers plants of 50,000 m^3/year with nitrification and denitrification processes, with total cost at 7 Euro/m^3 of manure (Flotats et al., 2011). Results under normal flow and drought conditions show that the installation of manure treatment plants maintains water withdrawals by agriculture and streamflow at the river mouth, but achieves significant abatement of both nitrate concentration at the Ebro mouth (by more than half to 5.5 and 8.6 mg/l NO_3^-, respectively for normal and drought years) and GHG emissions (down to 6.65 and 6.43 $MtCO_2e$, respectively). Environmental damages are curbed by around €80 million but the costs of this policy are close to €280 million, reducing both private and social benefits (Table 2.3). The investments in manure treatment plants would be reasonable for higher social carbon costs above the current estimates of 40 €/tCO_2e, or for river reaches where highly valuable aquatic ecosystems are damaged by nitrates. Also, manure treatment plants could be the only alternative in areas generating large quantities of manure that cannot be reused as fertilizer because of the lack of cropland in the surroundings.

2.5 Discussion

This research provides a comprehensive analysis of water allocation and agricultural nonpoint pollution in the Ebro basin under normal and drought events, together with the relationship between water quantity and quality. Drought conditions reduce agricultural withdrawals and pollution loads to water media and the atmosphere, although nitrate concentrations increase because of the substantial fall in stream flows. Yang et al., 2015 indicate that these tradeoffs between water quantity and quality are important in considering sustainable development outcomes.

The results on water allocation and agricultural pollution loads during normal weather and droughts provide useful information for decision making. Climate impacts would undermine the sustainability of water systems in the Ebro under current management practices, threatening both irrigated agriculture and environmental flows. The results of drought scenarios call for decisive policy interventions by local, state and federal stakeholders to reduce the vulnerability of the economic sectors, and also to protect the natural environment. This research evaluates several policies relevant for regional and basin water planning. These policies promote the efficient use of water and nutrients, enhance farming conditions and environmental outcomes, and increase farmer's income in some cases. Successful policy implementation and enforcement entail the involvement of water stakeholders in water planning, along with the general public support that would motivate political representatives.

Several policy initiatives have been taken in some countries to address the abatement of agricultural nonpoint pollution, such as the European Nitrates Directive (European Commission, 1991), limiting nitrogen emissions from farming systems to protect groundwater and surface waterways. The purpose is to reduce nitrate pollution into water bodies caused by excessive nitrogen fertilization and manure surplus. However, the achievements of the Nitrates Directive during the last three decades are questionable because the entry of nitrogen in soils has not been curtailed.[2] The main problems with the Directive are that the use of homogeneous measures across very heterogeneous European regions in terms of pollution loads, and the flimsy enforcement mechanism based on penalizing agricultural subsidies (Albiac et al., 2020). Another case is the conservation programs in the United States for reducing agricultural nonpoint pollution. Despite spending 5 billion US dollars per year in conservation programs over the last two decades, there is no clear general improvement of water quality in basins (Ribaudo, 2015).

Our results indicate that the selected policies contribute to the abatement of nonpoint pollution, and improve both water and air quality. The results reveal the tradeoffs and synergies between economic and environmental effects of these abatement policies. Nitrogen optimization (P1), manure fertilization (P2) and irrigation modernization (P3) are interesting policies that reduce polluting emissions into the atmosphere and watercourses, while enhancing the private benefits of farmers. Those policies deliver synergies between the economic and environmental outcomes. However, manure treatment plants (P4) deliver a strong reduction of nonpoint pollution and environmental damages, but they also reduce private benefits because of the high investment and operating costs. This reduction in farmers' income indicates that the uptake of this policy by farmers would be challenging, requiring strong command and control measures coupled with public incentives or subsidies. Drought conditions limit the effectiveness of pollution abatement policies compared with normal weather. However, these policies still have significant economic and environmental positive effects compared to drought conditions without policies. The

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[2] Examples of the limited success of the Nitrates Directive is the Seine River where nitrate pollution at the mouth has doubled since 1991 (Romero et al., 2016), the Po River where nitrate trends have been increasing (Musacchio et al., 2020), and the Thames River where nitrate pollution has not decreased since the 1990s (Howden et al., 2011).

analysis of mitigation policies supports decision making and contribute to the ongoing policy discussion for designing basin wide sustainable water management.

The use of manure as fertilizer is an effective policy to cut back nitrate concentration, improving water and atmosphere quality (Baccour et al, 2021). According to Strokal et al. (2020), incorporating manure as crop fertilizer is an effective strategy for drastically reduce eutrophication. This policy is considered an important solution to prevent the entry of nitrogen in soils by substituting synthetic fertilizers (Khan and Chang, 2018; Ma et al., 2019; MOA, 2018). Moreover, manure fertilization is quite interesting in the Ebro Basin, especially in Aragon, because the volume of available manure in the region can meet all nitrogen requirements by crops (Orus, 2006). Albiac et al. (2016) indicate that the use of organic fertilizers in Europe could decrease the use of synthetic fertilizers by almost half, thus reducing nitrous oxide emissions and nitrogen loads in watercourses, which would generate around €5,200 million in environmental benefits. Dalgaard et al. (2014) indicate the successful implementation of this policy in Denmark, with a mix of command and control (fines) and institutional instruments, by showing farmers that substitution of synthetic fertilizers with manure was profitable.

Another interesting policy is irrigation modernization, which enhances water efficiency at parcel level and abates pollution loads. According to Borrego-Marn and Berbel (2019), the impact of irrigation modernization on improved water quality is significant at the basin scale and the implementation of this strategy minimizes nitrogen leaching into water bodies, while providing economic benefits similar to our results. Garcia-Garizábal and Causapé (2010) estimate a 20% reduction in leached nitrogen following the adoption of water conservation measures in an irrigation district in the Ebro. Albiac et al. (2017) indicate that irrigation modernization in Spain could reduce GHG emissions by 2.1 $MtCO_2e$, but involves quite high investment costs. Grafton et al. (2018) emphasize the paradox of irrigation efficiency, which indicates that advanced irrigation technologies increase irrigation efficiency at district level, but could also increase water consumption in the basin. Gains in irrigation efficiency promote more water-intensive crops, double crops or irrigated land expansion, resulting in higher evapotranspiration and lower return flows to watersheds. To avoid the paradox, modernization projects of irrigation districts should include water balances that prevent increases in evapotranspiration.

The choice of policies depends on the objectives of decision makers, but also on the availability of biophysical and economic information. The uptake of policies is related to their cost-efficiency, acceptability by stakeholders, appropriate design of implementation and enforcement mechanisms, and resulting transaction costs. Successful implementation requires effective policies that are socially viable and include appropriate enforcement mechanisms ensuring compliance by stakeholders. A mix of command and control, economic and institutional instruments are needed to facilitate the implementation of sustainable water management. Better education is also important, as seen by the Science Technology Backyards Initiative in China, in which scientists, students, and farmers exchange their expertise. In other terms, collective action and cooperation among farmers, policymakers, scientists, and other stakeholders are needed to achieve sustainable policies (Jiao et al., 2016). Overall, implementing cost-effective management strategies requires the successful deployment and uptake of policies and technology packages by stakeholders, as well as organizing their active cooperation.

Our study is novel in two key aspects: First, an optimization model is used to analyze the tradeoffs between water quantity and quality in order to maximize the social benefits of water from agricultural activities and urban centers. Second, the evaluation of nutrient pollution into watercourses and GHG emissions into the atmosphere from irrigated, dryland, and livestock activities under normal and severe droughts conditions. The evaluation of selected policies with the model provides clues on suitable combinations of mitigation and adaptation policies for water and air quality enhancement.

A certain number of simplifying assumptions have been used in developing the hydroeconomic model. The model includes a reduced form hydrological framework, which does not include reservoirs and their linkages with streamflows. Moreover, the model is static and does not include dynamic aspects regarding water allocations, basin streamflows, and drought events. This may change the effectiveness of mitigation and adaptation policies over a multi-year horizon. Despite these limitations, the hydroeconomic model is a good analytical tool to assess the effects of drought scenarios under selected mitigation and adaptation policies for enhancing water allocation and curbing water and air pollution.

Future work could address model improvements such as incorporating significant additional biophysical processes (pollution transport and fate processes, other pollutants), and including water storage of reservoirs and hydropower generation. Other improvements are considering the headwater inflow variables stochastic, modifying the time step of the model from yearly to monthly, and improving the model calibration and validation. The introduction of stochastic variables would be an interesting advance for a better representation of droughts and climate change. This will improve the estimation of nonpoint pollution loads into water streams for a better assessment of policies. Another important aspect that could be included in the analysis is the strategic behavior of stakeholders in order to figure out the acceptability and stability of cooperative solutions for the abatement of water pollution loads and GHG emissions.

2.6 Conclusions

Water availability and agricultural nonpoint pollution in the Ebro River are analyzed under normal and drought conditions using an integrated hydroeconomic model. The study analyzes a set of mitigation and adaptation policies to address water scarcity and quality, and emissions of greenhouse gases. Results indicate that drought conditions reduce crops with low profitability and high water requirements, raising nitrate concentrations by up to 63 % and highlighting the tradeoff between nitrate concentrations and water availability. The assessment of mitigation and adaptation policies provides insights on the synergies and tradeoffs between environmental and economic objectives, as well as on the potential tradeoffs between water quantity and water quality. All evaluated policies improve water quality and reduce the emissions of greenhouse gases. However, the most cost-effective policies are the reduction of nitrogen fertilization, the substitution of synthetic fertilization by manure, and the improvement of irrigation technologies. These cost-effective policies would facilitate the achievement of sustainable water management goals in the basin. Our study could support the decision-making process by contributing to the ongoing policy discussions for the design of basin wide sustainable policies. The findings in the Ebro could have interest also for other rivers basin, especially in arid and semiarid regions with similar agricultural and climate conditions.

References

Aein, R., and Alizadeh, H., 2021. Integrated hydro-economic modeling for optimal design of development scheme of salinity affected irrigated agriculture in Helleh River Basin. Agric. Water Manag. 243, 106505. https://doi-org/10.1016/j.agwat.2020.106505

Ahmadi, B., Moradkhani, H., 2019. Revisiting hydrological drought propagation and recovery considering water quantity and quality. Hydrol. Process. 33(10), 1492-1505.

Albiac, J., Calvo, E., Esteban, E., Kahil, T., 2020. The challenge of irrigation water pricing in the Water Framework Directive. Water altern. 13(3), 674-690.

Albiac, J., Kahil, T., Notivol, E., Calvo, E., 2017. Agriculture and climate change: Potential for mitigation in Spain. Sci. Total Environ. 592, 495–502. https://doi.org/10.1016/j.scitotenv.2017.03.110

Albiac, J., Kahil, T., Calvo, E., Crespo, D., Esteban, E., 2016. Evaluación Socio-Económica del Proyecto "LIFE-MANEV: Gestión y Tecnologías de Tratamiento de Estiércol para la Protección Medioambiental y la Sostenibilidad de la Ganadería en Europa". Working Document 16-02. CITA-DGA. Zaragoza.

Arbués, F., Barberán, R., Villanúa, I., 2004. Price impact on urban residential water demand: A dynamic panel data approach. Water Resour. Res. 40, W11402. https://doi.org/10.1029/2004WR003092

Arbués, F., García-Valiñas, M.Á., Villanúa, I., 2010. Urban Water Demand for Service and Industrial Use: The Case of Zaragoza. Water Resour. Manage. 24, 4033–4048.https://doi.org/10.1007/s11269-010-9645-5

Babel, M.S., Gupta, A.D., Nayak, D.K., 2005. A Model for Optimal Allocation of Water to Competing Demands. Water Resour Manag. 19, 693–712. https://doi.org/10.1007/s11269-005-3282-4

Baccour, S., Albiac, J., Kahil, T., 2021. Cost-effective mitigation of greenhouse gas emissions in the agriculture of Aragon, Spain. Int. J. Environ. Res. Public Health. 18(3), 1084. https://doi.org/10.3390/ijerph18031084

Barbieri, M., Ricolfi, L., Vitale, S., Muteto, P., Nigro, A., Sappa, G., 2019. Assessment of groundwater quality in the buffer zone of Limpopo National Park, Gaza Province, Southern Mozambique. Environ Sci Pollut Res. 26, 62–77. https://doi.org/10.1007/s11356-018-3474-0

Berthet, A., Vincent, A., Fleury, P. 2021. Water quality issues and agriculture: An international review of innovative policy schemes. Land Use Policy. 109, 105654. https://doi.org/10.1016/j.landusepol.2021.105654.

Bekchanov, M., Ringler, C., Bhaduri, A., Jeuland, M., 2015. How would the Rogun Dam affect water and energy scarcity in Central Asia? Water Int. 40, 856–876. https://doi.org/10.1080/02508060.2015.1051788

Bekchanov, M., Sood, A., Pinto, A., Jeuland, M., 2017. Systematic Review of Water-Economy Modeling Applications. J. Water Resour. Plann. 143, 8. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000793

Bluemling, B., Wang, F., 2018. An institutional approach to manure recycling: Conduit brokerage in Sichuan Province, China. Resour. Conserv. Recy. 139, 396–406. https://doi.org/10.1016/j.resconrec.2018.08.001

Booker, J., Howitt, R., Michelsen, A., Young, R., 2012. Economics and the modeling of water resources and policies. Nat. Res.Model. 25, 168–218. https://doi.org/10.1111/j.1939-7445.2011.00105.x

Booker, J.F., Michelsen, A.M., Ward, F.A., 2005. Economic impact of alternative policy responses to prolonged and severe drought in the Rio Grande Basin. Water Resour. Res. 41, W02026 https://doi.org/10.1029/2004WR003486

Booker, J.F., Young, R.A., 1991. Economic impacts of alternative water allocation institutions in the Colorado River basin. Fort Collins, Colo. Colorado Water Resources Research Institute, Colorado State University.

Booker, J.F., Young, R.A., 1994. Modeling Intrastate and Interstate Markets for Colorado River Water Resources. J Environ Econ Manag. 26, 66–87. https://doi.org/10.1006/jeem.1994.1005

Brown, T., Harding, B., Payton, E., 1990. Marginal economic value of streamflow: A case study for the Colorado River Basin. Water Resour. Res. 26, 2845–2859. https://doi.org/10.1029/WR026i012p02845

Borrego-Marín, M. M., Berbel, J., 2019. Cost-benefit analysis of irrigation modernization in Guadalquivir River Basin. Agric. Water Manag. 212, 416-423. https://doi.org/10.1016/j.agwat.2018.08.032

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G.S., Limburg, K.E., Montes, I., Naqvi, S.W.A., Pitcher, G.C., Rabalais, N.N., Roman, M.R., Rose, K.A., Seibel, B.A., Telszewski, M., Yasuhara, M., Zhang, J., 2018. Declining oxygen in the global ocean and coastal waters. Sci. 359, eaam7240. https://doi.org/10.1126/science.aam7240

Büntgen, U., Urban, O., Krusic, P., Rybníček, M., Kolář, T., Kyncl, T., Ač, A., Koňasová, E., Čáslavský, J., Esper, J., Wagner, S., Saurer, M., Tegel, W., Dobrovolný, P., Cherubini, P., Reinig, F., Miroslav T. 2021. Recent European drought extremes beyond Common Era background variability. Nat. Geosci. 1-7. https://doi.org/10.1038/s41561-021-00698-0

Buendia, C., Batalla, R. J., Sabater, S., Palau, A., & Marcé, R., 2016. Runoff trends driven by climate and afforestation in a Pyrenean Basin. Land Degrad. Dev. 27(3), 823-838.

Cai, X., McKinney, D., Lasdon, L., 2003. Integrated hydrologic-agronomic-economic model for river basin management. J. Water Resour. Plann. 129(1). https://doi.org/10.1061/(ASCE)0733-9496(2003)129:1(4)

Cai, X., McKinney, D.C., Lasdon, L.S., 2002. A framework for sustainability analysis in water resources management and application to the Syr Darya Basin: Sutainability analysis in water resources management. Water Resour. Res. 38, 21-1-21–14. https://doi.org/10.1029/2001WR000214

Carolus, J. F., Bartosova, A., Olsen, S. B., Jomaa, S., Veinbergs, A., Zīlāns, A., et al., 2020. Nutrient mitigation under the impact of climate and land-use changes: A hydro-economic approach to participatory catchment management. J. Environ. Manage. 271, 110976. https://doi-org/10.1016/j.jenvman.2020.110976

Cammalleri C., Naumann G., Mentaschi L., Formetta G., Forzieri G., Gosling S., Bisselink B., De Roo A., and Feyen L. 2020. Global warming and drought impacts in the EU. Publications Office of the European Union, Luxembourg.

CEDEX, 2020. Anuario de Aforos 2010–2017, Dirección General del Agua. MAPAMA, Madrid. (https://ceh.cedex.es/anuarioaforos/afo/estafmapa_estaciones.asp?gr_cuenca_id=9&resolucres=1536).

CHE, 2015. Plan Hidrológico de la Demarcación Hidrográfica del Ebro, Memoria CHE. MAGRAMA, Zaragoza.

CHE, 2016. Plan Hidrológico de la Demarcación Hidrográfica del Ebro, Memoria CHE. MAGRAMA, Zaragoza.

CHE, 2020. Informe impress. Análisis de presiones, impactos y riesgos.

Crespo, D., Albiac, J., Kahil, T., Esteban, E., Baccour, S., 2019. Tradeoffs between Water Uses and Environmental Flows: A Hydroeconomic Analysis in the Ebro Basin. Water Resour. Manage. 33, 2301–2317. https://doi.org/10.1007/s11269-019-02254-3

Dalgaard, T., Hansen, B., Hasler, B., Hertel, O., Hutchings, N.J., Jacobsen, B.H., Jensen, L.S., Kronvang, B., Olesen, J.E., Schjorring, J.K., 2014. Policies for agricultural nitrogen management—trends, challenges and prospects for improved efficiency in Denmark. Environ. Res. Lett. 9 (11), 115002.

Dagnino, M., Ward, F., 2012. Economics of agricultural water conservation: empirical analysis and policy implications. Int. J. Water Resour. Dev. 28, 577–600. https://doi.org/10.1080/07900627.2012.665801

Dasgupta, P. 2021. The Economics of Biodiversity: The Dasgupta Review. London: HM Treasury.

Daudén, A., Teresa, M., Siegler, C., 2011. Proyecto demostrativo de gestión colectiva del purín en Aragón, Sociedad de Desarrollo Medioambiental de. Aragón. Zaragoza.

Divakar, L., Babel, M.S., Perret, S.R., Gupta, A.D., 2011. Optimal allocation of bulk water supplies to competing use sectors based on economic criterion – An application to the Chao Phraya River Basin, Thailand. J Hydrol. 401, 22–35. https://doi.org/10.1016/j.jhydrol.2011.02.003

Dogan, M. S., Fefer, M. A., Herman, J. D., Hart, Q. J., Merz, J. R., Medellín-Azuara, J., & Lund, J. R. (2018). An open-source Python implementation of California's hydroeconomic optimization model. Environ. Model. Softw. 108, 8-13. https://doi.org/10.1016/j.envsoft.2018.07.002

Escriva-Bou, A., Lund, J.R., Pulido-Velazquez, M., Hui, R., Medellín-Azuara, J., 2018. Developing a water-energy-GHG emissions modeling framework: Insights from an application to California's water system. Environm. Model. Softw. 109, 54-65. https://doi.org/10.1016/j.envsoft.2018.07.011

European Environment Agency, 2018. European waters: Assessment of status and pressures 2018 (EEA Report No 7). European Environment Agency. https://doi. org/10.2800/303664

European Commission, 1991. Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC) Off. J. Eur. Commun. L, 375 (1991), pp. 1-8.

Expósito, A., Beier, F., Berbel, J., 2020. Hydro-economic modelling for water-policy assessment under climate change at a river basin scale: A review. Water. 12(6), 1559. https://doi.org/10.3390/w12061559

Flotats, X., Foged, H., Blasi, A., Palatsi, J., Magri, A., Schelde, K., 2011. Future trends on manure processing activities in Europe. Technical Report No. II to the European Commission, Directorate-General Environment. Brussels.

Garcia-Garizábal, I., Causapé, J., 2010. Influence of irrigation water management on the quantity and quality of irrigation return flows. **J**. Hydrol. 385(1-4), 36-43. https://doi.org/10.1016/j.jhydrol.2010.02.002

Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G., 2018. The paradox of irrigation efficiency. Sci. 361, 748–750. https://doi.org/10.1126/science.aat9314

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S., Wada, Y., 2018. Global assessment of water challenges under uncertainty in water scarcity projections. Nat. Sustain. 1, 486–494. https://doi.org/10.1038/s41893-018-0134-9

Gunawardena, A., White, B., Hailu, A., Wijeratne, E. M. S., Pandit, R., 2018. Policy choice and riverine water quality in developing countries: An integrated hydro-economic modelling approach. J. Environ. Manage. 227, 44-54. https://doi-org/10.1016/j.jenvman.2018.08.065

Harou, J., Pulido-Velazquez, M., Rosenberg, D., Medellin-Azuara, J., Lund, J., Howitt, R., 2009. Hydro-economic models: concepts, design, applications, future prospects. J. Hydrol. 375, 627–643. https://doi.org/10.1016/j.jhydrol.2009.06.037

Heinz, I., Pulido-Velazquez, M., Lund, J., Andreu, J., 2007. Hydro-economic modeling in river basin management: implications and applications for the european water framework directive. Water Resour. Manag. 21, pp. 1103-1125, https://doi-org/10.1007/s11269-006-9101-8

Hernández, N., Gil, M., Garrido, A., Rodríguez, R., 2013. La sequía 2005-2008 en la cuenca del Ebro: Vulnerabilidad, impactos y medidas de gestión. CEIGRAM. Universidad Politécnica de Madrid. Madrid.

Herrero, A., Gutiérrez-Cánovas, C., Vigiak, O., Lutz, S., Kumar, R., Gampe, D., et al., 2018. Multiple stressor effects on biological quality elements in the Ebro River: Present diagnosis and predicted responses. Sci. Total Environ. 630, 1608-1618. https://doi.org/10.1016/j.scitotenv.2018.02.032

Howden, N., Burt, T., Worrall, F., Mathias, S., Whelan, M., 2011. Nitrate pollution in intensively farmed regions: What are the prospects for sustaining high-quality groundwater? Water Resour. Res. 47, W00L02. https://doi.org/10.1029/2011WR010843

IPCC, 2007. Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A. (Eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC, 2019a. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Chapter 11: N_2O Emissions from managed soils, and CO_2 emissions from lime and urea application. Geneva, Switzerland.

IPCC, 2019b. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Chapter 10: Emissions from livestock and manure management. Geneva, Switzerland.

Jiao, X., Lyu, Y., Wu, X., Li, H., Cheng, L., Zhang, C., Yuan, L., Jiang, R., Jiang, B., Rengel, Z., et al. 2016. Grain production versus resource and environmental costs: Towards increasing sustainability of nutrient use in China. J. Exp. Bot. 67, 4935–4949. https://doi.org/10.1093/jxb/erw282

Jury, W. A., and Vaux, H., 2005. The role of science in solving the world's emerging water problems. Proc. Natl. Acad. Sci. 102, 15715–15720. https://doi.org/10.1073/pnas.0506467102.

Kahil, T., Dinar, A., Albiac, J., 2015. Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. J. Hydrol. 522, 95-109. http://dx.doi.org/10.1016/j.jhydrol.2014.12.042

Kahil, T., Ward, F. A., Albiac, J., Eggleston, J., Sanz, D., 2016. Hydro-economic modeling with aquifer–river interactions to guide sustainable basin management. *J. Hydrol 539*, 510-524. http://doi.org/10.1016/j.jhydrol.2016.05.057

Kahil, T., Albiac, J., Dinar, A., Calvo, E., Esteban, E., Avella, L., Garcia-Molla, M., 2016. Improving the Performance of Water Policies: Evidence from Drought in Spain. Water. 8, 34. https://doi.org/10.3390/w8020034

Kahil, T., Parkinson, S., Satoh, Y., Greve, P., Burek, P., Veldkamp, T. I., et al., 2018. A continental-scale hydroeconomic model for integrating water-energy-land nexus solutions. Water Resour. Res. 54, 7511-7533. https://doi.org/10.1029/2017WR022478

Kanter, D.R., Wentz, J.A., Galloway, J.N., Moomaw, W.R., Winiwarter, W., 2017. Managing a forgotten greenhouse gas under existing U.S. law: an interdisciplinary analysis. Environ. Sci. Pol. 67, pp. 44-51. https://doi-org. /10.1016/j.envsci.2016.11.003

Khan, M., Chang, Y.-C., 2018. Environmental challenges and current practices in China—a thorough analysis. Sustainability. 10 (7), 2547. https://doi.org/10.3390/su10072547

Lassaletta, L., García-Gómez, H., Gimeno, B.S., Rovira, J.V., 2009. Agriculture-induced increase in nitrate concentrations in stream waters of a large Mediterranean catchment over 25 years (1981–2005). Sci. Total Environ. 407, 6034–6043. https://doi.org/10.1016/j.scitotenv.2009.08.002

Lassaletta, L., Romero, E., Billen, G., Garnier, J., García-Gómez, H., Rovira, J.V., 2012. Spatialized N budgets in a large agricultural Mediterranean watershed: high loading and low transfer. Biogeosciences. 9, 57–70. https://doi.org/10.5194/bg-9-57-2012

Ma, L., Bai, Z., Ma, W., Guo, M., Jiang, R., Liu, J., Oenema, O., Velthof, G.L., Whitmore, A., Crawford, J., 2019. Exploring future food provision scenarios for China. Environ. Sci. Technol. 53 (3), 1385–1393. https://doi.org/10.1021/acs.est.8b04375

Martínez, Y., Albiac, J., 2006. Nitrate pollution control under soil heterogeneity. Land Use Policy 23, 521–532. https://doi.org/10.1016/j.landusepol.2005.05.002

Myers, S.S., and Patz, J.A., 2009. Emerging threats to human health from global environmental change. Annu. Rev. Env. Resour., 34, 223–252. https://doi.org/10.1146/annurev.environ.033108.102650.

MOA, 2018. Utilization of livestock and poultry manure resources. Action Plan for 2017- 2020. Ministry of Agriculture and Rural Affairs of the People’s Republic of China. Retrieved in March 2019 from. http://m.mof.gov.cn/zcfb/201805/t201805112892899.htm

Moraes, M., Cai, X., Ringler, C., Albuquerque, B., da Rocha, S., Amorim, C., 2010. Joint Water Quantity-Quality Management in a Biofuel Production Area—Integrated Economic-Hydrologic Modeling Analysis. J. Water Resour. Plan. Manag. 136 (4), 502-511. https://doi.org 10/1061/(ASCE)WR.1943-5452.0000049

Musacchio, A., Re, V., Mas-Pla, J., Sacchi, E., 2020. EU Nitrates Directive, from theory to practice: Environmental effectiveness and influence of regional governance on its performance. Ambio. 49: 504-516.

NOAA, 2021. U.S. Billion-Dollar Weather and Climate Disasters. National Centers for Environmental Information. NOAA. Asheville.

Ollero, A., 2007. Channel adjustments, floodplain changes and riparian ecosystems of the middle Ebro River: assessment and management. Water Resour. Dev. 23(1), 73-90.

Orús, F., 2006. Fertilización nitrogenada: Guía de actualización. Informaciones Técnicas, Número extraordinario. Centro de Transferencia Agroalimentaria. Dirección General de Desarrollo Rural. Zaragoza.

Parris, k., 2011. Impact of Agriculture on Water Pollution in OECD Countries: Recent Trends and Future Prospects. Int. J. Water Resour. Dev. 27:1, 33-52. https://doi.org/10.1080/07900627.2010.531898

Peña-Haro, S., Pulido-Velazquez, M., and Sahuquillo, A., 2009. A hydro-economic modelling framework for optimal management of groundwater nitrate pollution from agriculture. J. Hydrol. 373, 193–203. https://doi.org/10.1016/j.jhydrol.2009.04.024

Peña-Haro, S., Pulido-Velazquez, M., and Llopis-Albert, C., 2011. Stochastic hydro-economic modeling for optimal management of agricultural groundwater nitrate pollution under hydraulic conductivity uncertainty. Environ. Model. Softw. 26, 999–1008. https://doi.org/10.1016/j.envsoft.2011.02.010

Poff, N. L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Ritcher, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime: A paradigm for river conservation and restoration. Bioscience. 47, 769–784. https://doi.org/10.2307/1313099.

Ribaudo, M., 2015. The limits of voluntary conservation programs. Choices, 30(2), 1-5.

Ringler, C., Huy, N. V., and Msangi, S., 2006. Water allocation policy modeling for the Dong Nai River basin: An integrated perspective. J. Am. Resour. Assoc., 42, 1465–1482.

Ringler, C., Cai, X., 2006. Valuing Fisheries and Wetlands Using Integrated Economic-Hydrologic Modeling—Mekong River Basin. J Water Resour Plan Manag. 132, 480–487. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:6(480)

Ringler, C., von Braun, J., Rosegrant, M., 2004. Water policy analysis for the Mekong River Basin. Water Int. 29, 30–42. https://doi.org/10.1080/02508060408691746

Rockström, J., Falkenmark, M., Karlberg, L., Hoff, H., Rost, S., Gerten, D., 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change, Water Resour. Res. 45, W00A12. https://doi.org/10.1029/ 2007wr006767.

Romero, E., Le Gendre, R., Garnier, J., Billen, G., Fisson, C., Silvestre, M., Riouf, P., 2016. Long-term water quality in the lower Seine: Lessons learned over 4 decades of monitoring. Environ. Sci. Policy. 58, 141-154. https://hal.sorbonne-universite.fr/hal-01288154

Simelton, E., Fraser, E.D.G., Termansen, M.T., Benton, G., Gosling, S.N., et al., 2012. The socioeconomics of food crop production and climate change vulnerability: A global scale quantitative analysis of how grain crops are sensitive to drought, Food Secur. 4, 163–179. https://doi.org/10.1007/s12571-012-0173-4.

Smith and Braathen, 2015. Monetary Carbon Values in Policy Appraisal: an Overview of Current Practices and Key Issues. OECD, Environment working Paper. París.

Strokal, M., Kahil, T., Wada, Y., Albiac, J., Bai, Z., Ermolieva, T., et al., 2020. Cost-effective management of coastal eutrophication: A case study for the yangtze river basin. Resour. Conserv. Recycl. 154, 104635. https://doi.org/10.1016/j.resconrec.2019.104635

UNESCO, 2021. Water scarcity and quality. https://en.unesco.org/themes/water-security/hydrology/water-scarcity-and-quality

Van Vliet, M.T., Flörke, M., Wada, Y., 2017. Quality matters for water scarcity. Nat. Geosci. 10, 800-802.

Vericat, D., and Batalla, R.J., 2006. Sediment transport in a large impounded river: The lower Ebro, NE Iberian Peninsula. Geomorphology. 79(1-2), 72-92. https://doi.org/10.1016/j.geomorph.2005.09.017

Ward, F. A., 2021. Hydroeconomic Analysis to Guide Climate Adaptation Plans. Front. Water. 3, 80. https://doi.org/10.3389/frwa.2021.681475

Ward, F.A., 2014. Economic impacts on irrigated agriculture of water conservation programs in drought. J. Hydrol. 508, 114–127. https://doi.org/10.1016/j.jhydrol.2013.10.024

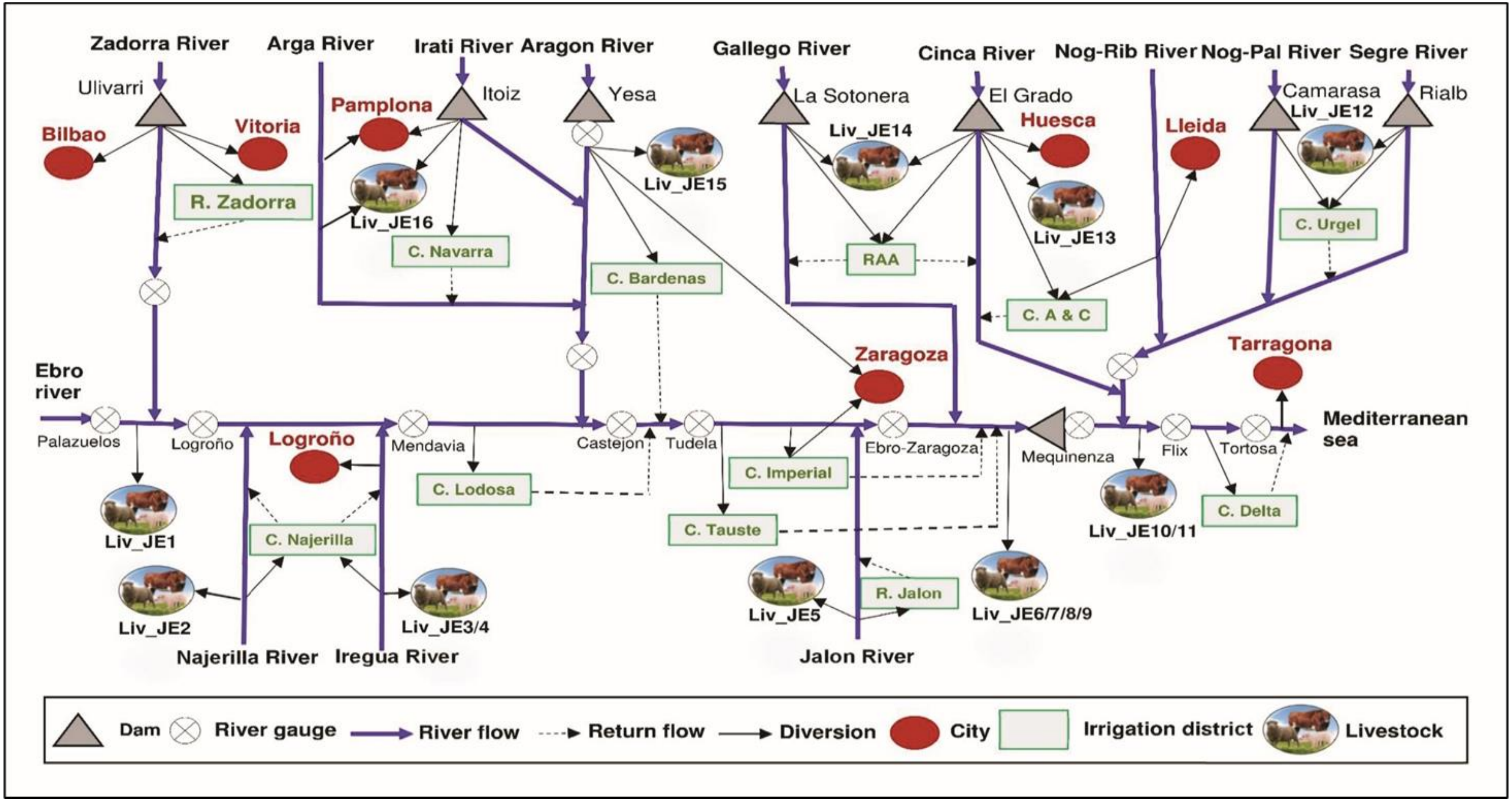
Ward, F.A., Pulido-Velazquez, M., 2012. Economic Costs of Sustaining Water Supplies: Findings from the Rio Grande. Water Resour Manag. 26, 2883–2909. https://doi.org/10.1007/s11269-012-0055-8.

Ward, F. A., and Pulido-Velazquez, M., 2008. Efficiency, equity, and sustainability in a water quantity-quality optimization model in the Rio Grande basin. Ecol. Econ. 66, 23–37. https://doi.org/10.1016/j.ecolecon.2007.08.018

Yang, Y., Yin, L., Zhang, Q. 2015. Quantity versus quality in China's South-to-North Water Diversion Project: A system dynamics analysis. Water. 7(5), 2142-2160. https://doi.org/10.3390/w7052142

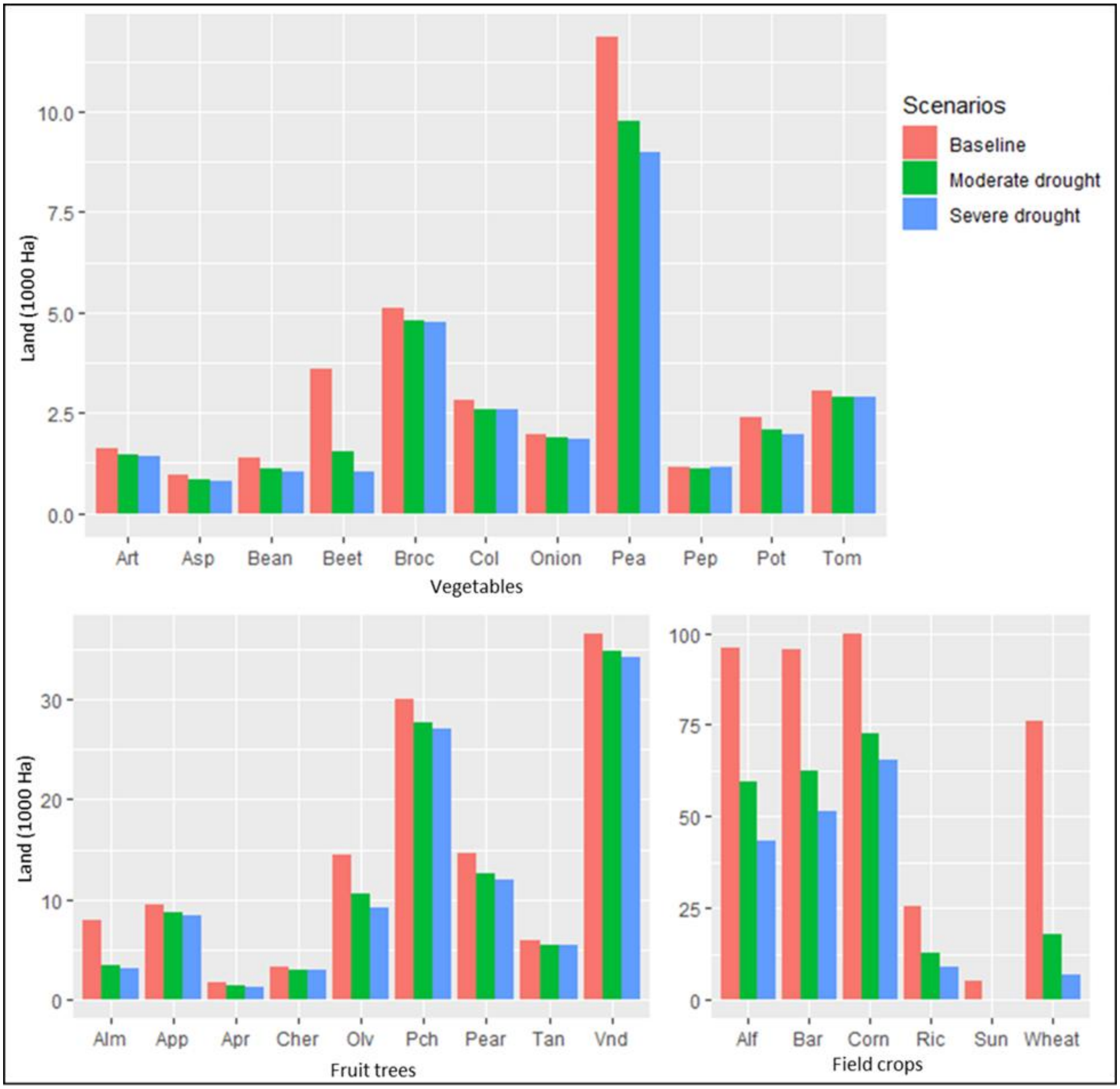
Appendix

Figure A2. 1. Hydrological system of the Ebro Basin



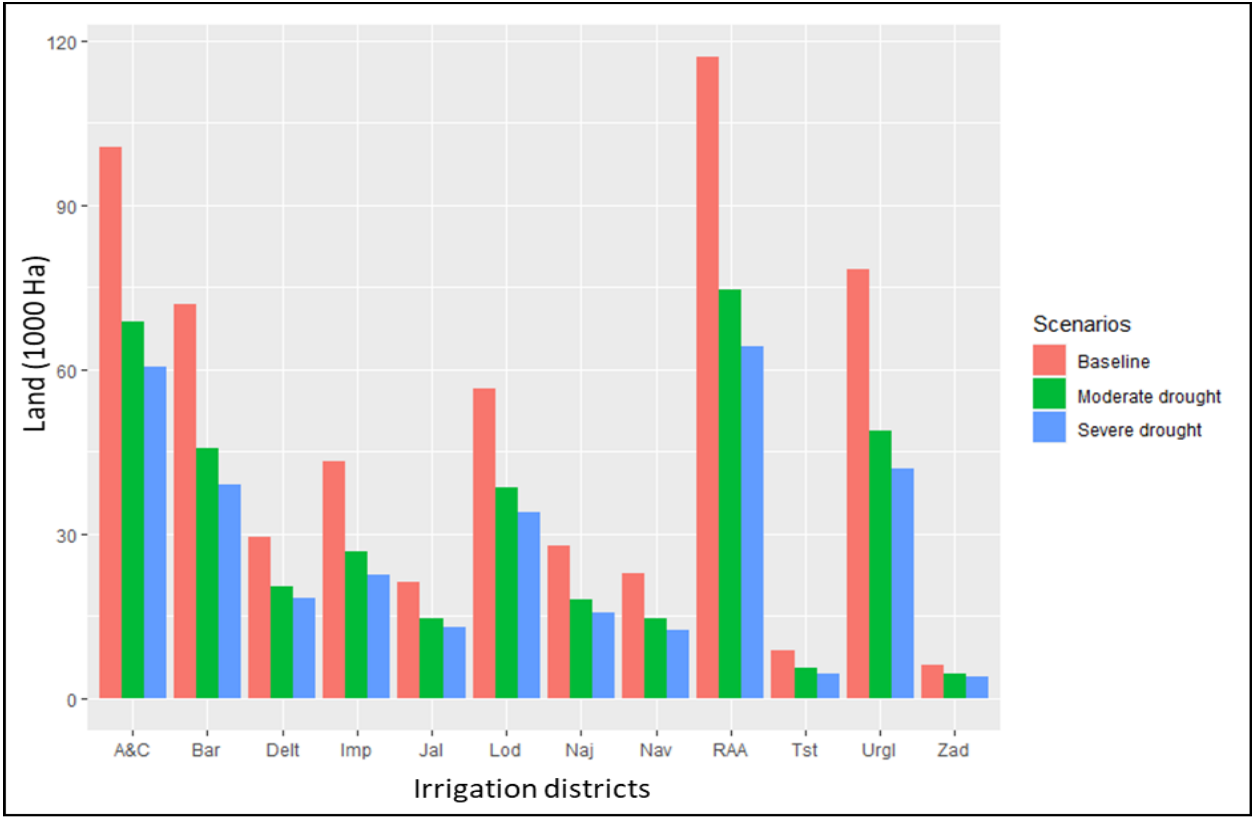
The irrigation districts are R. Zadorra: Riegos de Zadorra; C. Navarra: Canal de Navarra; C. Bardenas: Canal de Bardenas; C. Najerilla: Canales del Najerilla; C. Lodosa: Canal de Lodosa; C. Imperial: Canal Imperial; C. Tauste: Canal de Tauste; R. Jalon: Riegos del Jalón; RAA: Riegos del Alto Aragón; C. A & C: Canal de Aragón y Cataluña; C. Urgel: Canal de Urgel; C. Delta: Canales del Delta.
Livestock farming is represented by the number of the watershed board (Junta de Explotación).

Figure A2. 2. Land use under baseline and drought scenarios



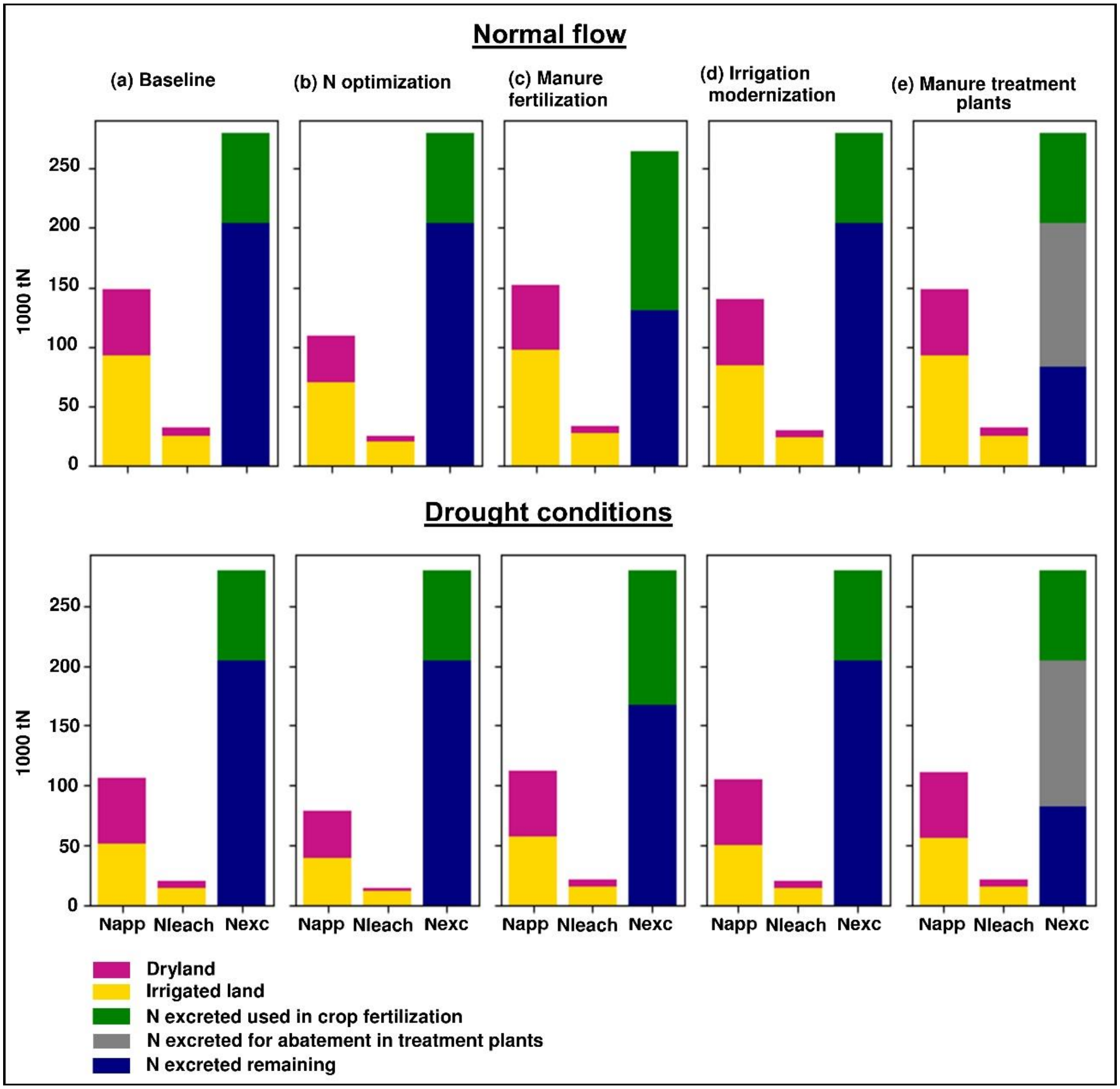
Crops assessed in this paper are **Vegetables**: Artichoke (Art), Asparagus (Asp), Bean (Bean), Beet (Beet), Broccoli (Broc), Cauliflower (Col), Onion (Onion), Pea (Pea), Pepper (Pep), Potato (Pot), Tomato (Tom); **Fruit trees**: Almond (Alm), Apple (App), Apricot (Apr), Cherry (Cher), Olive (Olv), Peach (Pch), Pear (Pear), Tangerine (Tan), Vineyard (Vnd); **Field crops**: Alfalfa (Alf), Barley (Bar), Corn (Corn), Rice (Ric), Sunflower (Sun), Wheat (Wheat).

Figure A2. 3. Land use in irrigation districts under baseline and drought scenarios



The irrigation districts are: A & C: Canal de Aragón y Cataluña; Bar: Canal de Bardenas; Delt: Canales del Delta; Imp: Canal Imperial; Jal: Riegos del Jalón; Lod: Canal de Lodosa; Nav: Canal de Navarra; Naj: Canales del Najerilla; RAA: Riegos del Alto Aragón; Tst: Canal de Tauste; Urgl: Canal de Urgel; Zad: Riegos de Zadorra.

Figure A2. 4. Nitrogen applied, leached, and excreted for each policy under normal and drought conditions



Napp is nitrogen applied to crops, which includes synthetic and organic fertilization, Nleach is nitrogen leached, and Nexc is nitrogen excreted from animals.

Figure A2. 5. Agricultural GHG emissions in the Ebro river basin for each policy under normal and drought conditions

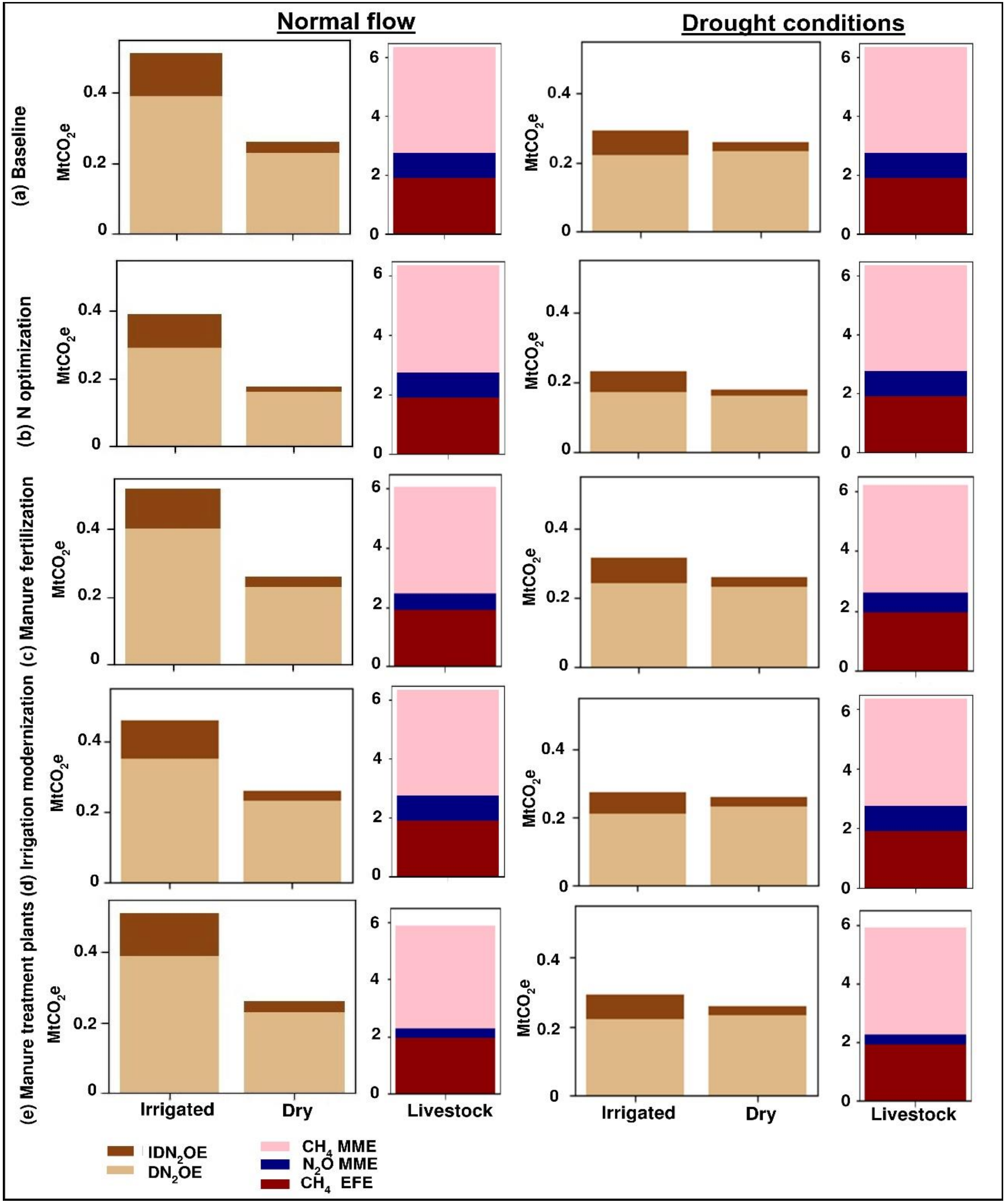


Figure shows the direct (DN$_2$OE) and indirect (IDN$_2$OE) N$_2$O emissions from crops, the CH$_4$ emissions from enteric fermentation (CH$_4$ EFE), and the N$_2$O (N$_2$O MME) and CH$_4$ (CH$_4$ MME) emissions from manure management.

Table A2. 1. Use of resources, pollution and benefits for each policy under normal and drought conditions

	Normal flow					**Drought conditions**				
Policies	**Without policies**	**P1**	**P2**	**P3**	**P4**	**Without policies**	**P1**	**P2**	**P3**	**P4**
Land (1,000 ha)										
Irrigated land	**557**	**584**	**584**	**566**	**557**	**315**	**330**	**332**	**328**	**315**
Field crops	399	423	423	407	399	184	197	199	193	184
Vegetables	36	37	37	36	36	28	29	29	29	28
Fruit trees	122	124	124	123	122	103	104	103	106	103
Dryland	**1,194**	**1,194**	**1,194**	**1,194**	**1,194**	**1,194**	**1,194**	**1,194**	**1,194**	**1,194**
Field crops	900	900	900	900	900	900	900	900	900	900
Fruit trees	294	294	294	294	294	294	294	294	294	294
Livestock (1,000 head)										
Swine	12,913	12,913	12,913	12,913	12,913	12,913	12,913	12,913	12,913	12,913
Sheep	2,380	2,380	2380	2,380	2,380	2,380	2,380	2,380	2,380	2,380
Beef cattle	724	724	724	724	724	724	724	724	724	724
Dairy cattle	74	74	74	74	74	74	74	74	74	74
Water use (Mm^3)										
Agriculture										
Irrigated land	3,497	3,654	3,654	3,173	3,497	2,098	2,189	2,187	1,903	2,098
Livestock	55	55	55	55	55	55	55	55	55	55
Urban	322	322	322	322	322	322	322	322	322	322
Total	**3,874**	**4,031**	**4,031**	**3,549**	**3,874**	**2,475**	**2,566**	**2,564**	**2,280**	**2,475**
Irrigation system (1,000 ha)										
Flood	292	312	312	26	292	129	138	140	9	129
Sprinkler	174	180	180	385	174	104	109	109	184	104
Drip	91	92	92	155	91	82	83	83	135	82
Streamflow (Mm^3)										
Ebro River mouth	9,272	9,160	9,160	9,290	9,272	5,406	5,341	5,342	5,416	5,406
Nitrogen emissions at the source (1000 tNO_3-N)										
Crops	32	25	34	30	32	21	16	22	20	22
Livestock	204	204	126	204	83	204	204	167	204	83
Nitrogen emissions entering water bodies (1000 tNO_3-N)										
Crops	13	10	14	12	13	8	6	11	8	9
Livestock	81	81	52	81	33	81	81	62	81	33
Nitrate concentration (mg/l NO_3^-)										
Ebro River mouth	11.3	11.0	7.7	11.1	5.5	18.4	18.2	15.7	18.3	8.6
GHG emissions (MtCO_2e)										
N_2O from crops	0.76	0.57	0.79	0.72	0.76	0.54	0.40	0.57	0.53	0.54
CH_4 from EF	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92	1.92
N_2O from MM	0.85	0.85	0.52	0.85	0.35	0.85	0.85	0.70	0.85	0.35
CH_4 from MM	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
Total	**7.15**	**6.96**	**6.85**	**7.11**	**6.65**	**6,93**	**6.79**	**6.81**	**6.92**	**6.43**
Private benefits (million Euro)										
Agriculture										
Irrigated land	813	841	843	825	813	705	731	730	739	706
Dryland	301	318	318	301	301	211	222	223	211	211
Livestock	811	811	811	811	528	811	811	779	811	527
Urban	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859
Total	**3.784**	**3,829**	**3,796**	**3,796**	**3.501**	**3,586**	**3,623**	**3,623**	**3,620**	**3,303**
Environmental damages (million Euro)										
Irrigated land	34	27	36	31	34	19	15	21	18	19
Dryland	14	9	14	14	14	14	10	14	14	14
Livestock	361	361	250	361	278	361	361	277	361	278
Total	**409**	**397**	**300**	**406**	**326**	**394**	**386**	**312**	**393**	**312**
Social benefits (million Euro)										
Agriculture										
Irrigated land	779	814	807	794	779	686	716	709	721	687
Dryland	287	309	304	287	287	197	212	209	197	197
Livestock	450	450	561	450	250	450	450	533	450	249
Urban	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859	1,859
Total	**3,375**	**3,432**	**3,531**	**3,390**	**3,175**	**3,192**	**3,237**	**3,311**	**3,227**	**2,992**

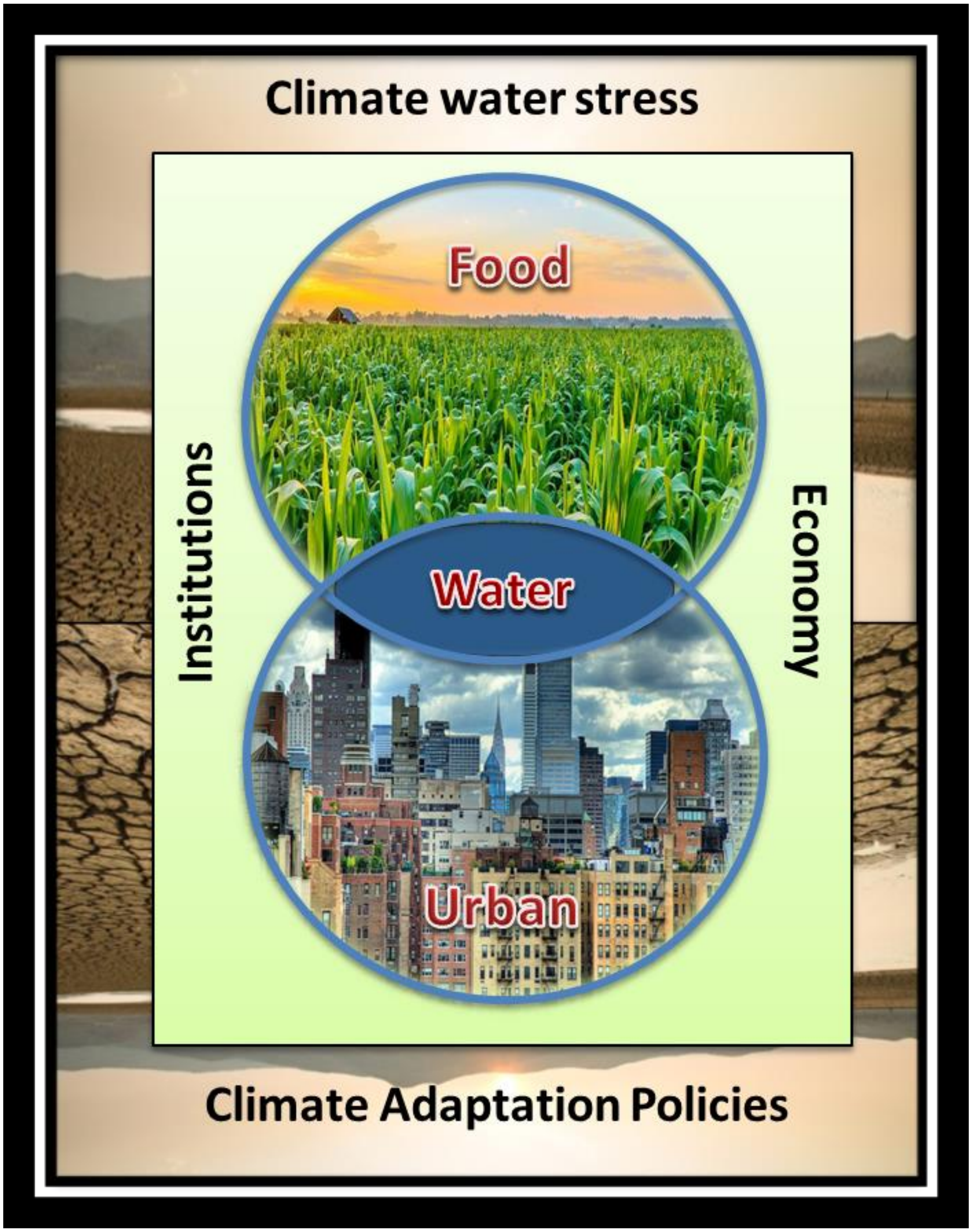
CHAPTER 3

CLIMATE ADAPTATION GUIDANCE: NEW ROLES FOR HYDROECONOMIC ANALYSIS

Chapter 3 Climate Adaptation Guidance: New Roles for Hydroeconomic Analysis

Abstract

Climate water stress internationally challenges the goal of achieving food, energy, and water security. This challenge is elevated by population and income growth. Increased climate water stress levels reduce water supplies in many river basins and elevate competition for water among sectors. Organized information is needed to guide river basin managers and stakeholders who must plan for a changing climate through innovative water allocation policies, trade-off analysis, vulnerability assessment, capacity adaptation, and infrastructure planning. Several hydroeconomic models have been developed and applied assessing water use in different sectors, counties, cultures, and time periods. However, none to date has presented an optimization framework by which historical water use and economic benefit patterns can be replicated while presenting capacity to adapt to future climate water stresses to inform the design of policies not yet been implemented. This paper's unique contribution is to address this gap by designing and presenting results of a hydroeconomic model for which optimized base conditions exactly match observed data water use and economic welfare for several urban and agricultural uses at several locations in a large European river basin for which water use supports a population of more than 3.2 million. We develop a state-of-the arts empirical dynamic hydroeconomic optimization model to discover land and water use patterns that optimize sustained farm and city income under various levels of climate-water stress. Findings using innovative model calibration methods allow for the discovery of efficient water allocation plans as well as providing insight into marginal behavioral responses to climate water stress and water policies. Results identify that water trade policy under climate water stress provides more economically efficient water use patterns, reallocating water from lower valued uses to higher valued uses such as urban water. The Ebro River Basin in Spain is used as an example to investigate water use adaptation patterns under various levels of climate water stress. That basin's issues and challenges can be of relevance to other river basins internationally.



Keywords: climate water stress, adaptation patterns, water sharing policies, optimization model.

3.1 Background

3.1.1. Introduction

Climate variability and growing population worldwide increase water demands for food production and urban use presenting an ongoing and growing challenge for climate water stress adaptation policies. Climate change is affecting the duration and the intensity of severe hydro-metrological events, causing climate water stress (Johnson and Weaver, 2009). This climate water stress poses difficulties in protecting food security and economic sustainability, notably in arid and semi-arid river basin. Increased water shortages and reduced water availability induced by climate change could ensue in an undesirable consequence on economic activities and environmental sustainability (Gohar et al., 2019). Climate water stress has been responsible for 41% of environmental disasters and 54% of economic losses in Europe over the last 50 years (WMO, 2021). A better understanding of the economic impacts of climate water stress on water use, water availability, water suppliers' livelihoods, and consumer welfare is required to provide a more efficient and sustainable adaptation policies.

3.1.2. Previous Work

Hydroeconomic analysis (HEA) has been a state-of-the arts approach for integrating physical and economic dimensions of water resource systems to guide policy debates (Booker et al., 2012; Boucher et al., 2012; Brouwer and Hofkes, 2008; Esteve et al., 2015; Foudi et al., 2015; George et al., 2011; Goor et al., 2011; Guan and Hubacek, 2007; Guan and Hubacek, 2008; Harou and Lund, 2008; Harou et al., 2010; Harou et al., 2009; Heinz et al., 2007; Howitt et al., 2012; Jalilov et al., 2016; Kahil et al., 2015; Klein and Whalley, 2015; Kragt et al., 2011; Maneta et al., 2009; Pulido-Velazquez et al., 2008; Qureshi et al., 2013; Varela-Ortega et al., 2011; Verkade and Werner, 2011; Ward and Pulido-Velazquez, 2008; Yang et al., 2016). This capacity of HEM to guide policy choices sees growing importance in light of ongoing debates over methods to inform policy design for adapting to climate-water stress.

Much HEA has been conducted for European watersheds (Alamanos et al., 2019; Alamanos et al., 2021; Blanco-Gutierrez et al., 2013; Carolus et al., 2020; Escriva-Bou et al., 2017; Graveline, 2020; Heinz et al., 2007; Herivaux et al., 2013; Hervas-Gamez and Delgado-Ramos, 2020; Koch and Grunewald, 2009; Molina et al., 2013; Pena-Haro et al., 2009; Pulido-Velazquez et al., 2008; Ruperez-Moreno et al., 2017; Udias et al., 2016). Some of Europe's best known contributions have come from Spain that has a long history of climate stress and intense competition for water (Blanco-Gutierrez et al., 2013; Crespo et al., 2019; Essenfelder et al., 2018; Kahil et al., 2015; Kahil et al., 2016; Lopez-Nicolas et al., 2018; Perez-Blanco et al., 2021; Ruperez-Moreno et al., 2017; Varela-Ortega et al., 2016; Varela-Ortega et al., 2011). Several watersheds in Asia have also been analyzed (Bekchanov and Lamers, 2016; Bekchanov et al., 2018; Bekchanov et al., 2015; Bekchanov et al., 2016; Jalilov, 2021; Jalilov et al., 2016; Jalilov et al., 2015; Nechifor and Winning, 2018; Ray et al., 2015; Sadoff et al., 2013; Satoh et al., 2017; Ward et al., 2021; Yang et al., 2016).

Many other studies have been published that integrate the disciplines of hydrology, irrigation, economics, and policies to discover resilient adaptations to drought and climate stress. One important policy analysis was conducted for Niger Basin that has a sophisticated integration of hydrology, economics, and institutional analysis (Ward and Kaczan, 2014). Notable contributions have been conducted in Spain to address policy adaptation to climate change (Esteve et al., 2015; Kahil et al., 2015). Another study for the Murray Darling Basin in Australia assesses climate adaptation policies (Kirby et al., 2014).

3.1.3. Gaps

Several hydroeconomic modeling works have been conducted assessing water use in varying sectors in varying locations of the world and for various time periods. However, few have presented an optimization framework by which historical water use and economic benefit patterns can be replicated while developing capacity to adapt to future climate water stresses to inform the design of policies not yet implemented. Successfully addressing this pair of gaps informs water policy debates on efficient water distributions to face future climate conditions to adapt to climate stress in the world, especially in arid and semi-arid areas.

3.1.4. Contribution

This paper's unique contribution is to address this gap by designing and presenting results of a dynamic hydroeconomic model (HEM) for which optimized base conditions match observed data on water use and economic welfare for several urban and agricultural uses at numerous locations in a large European river basin for which water use supports a population of more than 3.2 million. This innovative model framework integrates hydrology, economics, climate stress, and institutional water sharing to address climate water stress variability and identify opportunities for water sharing policies to adapt to climate water stress to protect future sustainable water resources, especially in new climate conditions. Our model also evaluates the potential of water sharing alternatives under different levels of climate water stress in providing an efficient water allocation across sectors and spatial locations, as well as presenting outcomes that could reduce total economic losses that would otherwise be incurred by that climate water stress. The model we developed permits assessments of alternative water sharing policies to protect future sustainability of water resources in new climate conditions not previously experienced. Furthermore, this model uses innovative calibration methods to ensure that optimized base water use and water use outcomes match historically observed data water use and economic welfare. After performing this calibration, the calibrated model is used to discover efficient water allocation plans for adapting to shortages under alternative water shortage sharing methods, providing insight into important behavior responses to climate water stress adaptation policies.

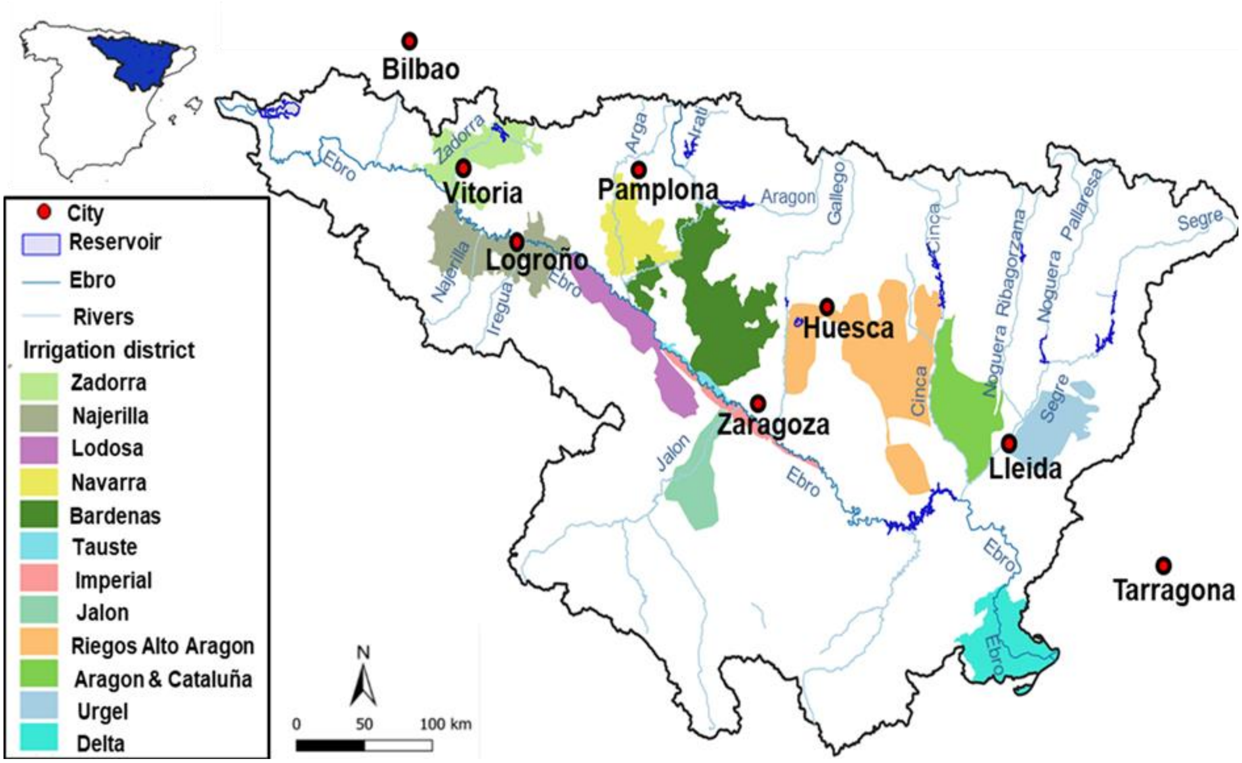
3.2 Methods of Analysis

3.2.1. Study Area

The Ebro River Basin is one of the main European Mediterranean basins and the largest river in Spain. It represents 17% of the Spanish peninsular territory with a river length of 910 km and an annual water supply of about 15,000 million cubic meters (CHE, 2020). The mainstream river is supplied by several main tributaries, most of them are Zadorra, Aragon, Gallego, Cinca, and Segre, and the basin drained by the River terminates in the Mediterranean Sea (Figure 3.1). The Basin includes about 85,600 km^2 and is home to 3.2 million. Water withdrawals in the Ebro amount to 8,460 Mm^3 in recent years, from which its largest supplies comes from surface water with a share of about 97% (CHE, 2015). The Ebro water system supplies water for different irrigation districts with agricultural water use of about 7,680 Mm^3 and urban use of about 630 Mm^3.

The climate in the Ebro Basin is highly heterogeneous due to its great spatial extent and the contribution of both Continental and Mediterranean climate influences. Precipitation falls mostly in the Pyrenees, where it exceeds 1000 mm/year, while it does not exceed 350 mm/year in the basin's center region, where conditions are semi-arid (CHE, 2015). The Ebro basin suffers from long dry spells in summer with annual potential evapotranspiration of about 700 mm (Bovolo et al., 2010). This climate heterogeneity and variability have long provided water stress challenges in the basin. To address these special challenges in that basin, this paper formulates and applies an innovative approach to inform policy debates in the basin under future climate water stress in order to get the best ways to manage water for its many competing uses and to provide adaptation patterns.

Figure 3. 1. Ebro River Basin.



3.2.2. Data

Data were gathered from several reliable sources to establish a foundation for an integrated analysis. Monthly data on streamflow and reservoir storage for all five years (2012-2016) come from the Ebro basin Authority and CEDEX (CEDEX, 2016; CHE, 2016). Several sources of data on yield, prices, production costs, crops water requirement and land in production were secured from the Spanish Ministry of Agriculture and State Governments. Table 3.1 and Table 3.2 present some of the most important data such as land in production and associated water use, water applied for cities, and the economic information for the agricultural and urban sectors.

Table 3.1 shows that land in crop production under the normal climate condition in the Ebro basin amounts to 584,000 ha from the 12 irrigation districts. Agricultural activities use 3688 million cubic meters (Mm^3) of water, providing economic benefits of about 1,022 million Euro. The most economically important irrigation districts are the Aragon and Cataluña canal, Riegos del Alto Aragon and Urgel canal, providing 54% of the total benefits of the basin's cropland activities. Table 3.2 indicates that urban water use in main cities is about 422 Mm^3 with total economic benefits (consumer surplus) at about 2,435 million Euro.

Table 3. 1. Water, Land, and benefits data. Ebro River, Spain.

Variable	**Water used**	**Land in production**	**Base Total benefits**
Units	**Mm^3**	**1000 ha**	**Million Euro**
Bardenas canal	447.51	71.99	73.02
Aragon and Cataluña canal	593.17	100.53	276.51
Imperial canal	306.13	43.33	49.89
Jalon canal	109.43	21.32	64.29
Lodosa canal	269.18	56.58	122.11
Navarra canal	130.17	22.69	33.25
Tauste canal	60.01	8.84	9.82
Urgel canal	536.29	78.19	143.57
Delta canal	325.77	29.34	42.60
Rioja canal	121.85	27.90	60.58
Riegos Alto Aragon	749.71	117.02	131.38
Zadorra canal	38.87	6.21	15.09
Total	**3688**	**584**	**1022**

Table 3. 2. Urban Data.

Variable	**Water Withdrawals**	**Price**	**Costs**	**Consumer Surplus**	**Benefits**
Units	**Mm^3/year**	**Million Euro/ Mm^3**	**Million Euro/ Mm^3**	**Million Euro**	**Million Euro**
City					
Vitoria	21	1.04	1.04	72.80	72.80
Bilbao	195	1.73	1.73	1124.50	1124.50
Logroño	20	1.37	1.37	91.332	91.332
Pamplona	37	1.33	1.33	164.028	164.028
Zaragoza	59	1.53	1.53	300.09	300.09
Huesca	6	1.63	1.63	32.604	32.604
Lerida	14	2.21	2.21	103.28	103.28
Tarragona	70	2.34	2.34	546.00	546.00
Total					**2434.63**

3.2.3. Dynamization of the model

The analysis of the policies and the different scenarios in this work has been carried out after improving the specification of the hydroeconomic model since the periodicity of the model has been changed from annual to monthly, and the model has been transformed from static to dynamic with the inclusion of the reservoirs in the hydrological network.

The reservoir capacity of the Ebro basin is approximately 8,000 Mm^3, which means that around 55% of the basin's annual renewable resources can be stored. However, the reservoirs also have some negative effects such as the modification of the riverbeds and regimes, which causes a great impact on the environment. The dynamics of stored water are determined by the inputs and outputs of water from the reservoirs, which depend on weather conditions, evaporation, precipitation, and water discharge.

The hydrological component is a reduced form hydrological setting of the Ebro basin, calibrated with observed stream flows. The reduced form hydrological model is a node-link network, in which nodes represent physical units impacting the stream system, and links represent the connection between these units (Baccour et al., 2021), (see chapter 2). Reservoir storage $Z_{res,t,m}$ at each reservoir *res*, period *t* and month m, is equal to the sum of storage in previous month $Z_{res,t,m-1}$ and precipitation $P_{res,t,m}$, minus reservoir evaporation $Evp_{res,t,m}$ and net releases (outflows minus inflows) from the reservoir $Wrel_{d,t,m}^{res}$ (Equation 4). Net water releases add flow to the downstream node in the river reach. The reservoir storage equations are represented as follows:

$$Z_{res,t,m} = Z_{res,t,m-1} + P_{res,t,m} - Wrel_{d,t,m}^{res} - Evp_{res,t,m} \tag{3.1}$$

$$Z_{res,t1,m1} = Z_{res,0} \tag{3.2}$$

$$Z_{res,t,m} \leq Cmax_{res} \tag{3.3}$$

$$Z_{res,t,m} \geq Cmin_{res} \tag{3.4}$$

$$Evp_{res,t,m} = Evprate_{res} \cdot Surf_{res,t,m} \tag{3.5}$$

$$P_{res,t,m} = Prate_{res} \cdot Surf_{res,t,m} \tag{3.6}$$

$$Surf_{res,t,m} = \beta 1_{res} \cdot Z_{res,t,m} + \beta 2_{res} \cdot Z_{res,t,m}^{2} + \beta 3_{res} \cdot Z_{res,t,m}^{3} \tag{3.7}$$

where equation (3.2) defines the initial conditions of reservoir storage $Z_{res,t,m}$ at m = 1 and t =1, and equations (3.3) and (3.4) constraint reservoir storage at the maximum $Cmax_{res}$ and minimum $Cmin_{res}$ capacity of the reservoir. Equations (3.5) and (3.6) state the reservoir evaporation $Evp_{res,t,m}$ and precipitation $P_{res,t,m}$, which are proportional to the reservoir surface area $Surf_{res,t,m}$. The reservoir surface area is a polynomial relationship between reservoir area and reservoir storage (Equation (3.7)).

3.2.4. Calibration: Climate Water Stress Adaptation

We formulate a model calibration and climate water stress adaptation framework using a mathematical programming model. The optimization model developed integrates economics, hydrology, climate stress, and institutional water sharing policy design. The earliest breakthrough using this method was developed by Howitt (Howitt, 1995). This approach is to build an optimization model for which the principal observed behavior of water supply and land use patterns is used to infer the underlying parameters of the agricultural production function, for which this paper advances that method by developing a similar approach to infer the parameters of the urban water demand functions. In this study, we develop an optimization framework that infers the relevant parameters that reproduce observed data that would have been seen under a benefits maximization model for both farming and urban regions. Our method advances the PMP (Positive Mathematical Programming) calibration for agricultural and urban sectors.

The PMP calibration for the agricultural sector was originally described by Dagnino and Ward (Dagnino and Ward, 2012) and used in many studies in order to reproduce observed land and water use under the baseline scenario. However, no study to date that we were able to find uses the PMP calibration approach for the urban sector. An innovative PMP calibration method is developed for the consumer surplus of the urban sector, which allows replicating the observed water use behavior. The PMP calibration predicts urban water use under the constraint that total revenues equal total costs and water using behavior is derived from the "first-order conditions" for optimal water use. More details of PMP calibration coding for the agricultural and urban sectors are shown in the complete GAMS code.

The PMP calibration of agricultural and urban sectors under an optimization model provides a starting point for observed data where there is a competition for water among uses and sectors. This competition increases in extent with a greater severity of climate water stress. This PMP model is well-suited to dealing with challenges posed by climate water stress, providing important information to support adaptation policy design on the economic value of scare water when climate water stress becomes more severe.

Hydrologic calibration is also provided based on observed monthly historical data (2012-2016) in order to achieve predicted gauged flows and reservoirs storage consistent with the observed data. The calibration procedure also entails introducing slack variables in each river reach in order to balance supply and demand at each node. These variables represent unmeasured sources or uses of water. This calibration procedure reproduces the water flows and the reservoir storage observed in the reference conditions.

3.2.5. Integration

This paper investigates the economic performance of agricultural and urban sectors under different levels of climate water stress and water sharing policies through the development of an empirical dynamic hydroeconomic optimization procedure using the software GAMS® (General Algebraic Modeling System) (Figure 3.2). In this model, water supply, water demand, and water allocation between sectors were significant dimensions over which optimization took place. Figure 3.4 represents the detailed network schematic diagram for the Ebro Basin showing the water distribution among rivers, reservoirs and water users. The optimization framework has the feature of discovering least cost adaptation methods for allocating water among sectors and time periods to protect food security under climate water stress. Total economic welfare is defined as farm income plus urban consumer surplus, over different climate stress levels and water sharing policies.

Farm Income

Farm income is secured by water consumption at use node for irrigated agriculture and the willingness to pay is determined by the contribution of water to net farm income. This income from agricultural activities is set at the irrigation district scale to maximize the crops benefits subject to a set of technical, resource, and institutional constraints. The optimization problem is as follows:

$$Max\ B_{kt}^{IR} = \sum_{ij} C_{ijkt}^{\prime(IR)} \cdot X_{ijkt}^{IR} \tag{3.8}$$

subject to

$$\sum_{i} X_{ijkt}^{IR} \leq Tland_{kjt}; \quad i: crop;\ j: flood, sprinkler, drip; k: irrigation\ district \tag{3.9}$$

$$\sum_{ij} W_{ijkt} \cdot X_{ijkt}^{IR} \leq Twater_{kt} \tag{3.10}$$

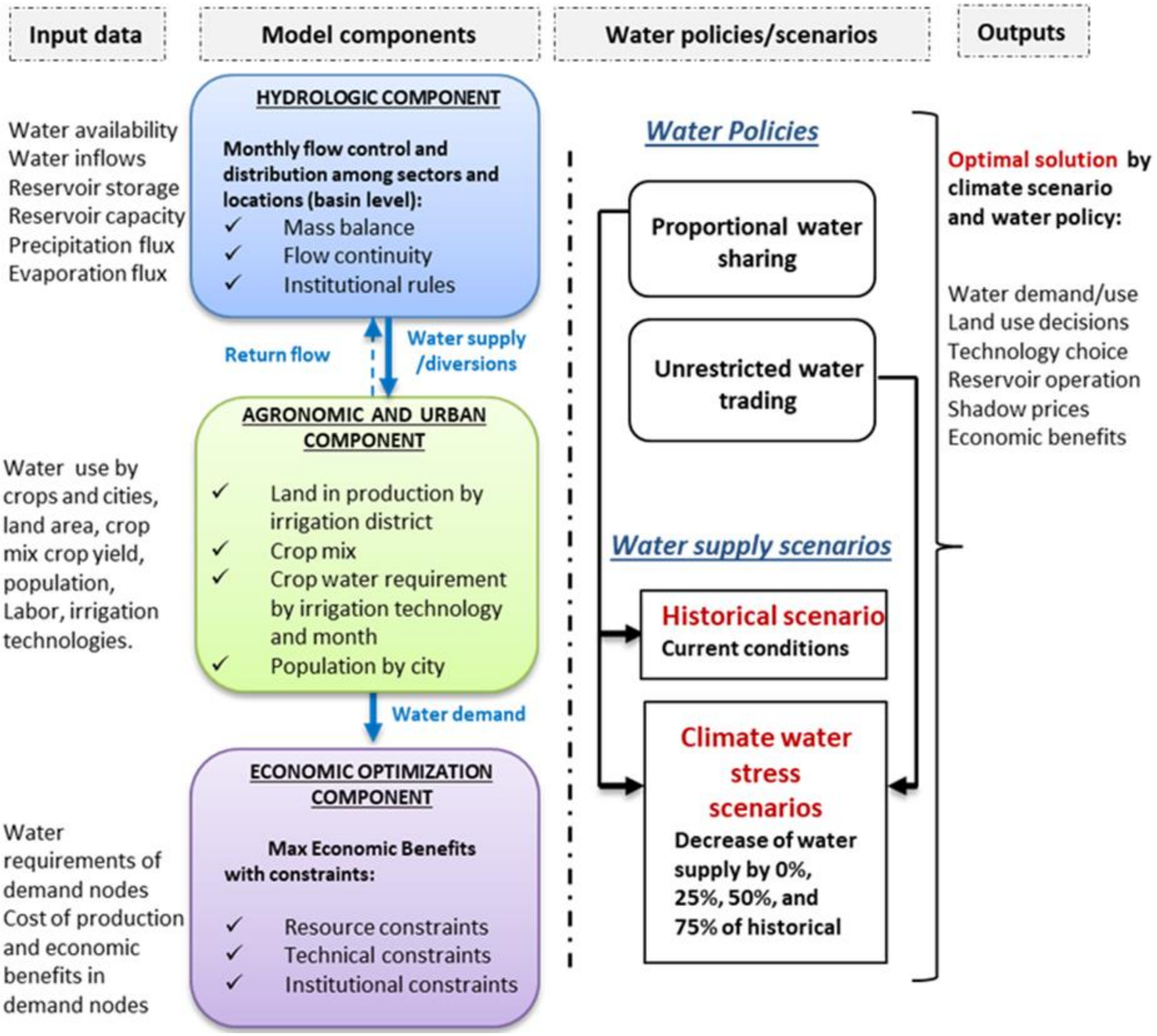
$$\sum_{ij} L_{ijkt} \cdot X_{ijkt}^{IR} \leq Tlabor_{kt} \tag{3.11}$$

$$X_{ijkt}^{IR} \geq 0 \tag{3.12}$$

where B_{kt}^{IR} represents the private benefit in each irrigation district *k* in the years *t*, that is equal to the net farm income per hectare of crop *i* using irrigation system *j* $C_{ijkt}^{\prime(IR)}$ multiplied by the decision variable of the optimization problem which is the land in production of each crop *i* and irrigation technology *j* in the irrigation district *k,* X_{ijkt}^{IR}.

Equation (3.9), (3.10), and (3.11) represent the land, water, and labor constraints, indicating the land available in each irrigation district *k* equipped with irrigation system *j,* $Tland_{kjt}$; the water available in each irrigation district *k*, $Twater_{kt}$; and the labor available in each irrigation district *k*, $Tlabor_{kt}$ per year. Equation (3.12) is the non-negativity constraint of the crop surface area which can become binding as water supplies fall much below historically observed levels. They are not binding under historical data.

Figure 3. 2. Flow chart showing model component and climate water stress adaptation policies.



Net farm income $C'^{(IR)}_{ijkt}$ is equal to crop price P_i multiplied by yield Y_{ijkt} minus production costs CP_i, where the price is the selling amount received by farmers where crops are sold commercially and measured in million Euro per 1000 tons. Yield is the production of each crop by irrigation technologies per unit of land, measured here in 1000 tons per 1000 ha. Costs are the production costs of each crop and measured by million Euro per 1000 ha (Equation (3.13)). The yield function is determined using the Ricardian rent principle, assuming that yields decline linearly with an expanded scale of production (Equation (3.14)). The PMP procedure is used to calibrate crop production and to estimate the linear yield function parameters $\beta0_{ijk}$ and $\beta1_{ijk}$.

$$C'^{(IR)}_{ijkt} = P_i Y_{ijkt} - CP_i \tag{3.13}$$

$$Y_{ijkt} = \beta 0_{ijk} + \beta 1_{ijk} X^{IR}_{ijkt} \tag{3.14}$$

The total farm income is calculated by multiplying the net farm income by the total land in production by crop and irrigation technology in each irrigation district. Total farm income calculation has great importance; it informs farmers and policymakers about the range of benefits that would result in a determined water supply under climate water stress and water allocation rules. It helps to answer concerns regarding knowing the advantages and the costs of adopting water-sharing policies on climate water stress conditions and cropping patterns.

Urban welfare

The economic benefit from urban sector is secured by water use from cities, maximizing the urban consumer surplus and the urban benefits for the main urban centers in the Ebro Basin, subject to the water supply and demand balance constraint. The water use by city depends on the population growth in each city, increasing the urban welfare over years. The optimization problem is expressed as follows:

$$Max\ B^{URB}_{ut} = [-\frac{1}{2} \cdot b1_{du} \cdot Q^2_{dut} + UR_{ut}] - UC_{ut} \tag{3.15}$$

subject to

$$Q_{dut} - Q_{sut} \leq 0 \tag{3.16}$$

$$Q_{dut}\ ;\ Q_{sut} \geq 0 \tag{3.17}$$

where, the urban welfare B^{URB}_{ut} in each urban center *u* and year *t* is equal to the consumer surplus and urban revenue UR_{ut}, minus urban production cost UC_{ut} for urban center *u* and year *t*. Q_{dut} is the water demand in urban center *u* and $b1_{du}$ is the slope of the inverse water demand function. The urban price used in this study is a linear function of water use and price elasticity of demand. Equation (3.16) indicates that water supply Q_{sut} is greater than or equal to demand Q_{dut} in year *t*.

Total Economic Welfare

The modeling framework in this study is a dynamic hydroeconomic optimization model. It is formulated to determine water allocation and adaptation patterns under climate water stress that optimize the objective of discounted net present value (DNVP) of economic benefits summed over sectors and periods (Jalilov et al., 2018; Primavera, 1991). This model includes agricultural and urban sectors and maximizes the total economic welfare of sectors subject to hydrological, resources, and institutional constraints. We achieve this aim under the baseline condition by employing the innovative calibration method described above. It is also implemented under the four climate stress levels and the two institutional constraints for water sharing shortfalls in order to suggest sustainable adaptation policies. The objective function of the Ebro Basin takes the following form:

$$Max\ DNVP = \frac{\sum_{kt} B_{kt}^{IR} + \sum_{ut} B_{ut}^{URB}}{(1+r)^{t}} \tag{3.18}$$

This DNPV term indicates that the net present value of the total water-based benefits for all water use nodes in the Ebro Basin sums over time periods to secure total discounted net present value. The discount rate r used in the analysis is 3%.

3.2.6. Policy Analysis

The policy analysis examines the level, distribution, and economic implications of managing different water supply scenarios under water shortage allocation policies. Water supply scenarios are presented by specifying different levels of climate water stress. The annual water supply in the historical climate conditions in the Ebro Basin model is estimated at 12.430 Mm^3. Several climate water stress forecasts have been presented and documented in recent years. For example, the IPCC Sixth Assessment Report (IPCC, 2021) predicts falling precipitation in the Mediterranean region, with reductions in the Iberian Peninsula up to 20% by the end of the century depending on the emission scenarios. Reduced stream flows in Spanish basins and more intense drought spells are also predicted by the European Environment Agency (EEA, 2007) and other studies (Forero-Ortiz et al., 2020; Koutroulis et al., 2018; Roudier et al., 2016). Climate projections in the Ebro Basin show lower precipitation patterns, higher evapotranspiration, and falling stream flows in future climate conditions (CEDEX., 2017; MAPAMA, 2017). Each of these assessments produces different results, as expected.

Our model assesses four levels of climate water stress relative to historical levels: 0% (historical climate condition), 25%, 50%, and 75% as percentages of the historical baseline. The different levels of climate water stress (0%, 25%, 50% and 75%) are based on the combination of historical drought spells patterns and future negative trends in stream flow supplies from climate change. Droughts in the Ebro basin could be quite severe, according to historical inflows, and droughts with inflows falling by 40-50 percent have been observed in recent decades in years 1989, 2005, and 2012. The four climate water stress levels merge recent severe drought events (up to 40-50% falling inflows) with the predicted climate change negative trends in the Ebro along this century up to 12% under RCP 4.5 and 26% under RCP 8.5 in 2070-2100 (CEDEX., 2017).

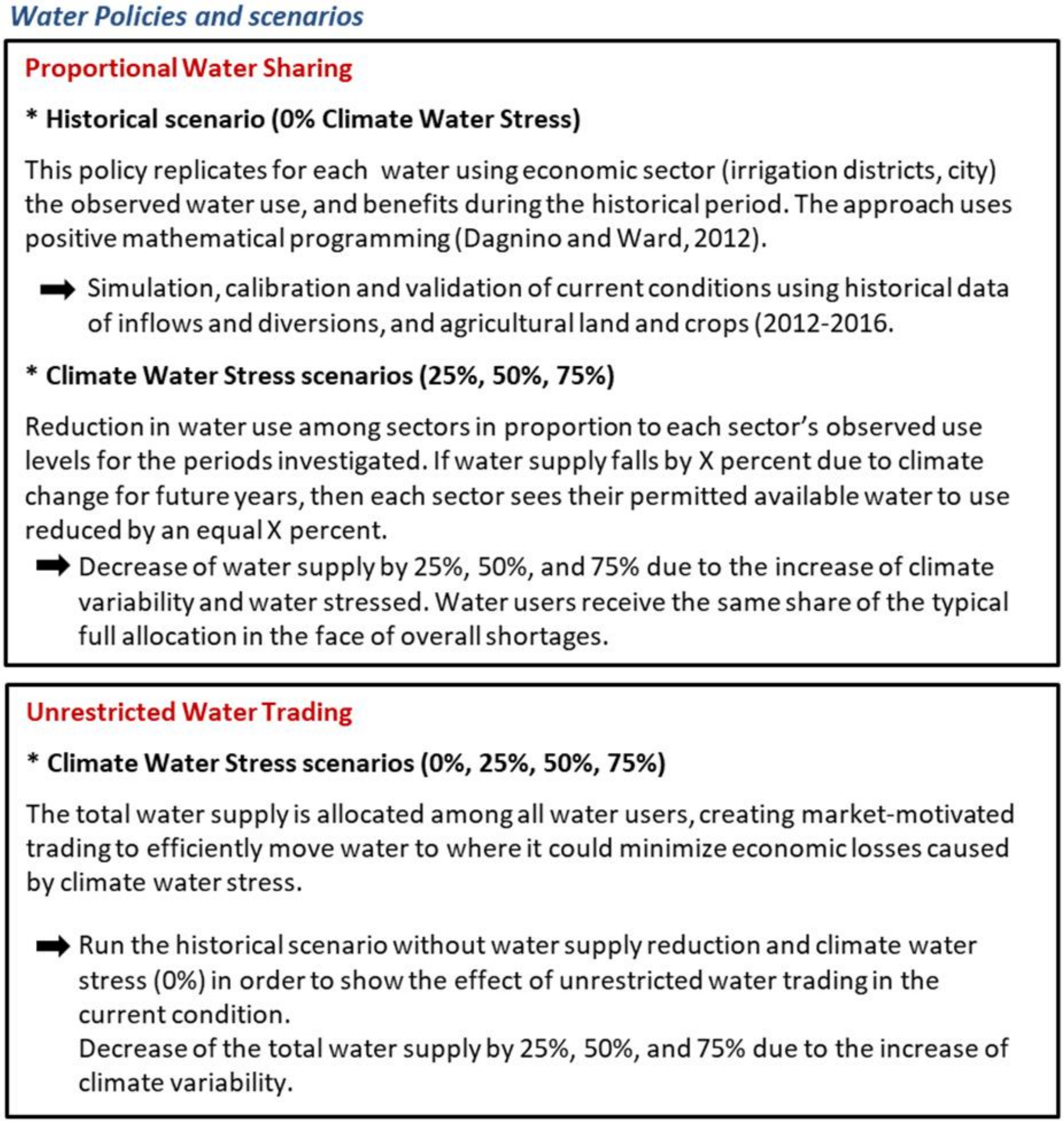
These four climate water stress scenarios we modelled represent selected levels of progressively higher water scarcity in which drought events and inflow trends from the climate change reports described above are combined. The economic implications of future climate water stress scenarios are also examined, considering that population growth in each city of the Ebro Basin increases urban water usage.

In light of the various shortage levels described, our model was built with sufficient flexibility to adapt to whichever of those climate scenarios plays out. Those shortage levels are the ones our model allows for adaptation: 25% shortage, 50% shortage, and 75% shortage. For each of those shortage levels our model demonstrates economically optimized (economic loss-minimizing) water allocation under each relative to the base water supply. This model design illustrates how flexibility in water shortage sharing policies can play an important informing role in adapting climate water stress levels even in severe conditions.

The two water sharing alternatives assessed are proportional sharing of shortages and unrestricted water trading. A proportional water sharing arrangement refers to river water shortages that are shared proportionally, and this is the current policy in the Ebro basin. This policy reduces water users' permitted water allocations by a percentage relative to historical levels, depending on the level of climate water scenario. Under this policy each irrigation district and city receive the same share of the typical full allocation in the face of overall shortages. This water sharing rule ensures that all irrigation districts and regions in the basin face the same share of the risk of water shortages and that no region, such as the basin's lower parts, bears a non-proportional burden of shortage risks (Ward et al., 2013), (Figure 3.3).

The unrestricted water trading arrangement reduces the total water supply in the basin relative to the historical level, depending on the climate water stress scenario, and allows market-motivated trading to efficiently move water to where it could minimize economic losses caused by climate water stress. This kind of water sharing rules in which water is exchanged and moved to the combination of regions and crops, produce the best and optimal total income. The implementation of this water sharing policy would require careful planning and execution in order to account for local institutions and beliefs on justice, the rule of law, and custom. This policy has a potential economic gain from improved economic efficiency (Figure 3.3).

Figure 3. 3. Description of climate water stress adaptation policies.



Water Policies and scenarios

Proportional Water Sharing

*** Historical scenario (0% Climate Water Stress)**

This policy replicates for each water using economic sector (irrigation districts, city) the observed water use, and benefits during the historical period. The approach uses positive mathematical programming (Dagnino and Ward, 2012).

➡ Simulation, calibration and validation of current conditions using historical data of inflows and diversions, and agricultural land and crops (2012-2016.

*** Climate Water Stress scenarios (25%, 50%, 75%)**

Reduction in water use among sectors in proportion to each sector's observed use levels for the periods investigated. If water supply falls by X percent due to climate change for future years, then each sector sees their permitted available water to use reduced by an equal X percent.

➡ Decrease of water supply by 25%, 50%, and 75% due to the increase of climate variability and water stressed. Water users receive the same share of the typical full allocation in the face of overall shortages.

Unrestricted Water Trading

*** Climate Water Stress scenarios (0%, 25%, 50%, 75%)**

The total water supply is allocated among all water users, creating market-motivated trading to efficiently move water to where it could minimize economic losses caused by climate water stress.

➡ Run the historical scenario without water supply reduction and climate water stress (0%) in order to show the effect of unrestricted water trading in the current condition.
Decrease of the total water supply by 25%, 50%, and 75% due to the increase of climate variability.

3.2.7. Economic Value of Additional Water (Shadow Price)

The shadow price approach has different economic explanations and definitions in the literature. A 2015 work (Ziolkowska, 2015) evaluates the water shadow prices for irrigation under extreme weather conditions and demonstrates that shadow prices could be useful to predict the future economic value of water in drought conditions, and used to design water management policies. The shadow prices can also be referred to as the marginal value of water that is related to the efficiency gained from water reallocation (Bierkens et al., 2019; Wang and Lall, 2002; Ziolkowska, 2015). The shadow price is the maximum price that is affordable for an extra unit of scarce water. This shadow price represents the value of each additional unit of water, in added farm income and urban consumer surplus, if water were available. That economic value of the additional river flow derives by putting that water to its optimal use somewhere in the basin while adhering to all the constraints imposed on the use of the water that was outlined previously in this paper. The shadow price is interpreted as the marginal economic value gained by relaxing the water supply restriction by one unit.

The shadow price carries greater relevance in the design of water policies and could be a good indicator for addressing urgent question such as water conservation and climate water stress adaptation. The use of the shadow price indicator is motivated by the fact that it provides information on the marginal economic value of crops or cities that can be generated by the marginal unit of water supply. This could be useful for forecasting future economic value in climate water stress conditions or demonstrating the benefit loss of increasing the annual water supply shortfall by one cubic meter.

3.3 Results

Tables 3.3, 3.4, 3.5, and 3.6 and figures 3.4, 3.5 and 3.6 show detailed findings for several important elements of the Ebro River Basin. These findings show that understanding the relationship of water sharing policy, climate water stresses, cropping patterns, and water use by sectors provides a comprehensive assessment for insight into water use adaptation patterns under various levels of climate water stress.

3.3.1. Water Use

Table 3.3 shows the total amount of water used for urban and agricultural activities by climate water stress and water-sharing policies in million cubic meters per year. The water use in each irrigation district is summed over crops and irrigation technologies.

Table 3.3 and its corresponding figure 3.4 show important results. Agriculture uses most of the water under base conditions. This table shows that irrigated land accounts for 90 percent of overall water use while urban activities use only 10 percent under the base conditions. This large amount of agricultural water use is delivered to 27 crops in several irrigation districts. The most important irrigation districts are Riegos del Alto Aragon, Aragon and Cataluña Canal, and Urgel Canal with water use of about 750 Mm^3/year, 593 Mm^3/year, and 536 Mm^3/year, respectively.

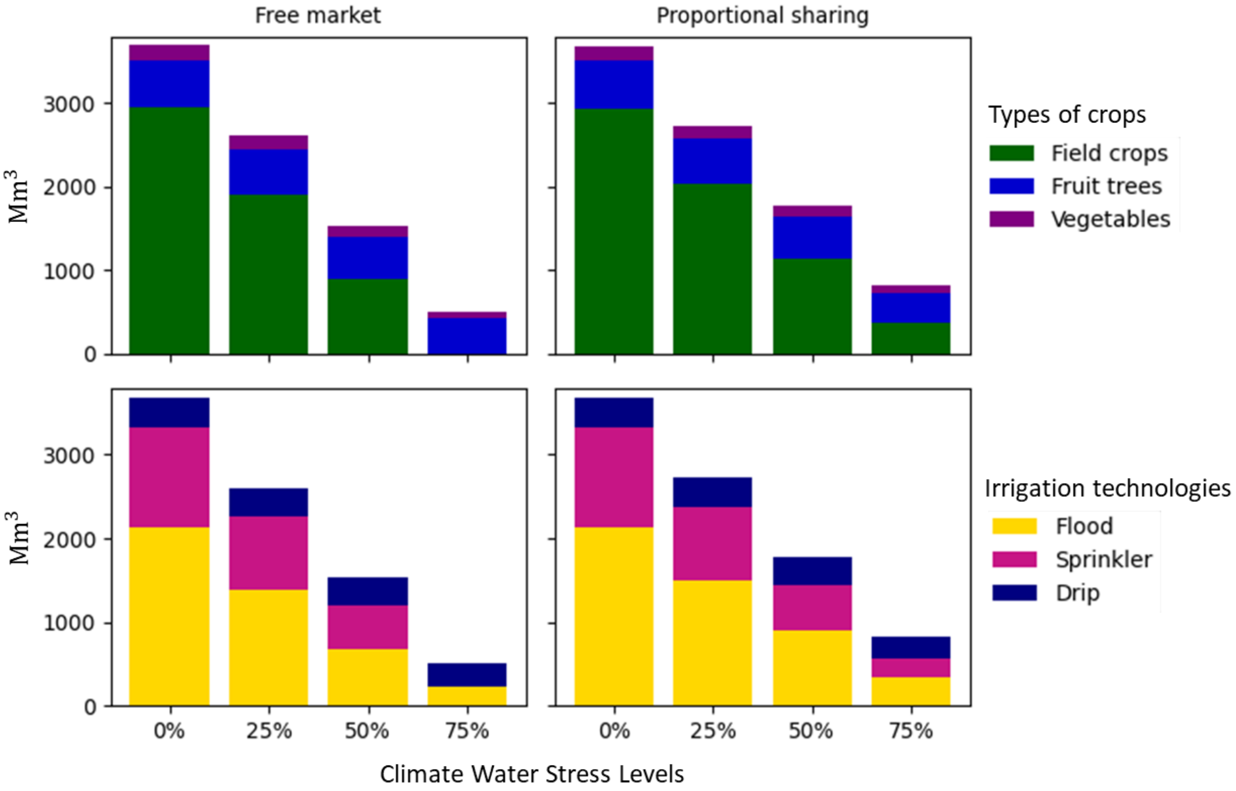
Table 3. 3. Water use Results by sector, Climate Water Stress, and Water Sharing policies. Ebro River. Spain. averaged over 5 years (Mm^3).

Water rules policies		**Free market**				**Proportional sharing**			
Climate water stress	**Sector**	**0%**	**25%**	**50%**	**75%**	**0%**	**25%**	**50%**	**75%**
Bilbao	U	194.61	192.48	190.16	184.03	194.61	145.96	97.31	48.65
Huesca	U	6.05	6.03	6.00	5.94	6.05	4.54	3.02	1.51
Lerida	U	14.28	14.25	14.21	14.10	14.28	10.71	7.14	3.57
Logroño	U	20.36	20.28	20.19	19.94	20.36	15.27	10.18	5.09
Pamplona	U	37.45	37.29	37.11	36.65	37.45	28.09	18.72	9.36
Tarragona	U	72.28	71.69	71.05	69.37	72.28	54.21	36.14	18.07
Vitoria	U	21.34	21.22	21.10	20.76	21.34	16.00	10.67	5.33
Zaragoza	U	59.83	59.61	59.37	58.73	59.83	44.87	29.92	14.96
Total		**426.20**	**422.84**	**419.18**	**409.53**	**426.20**	**319.65**	**213.10**	**106.55**
Bardenas canal	A	447.51	292.66	137.84	17.43	447.51	332.56	217.62	103.62
Aragon and Cataluña canal	A	593.17	459.92	320.99	141.02	593.17	437.63	283.48	129.74
Imperial canal	A	306.13	208.18	102.25	11.17	306.13	228.21	150.30	72.42
Jalon canal	A	109.43	90.10	69.11	44.24	109.43	78.37	47.88	16.37
Lodosa canal	A	269.18	214.27	158.06	93.72	269.18	194.96	121.56	46.36
Navarra canal	A	130.17	93.12	54.98	12.74	130.17	96.08	62.10	28.38
Tauste canal	A	60.01	40.66	19.64	2.51	60.01	44.79	29.57	14.35
Urgel canal	A	536.29	393.01	238.05	83.36	536.29	398.34	260.42	123.44
Delta canal	A	325.77	156.89	37.51	25.61	325.77	240.23	154.68	69.13
Rioja canal	A	121.85	99.59	75.39	45.56	121.85	89.58	57.59	23.61
Riegos Alto Aragon	A	749.71	525.42	293.34	20.68	749.71	558.49	367.61	179.79
Zadorra canal	A	38.87	31.95	24.43	14.39	38.87	28.83	18.80	8.33
Total		**3688.11**	**2605.78**	**1531.58**	**512.44**	**3688.11**	**2728.08**	**1771.60**	**815.54**
Ebro Water Use		**4114.31**	**3028.62**	**1950.76**	**921.97**	**4114.31**	**3047.73**	**1984.70**	**922.08**

Urban water use is distributed across several cities, which the large cities such as Zaragoza and Lerida, with a population of about 771,000 using just 60 Mm^3/year, and a population of approximately 414,000 using 14 Mm^3/year, respectively. Those cities provide a water use per capita of about 78 m^3 per capita in Zaragoza and 34 m^3 per capita in Lerida. Huesca is the smallest city, with a population of about 219,000 inhabitants and water use of 27 m^3 per capita. Bilbao and Tarragona have the highest per capita water use, with 199 m^3 and 97 m^3 per capita, respectively.

Figure 3.4 shows the distribution of agricultural water withdrawals by type of crop and by irrigation technology. This figure illustrate that field crops show the highest water use (79%) because of the high water requirement of some crops such as corn and rice, followed by fruit trees and vegetables with a water use share of 16% and 5%, respectively. As expected, a considerable amount of water is applied by using less efficient irrigation technologies (58%) followed by sprinkler (32%) and drip (10%) irrigation systems. This highest water use of agricultural sectors illustrates the importance of agriculture development in the Ebro basin with crops diversification in order to improve food security with current climate stress and population growth.

Figure 3. 4. Water use by types of crops, irrigation technologies, climate water stress, and water sharing policies. Ebro River. Spain (Mm^3).



Results highlight that agriculture bears the lion's share of the shortages as drought/climate stress becomes more severe. Table 3.3 shows that severe climate water stress reduces agricultural water use by 3,176 Mm^3/year under unrestricted water trading and 2,873 Mm^3 under proportional sharing. However, water withdrawal by the urban sector is reduced only by a much smaller 17 Mm^3/year and 320 Mm^3/year for water trading and proportional sharing, respectively. These results highlight that climate water stress imposes a much large water adaption stress on the agriculture prioritizing the use of water for urban activities compared to that for irrigated land. This vividly shows that a reduction in water supply exacerbates competition among sectors and spatial locations, allocating scarce water based on their economic values and water use efficiency. A climate water stress management framework that is transferable to other parts of the world needs real attention both by scholars and policymakers to adapt to the impact of growing water scarcity, supporting policy decision making.

Irrigated regions with higher valued crops bear a smaller percentage of shortages than those with lower valued crops as climate stress intensifies. Figure 3.4 and Figure 3.6 show that climate water stress reduces mainly field crops and some vegetables, maintaining fruit trees, showing the greatest reduction for the lowest economic valued crops. Table 3.3 and Figure 3.6 highlight that the irrigation districts of

Aragon and Cataluña canal, Jalon canal, Lodosa canal, and Rioja canal have a high proportion of high crop values, with water use declining by roughly 60% during severe climatic water stress. However, Delta canal and Riegos del Alto Aragon are irrigation regions with low crop economic values, with water use decreasing by 97%, 92%, respectively, during severe climate water stress. This difference in water shortages is linked to the type and the economic value of crops, and the efficiency of irrigation technology in each irrigated region.

Findings indicate that agriculture bears an even larger percentage of the shortage under unrestricted water trading as climate stress becomes more severe. Table 3.3 shows that severe climate water stress reduces agricultural water shortage by 86% in free water trading, while it declines 78% in proportional sharing. This is explained by the effective water reallocation in free water trading, minimizing overall losses in economic welfare. In other words, water trading reallocates scarce water towards crops or regions with the highest value and most efficient use. Free water markets analysis intends to identify a water allocation system that minimizes the loss in economic benefits by efficiently sharing water supplies when the inevitable climate water stress occurs.

Larger cities bear larger proportion of shortages as climate stress becomes more severe, but a smaller share under market trading than under proportional sharing. Table 3.3 illustrates a large reduction of urban water use of about 75% under proportional sharing, while water trading reduces urban shortage only by 39% under severe climate water stress. Water withdrawal in larger cities such as Bilbao is reduced by 75% under proportional sharing and severe climate stress. That city’s use only falls by 5% under water trading and increased climate stress. Smaller cities such as Huesca have a reduction of water use by 2% under unrestricted water trading.

Unrestricted water trading could play a significant role in increasing water use efficiency among sectors and spatial locations, stave off the worst effect of reduced water supply and increased climate water stress. Water trading increases the flexibility in response to water scarcity and incentivizes the allocation of water to higher value use, playing an important role in limiting the economic losses associated with climate water stress.

3.3.2. Land in Production

Table 3.4 shows the amounts of irrigated land in production in 1000 ha summed by several climate water stress levels and water sharing rules. Increases in climate water stress would reduce the base irrigated land under water sharing rules. Figure 3.5 show the irrigated land by types of crops and irrigation technologies.

The results of this table and figure show several key messages:

Land use changes are based on how severe climate water stress is. Table 3.4 shows that climate stress affects land productivity depending on the severity of drought and water scarcity. Results indicate that under a lower climate water stress level, agricultural land decreases only by 26%, while it declines by 81% under severe climate stress. Climate water stress level assessments are critical for understanding future droughts and the resulting impacts of water scarcity on the basin's economic benefits. Understanding the ensuring effects of climate water stress has implications for adaptations policies.

Climate water stress reduces cropland with less efficient irrigation technologies and high water requirement. Figure 3.5 shows that severe climate stress reduces land in production by 100 % for all field crops, followed by 43% of vegetables and 27% of fruit trees under water trading. However, for proportional sharing, severe climate reduces 88% of field cropland, 49% of vegetables, and 39% of fruit trees. Findings illustrate also that a severe climate stress decreases cropland in production with flood irrigation technology by 270,000 ha, followed by sprinkler irrigation system with a reduction of 180,000 ha and drip irrigation system with 19,000 ha under free water trading, highlighting the most efficient water use. Our results highlight that climate water stress reduces crops the most for which there is a low profitability and high water requirement, and cropland production with less efficient irrigation technologies.

Market trading of water reduces more the total cropland as climate stress become more severe compared with proportional sharing. Table 3.4 illustrates that under severe climate, the total land in production decreases by 81% to 111,000 ha for the unrestricted water trading, while it declines only by 75% to 146,000 ha for proportional sharing. However, in some irrigation districts like Aragon and Cataluña canal, Jalon canal, Lodosa canal, and Rioja canal, land in production in water trading are higher than under proportional sharing. This occurs because the distribution of water depends on the crops' water needs and crop profitability, which improves the productivity of land and the efficiency of water use patterns. The intuition that water trading reallocates water resources towards land with the highest valued and most efficient use shows that water trading could serve as an adaptive policy identifying their potential to address climate water stress variability.

Table 3. 4. Land by irrigation district, Climate Water Stress, and Water Sharing Policies. Ebro River. Spain. average over 5 years (1000 ha).

Water rules policies		**Free market**				**Proportional sharing**			
Climate water stress	**Sector**	**0%**	**25%**	**50%**	**75%**	**0%**	**25%**	**50%**	**75%**
Bardenas canal	A	71.99	48.39	24.08	4.86	71.99	54.49	36.99	18.40
Aragon and Cataluña canal	A	100.53	79.51	57.23	27.78	100.53	76.02	51.09	25.59
Imperial canal	A	43.33	29.80	15.17	2.93	43.33	32.57	21.82	11.09
Jalon canal	A	21.32	18.09	14.59	10.06	21.32	16.14	10.93	3.59
Lodosa canal	A	56.58	46.99	36.95	24.18	56.58	43.63	30.25	12.32
Navarra canal	A	22.69	16.65	10.43	3.66	22.69	17.14	11.61	6.26
Tauste canal	A	8.84	6.07	3.06	0.72	8.84	6.66	4.48	2.31
Urgel canal	A	78.19	57.70	35.55	13.77	78.19	58.48	38.79	19.65
Delta canal	A	29.34	16.67	7.51	5.09	29.34	22.93	16.52	10.11
Rioja canal	A	27.90	22.86	17.37	10.57	27.90	20.59	13.32	6.08
Riegos Alto Aragon	A	117.02	82.81	46.98	4.85	117.02	87.88	58.79	29.24
Zadorra canal	A	6.21	5.27	4.24	2.76	6.21	4.84	3.48	1.73
Ebro land		**583.94**	**430.81**	**273.16**	**111.23**	**583.94**	**441.38**	**298.07**	**146.38**

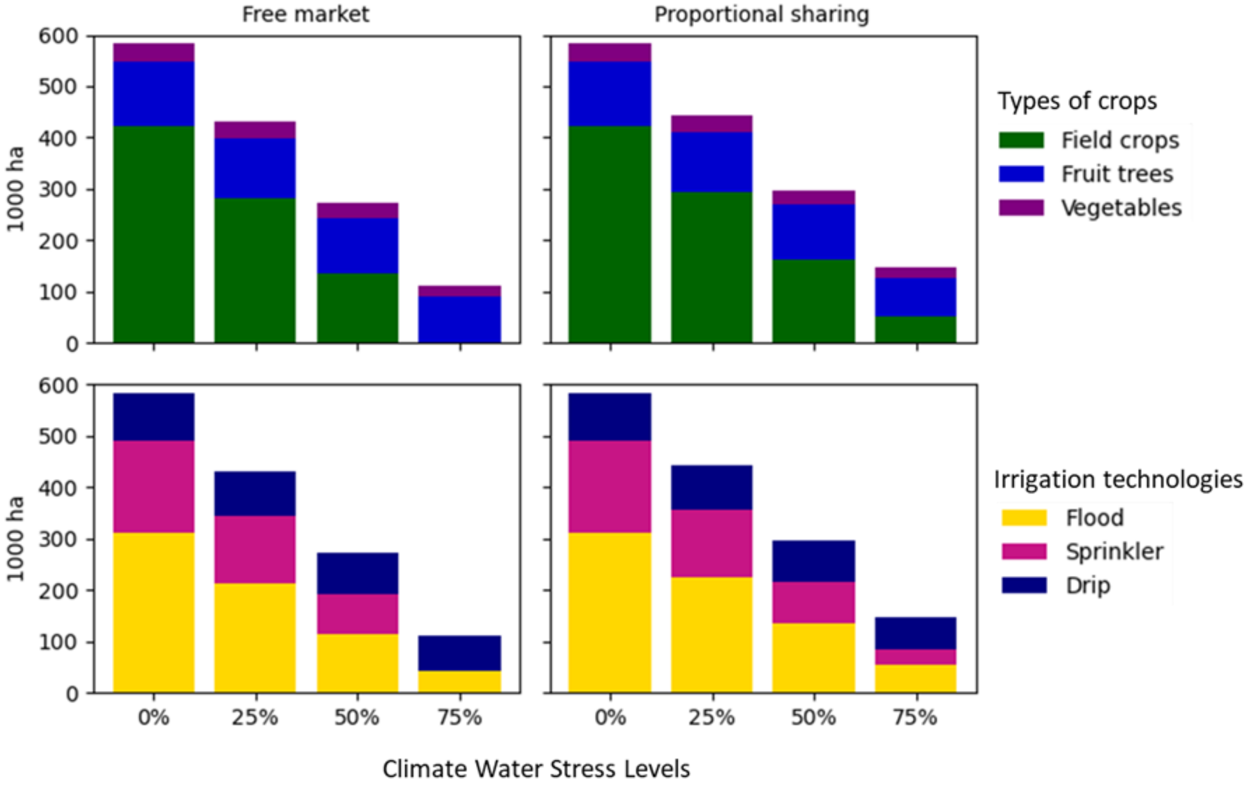
Climate water stress levels and water sharing policies illustrate the more efficient water and land management options for adaptation to water shortage, which vary by irrigation districts and respond to factors such as crop diversification, the efficiency of irrigation systems, and the access of water resources.

3.3.3. Economic Welfare

Table 3.5 presents results of the economic benefits of agricultural and urban sectors by climate water stress levels and water sharing policies in Millions of Euros per year. Results provide baseline information on benefits by crops, irrigation technologies in each irrigation district, and a consumer surplus by each city, using the Positive Mathematical Programming (PMP) in order to assess deviations from base policy and baseline water supply.

The results of this table show important two messages: First, the lion's share of economic benefits is produced by urban water use. Table 3.5 shows that 71% of the total economic welfare comes from urban consumer surplus, while farm income is only 29% of the Ebro benefits under the baseline condition. Climate stress reduces the economic benefits for agricultural and urban sectors. Under severe climate stress, urban benefits decline by 56% for proportional sharing policies and 0.2% for water trading. Despite this huge benefit loss under the proportional sharing policy, the urban sector still has a greater welfare share of overall benefits than agriculture. The high benefits losses are explained by the proportional decrease in water withdrawals in cities. The preservation of the water trading policy of urban benefits comes from free markets reallocation of scarce water from the lower-valued to higher-valued.

Figure 3. 5. Land in production by types of crops, irrigation technologies, climate water stress, and water sharing policies. Ebro River. Spain (1000 ha).



Second, unrestricted market trading minimizes the total benefits lost under each of the climate water stress levels, providing a smaller reduction in water use in cities. Table 3.5 shows that under the water trading policy, a reduction of 25% of the total water supply declines the economic benefits only by 1%. However, under severe climate stress, the total water supply decreases by 75%, and the economic welfares fall by 12.5%. These results highlight an interesting and counterintuitive message that states water trading minimizes the total benefits lost in the face of a large reduction of water use due to climate stress. This is explained by the low crop and city price elasticity of demand, which lower water use by city and agricultural production increase prices. This has the effect of increasing revenues more than boosts costs of production. Furthermore, water trading preserves the economic benefits of urban activity in all climate water stress levels. This is explained by the higher value of urban water use compared with crops value.

Table 3. 5. Economic Benefits by sectors by Climate Water Stress and Water Sharing policies. Ebro River. Spain. average over 5 years (Million Euro).

Water rules policies		**Free market**				**Proportional sharing**			
Climate water stress	**Sector**	**0%**	**25%**	**50%**	**75%**	**0%**	**25%**	**50%**	**75%**
Bilbao	U	1122.25	1122.12	1121.67	1118.94	1122.25	1052.11	841.69	490.99
Huesca	U	32.86	32.86	32.86	32.85	32.86	30.81	24.65	14.38
Lerida	U	105.22	105.22	105.21	105.20	105.22	98.64	78.91	46.03
Logroño	U	92.99	92.99	92.99	92.95	92.99	87.18	69.74	40.68
Pamplona	U	166.01	166.01	166.00	165.94	166.01	155.64	124.51	72.63
Tarragona	U	563.75	563.72	563.59	562.84	563.75	528.52	422.82	246.64
Vitoria	U	73.97	73.97	73.96	73.92	73.97	69.35	55.48	32.36
Zaragoza	U	305.14	305.14	305.12	305.04	305.14	286.07	228.86	133.50
Total		**2462.21**	**2462.02**	**2461.41**	**2457.68**	**2462.21**	**2308.32**	**1846.66**	**1077.22**
Bardenas canal	A	73.02	66.87	48.13	20.38	73.02	69.64	59.48	42.07
Aragon and Cataluña canal	A	276.51	270.58	251.50	203.37	276.51	268.44	243.95	198.79
Imperial canal	A	49.89	45.89	32.54	11.99	49.89	47.37	39.79	27.13
Jalon canal	A	64.29	63.50	60.83	54.62	64.29	62.24	55.95	31.86
Lodosa canal	A	122.11	119.94	113.16	97.41	122.11	118.16	105.88	69.38
Navarra canal	A	33.25	31.72	26.89	16.39	33.25	31.96	28.07	21.36
Tauste canal	A	9.82	9.05	6.45	2.72	9.82	9.34	7.91	5.52
Urgel canal	A	143.57	137.86	118.81	84.35	143.57	138.29	122.44	95.86
Delta canal	A	42.60	36.17	23.85	20.32	42.60	40.95	36.01	27.78
Rioja canal	A	60.58	59.67	56.62	49.24	60.58	58.67	52.93	36.11
Riegos Alto Aragon	A	131.38	121.55	90.20	18.56	131.38	124.25	102.83	66.26
Zadorra canal	A	15.09	14.81	13.89	11.50	15.09	14.51	12.78	8.32
Total		**1022.10**	**977.61**	**842.87**	**590.87**	**1022.10**	**983.81**	**868.03**	**630.45**
Ebro Benefits		**3484.31**	**3439.63**	**3304.28**	**3048.55**	**3484.31**	**3292.13**	**2714.69**	**1707.67**

3.3.4. Economic Value of Additional Water

Information for Climate Adaptation Plans

The shadow prices provide critical information to decision-makers, water stakeholders, and other interest groups seeking information on the performance and efficiency of policies. It guides a clearer understanding of the costs and benefits of policies. These values guide the economic attractiveness of climate water stress adaptation patterns and motivate the implementation of an alternative innovative water sharing policies. It measures the benefits of additional water that can be compared with raising costs of making the water available. Those shadow prices carry greater relevance especially in unrestricted water trading because the market forces efficiently allocate shortage-sharing responsibilities, for which marginal discounted net present value remains equal in all uses and time periods. The equalization of the shadow price across all cities and irrigation districts in the basin guides water management among all uses unless or until the marginal economic value of additional water becomes equal. An interactive decision-making discussion addresses urgent question of water pricing, water conservation, and climate water stress adaptation.

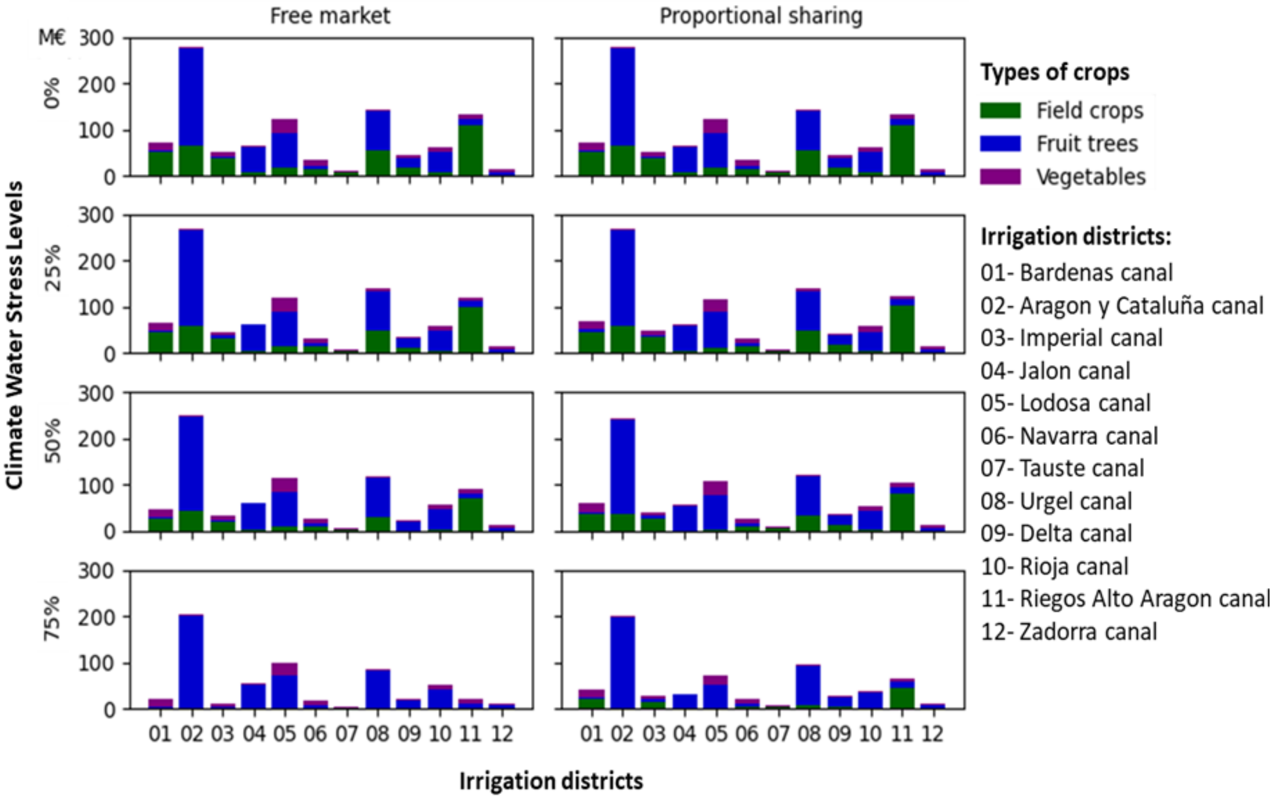
Guides for Efficient Policy Design

Table 3.6 shows the shadow price of water by city and irrigation district by climate water stress and water sharing policies in Euro per cubic meter. Shadow prices are zero under the baseline condition, and therefore under the baseline with full water supply, the shadow price of water is zero by water-sharing policies. This indicates that all farmers and cities are satisfied and there is no economic motivation to move water among cities and irrigation districts.

Shadow prices are uniformly higher when climate water stress becomes more severe. Table 3.6 illustrates as it is expected higher values of shadow prices with higher levels of climate water stress under water-sharing policies. The shadow price in lower climate stress by the free-market policy is equal to 0.12 Euro/m^3, which increases to 0.60 Euro/m^3 under severe climate stress. For proportional sharing, results indicate lower shadow price in each city and irrigation district under lower climate stress and higher values when climate stress become more intense. For example, the shadow price in Aragon and Cataluña canal is about 0.14 Euro/m^3 in lower climate water stress and increases to 0.77 Euro/m^3 under severe climate stress. This increase of shadow price under water scarcity and higher climate water stress levels highlights that climate water stress produces more difficulty in delivering water. These shadow prices shown in table 3.6 under different climate water stress indicate the maximum price that may be paid for an extra unit of scarce water if that extra water can be obtained through climate water adaptation policies. In addition, the high shadow price values in severe climate water stress demonstrates the climate plan informing utility of a basin scale hydroeconomic model, where complex hydrological, economic, and political interactions must be resolved.

Equalizing shadow prices among cities and irrigation districts under market trading, which is the least cost way to adapt to climate water stress. Table 3.6 shows an equal shadow price across all cities and irrigation districts under each climate water stress level for unrestricted water trading. This indicates that water moves among cities and irrigation districts until achieves an equal marginal value of an extra unit of water in all cities and irrigation districts. In other words, farms and cities are still moving water through markets buying and selling water in order to achieve an equal marginal economic value of water. The economic marginal value of water provides important information guiding the economic attractiveness of climate adaptation policies. It gives insight into the least cost way to adapt to climate water stress and the benefits of additional water, which can be compared with rising costs of making the water available.

Figure 3. 6. Economic value of crops by irrigation district, climate water stress, and water sharing policies. Ebro River. Spain (million Euro).



These findings suggest that the Ebro water authority and policymakers would secure a significant economic advantage from introduce an unrestricted water trading policy to replace or at least supplement the old and traditional method of water sharing. Similarly, implementing a proportionate sharing system would produce almost the high gain and may be more culturally acceptable. It should be noted that water trading is not always acceptable to all cultures in all time periods (Appelgren and Klohn, 1999).

3.3.5. Calibration for Climate Water Stress Adaptation: Positive Mathematical Programming

An innovative calibration model for urban and agricultural activities and climate water stress adaptation predictor is developed in this work using a mathematical programming model. These calibrated optimized values involved the observed values under base condition. In the tables 3.3, 3.4 and 3.5, we can see that the optimized calibrated value of water use by irrigated land, land in production and agricultural benefits in the base condition without climate water stress (0%) under water sharing policies equal to the observed values presented in the table 3.1. PMP calibration can replicate the observed resource use behavior and involve the first order conditions for profit maximization. The first order conditions for optimal resource use are used to estimate crop yield function parameters (Dagnino and Ward, 2012). Many studies use the

PMP calibration methods in agricultural sector (Baccour et al., 2021; Crespo et al., 2019; Kahil et al., 2015; Kahil et al., 2016; Salman et al., 2017). However, there is no study use the PMP calibration for consumer surplus of urban sector. The optimized value of water use by cities in the base conditions and the first years replicates the observed resource use behavior. For later years, the water use in urban cities increases with population growth. The calibration of both sectors under an optimization model provides a better assessment of water allocation, creating a water competition between cities and crops production especially under climate water stress levels. Our findings indicate that the competition among spatial locations move water from low valued to higher valued crops and cities, in order to minimize economic welfare losses.

This innovative model calibration enables the development of effective water allocation strategies and gives insight into the marginal behavioral reactions to climate water stress and water sharing policy. This important information support policy makers on the design of adaptation policies and could help to handle challenges posed by climate water stress.

3.4 Discussion

This paper has contributed to the literature by pointing the way to discover programs that control the economic benefits from water allocation between agricultural and urban sectors under climate water stress, while also respecting institutional needs for handling water shortages. Our research allows analysis of a variety of shortage sharing institutions related to the economic consequences of each institution. Furthermore, this study shows the potential of hydroeconomic modeling in promoting integrated assessment under various climate water stress adaptation policies, demonstrating that hydroeconomic modeling can inform climate adaptation plans by reducing the economic costs of responding to climate water stress. Results can help to identify the best policy options for climate adaptation, guiding policymakers in implementing these alternatives.

Designing and enacting unrestricted water trading or proportional sharing policy of water shortages demonstrate goals and means to allocate water efficiently among sectors reducing water use at minimum low costs to motivate and guide policy design. Well-informed water management will support optimized planning. That plan carries the potential to inform and guide decisions on the best economically and institutionally choices over periods. This work incrementally advances our understanding of measures to sustainably protect water resources under climate water stress that adapt to economic, hydrologic, and institutional features.

Table 3. 6. Incremental Value of Water by Climate Water Stress and Water Sharing Policies (Euro/cubic meter).

Climate water stress		**0%**	**25%**	**50%**	**75%**
Free market		0.00	0.12	0.25	0.60
Proportional sharing	**Sector**				
Bilbao	U	0.00	2.76	5.52	8.28
Huesca	U	0.00	8.67	17.34	26.00
Lerida	U	0.00	11.75	23.50	35.26
Logroño	U	0.00	7.28	14.57	21.85
Pamplona	U	0.00	7.07	14.14	21.22
Tarragona	U	0.00	3.73	7.47	11.20
Vitoria	U	0.00	5.53	11.06	16.59
Zaragoza	U	0.00	8.14	16.27	24.41
Bardenas canal	A	0.00	0.09	0.18	0.29
Aragon and Cataluña canal	A	0.00	0.14	0.29	0.77
Imperial canal	A	0.00	0.10	0.19	0.29
Jalon canal	A	0.00	0.19	0.46	1.95
Lodosa canal	A	0.00	0.16	0.36	1.37
Navarra canal	A	0.00	0.11	0.23	0.36
Tauste canal	A	0.00	0.10	0.19	0.29
Urgel canal	A	0.00	0.12	0.23	0.36
Delta canal	A	0.00	0.06	0.12	0.18
Rioja canal	A	0.00	0.18	0.36	1.42
Riegos Alto Aragon	A	0.00	0.10	0.21	0.32
Zadorra canal	A	0.00	0.18	0.35	1.16

Some simplifying assumptions were made for this work. For example, we present ongoing debates only between agricultural and urban sectors. The inclusion of other water users such as livestock, hydroelectric, and ecosystems could improve the assessment of water competition between uses to guide a broader sectoral scope of efficient allocation under climate water stress. Another simplification is that our climate change water stress scenarios abstract from the full range of complexities characterizing the frequency, intensity, and duration, and seasonality of future climate water stress conditions. Our work abstracts from these complexities by selecting only four selected levels of water climate stress, which are based on recent variations in headwater supplies. With the context of water sharing policies to adapt to climate water stress, the assessment of other water sharing institutions like the upstream or downstream institutions could have a great interest by scientists, stakeholders, and policymakers.

With the risks of climate water stress in Spain or other arid and semi-arid areas increasing the uncertainties over the sustainability of water resources, implementing economically efficient water sharing policies will face a growing interest. This interest will be sustained along with increased scrutiny as practical ways to adapt to the impacts of climate stress. However, the adoption of new policies such as unrestricted water trading must be culturally compatible with the institutions of the country.

Climate water stress, population growth, and poorly developed water sharing institutions in many arid and semi-arid river basins have increased the importance of designing institutions that adapt climate water stress and water supply variability. Despite limitations stated above, our findings provide an inspiring message to policy makers, water authorities, farm managers, and stockholders to design and implement practical water sharing institutions. Future economically motivated works could investigate sustainable water allocation by integrating climate, water, food, energy, and ecosystems with the rest of the economy, while also using the PMP calibration methods used in this study which would be a remarkable advance. Inclusion of water quality into the assessment of water scarcity is a topic of greater relevance, especially with climate variability and the high levels of contaminants entering water river basins from agricultural activities. Considering this is a coherent and important challenge for hydroeconomic adaptation.

Agent based modeling is also an innovative topic to address climate water stress adaptation and could be employed to determine the economic implications of the water users in our study area. Agent based modeling could also examine the effectiveness of several pathways towards the adoption of water conservation technologies in order to combat water scarcity and solve water resources depletion (Rasoulkhani et al., 2018).

3.5 Conclusions

This paper’s contribution has been to investigate the economic performance of a variety of water sharing policies to adapt to climate water stress and to protect water resources and food security under future uncertainties of climate variability while meeting growing demands for foods linked with raised population. To meet this gap, an empirical dynamic hydroeconomic model is developed for which optimized base conditions reflect the observed data of water use and economic welfare for several urban and irrigation districts in an important European river basin. This model is used to identify the efficiency of water sharing mechanisms in improving water allocation between sectors and reducing economic losses while protecting water resources and food security. Moreover, results using an innovative model calibration approach provide optimal water allocation plans, giving insight into marginal behavior responses to climate water stress policies.

The take home message from our findings is those accomplishments under unrestricted water trading or a proportional sharing of shortages provide significant grounds for optimism, made more pronounced in light of the economic value of additional water that offers critical information for decision makers in the assessment of the performance and efficiency of policies. Those values provide a clearer understanding of the costs and benefits of policies, giving the economic attractiveness of climate water stress adaptation patterns.

References

Alamanos A, Latinopoulos D, Papaioannou G, Mylopoulos N. Integrated Hydro-Economic Modeling for Sustainable Water Resources Management in Data-Scarce Areas: The Case of Lake Karla Watershed in Greece. Water Resources Management 2019; 33: 2775-2790.

Alamanos A, Tsota M, Mylopoulos N. Applying a novel framework for the estimation of the full cost of water in a degraded rural watershed. Water Policy 2021; 23: 617-632.

Appelgren B, Klohn W. Management of water scarcity: A focus on social capacities and options. Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere 1999; 24: 361-373.

Baccour S, Albiac J, Kahil T, Esteban E, Crespo D, Dinar A. Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain. Journal of Cleaner Production 2021; 327: 13.

Bekchanov M, Lamers JPA. The Effect of Energy Constraints on Water Allocation Decisions: The Elaboration and Application of a System-Wide Economic-Water-Energy Model (SEWEM). Water 2016; 8: 26.

Bekchanov M, Ringler C, Bhaduri A. A WATER RIGHTS TRADING APPROACH TO INCREASING INFLOWS TO THE ARAL SEA. Land Degradation & Development 2018; 29: 952-961.

Bekchanov M, Ringler C, Bhaduri A, Jeuland M. How would the Rogun Dam affect water and energy scarcity in Central Asia? Water International 2015; 40: 856-876.

Bekchanov M, Ringler C, Bhaduri A, Jeuland M. Optimizing irrigation efficiency improvements in the Aral Sea Basin. Water Resources and Economics 2016; 13: 30-45.

Bierkens MFP, Reinhard S, de Bruijn JA, Veninga W, Wada Y. The Shadow Price of Irrigation Water in Major Groundwater-Depleting Countries. Water Resources Research 2019; 55: 4266-4287.

Blanco-Gutierrez I, Varela-Ortega C, Purkey DR. Integrated assessment of policy interventions for promoting sustainable irrigation in semi-arid environments: A hydro-economic modeling approach. Journal of Environmental Management 2013; 128: 144-160.

Booker JF, Howitt RE, Michelsen AM, Young RA. ECONOMICS AND THE MODELING OF WATER RESOURCES AND POLICIES. Natural Resource Modeling 2012; 25: 168-218.

Boucher MA, Tremblay D, Delorme L, Perreault L, Anctil F. Hydro-economic assessment of hydrological forecasting systems. Journal of Hydrology 2012; 416: 133-144.

Bovolo C, Blenkinsop S, Majone B, Zambrano-Bigiarini M, Fowler H, Bellin A, et al. Climate Change, Water Resources and Pollution in the Ebro Basin: Towards an Integrated Approach. In The Ebro River Basin, Springer-Verlag Berlin Heidelberg, 2010, pp. 295-329.

Brouwer R, Hofkes M. Integrated hydro-economic modelling: Approaches, key issues and future research directions. Ecological Economics 2008; 66: 16-22.

Carolus JF, Bartosova A, Olsen SB, Jomaa S, Veinbergs A, Zilans A, et al. Nutrient mitigation under the impact of climate and land-use changes: A hydro-economic approach to participatory catchment management. Journal of Environmental Management 2020; 271: 13.

CEDEX. (Center for Studies and Experimentation of Public Works), Anuario de Aforos 2015–2016, Dirección General del Agua. MAPAMA, Madrid., 2016.

CEDEX. (Center for Studies and Experimentation of Public Works). Evaluación del impacto del cambio climático en los recursos hídricos y sequías en España. Anexo 1: Tendencias y cambio de estadísticos para cada proyección. MAPAMA, Madrid., 2017.

CHE. (Confederación Hidrográfica del Ebro), Plan Hidrológico de la Demarcación Hidrográfica del Ebro, Memoria. MAPAMA. Zaragoza., 2015.

CHE. (Confederación Hidrográfica del Ebro), Prospecto del Plan Hidrológico de la Demarcación

Hidrográfica del Ebro., MAPAMA, Zaragoza., 2016.

CHE. (Confederación Hidrográfica del Ebro), Memoria. MITECO. Zaragoza., 2020.

Crespo D, Albiac J, Kahil T, Esteban E, Baccour S. Tradeoffs between Water Uses and Environmental Flows: A Hydroeconomic Analysis in the Ebro Basin. Water Resources Management 2019; 33: 2301-2317.

Dagnino M, Ward FA. Economics of Agricultural Water Conservation: Empirical Analysis and Policy Implications. International Journal of Water Resources Development 2012; 28: 577-600.

EEA. Climate impacts on water resources., 2007.

Escriva-Bou A, Pulido-Velazquez M, Pulido-Velazquez D. Economic Value of Climate Change Adaptation Strategies for Water Management in Spain's Jucar Basin. Journal of Water Resources Planning and Management 2017; 143: 13.

Essenfelder AH, Perez-Blanco CD, Mayer AS. Rationalizing Systems Analysis for the Evaluation of Adaptation Strategies in Complex Human-Water Systems. Earths Future 2018; 6: 1181-1206.

Esteve P, Varela-Ortega C, Blanco-Gutierrez I, Downing TE. A hydro-economic model for the assessment of climate change impacts and adaptation in irrigated agriculture. Ecological Economics 2015; 120: 49-58.

Forero-Ortiz E, Martinez-Gomariz E, Monjo R. Climate Change Implications for Water Availability: A Case Study of Barcelona City. Sustainability 2020; 12: 15.

Foudi S, Oses-Eraso N, Tamayo I. Integrated spatial flood risk assessment: The case of Zaragoza. Land Use Policy 2015; 42: 278-292.

George B, Malano H, Davidson B, Hellegers P, Bharati L, Massuel S. An integrated hydro-economic modelling framework to evaluate water allocation strategies I: Model development. Agricultural Water Management 2011; 98: 733-746.

Gohar AA, Cashman A, Ward FA. Managing food and water security in Small Island States: New evidence from economic modelling of climate stressed groundwater resources. Journal of Hydrology 2019; 569: 239-251.

Goor Q, Kelman R, Tilmant A. Optimal Multipurpose-Multireservoir Operation Model with Variable Productivity of Hydropower Plants. Journal of Water Resources Planning and Management 2011; 137: 258-267.

Graveline N. Combining flexible regulatory and economic instruments for agriculture water demand control under climate change in Beauce. Water Resources and Economics 2020; 29: 20.

Guan D, Hubacek K. Assessment of regional trade and virtual water flows in China. Ecological Economics 2007; 61: 159-170.

Guan D, Hubacek K. A new and integrated hydro-economic accounting and analytical framework for water resources: A case study for North China. Journal of Environmental Management 2008; 88: 1300-1313.

Harou JJ, Lund JR. Ending groundwater overdraft in hydrologic-economic systems. Hydrogeology Journal 2008; 16: 1039-1055.

Harou JJ, Medellin-Azuara J, Zhu TJ, Tanaka SK, Lund JR, Stine S, et al. Economic consequences of optimized water management for a prolonged, severe drought in California. Water Resources Research 2010; 46: 12.

Harou JJ, Pulido-Velazquez M, Rosenberg DE, Medellin-Azuara J, Lund JR, Howitt RE. Hydro-economic models: Concepts, design, applications, and future prospects. Journal of Hydrology 2009; 375: 627-643.

Heinz I, Pulido-Velazquez M, Lund JR, Andreu J. Hydro-economic modeling in river basin management: Implications and applications for the European Water Framework Directive. Water Resources Management 2007; 21: 1103-1125.

Herivaux C, Orban P, Brouyere S. Is it worth protecting groundwater from diffuse pollution with agri-environmental schemes? A hydro-economic modeling approach. Journal of Environmental Management 2013; 128: 62-74.

Hervas-Gamez C, Delgado-Ramos F. Cross-Subsidies between Water Users in Spain: the Guadalquivir River Basin Case. Water Resources Management 2020; 34: 4577-4591.

Howitt RE. POSITIVE MATHEMATICAL-PROGRAMMING. American Journal of Agricultural Economics 1995; 77: 329-342.

Howitt RE, Medellin-Azuara J, MacEwan D, Lund JR. Calibrating disaggregate economic models of agricultural production and water management. Environmental Modelling & Software 2012; 38: 244-258.

IPCC. Climate Change 2021: The Physical Science Basis. Working Group I to the Six Assessment Report of the Intergovernmental Panel on Climate Change. WMO-UNEP, Geneva., 2021.

Jalilov SM. Emergence of Water-Energy-Food Nexus Resulting from Interbasin Water Transfer: Economic Analysis for a Transboundary River Basin in South Asia. Journal of Water Resources Planning and Management 2021; 147: 15.

Jalilov SM, Amer SA, Ward FA. Managing the water-energy-food nexus: Opportunities in Central Asia. Journal of Hydrology 2018; 557: 407-425.

Jalilov SM, Keskinen M, Varis O, Amer S, Ward FA. Managing the water-energy-food nexus: Gains and losses from new water development in Amu Darya River Basin. Journal of Hydrology 2016; 539: 648-661.

Jalilov SM, Varis O, Keskinen M. Sharing Benefits in Transboundary Rivers: An Experimental Case Study of Central Asian Water-Energy-Agriculture Nexus. Water 2015; 7: 4778-4805.

Johnson T, Weaver C. A Framework for Assessing Climate Change Impacts on Water and Watershed Systems. Environmental Management 2009; 43: 118-134.

Kahil MT, Dinar A, Albiac J. Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. Journal of Hydrology 2015; 522: 95-109.

Kahil MT, Ward FA, Albiac J, Eggleston J, Sanz D. Hydro-economic modeling with aquifer-river interactions to guide sustainable basin management. Journal of Hydrology 2016; 539: 510-524.

Kirby JM, Connor J, Ahmad MD, Gao L, Mainuddin M. Climate change and environmental water reallocation in the Murray-Darling Basin: Impacts on flows, diversions and economic returns to irrigation. Journal of Hydrology 2014; 518: 120-129.

Klein SJW, Whalley S. Comparing the sustainability of US electricity options through multi-criteria decision analysis. Energy Policy 2015; 79: 127-149.

Koch H, Grunewald U. A Comparison of Modelling Systems for the Development and Revision of Water Resources Management Plans. Water Resources Management 2009; 23: 1403-1422.

Koutroulis AG, Papadimitriou LV, Grillakis MG, Tsanis IK, Wyser K, Betts RA. Freshwater vulnerability under high end climate change. A pan-European assessment. Science of the Total Environment 2018; 613: 271-286.

Kragt ME, Newham LTH, Bennett J, Jakeman AJ. An integrated approach to linking economic valuation and catchment modelling. Environmental Modelling & Software 2011; 26: 92-102.

Lopez-Nicolas A, Pulido-Velazquez M, Rouge C, Harou JJ, Escriva-Bou A. Design and assessment of an efficient and equitable dynamic urban water tariff. Application to the city of Valencia, Spain. Environmental Modelling & Software 2018; 101: 137-145.

Maneta MP, Torres MO, Wallender WW, Vosti S, Howitt R, Rodrigues L, et al. A spatially distributed hydroeconomic model to assess the effects of drought on land use, farm profits, and agricultural employment. Water Resources Research 2009; 45: 19.

MAPAMA. (Spanish Ministry of Agriculture and Fisheries, Food and Environment). Evaluación del impacto del cambio climático en los recursos hídricos y sequías en España. 2017.

Molina JL, Pulido-Velazquez M, Llopis-Albert C, Pena-Haro S. Stochastic hydro-economic model for groundwater quality management using Bayesian networks. Water Science and Technology 2013; 67: 579-586.

Nechifor V, Winning M. Global Economic and Food Security Impacts of Demand-Driven Water Scarcity-Alternative Water Management Options for a Thirsty World. Water 2018; 10: 20.

Pena-Haro S, Pulido-Velazquez M, Sahuquillo A. A hydro-economic modelling framework for optimal management of groundwater nitrate pollution from agriculture. Journal of Hydrology 2009; 373: 193-203.

Perez-Blanco CD, Gonzalez-Lopez H, Hrast-Essenfelder A. Beyond piecewise methods: Modular integrated hydroeconomic modeling to assess the impacts of adaptation policies in irrigated agriculture. Environmental Modelling & Software 2021; 136: 16.

Primavera JH. INTENSIVE PRAWN FARMING IN THE PHILIPPINES - ECOLOGICAL, SOCIAL, AND ECONOMIC-IMPLICATIONS. Ambio 1991; 20: 28-33.

Pulido-Velazquez M, Andreu J, Sahuquillo A, Pulido-Velazquez D. Hydro-economic river basin modelling: The application of a holistic surface-groundwater model to assess opportunity costs of water use in Spain. Ecological Economics 2008; 66: 51-65.

Qureshi ME, Hanjra MA, Ward J. Impact of water scarcity in Australia on global food security in an era of climate change. Food Policy 2013; 38: 136-145.

Rasoulkhani K, Logasa B, Reyes MP, Mostafavi A. Understanding Fundamental Phenomena Affecting the Water Conservation Technology Adoption of Residential Consumers Using Agent-Based Modeling. Water 2018; 10: 24.

Ray PA, Yang YCE, Wi S, Khalil A, Chatikavanij V, Brown C. Room for improvement: Hydroclimatic challenges to poverty-reducing development of the Brahmaputra River basin. Environmental Science & Policy 2015; 54: 64-80.

Roudier P, Andersson JCM, Donnelly C, Feyen L, Greuell W, Ludwig F. Projections of future floods and hydrological droughts in Europe under a+2 degrees C global warming. Climatic Change 2016; 135: 341-355.

Ruperez-Moreno C, Senent-Aparicio J, Martinez-Vicente D, Garcia-Arostegui JL, Calvo-Rubio FC, Perez-Sanchez J. Sustainability of irrigated agriculture with overexploited aquifers: The case of Segura basin (SE, Spain). Agricultural Water Management 2017; 182: 67-76.

Sadoff C, Harshadeep NR, Blackmore D, Wu X, O'Donnell A, Jeuland M, et al. Ten fundamental questions for water resources development in the Ganges: myths and realities. Water Policy 2013; 15: 147-164.

Salman D, Amer SA, Ward FA. Protecting food security when facing uncertain climate: Opportunities for Afghan communities. Journal of Hydrology 2017; 554: 200-215.

Satoh Y, Kahil T, Byers E, Burek P, Fischer G, Tramberend S, et al. Multi-model and multi-scenario assessments of Asian water futures: The Water Futures and Solutions (WFaS) initiative. Earths Future 2017; 5: 823-852.

Udias A, Gentile A, Burek P, de Roo A, Bouraoui F, Vandecasteele I, et al. Multi-Criteria Framework to Assess Large Scale Water Resources Policy Measures. Water 2016; 8: 21.

Varela-Ortega C, Blanco-Gutierrez I, Esteve P, Bharwani S, Fronzek S, Downing TE. How can irrigated agriculture adapt to climate change? Insights from the Guadiana Basin in Spain. Regional Environmental Change 2016; 16: 59-70.

Varela-Ortega C, Blanco-Gutierrez I, Swartz CH, Downing TE. Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: An integrated hydro-economic modeling framework. Global Environmental Change-Human and Policy Dimensions 2011; 21: 604-619.

Verkade JS, Werner MGF. Estimating the benefits of single value and probability forecasting for flood warning. Hydrology and Earth System Sciences 2011; 15: 3751-3765.

Wang H, Lall S. Valuing water for Chinese industries: a marginal productivity analysis. Applied Economics 2002; 34: 759-765.

Ward FA, Amer SA, Ziaee F. Water allocation rules in Afghanistan for improved food security. Food Security 2013; 5: 35-53.

Ward FA, Pulido-Velazquez M. Efficiency, equity, and sustainability in a water quantity-quality optimization model in the Rio Grande basin. Ecological Economics 2008; 66: 23-37.

Ward FA, Salman D, Amer SA. Managing food-ecosystem synergies to sustain water resource systems. Science of the Total Environment 2021; 796: 16.

Ward J, Kaczan D. Challenging Hydrological Panaceas: Water poverty governance accounting for spatial scale in the Niger River Basin. Journal of Hydrology 2014; 519: 2501-2514.

WMO. (World Meteorological Organization), 2021 STATE OF CLIMATE SERVICES WATER, 2021.

Yang YCE, Wi S, Ray PA, Brown CM, Khalil AF. The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories. Global Environmental Change-Human and Policy Dimensions 2016; 37: 16-30.

Ziolkowska JR. Shadow price of water for irrigation - A case of the High Plains. Agricultural Water Management 2015; 153: 20-31.

CHAPTER 4

ECOSYSTEMS IN WEFE NEXUS PLANNING ENHANCE WATER SECURITY AND BIODIVERSITY FOR CLIMATE RESILIENCE

Chapter 4 Ecosystems in WEFE nexus planning enhance water security and biodiversity for climate resilience

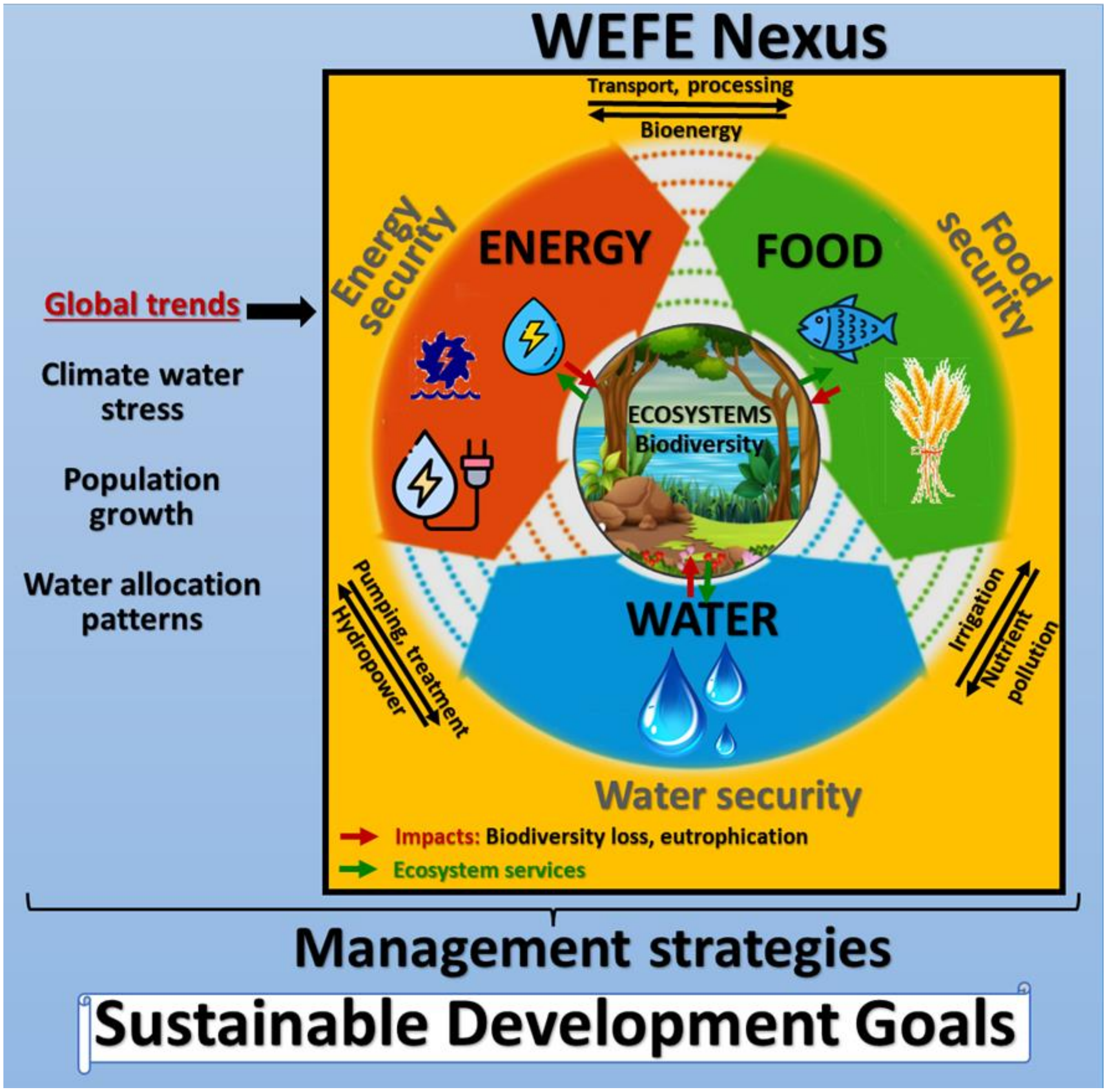
Abstract

Safe, reliable, and equitable water access is critical for sustaining healthy livelihoods. Climate water stress is a growing challenge internationally making it difficult to achieve sustainable management of river basins. Addressing the problem requires bold untried integrated multi-sector water management strategies for climate resilience. The Water-Energy-Food-Ecosystems (WEFE) nexus offers promises as an innovative and comprehensive framework to guide science-based plans for sustainable development goals. Several nexus approaches have been proposed in previous works. However, none to date has conceptualized, formulated, tested, validated, and applied a comprehensive dynamic optimization framework that includes several water-using sectors including ecosystems for a significant river basin supporting livelihoods of large numbers of people. None to date has assessed tradeoffs among competing water uses that could measurably advance water, food, energy, and environmental security. The original contribution of this paper is to make headway on filling these gaps, taking Spain's Ebro Basin as a case study, providing evidence to guide science-based policy reform. This work's innovations illustrate the previously untried use of information to guide proposed water allocations among several economic sector including protection of key ecological assets. Results provide a rigorous framework for measuring the level and distribution of benefits and costs among sectors and stakeholders. Findings support science-informed design of efficient, flexible, and equitable water planning. Results show outcomes that reduce sectoral vulnerabilities and promote sustainable development. Results indicate a range of options that improve the hydrologic and economic performance of water management compared to the current policy for addressing with climate change. Policy options that systematically account for the full range of benefits of environmental flows guide science-informed strategies for climate resilience. They can increase stream flows in rivers, enhance water security and biodiversity, and reduce the economic burdens imposed by climate risks.

Significance Statement

Discovering sustainable water management strategies for adapting to climate stress requires discovery of realistic synergies and tradeoffs within the water-food-energy-ecosystem nexus, requiring an integrated modeling approach. This study conceptualizes and formulates an integrated optimization framework at basin scale that accounts for spatial and temporal water allocations in economic and environment sectors.

Forecast outcomes from future climate stress scenarios are assessed under a range of potential management options. Findings reveal that systematically accounting for ecosystem services to guide integrated multi sector water plans advance human water security and natural biodiversity, while limiting sectoral vulnerability and future climate risks.



Keywords: WEFE nexus, hydroeconomic modeling, environmental flows, climate resilience and adaptation, management strategies.

4.1 Introduction

Communities internationally face hard choices to sustain supplies of water, energy, land, and food, while protecting key ecological assets. Pressure on these resources is driven by the growing global population, wealth, urbanization, and consumption (Future Earth, 2018; Zhang et al., 2018). The question remains how to meet sustainable economic and environmental goals with the current or potential natural resources, which have been stressed by poorly-informed management in recent decades (Harwood, 2018). The response has been a growing international call for a 'nexus approach' linking development, conservation, and use of natural resources (Finley and Seiber, 2014). The Bonn Conference addressed the interaction of sectors, focusing on how a nexus approach if implemented could grow water, energy, and food security if a science-informed framework could be established to promote cross sector complementarities (Hoff, 2011; The Nexus Resource Platform, 2011). The Food and Agriculture Organization of the United Nations has investigated the potential gains from applying the nexus approach (FAO, 2013; Flammini et al., 2014), and the European Commission has included food-energy-water-climate linkages among challenges facing its Horizon research and innovation program (European Commission, 2021).

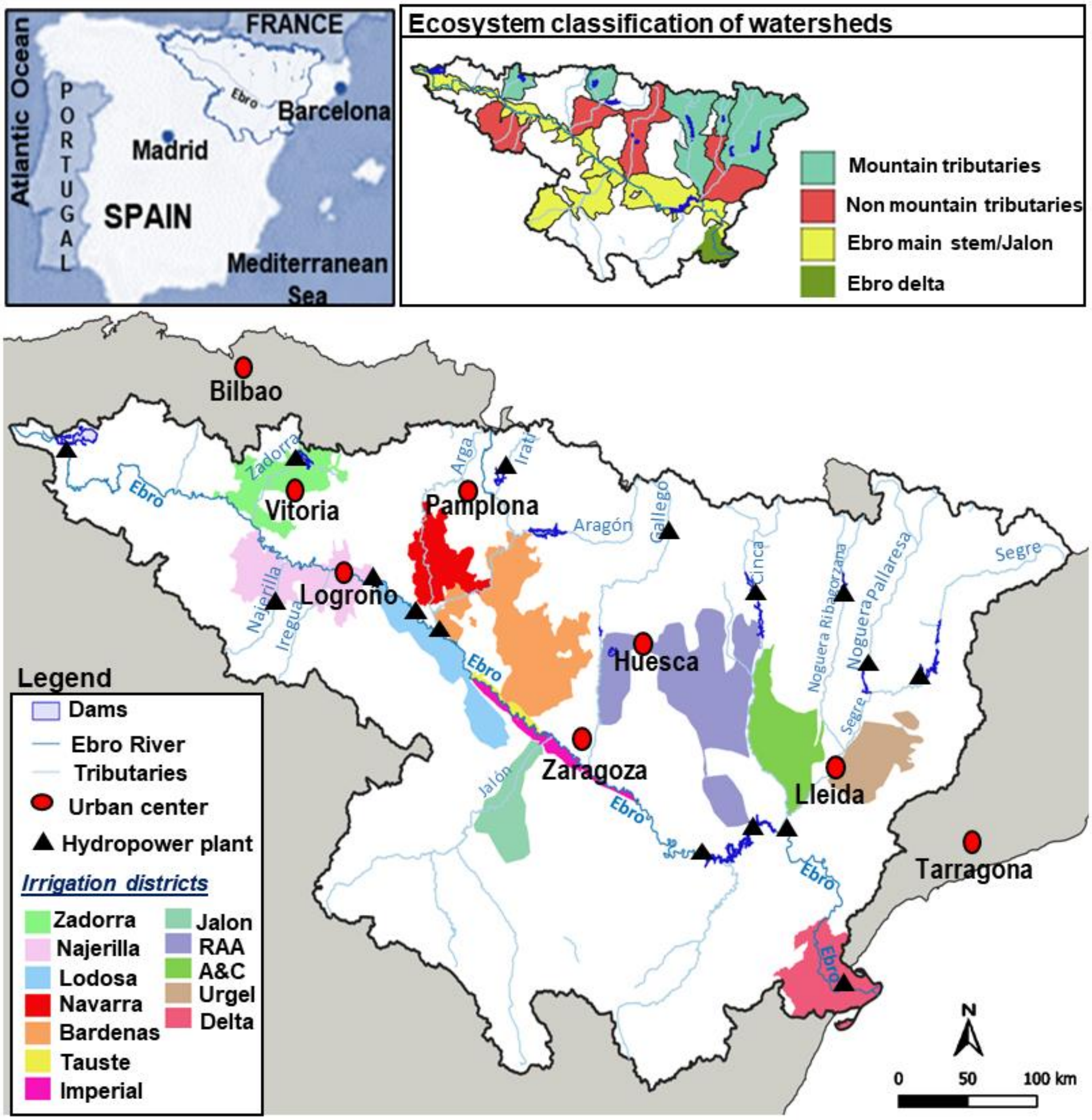
The nexus is a systems-based approach representing links among water, energy, food, and environmental systems. This cross-sectoral integration if implemented systematically when underpinned by rigorous science is believed to have the capacity to achieve sustainable development (Endo et al., 2017). The nexus approach is believed to have the capacity discover latent synergies among sectors, to light the path to improve water, energy, food and environmental security. A few works have implemented elements of the nexus approach to identify some sector interactions in basins. The hydropower sector has been examined to assess effects of energy taxes (Sun et al., 2021) and power y prices (Gaudard et al., 2018) as well as links among energy, water and ecosystems (Amjath-Babu et al., 2019; Basso et al., 2020; Chen et al., 2020). Other works have implemented the nexus approach to assess sustainability of environmental resources (Biggs et al., 2015; Conway et al., 2015; Daher and Mohtar, 2015; Liu et al., 2018; Rasul, 2014; Rasul and Sharma, 2016; Wang et al., 2018). Others have implemented a nexus approach to advance Sustainable Development Goals (Liu et al., 2018; Yoon et al., 2021).

The integration of ecosystem services as an element of the nexus approach has been recognized recently for sustainable resource management, although environmental services have to date been weakly-addressed in nexus studies (Hulsmann et al., 2019; Liu et al., 2017; Liu et al., 2018). Both the global 2030 Agenda for Sustainable Development and the European Green Deal with an aim of making Europe climate neutral by 2050 have called for including ecosystem services in nexus studies. Works by Carmona-Moreno et al. (2021) and Kebede et al. (2021) accounted for ecosystems in their nexus implementation. Also, several authors and institutions (ICIMOD, 2012; Karabulut et al., 2018; UNECE, 2018; Yuan and Lo, 2020) indicate the pivotal role played by ecosystems in nexus interconnections: ecosystem services are pillars to maintain biodiversity and support availability of food, water, land, and energy. The problem for including the environment in the nexus is information to systematically account for ecosystem benefits at the basin scale is rarely available at present.

Despite significant advances in nexus modeling at the basin scale, there remain numerous challenges to develop comprehensive and reliable nexus model implementations capable of representing the basin hydrological network, resource user behavior by sector and location, and ecosystem responses to variations in streamflow. Bekchanov et al. (2019) propose using the hydroeconomic modeling framework for addressing the water-food-energy-environment nexus at the basin scale. However, reviews of the peer-reviewed hydroeconomic literature concludes that feedbacks across nexus elements are incomplete, the institutional and policy features are weakly-included in modeling, and nexus principles are disconnected from decision tools provided by hydroeconomic modeling, precluding practical and integrated policy guidance. There are many nexus studies dealing with different sectors in several locations. Still, few have presented an integrated hydroeconomic optimization framework that assesses the spatial and temporal interconnections among water, food, energy and ecosystems, under climate change scenarios for selected climate adaptation policies. Hulsmann et al. (2019) indicate that ecosystems are mostly missing in nexus assessments despite being essential for sustainable management, leading to a call for a more rigorous accounting of ecosystem elements in nexus assessments.

This paper addresses these gaps by conceptualizing, formulating, applying, and assessing an integrated hydroeconomic modeling framework addressing future climate risks in order to identify affordable and sustainable climate adaptation strategies. The model systematically accounts for nexus elements among competing sectors (agriculture, energy, urban and ecosystems) for a series of water management strategies under climate water stress scenarios (CC-2070, CC-2100), taking Spain's Ebro River Basin as a case study (Figure 4.1). The cross-sectoral integration, after being conceptualized, is applied to discover synergies among sectors and spatial locations, uncovering insights into the extent of gains and losses among the elements. This analysis shows the efforts and related compensations among groups of stakeholders as well as workable interventions that could bring about resilience and adaptation to drought events.

Figure 4. 1. Case study.



The potential of water management strategies to achieve water, food, and energy security and ecosystem protection is assessed. Findings reveal affordable measures that have a measured potential to limit sector vulnerability, reduce risks of water stress, and improve climate resilience. Results provide information on water reallocations among economic and environmental sectors, locations, and time periods and the associated distribution of benefits and cost of polices among those same dimensions. Findings provided can inform improved management to enhance water, food and energy security as well as ecosystems protection through improved environmental flows. Findings are important to guide decision making in arid and semiarid regions, which are strongly vulnerable to human activities as well as elevated water stress induced by climate change.

4.2 Materials and methods

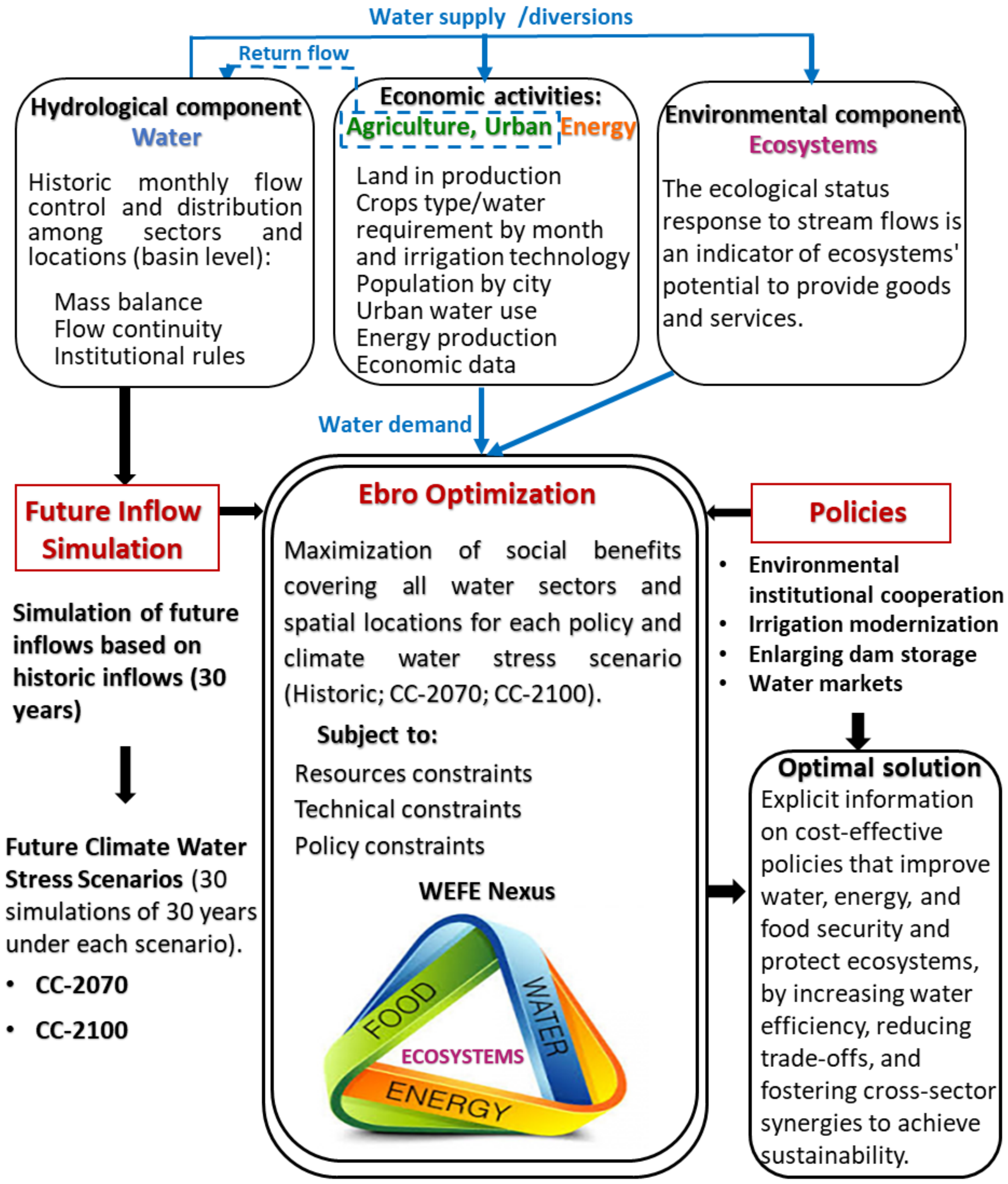
4.2.1 Modeling framework

The WEFE nexus is characterized by using integrated hydroeconomic modeling, where water can be spatially and temporally allocated between different sectors (agriculture, urban, hydropower, and ecosystems), under a range of policy options and climate water stress scenarios. The challenge of combining the use of water, energy, food and ecosystem services into one integrated planning and management framework is demanding, and calls for an intensive use of data and advanced methods. The WEFE nexus assessment is based on an empirical hydroeconomic model developed using the GAMS® (General Algebraic Modeling System with the CONOPT4 solver) software. The model is an extension of previous modeling work (Baccour et al., 2021; Baccour et al., 2022). The model is specified as a dynamic optimization problem with multisector benefits in the objective function, and with biophysical, technical, resource availability and institutional information in the constraints. The objective function maximizes social benefits of WEFE sectors across basin locations, under current and future climate conditions. There are three components in the model; the hydrological, regional economic, and environmental components (Figure 4.2), which are described below.

The hydrological component is a reduced form hydrological representation of the Ebro basin. It represents flows between supply and demand nodes, using the hydrological principles of water mass balance and flow continuity in the river (Figure 4.3). The hydrological component shows the spatial distribution of water between economic sectors and environmental flows, and the model dynamics is driven by the water storage in reservoirs. This component is calibrated introducing auxiliary variables for river reaches, so that predicted gauged flows are broadly consistent with observed flows at each river gauge (see chapter 2 and 3).

The regional economic component consists of optimization problems for water allocated to irrigation districts, hydropower plants, and urban settlements. There is an optimization program 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 (see chapter 2). The optimization program for urban water maximizes economic surplus, the sum of consumer and producer surpluses in the basin's main cities (see chapter 3), and the optimization of hydropower maximizes the benefits of electricity production. Positive Mathematical Programming (PMP) is used to calibrate agriculture and urban sectors at the baseline observed data of water allocations, following Baccour et al. (2022).

Figure 4. 2 WEFE nexus modeling framework.



Electricity generated at hydropower plants in the Ebro basin comes mostly from power plants in reservoirs that have an elevation drop, with some additional generation from run-of-the-river power plants. The water stored in dams is used to power turbines that convert the fallowing water into mechanical energy and then to electricity. Hydropower production in the Ebro basin comes from hydropower plants operated in most reservoirs in the basin, such as Ebro, Ulivarri, Grado-Mediano, Mequinenza, La Sotonera, Camarasa, Rialb-Oliana and Santa Ana, and from some "run-of-the-river" power plants located in the mainstream of the Ebro.

The benefit from hydroelectric production $B_{HPplant,t}^{HP}$ is determined by maximizing the net income from energy generation. The hydropower benefit is equal to the amount of energy produced each month $HPprod_{HPplant,t,m}$ multiplied by the monthly electricity price $Pelec_m$, minus production costs C in the plant. The production features of each hydropower plant $HPplant$ are embedded in equations (4.2) to (4.5). Equation (4.2) shows the upper limit of water that can feed the turbines in plant $HPplant$ each month, which depends on the capacity of turbines. Equation (4.3) represents the head of each reservoir which is function of reservoir storage. Equation (4.4) relates the production of electricity in plant $HPplant$ with the water fed to the turbines, where $W_{HPplant,t,m}$ is fed water in Mm^3, $Prod_{HPplant,t,m}$ is hydropower production per unit of water (GWh/Mm^3), and $(H_{HPplant,t,m}/Hmax_{HPplant,t,m})$ is the water level in the reservoir divided by the maximum reservoir water level. Equation (4.5) shows the hydropower plant's capacity to produce energy and limits the annual energy production by summing the hydropower generated each month.

$$Max\ B_{HPplant,t}^{HP} = \sum_m HPprod_{HPplant,t,m} \cdot (Pelec_m - C) \tag{4.1}$$

subject to

$$W_{HPplant,t,m} \leq UpLimWater_{HPplant,t,m} \tag{4.2}$$

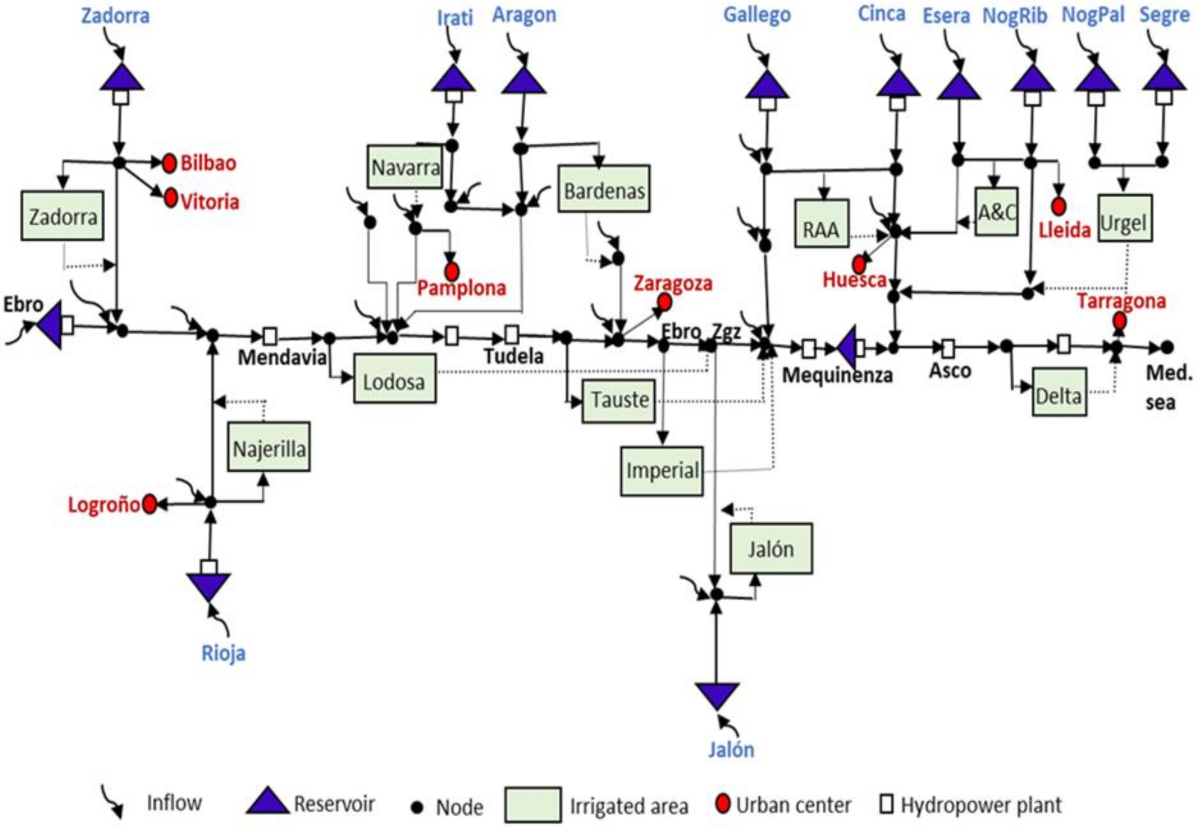
$$H_{HPplant,t,m} = b_1\, Z_{resHP,t,m} + b_2\, {Z_{resHP,t,m}}^2 + b_3\, {Z_{resHP,t,m}}^3 \tag{4.3}$$

where index *resHP* only includes reservoirs having hydropower plants

$$HPprod_{HPplant,t,m} = (H_{HPplant,t,m}/Hmax_{HPplant,t,m}) * W_{HPplant,t,m} * Prod_{HPplant,t,m} \tag{4.4}$$

$$\sum\nolimits_m HPprod_{HPplant,t,m} \leq THPprod_{HPplant,t} \tag{4.5}$$

Figure 4. 3. Network of the Ebro Basin.



The environmental component includes the ecosystem health levels and associated environmental benefits. The approach for establishing environmental flows is based on the habitat's simulation analysis, where habitat suitability is related to water velocity, river depth, and riverbed composition. Habitat's simulation methodology evaluates the environmental flow requirement, and accounts for hydrological, physical, mechanical proprieties, and biological relationships. The suitability values are assigned to the area of river reaches to determine the weighted usable area WUA. The river reach is divided into cells where river depth and water velocity are simulated for streamflow levels. The simulation results and riverbed composition by the cell are evaluated using indexes in the habitat preference function, which connects streamflow and habitat adequacy. The WUA is the sum of the suitability habitats index weighted by the size of the cell over the total area of river reach, determining the habitat potential to host some aquatic species given the river streamflow.

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. This 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 (Lamouroux and Jowett, 2005; Wilding et al., 2014). The relationship relating WUA with streamflow is a linear function with a plateau, which approximates well the empirical data provided by the Ebro basin authority on river reaches (CHE, 2015). The variable $WUA_{e,t,m}$ is defined as the fraction of WUA over the maximum WUA attained in river reach e, so the variable range is between zero when flow is zero and one as flow rises. The WUA equation is given by:

$$WUA_{e,t,m} = \propto_e \cdot W_{e,t,m} \tag{4.6}$$

where $WUA_{e,t,m}$ depends on water flow $W_{e,t,m}$ at each river reach *e*, time *t* and month *m*. Parameter $\propto_e$ has been estimated for each of the 14 river reaches *e*, based on the ecological studies of the Ebro basin authority for setting environmental flows (CHE, 2015).

Equation (4.7) defines the health status $EW_{e,t,m,s,p}^{ecos}$ of ecosystem *ecos* in river reach e, which is equal to $WUA_{e,t,m}$, and takes values between zero and one.

$$EW_{e,t,m}^{ecos} = WUA_{e,t,m} \tag{4.7}$$

The benefits of ecosystem services in each river reach are defined by:

$$B_{e,t}^{ecos} = \sum_m EW_{e,t,m}^{ecos} \cdot l_e \cdot EV_e \tag{4.8}$$

where environmental benefits $B_{e,t}^{ecos}$ depend on the ecosystem health status $EW_{e,t,m}^{ecos}$ (between 0 and 1), multiplied by l_e which is the length in kilometers of river reach *e*, and by EV_e which is the economic valuation in Euro/km of ecosystem services in river reach *e*.

The economic valuation of ecosystem services EV_e is obtained from published studies in the literature. Values are usually given in euros per hectare and year for the 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 of freshwater bodies and wetlands in the literature ranges from 20,000 to 75,000 Euro/ha per year of riverbed covered by water (TEEB, 2010; Troy and Bagstad, 2009; Troy and Wilson, 2006). From this range we select an average value of 40,000 Euro/ha per year for ecosystems' services in the Ebro. The area covered by water in the Ebro basin is 68,000 ha with a total length of 8,900 km, therefore the average value in euros per kilometer is 0.31 million Euro/km (40,000 Euro/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 (MARM, 2010). Following the range of valuation in the literature, four valuation levels are chosen: a low value (0.12 million Euro/km) for river reaches with moderate environmental value in the main stem of the Ebro and some right bank tributaries, a medium value (0.31 million Euro/km) for non-mountain Ebro tributaries, a high value (0.77 million Euro/km) for mountain river reaches, and a very high value (1.95 million Euro/km) for the Ebro mouth where the Ebro Delta is located (Figure 4.4).

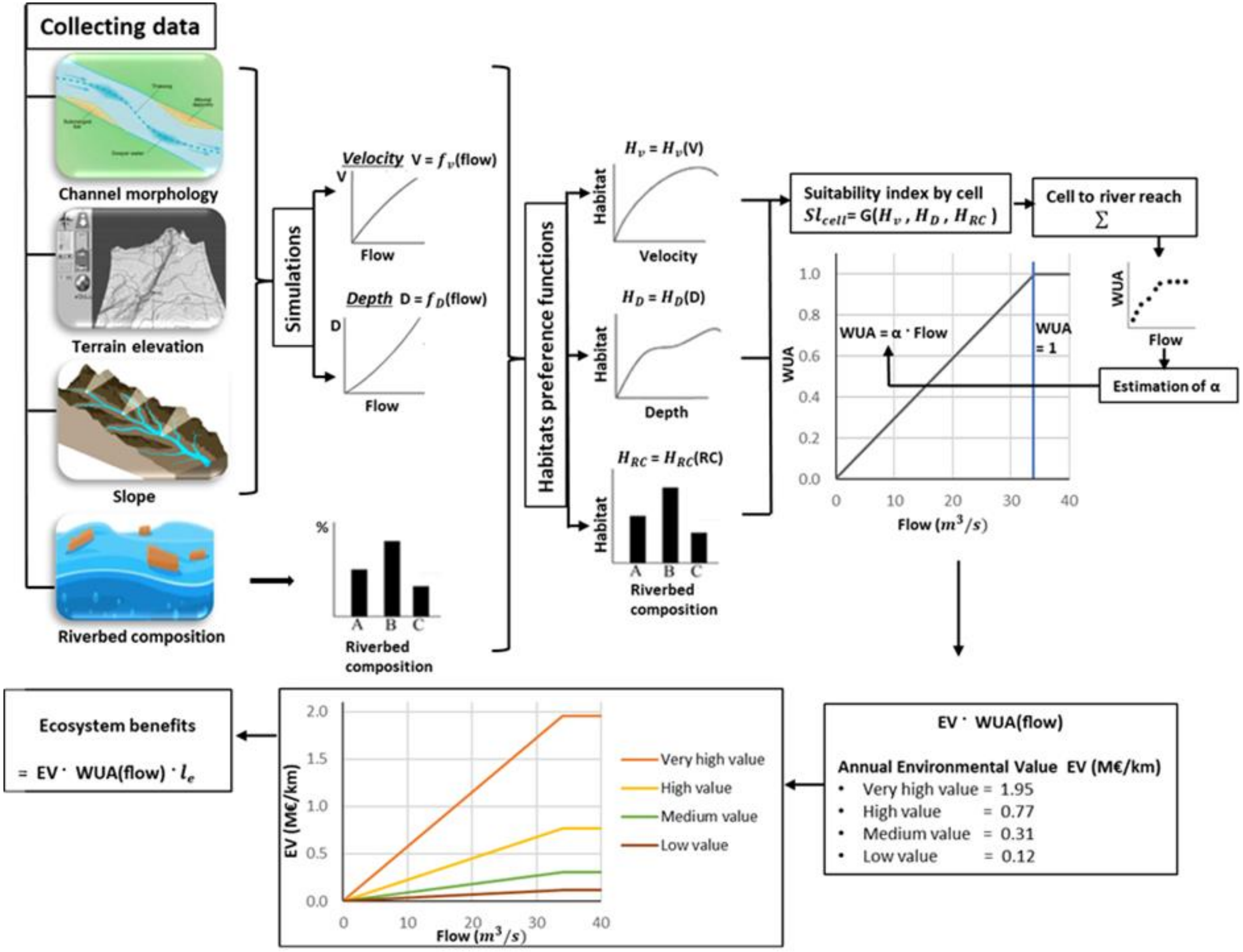
The optimization problem in the hydroeconomic model maximizes the discounted net present value of social benefits added over sectors and periods. Social benefits are the sum of private and environmental benefits coming from water withdrawals at nodes for irrigated agriculture and urban centers, by water flowing through turbines that generate energy, and by environmental flows in river reaches that support aquatic ecosystems. The objective function takes the following form:

$$\text{Max } \frac{\sum_{k,t} B_{k,t}^{Irr} + \sum_{u,t} B_{u,t}^{Urb} + \sum_{HPplant,t} B_{HPplant,t}^{HP} + \sum_{e,t} B_{e,t}^{ecos}}{(1+r)^t} \tag{4.9}$$

subject to all hydrological, economic, institutional constraints in the basin. $B_{k,t}^{Irr}$ is private benefit from irrigation district *k*, $B_{u,t}^{Urb}$ is urban economic surplus from urban center *u*, $B_{HPplant,t}^{HP}$ is hydropower benefit from hydropower plant *HPplant*, and $B_{e,t}^{ecos}$ is environmental benefit from river reach *e*. The discount rate r used in the analysis is 2%.

Future climate water stress scenarios are developed to discover the potential of water management strategies in reducing climate risks. The impacts of water scarcity on the interlinked water-energy-food-environmental systems are analyzed for calculating trade-offs, synergies and welfare effects across sectors and locations. Welfare effects by groups of stakeholders are important for evaluating the efforts and related just transition compensations for acceptability and uptake of policy interventions. Several management strategies have been assessed for improving climate resilience and adaptive capacity of irrigated agriculture, energy production, urban use, and the environment. The selected interventions are water reallocation by the basin authority with stakeholders' cooperation, full consideration of ecosystem benefits in settling environmental flows, modernizing irrigation systems, expanding dam storage, and water markets. The resulting trade-offs and synergies between water-energy-food-ecosystems under future climate conditions are used to rank the performance of policy alternatives.

Figure 4. 4 Environmental benefit response using the WUA weighted usable area.



4.2.2 Generation of future climate water stress scenarios

Future climate scenarios up to 2100 are developed based on the Ebro basin inflow projections under climate change estimated by CEDEX (2017). The basin series of headwaters are generated using the statistical delta change downscaling method (Escriva-Bou et al., 2017; Fowler et al., 2007). The CEDEX projections are derived form a set of Global Climate Models (GCM). These projections are arranged in four time periods between 1960 and 2100, and include two scenarios of Representative Concentration Pathways (RCP4.5 and RCP8.5). This study focuses on the worst-case scenario RCP8.5 from the projections of CEDEX based on the GCMs by the Centre National de Recherches Meteorologiques and the Max Planck Institute. Future monthly inflow series are generated for each headwater node in the Ebro basin. Thirty series of future basin inflows are simulated per node covering a horizon of 30 years for periods 2040-2070 (CC-2070) and 2070-2100 (CC-2100). The procedure consists in altering the historical monthly series between 1986 and 2016, by using the CEDEX information to generate future basin inflows for climate water scenarios.

The statistical delta change approach (Diaz-Nieto and Wilby, 2005; Escriva-Bou et al., 2017; Fowler et al., 2007) is applied to the historical inflow series by modifying the mean and standard deviation according to the CEDEX inflow predictions. The procedure generates future stream flows under climate water stress scenarios for 2040-2070 and 2070-2100 (CC-2070; CC-2100). The procedure involves the following steps:

1. The monthly historical data time series of each basin headwater $h_{d_{hw}t,m}$ is standardized using the corresponding monthly statistical parameters, where d_{hw} indicates the subset of river reaches corresponding to basin headwaters.

$$SW_{d_{hw},t,m}\left(h_{d_{hw},t,m}\right) = \frac{\left|h_{d_{hw},t,m} - \mu(h_{d_{hw},t,m})\right|}{\sigma(h_{d_{hw},t,m})} \tag{4.10}$$

where $SW_{d_{hw},t,m}\left(h_{d_{hw},t,m}\right)$ is the standardized time series for each basin headwater d_{hw}, in year *t* and month *m*.

2. The average relative change in mean and standard deviation for the 12 months that correspond to the average year, is obtained for each climate scenario (CC-2070; CC-2100). The change is calculated from the mean and standard deviation of the historical series $h_{d_{hw},m}$ and the future series $f_{d_{hw},m}$, where the future series are the projections provided by CEDEX (2017).

$$\Delta\mu_{d_{hw},m} = \frac{\left[\mu(f_{d_{hw},m}) - \mu(h_{d_{hw},m})\right]}{\mu(h_{d_{hw},m})} \quad ; \quad \Delta\sigma_{d_{hw},m} = \frac{\left[\sigma(f_{d_{hw},m}) - \sigma(h_{d_{hw},m})\right]}{\sigma(h_m)} \tag{4.11}$$

where $\Delta\mu_{d_{hw},m}$ and $\Delta\sigma_{d_{hw},m}$ are the changes in mean and standard deviation of month *m* in headwater d_{hw}. There is not significant and systematic change detected between the variances of historical and future series, and therefore the $\Delta\sigma_{d_{hw},m}$ are considered equal to zero.

3. Finally, the future time series for each climate scenario is obtained by applying the relative changes in statistical parameters to the historical standardized series. Thirty simulations are generated for climate scenarios, each with a time span of thirty years (30 simulations for CC-2070 and 30 simulations for CC-2100).

4.2.3 Management strategies for climate resilience

Cross-sectoral water management and enhanced climate resilience are needed to lessen future economic losses. Several recent contributions in the literature address climate resilience in river basins. The range of intervention measures found in the literature deal mostly with the agricultural sector, because irrigation represents 70% of withdrawals and 90% of water consumption both worldwide and in the Ebro basin. Recommendations include reducing demand, increasing supplies, dam storage and water transfers (Scanlon et al., 2017), better management and improved irrigation practices to reduce losses (Hoff et al., 2010), irrigation area expansion in water abundant regions (Elliott et al., 2014), and unconventional sources such as treated urban wastewater and desalinated seawater in coastal areas. As indicated above, protection of environmental flows has become an important issue in nexus studies to advance sustainable management.

Institutional cooperation (IC): IC is the primary management policy in the Ebro for water allocation. This current management by the Ebro basin authority is based on the effective involvement and cooperation of stakeholders. In this study, the IC policy is combined with a stronger protection of ecosystems, which is called environmental institutional cooperation (EIC). The current cooperation policy (IC) under drought conditions is that the basin authority reduces water allocations to irrigation districts in proportion to the fall in inflows. Also, environmental flows are lowered during droughts trying to abide by minimum thresholds. Allocations to urban networks and hydropower are reduced only in cases of a very severe drought. These water reallocations under drought are undertaken by the basin authority with stakeholders' cooperation.

Environmental institutional cooperation (EIC): EIC would achieve a more sustainable management, by including the environmental benefits generated by stream flows in the basin. This implies higher environmental flows that enhance social welfare. The procedure for enlarging flows is that the basin authority purchases water for the river in order to maximize social benefits, the sum of both private and environmental benefits. The basin authority buys water for the different river reaches, by first selecting purchases in irrigation districts with less profitable crops, where the shadow price of water is low.

Irrigation modernization (IM): Farmers could face water scarcity and reduced water allocations from the basin authority during droughts by modernizing irrigation systems. Investments in modernization involve upgrading irrigation technologies, which enhance the efficiency of water use. All surface irrigation systems in irrigation districts are substituted by sprinkler and drip systems (except rice). The implementation of this policy should involve a cutback of water withdrawals by irrigation districts, because maintaining water withdrawals would increase crop evapotranspiration and reduce return flows (from more water demanding crops, double crops, or acreage expansion), with a fall in basin stream flows (Grafton et al., 2018). Advanced irrigation technologies increase yields and farmers' revenue, although the costs of modernization are substantial. Both revenue and cost effects have been included in benefit calculations. The modernization policy is combined with the proportional reduction in allocations during droughts (farmers cooperation), and with the buying of water for environmental flows by the basin authority.

Enlarging dam storage (EDS): The response to water scarcity by the basin authority is to protect basin storage through proportional reduction of water allocations. The substantial water withdrawals in the Ebro (60% of yearly stream flows) in relation with the low storage capacity in dams (50% of yearly stream flows), call for augmenting dam storage capacity. The increase in water storage in the basin is set at a 50% increase in dam storage capacity, and the investment costs are included in social benefits. Also, the basin authority buys water for the river.

Water markets (WM): Farmers and urban centers receive reduced water allocations from the basin authority during droughts. Then these water allocations can be exchanged among irrigation districts and urban centers, maximizing the private benefits of water use. There is no direct exchange of water between sellers and buyers, but rather the sellers (irrigation districts) reduce withdrawals, and the buyers augment withdrawals in their respective river reaches. Water is traded between irrigation districts and urban centers, and the basin authority participates as well in the water market by acquiring water for the river. This policy enhances both private and environmental gains, so it is an appealing policy to capture the private benefits of markets while protecting ecosystems.

4.3 Results

4.3.1 Enhancing environmental flows in the current Institutional cooperation

Adjusting the current Institutional cooperation (IC) in the Ebro basin augmented by Environmental institutional cooperation (EIC) is prescribed by fully accounting for the benefits of environmental flows in river reaches. In this light, EIC achieves better ecosystem protection than IC, delivering more environmental flows even with reduced cultivated land (-13%) and energy generation (-5%) (Figure 4.5a). The EIC policy generates a significant increase of environmental flows in all rivers reaches, enlarging the streamflow at the Ebro mouth by about 180 Mm^{3}per year. There is a significant improvement of ecosystem status across the full range of watersheds in the basin (Figure 4.5c).

Water use in agriculture under EIC compared to IC is reduced by 14%, although impacts on agricultural economic benefits are small (-2%) because farmers reduce cultivation of field crops, which have high water requirements and low income generating capacity. Social economic benefits increase with gains in environmental benefits of €170 million, and benefit losses around €20 million for both energy and agriculture (Figure 4.5b). These results reveal trade-offs between the environment and the economic sectors, if decision makers implement the protection of environmental flows.

Reduced withdrawals by the largest water consuming sector (agriculture) increase stream flows in rivers across the basin. The increase is an important buffer during droughts for protecting ecosystems and economic activities. Therefore, relative to unadjusted IC, EIC enhances both economic water security and aquatic biodiversity during periods of water scarcity and represents a risk adaptive policy to advance sustainable water management.

4.3.2 Sectoral responses and competition: Tradeoffs analysis under future climate scenarios

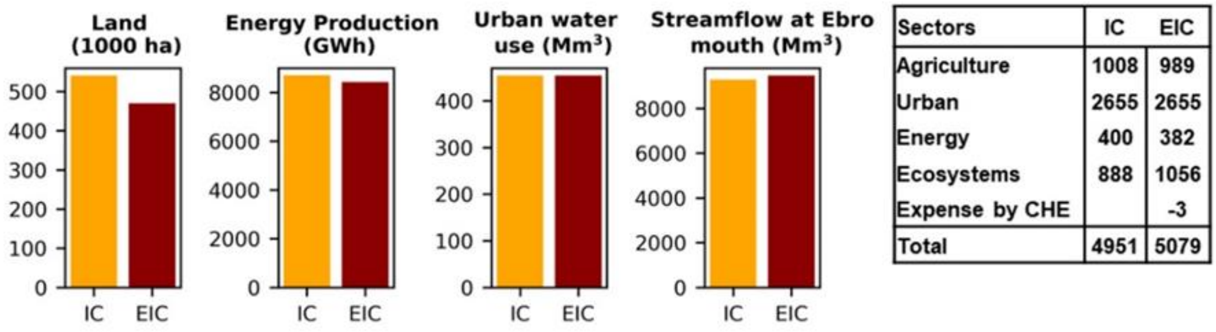
Understanding the complex relationship among water, energy, food and ecosystems provides critical insights for development of future sustainable water planning. Tradeoffs among competing water uses in the Ebro basin by policy (IC, EIC, IM, EDS and WM: See Management Strategies in section 4.2.3) and climate scenario (CC-2070 and CC-2100), are presented in Figure 4.6. Information from the tradeoff analysis informs the design of water management strategies. These strategies have the capacity to address challenges of future elevated water vulnerability by implementing workable and science-informed benefit-sharing schemes. Climate change reduces considerably baseline inflows, by 1500 and 3000 Mm^3 for CC-2070 and CC-2100 scenarios, respectively. The agriculture and urban water consuming sectors would curtail water withdrawals, depending on the policy option. An unadjusted IC policy (business as usual) is the weakest-performing strategy for climate change, for which there is a negative benefit gap, largely explained by lower ecosystem benefits, driven by smaller environmental flows as a result of high irrigation withdrawals (Table 4.1).

Under the EIC, IM, EDS, and WM policy options, the water authority assigns water for the environment to improve ecosystem status. These policies deliver higher social benefits than an unadjusted IC, lowering the risks of water stress and improving environmental sustainability under climate change. The EIC, IM, and WM policies deliver more environmental flows, while reducing irrigated land and energy production, compared to IC (Table 4.1, Figure 4.6a). The EDS policy increases energy production and environmental flows over any other policy, while reducing cultivated acreage compared to IC (Figure 4.6). These results show the tradeoffs between environmental and economic activities under future climate scenarios. They also highlight the difficulties of achieving win-win outcomes that jointly ensure water, energy and food security, together with ecosystem protection in large and complex basins.

Figure 4. 5 IC and EIC under baseline inflows.

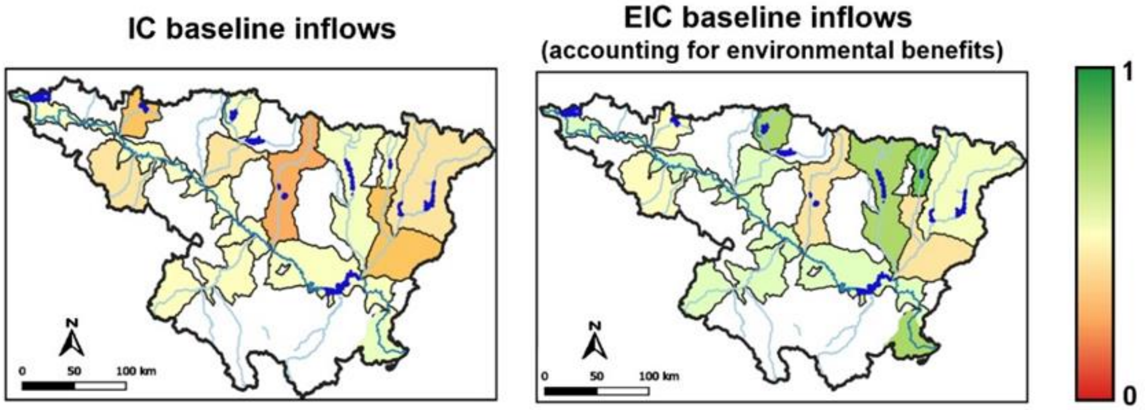
(a) Land, Energy production, Urban water use, and Streamflow at Ebro mouth

(b) Benefits (M€)



Sectors	IC	EIC
Agriculture	1008	989
Urban	2655	2655
Energy	400	382
Ecosystems	888	1056
Expense by CHE		-3
Total	4951	5079

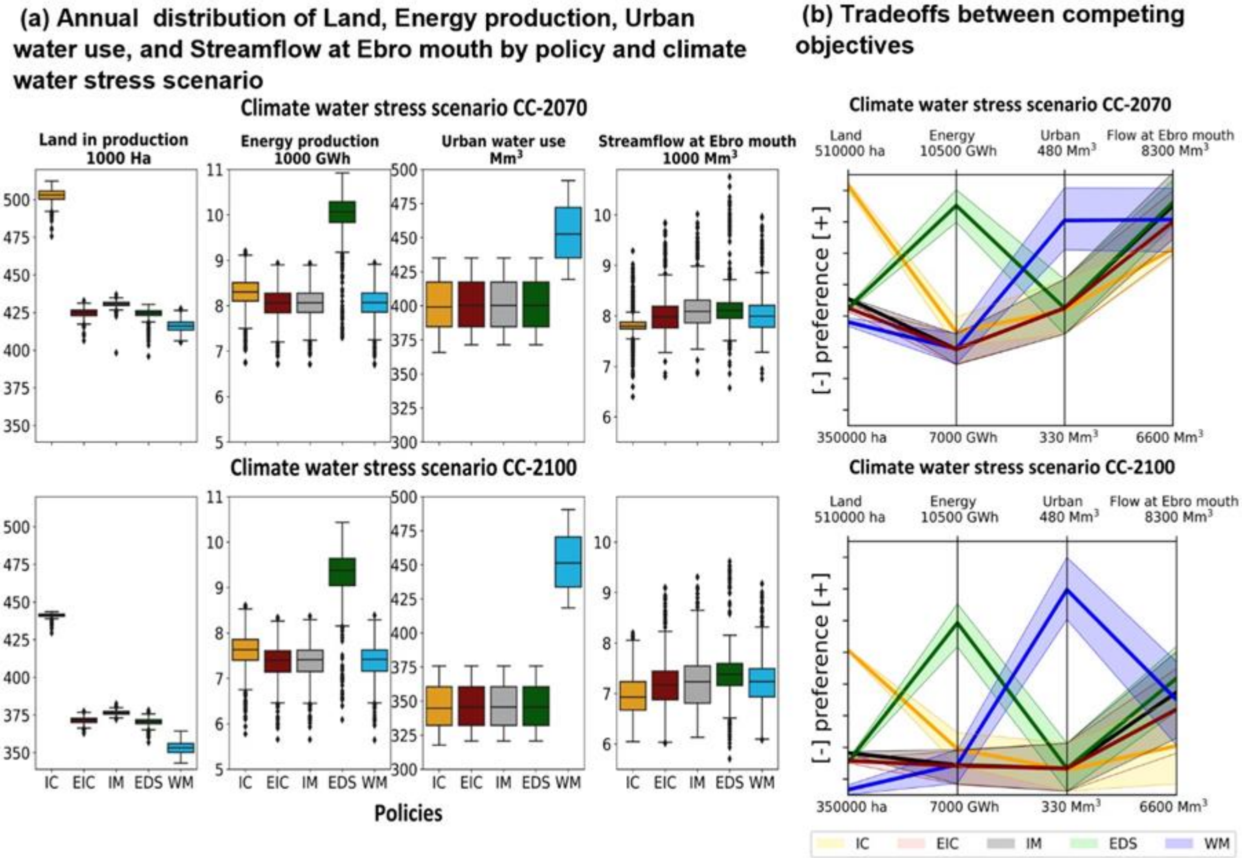
(c) Ecosystem status (unitless)



(a) Land (1000 ha), energy production (GWh), urban water use (Mm^3) and streamflow at the Ebro mouth (Mm^3), under IC and EIC. **(b)** Benefits (million Euro). **(c)** Ecosystem status in watersheds under IC and EIC. IC: Institutional cooperation and EIC: Environmental institutional cooperation.

The pattern of changes between IC and EIC under climate change are the same as under baseline climate conditions. The EIC policy reallocates water between economic activities and the environment to maximize social welfare, by reducing irrigation withdrawals and increasing environmental flows, augmenting streamflow at Ebro mouth by 300 and 200 Mm^3 for CC-2070 and CC-2100 scenarios, respectively. In both climate scenarios, EIC increases environmental benefits by around €170 million and social benefits by around €100 million, compared to IC (Table 4.1). The water authority acquires 670 Mm^3 of water for the river at a cost of €13 million in CC-2070, and 630 Mm^3 at a cost of €25 million in CC-2100 (Table A4.1-A4.2). The EIC policy requires planning for resource and benefit sharing that would advance ecosystem biodiversity, water security, and resilience and adaptation to climate change.

Figure 4. 6 Trade-offs analysis.



(a) Boxplots of the distribution of land, energy production, urban water use, and streamflow at Ebro mouth, by policy and climate scenario. **(b)** Parallel coordinate plot showing the tradeoffs between competing sectors under climate scenarios. The average of sector indicators by policy and climate scenario is represented by lines (30 simulations of 30 years), and the area is the interquartile range between the 25th and 75th percentiles. IC: Institutional cooperation. EIC: Environmental institutional cooperation. IM: Irrigation modernization. EDS: Enlarging dam storage. WM: Water markets.

The food security goal is elevated under the unadjusted IC and IM policies. However, IM has clear advantages over IC because modernization investments involve upgrading irrigation technologies, which improve water use efficiency in irrigation, boost ecosystem status, and increase private and social benefits. Compared to IC, modernizing irrigation systems could reduce agricultural water withdrawals by around 1,000 Mm^3 and increase streamflow at Ebro mouth by 300 Mm^3, with large gains in social benefits between 120 and €150 million for future climate scenarios. The water authority purchases around 1000 Mm^3 under the IM policy, spending €41 million in CC-2070 and €65 million in CC-2100 (Table A4.1-A4.2), and increasing environmental benefits by around €170 million. The IM policy remains instrumental for achieving water and food security goals and enhancing aquatic biodiversity in the Ebro basin.

Table 4. 1 Land, energy production, water use, and benefits by climate change scenario and management policy.

Climate scenarios	**Baseline**	**CC-2070**					**CC-2100**				
Policies	**IC**	**IC**	**EIC**	**IM**	**EDS**	**WM**	**IC**	**EIC**	**IM**	**EDS**	**WM**
Land (1000 ha)	**541**	**503**	**425**	**431**	**424**	**416**	**441**	**371**	**377**	**371**	**353**
Field crops	384	351	277	282	276	268	299	229	233	228	211
Fruits trees	121	116	115	115	115	115	109	111	112	111	111
Vegetables	36	35	33	34	33	33	33	31	32	32	31
Flood	293	265	214	17	213	208	225	180	14	180	168
Sprinkler	158	151	125	268	125	122	133	107	222	107	101
Drip	90	87	86	146	86	86	83	84	141	84	84
Hydropower (GWh)	**8710**	**8288**	**8060**	**8064**	**9975**	**8068**	**7553**	**7361**	**7373**	**9263**	**7384**
Reservoir	6401	5987	5835	5837	7130	5840	5425	5286	5296	6574	5298
Run-of-river	2309	2301	2225	2227	2845	2228	2128	2075	2077	2689	2086
Water use (Mm^3)											
Agriculture[1]	4248	3948	3282	2953	3285	3206	3459	2831	2539	2830	2665
Urban	454	401	401	401	401	454	346	346	346	346	452
Energy	32082	30935	32437	32487	31930	32465	28905	29980	30017	29610	30028
Streamflow at Ebro mouth (Mm^3)	**9287**	**7827**	**8014**	**8124**	**8156**	**8028**	**6983**	**7183**	**7312**	**7406**	**7238**
Social benefits (M€)	**4951**	**4772**	**4896**	**4923**	**5002**	**4931**	**4494**	**4596**	**4615**	**4697**	**4741**
Agriculture	1008	1006	980	1027	981	980	981	956	1005	957	963
Urban	2655	2617	2617	2617	2617	2654	2502	2502	2502	2502	2647
Energy	400	382	368	369	463	368	349	337	338	429	338
Ecosystems	888	767	944	951	955	948	662	826	834	835	834
Expenses by CHE[2]			-13	-41	-14	-19		-25	-65	-26	-42

Figures for climate change scenarios are yearly averages of 30 simulation runs over the 30 years periods 2040-2070 and 2070-2100. IC: Institutional cooperation, EIC: Environmental institutional cooperation, IM: Irrigation modernization, EDS: Enlarging Dam Storage, WM: Water markets.

[1]: Water use for agriculture is the sum of net withdrawals entering irrigation districts, without including losses of upstream main canals.

[2]: Expenses by CHE are the public funds used by the basin authority to buy water for the river.

EDS is a crucial policy for adapting to periods of water scarcity during droughts. It buffers against fluctuations in water supply by augmenting water storage in reservoirs, with releases covering economic and environmental demands in a controlled manner which dampen effects of droughts. The EDS policy achieves good results for social benefits and the best result for energy security, in both CC-2070 and CC-2100 scenarios. For both scenarios, it provides around 1,700-1,800 GWh of additional energy generation and around €100 million of additional energy benefits. This policy achieves also better ecosystem protection especially in mountain and delta watersheds, by delivering more water for the environment. The water authority purchases around 650 Mm^3 of water for the river, spending €14 million in CC-2070 and €26 million in CC-2100. Compared to other policies, EDS increases streamflow at the Ebro mouth between 30 and 330 Mm^3 in CC-2070, and between 100 and 420 Mm^3 in CC-2100. EDS is an important policy for supplying clean energy, protecting ecosystems, and improving water and energy security. It is a good policy option to build resilience and adaptation to climate change.

The WM policy reallocates the available water among sectors from low to high profitable uses. Water trading takes place not only between economic activities but also with the environment, through water purchases for the river by the basin authority. Market trading results in welfare gains by efficiently moving water among sectors and locations, dealing with the economic impacts of future climate water stress. This policy enhances urban use, the more profitable sector for water allocation, but generates moderate outcomes for agriculture and energy. Water exchanges among irrigation districts are only 8 and 25 Mm^3 in CC-2070 and CC-2100, respectively. Water trading from irrigation districts to urban centers is around 50 Mm^3 in CC-2070 and 100 Mm^3 in CC-2100. Purchases of water for the river by the basin authority from irrigation districts amount to around 690 Mm^3, with costs at €20 million in CC-2070 and €40 million in CC-2100 (Table A4.3). These efficient water reallocations between competing sectors achieve the best social benefits in CC-2100 (€4,741 million), and the second-best social benefits in CC-2070 (€4,931 million) only behind EDS. This policy achieves the best urban benefits, which guarantee human water security, while providing also ecosystems protection.

Policy choices for future climate water stress would depend on society's goals. If the priority is food production, then both unadjusted IC and IM deliver higher agricultural benefits, although IM frees higher stream flows across the basin and environmental benefits. The policy choice for energy priority is EDS, which delivers higher energy production with gains in energy benefits close to 30% over other policies. The choice for urban supply priority is WM which augments urban water use (+30%) and benefits (+6%) over other policies, but reduces food production. If ecosystems are a priority, then all policies deliver high environmental benefits except the current unadjusted IC.

4.3.3 Climate risk management: resilience and adaptation

There is considerable and growing interest by policymakers in finding ways to improve the climate resilience of water sectors, and to better deal with shrinking water supplies in arid and semi-arid regions. Various strategies could be undertaken for reducing the risks of water stress and its subsequent economic losses. Results in the Ebro under climate change indicate that compared to IC (business as usual), all other management strategies (EIC, IM, EDS, WM) reduce agricultural water withdrawals and increase stream flows across all watersheds in the basin (Figure 4.7). Improving the resilience of water resources to climate risk involves more efficient use of water and larger environmental flows, while finding an appropriate balance between food, energy and human water security.

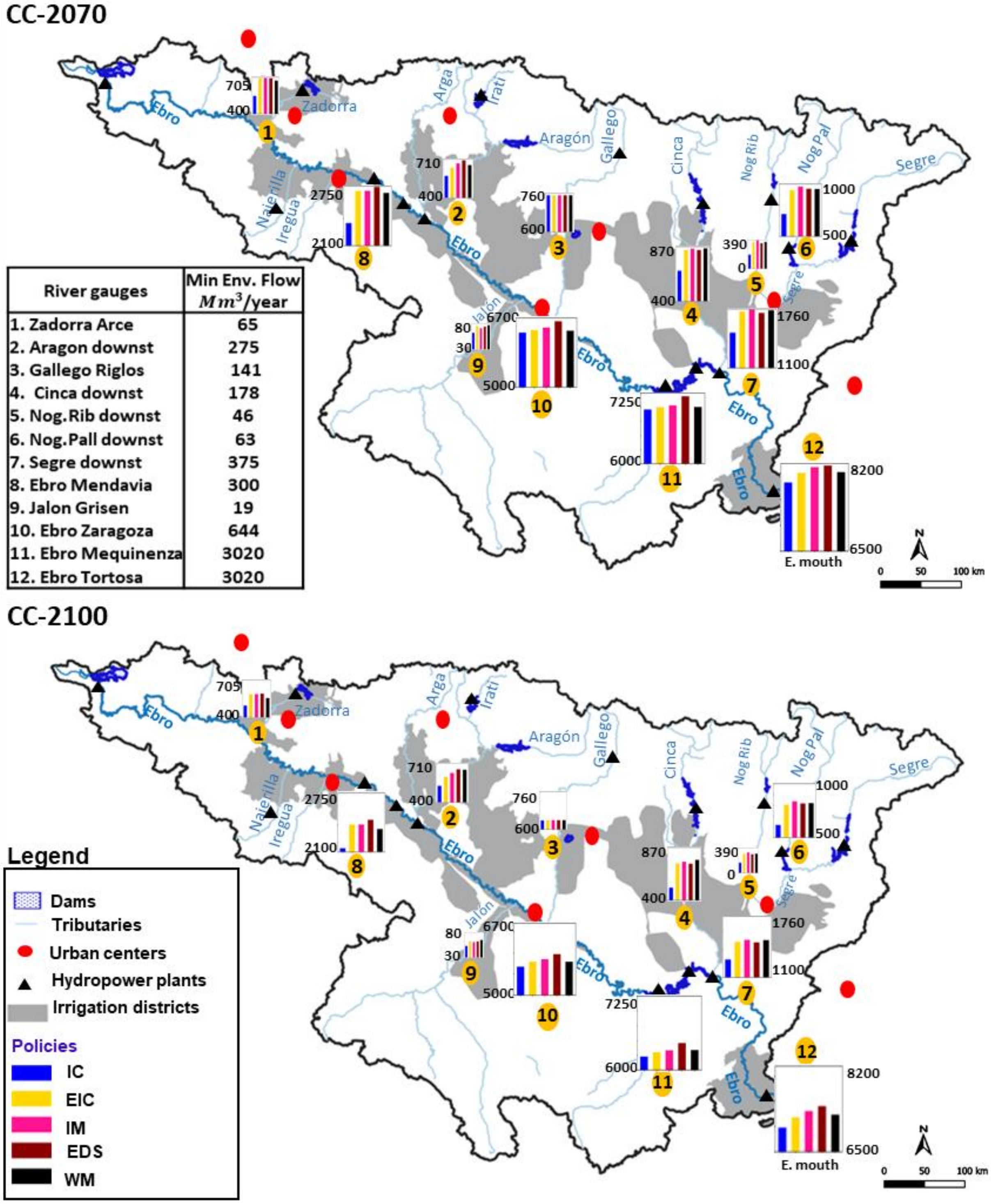
The economic analysis of strategies provides the costs and benefits of policies for sectors, groups of stakeholders, and spatial locations. This is a valuable tool for informing policy debates and guiding adaptation to the ongoing evidence of climate change. The success or failure of policy interventions would depend on the equitable sharing of costs and benefits among stakeholders, including compensations for loser groups. Findings indicate that all alternatives to the current policy (IC) increase social benefits (Table 4.1), despite the high investment and operating costs associated with some water management strategies, such as high investments in irrigation modernization (IM) or in additional dam storage (EDS). These gains in social benefits could cover compensations to groups of stakeholders that may sustain losses from policy changes.

Water resources support sector productivity, biodiversity, and well-being of inhabitants, and the cross-sectoral relationships in this nexus analysis are key in the assessment of strategies to confront climate change. This integrated water resources management approach could enrich the policy dialogue for promoting sustainable outcomes that limit sector vulnerabilities and are resilient to climate impacts.

4.4 Discusion and conclusions

Integrated water resources management and measures for climate risk reduction are needed for affordably maintaining irrigated agriculture, energy production, urban use, and ecosystem biodiversity, which are threatened by more frequent, intense and long- lasting supply unreliability from climate change extreme events. Our research informs the nexus dialogue between water, energy, food, and ecosystems that would improve cross-sectoral planning and achieve equitable tradeoffs. The results show that the current Institutional cooperation (IC, business as usual) is the worst policy option to deal with climate change challenges. In contrast, the other management options (EIC, IM, EDS, and WM) increase water in rivers, enhance biodiversity, and promote the resilience of sectors by lowering the risks of climate stress. Therefore, integrated water management is needed to coordinate the groups of stakeholders and build adaptive capacity to climate change impacts. Furthermore, considerable trade-offs between economic activities and the environment are shown, when ecosystem benefits are considered in the allocation of water among sectors and locations in the basin. The specification of those trade-offs fosters the design of innovative governance arrangements and practices that decrease sectoral vulnerability and maximize social benefits, without jeopardizing ecosystem sustainability.

Figure 4. 7 Average stream flow in selected gauges by policy alternative and climate scenario, and minimum environmental flows (Mm^3/year).



River gauges	Min Env. Flow Mm^3/year
1. Zadorra Arce	65
2. Aragon downst	275
3. Gallego Riglos	141
4. Cinca downst	178
5. Nog.Rib downst	46
6. Nog.Pall downst	63
7. Segre downst	375
8. Ebro Mendavia	300
9. Jalon Grisen	19
10. Ebro Zaragoza	644
11. Ebro Mequinenza	3020
12. Ebro Tortosa	3020

IC: Institutional cooperation. EIC: Environmental institutional cooperation. IM: Irrigation modernization. EDS: Enlarging dam storage. WM: Water markets. Averages from 30 simulations of 30 years length.

The irrigation modernization policy may have the potential for water conservation if gains in irrigation efficiency do not increase water consumption, which requires reductions in water withdrawals and water reallocation to the environment. A successful IM strategy will support farm income and social benefits, delivering water and food security and better ecosystem protection in the Ebro basin, which is in line with other studies such as (Jagermeyr et al., 2015; 2016; Kang et al., 2017). According to Perez-Blanco et al. (2020), irrigation modernization ("water conservation technologies") increases water consumption but stabilizes agricultural water productivity and increases farmers' income. This has been called "the paradox of irrigation efficiency" (Grafton et al., 2018), and the issue was already raised by Ward and Pulido-Velazquez (2008). The catch for irrigation modernization delivering water conservation at basin level is avoiding the increase in water consumption (withdrawals minus return flows) in irrigation districts. This is a considerable challenge that requires stakeholders' cooperation in basins, and clear enforcement by water authorities based on reliable measurements of withdrawals, water consumed, and return flows in irrigation districts. However, water authorities could impose water measuring and enforcement when designing irrigation modernization policies that usually involve public subsidies. Ward (2022) indicates that there is little published research describing economically affordable measures for water conservation, especially for technologies or polices in irrigated agriculture that could reverse depletion trends in water systems and engage climate water stress.

Enlarging dam storage is another attractive management option to cope with the temporal variability of water resources (Gaupp et al., 2015), enhancing energy and water security and boosting ecosystem status. The EDS is considered an option to confront water shortages, and improve climate resilience and adaptation (Ward, 2022). However, there is at present a significant opposition to building new dams from environmental NGOs which have been successful at stopping water storage projects in judicial courts. Setting up water markets enable trading between economic activities by moving water from low to high valued uses that generate welfare gains, and also minimize economic losses associated with climate water stress (Baccour et al., 2022; Wheeler et al., 2014). But experience with fully developed water markets in Australia and Chile shows that the protection of environmental flows is not evident, either with public buying of water for the river in Australia (Colloff et al., 2020; Grafton, 2019), or with limitations of withdrawals in Chile (Macpherson and Salazar, 2020).

Policymakers at present are left with great ambiguity on how to address climate change with cross-sectoral water management. The reason is the scarcity and inadequacy of information to buttress resiliency to climate water stress in basins, either with first best or even second best cost-efficient policies.

The choice among policies would depend on the priorities of society among sectors in coping with climate change. These priorities depend on the collective action arrangements among groups of stakeholders. Since water resources in arid and semi-arid basins are scarce, water management is highly political with interventions responding to the distribution of power among groups of stakeholders. Therefore, water allocations could respond to the priorities of some sectors rather than to the social welfare of the whole basin.

Future studies should improve hydrologic projections using sophisticated methodologies that could address spatial and temporal variabilities, and better deal with uncertainties. Another limitation is that we don’t assess the impact of water management options on water quality. Including water quality in the analysis could be a relevant information for decision makers. Despite these limitations, our modeling approach generates useful insights for improving cross-sectoral planning that could jointly deliver water, food, energy, and environmental security, and also promote climate resilience and adaptive capacity of sectors. Those inspiring messages could help policymakers in the design of measures for the management of climate risks.

References

Amjath-Babu TS, Sharma B, Brouwer R, Rasul G, Wahid SM, Neupane N, et al. Integrated modelling of the impacts of hydropower projects on the water-food-energy nexus in a transboundary Himalayan river basin. Applied Energy 2019; 239: 494-503.

Baccour S, Albiac J, Kahil T, Esteban E, Crespo D, Dinar A. Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain. Journal of Cleaner Production 2021; 327: 13.

Baccour S, Ward FA, Albiac J. Climate adaptation guidance: New roles for hydroeconomic analysis. Science of the Total Environment 2022; 835: 14.

Basso S, Lazzaro G, Bovo M, Soulsby C, Botter G. Water-energy-ecosystem nexus in small run-of-river hydropower: Optimal design and policy. Applied Energy 2020; 280: 12.

Bekchanov M, Pakhtigian E, Sood A, Jeuland M. Hydro-Economic Modeling Framework to Address Water-Energy-Environment-Food Nexus Questions at River Basin Scale. Working Paper. Sanford School of Public Policy. Duke University. Durham. 2019.

Biggs EM, Bruce E, Boruff B, Duncan JMA, Horsley J, Pauli N, et al. Sustainable development and the water-energy-food nexus: A perspective on livelihoods. Environmental Science & Policy 2015; 54: 389-397.

Carmona-Moreno C, Crestaz E, Cimmarrusti Y, Farinosi F, Biedler M, Amani A, et al. Implementing the Water–Energy–Food–Ecosystems Nexus and Achieving the Sustainable Development Goals. Retrieved from Agency of Natural Resources Department of Environmental Conservation, UNESCO, European Union and IWA Publishing. 2021.

CEDEX. (Centro de Estudios y Experimentación de Obras Públicas). Evaluación del impacto del cambio climático en los recursos hídricos y sequías en España. Anexo 1: Tendencias y cambio de estadísticos para cada proyección. MAPAMA, Madrid. 2017.

Colloff M, Rocheta E, Hillman T, al. e. Assessment of river flows in the Murray-Darling Basin: Observed versus expected flows under the Basin Plan 2012-2019. Wentworth Group of Concerned Scientists. Sydney. https://wentworthgroup.org/wp-content/uploads/2020/08/MDB-flows.pdf. 2020.

Conway D, van Garderen EA, Deryng D, Dorling S, Krueger T, Landman W, et al. Climate and southern Africa's water-energy-food nexus. Nature Climate Change 2015; 5: 837-846.

CHE. (Confederacion Hidrografica del Ebro). Plan Hidrologico de la Demarcacion Hidrografica del Ebro, Documentacion sobre Caudales Ecologicos. Zaragoza: CHE, Ministerio de Agricultura y Medio Ambiente (MAGRAMA). 2015.

Chen L, Huang KD, Zhou JZ, Duan HF, Zhang JH, Wang DW, et al. Multiple-risk assessment of water supply, hydropower and environment nexus in the water resources system. Journal of Cleaner Production 2020; 268: 15.

Daher BT, Mohtar RH. Water-energy-food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water International 2015; 40: 748-771.

Diaz-Nieto J, Wilby RL. A comparison of statistical downscaling and climate change factor methods: Impacts on low flows in the River Thames, United Kingdom. Climatic Change 2005; 69: 245-268.

Elliott J, Deryng D, Mueller C, Frieler K, Konzmann M, Gerten D, et al. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proceedings of the National Academy of Sciences of the United States of America 2014; 111: 3239-3244.

Endo A, Tsurita I, Burnett K, Orencio PM. A review of the current state of research on the water, energy, and food nexus. Journal of Hydrology-Regional Studies 2017; 11: 20-30.

Escriva-Bou A, Pulido-Velazquez M, Pulido-Velazquez D. Economic Value of Climate Change Adaptation Strategies for Water Management in Spain's Jucar Basin. Journal of Water Resources Planning and Management 2017; 143: 13.

European Commission. Horizon 2020 Topic: Integrated Approaches to Food Security, Low-Carbon Energy, Sustainable Water Management and Climate Change Mitigation. Available online: http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/water-2b-2015.html. 2015.

European Commission. Strategic Research and Innovation Agenda. European Partnership WATER 4ALL "Water Security for the Planet". Available online: http://www.waterjpi.eu/implementation/water-challenges-in-horizon-europe/water4all-_2nd_draftsria_08022021_fordistribution.pdf. 2021.

FAO. (Food and Agriculture Organisation of the United Nations), An Innovative Accounting Framework for the Food-Energy-Water Nexus—Application of the MuSIASEM Approach to Three Case Studies; FAO: Rome, Italy. 2013.

Finley JW, Seiber JN. The Nexus of Food, Energy, and Water. Journal of Agricultural and Food Chemistry 2014; 62: 6255-6262.

Flammini A, Puri M, Pluschke L, Dubois O. Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative; Food and Agriculture Organisation of the United Nations (FAO): Rome, Italy. 2014.

Fowler HJ, Blenkinsop S, Tebaldi C. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. International Journal of Climatology 2007; 27: 1547-1578.

Future Earth. Water-Energy-Food Nexus: We are the Nexus! https://futureearth.org/2018/07/30/water-energy-food-nexus-we-are-the-nexus/. 2018.

Gaudard L, Avanzi F, De Michele C. Seasonal aspects of the energy-water nexus: The case of a run-of-the river hydropower plant. Applied Energy 2018; 210: 604-612.

Gaupp F, Hall J, Dadson S. The role of storage capacity in coping with intra- and inter-annual water variability in large river basins. Environmental Research Letters 2015; 10: 12.

Grafton RQ. Policy review of water reform in the Murray-Darling Basin, Australia: the "do's" and "do'nots". Australian Journal of Agricultural and Resource Economics 2019; 63: 116-141.

Grafton RQ, Williams J, Perry CJ, Molle F, Ringler C, Steduto P, et al. The paradox of irrigation efficiency. Science 2018; 361: 748-750.

Harwood SA. In search of a (WEF) nexus approach. Environmental Science & Policy 2018; 83: 79-85.

Hoff H. Understanding the NEXUS, Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus 2011. Stockholm Environment Institute. Stockholm. 2011.

Hoff H, Falkenmark M, Gerten D, Gordon L, Karlberg L, Rockstrom J. Greening the global water system. Journal of Hydrology 2010; 384: 177-186.

Hulsmann S, Susnik J, Rinke K, Langan S, van Wijk D, Janssen ABG, et al. Integrated modelling and management of water resources: the ecosystem perspective on the nexus approach. Current Opinion in Environmental Sustainability 2019; 40: 14-20.

ICIMOD. (The International Centre for Integrated Mountain Development), Contribution of Himalayan ecosystems to water, energy, and food security in South Asia: a nexus approach. URL https://lib.icimod.org/record/1898. 2012.

Jagermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M, Lucht W. Water savings potentials of irrigation systems: global simulation of processes and linkages. Hydrology and Earth System Sciences 2015; 19: 3073-3091.

Jagermeyr J, Gerten D, Schaphoff S, Heinke J, Lucht W, Rockstrom J. Integrated crop water management might sustainably halve the global food gap. Environmental Research Letters 2016; 11: 14.

Kang SZ, Hao XM, Du TS, Tong L, Su XL, Lu HN, et al. Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. Agricultural Water Management 2017; 179: 5-17.

Karabulut AA, Crenna E, Sala S, Udias A. A proposal for integration of the ecosystem-water-food-land-energy (EWFLE) nexus concept into life cycle assessment: A synthesis matrix system for food security. Journal of Cleaner Production 2018; 172: 3874-3889.

Kebede A, Nicholls R, Clarke D, Savin C, Harrison P. Integrated assessment of the food-water-land-ecosystems nexus in Europe: Implications for sustainability. Science of the Total Environment 2021; 768: 12.

Lamouroux N, Jowett IG. Generalized instream habitat models. Canadian Journal of Fisheries and Aquatic Sciences 2005; 62: 7-14.

Liu J, Yang H, Cudennec C, Gain AK, Hoff H, Lawford R, et al. Challenges in operationalizing the water-energy-food nexus. Hydrological Sciences Journal 2017; 62: 1714-1720.

Liu JG, Hull V, Godfray HCJ, Tilman D, Gleick P, Hoff H, et al. Nexus approaches to global sustainable development. Nature Sustainability 2018; 1: 466-476.

Macpherson EJ, Salazar PW. Towards a Holistic Environmental Flow Regime in Chile: Providing for Ecosystem Health and Indigenous Rights. Transnational Environmental Law 2020; 9: 481-519.

MARM. (Ministerio de Medio Ambiente y Medio Rural y Marino). Valoracion de los activos naturales de España (VANE). MARM, Centro de Publicaciones, Madrid. 2010.

Perez-Blanco CD, Hrast-Essenfelder A, Perry C. Irrigation Technology and Water Conservation: A Review of the Theory and Evidence. Review of Environmental Economics and Policy 2020; 14: 216-239.

Rasul G. Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. Environmental Science & Policy 2014; 39: 35-48.

Rasul G, Sharma B. The nexus approach to water-energy-food security: an option for adaptation to climate change. Climate Policy 2016; 16: 682-702.

Scanlon BR, Ruddell BL, Reed PM, Hook RI, Zheng CM, Tidwell VC, et al. The food-energy-water nexus: Transforming science for society. Water Resources Research 2017; 53: 3550-3556.

Sun YY, Zhang J, Mao XQ, Yin XA, Liu GY, Zhao YW, et al. Effects of different types of environmental taxes on energy-water nexus. Journal of Cleaner Production 2021; 289: 11.

Tharme RE. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. River Research and Applications 2003; 19: 397-441.

TEEB. The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB. Ecological and Economic Foundation, Earthscan, London and Washington. 2010.

The Nexus Resource Platform. Messages From the Bonn 2011 Conference: The Water, Energy And Food Security Nexus Solutions for a Green Economy Bonn, Germany. 2011.

Troy A, Bagstad K. Estimating Ecosystem Services in Southern Ontario. Spatial Informatics Group, LLC 3248 Northampton Ct. Pleasanton, CA 94588 USA. 2009.

Troy A, Wilson MA. Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer. Ecological Economics 2006; 60: 435-449.

UNECE. Methodology for assessing the water-food-energy-ecosystems nexus in transboundary basins and experiences from its application: synthesis. URL https://unece.org/environment-policy/publications/methodology-assessing-waterfood-energy-ecosystems-nexus. 2018.

Wang Q, Li SQ, He G, Li RR, Wang XF. Evaluating sustainability of water-energy-food (WEF) nexus using an improved matter-element extension model: A case study of China. Journal of Cleaner Production 2018; 202: 1097-1106.

Ward FA. Enhancing climate resilience of irrigated agriculture: A review. Journal of Environmental Management 2022; 302: 15.

Ward FA, Pulido-Velazquez M. Water conservation in irrigation can increase water use. Proceedings of the National Academy of Sciences of the United States of America 2008; 105: 18215-18220.

Wilding TK, Bledsoe B, Poff NL, Sanderson J. PREDICTING HABITAT RESPONSE TO FLOW USING GENERALIZED HABITAT MODELS FOR TROUT IN ROCKY MOUNTAIN STREAMS. River Research and Applications 2014; 30: 805-824.

Wheeler S, Loch A, Zuo A, Bjornlund H. Reviewing the adoption and impact of water markets in the Murray-Darling Basin, Australia. Journal of Hydrology 2014; 518: 28-41.

Yoon J, Klassert C, Selby P, Lachaut T, Knox S, Avisse N, et al. A coupled human-natural system analysis of freshwater security under climate and population change. Proceedings of the National Academy of Sciences of the United States of America 2021; 118: 12.

Yuan MH, Lo SL. Ecosystem services and sustainable development: Perspectives f1 rom the food-energy-water Nexus. Ecosystem Services 2020; 46: 10.

Zhang C, Chen XX, Li Y, Ding W, Fu GT. Water-energy-food nexus: Concepts, questions and methodologies. Journal of Cleaner Production 2018; 195: 625-639.

Appendix

Table A4.1 Water exchanges between irrigation districts and water authority (CHE) for the EIC, IM and EDS policies.

	Water sales by irrigation districts (Mm^3)					
Climate scenarios	**CC-2070**			**CC-2100**		
Policies	**EIC**	**IM**	**EDS**	**EIC**	**IM**	**EDS**
Bardenas	172	211	172	150	182	150
A&C	89	122	91	101	131	102
Imperial	28	81	28	24	69	24
Jalon	23	24	23	16	21	16
Lodosa	10	52	10	6	42	6
Navarra	44	53	44	38	45	38
Tauste	2	12	2	2	10	2
Urgel	118	190	117	96	162	97
Delta	21	25	21	20	24	20
Rioja	9	25	4	3	19	2
RAA	146	181	147	169	202	169
Zadorra	3	20	3	3	14	3
Water purchases by the water authority (CHE)	**665**	**996**	**662**	**628**	**921**	**629**

Table A4.2 Water shadow prices in irrigation districts and costs of purchases by policy (EIC, IM and EDS) and climate scenario.

	Shadow prices (Euro/m^3)						Costs of water exchanges (million Euro)					
Climate scenarios	**CC-2070**			**CC-2100**			**CC-2070**			**CC-2100**		
Policies	**EIC**	**IM**	**EDS**	**EIC**	**IM**	**EDS**	**EIC**	**IM**	**EDS**	**EIC**	**IM**	**EDS**
Bardenas	0.02	0.04	0.02	0.03	0.06	0.02	2.7	9.2	2.6	4.2	11	3.6
A&C	0.03	0.04	0.02	0.06	0.07	0.06	2.3	4.5	2.2	6.1	9.7	6
Imperial	0.03	0.04	0.03	0.06	0.08	0.06	0.9	3.2	0.9	1.5	5.3	1.5
Jalon	0.02	0.03	0.02	0.02	0.06	0.02	0.4	0.7	0.4	0.4	1.2	0.4
Lodosa	0.05	0.06	0.05	0.11	0.12	0.10	0.5	3.3	0.5	0.6	5.2	0.6
Navarra	0.02	0.05	0.02	0.04	0.07	0.04	0.8	2.5	0.9	1.5	3.2	1.5
Tauste	0.03	0.04	0.03	0.06	0.08	0.06	0.1	0.4	0.1	0.1	0.8	0.1
Urgel	0.02	0.06	0.03	0.04	0.1	0.06	1.8	10.6	3.2	4	16	5.4
Delta	0.02	0.02	0.02	0.04	0.04	0.04	0.4	0.5	0.4	0.9	1	0.9
Rioja	0.02	0.03	0.02	0.06	0.08	0.07	0.2	0.8	0.1	0.2	1.6	0.1
RAA	0.02	0.03	0.02	0.03	0.05	0.03	2.6	4.9	2.7	5.7	9.7	5.4
Zadorra	0.03	0.01	0.03	0.07	0.01	0.08	0.1	0.2	0.1	0.2	0.1	0.2
Purchases CHE							**13**	**41**	**14**	**25**	**65**	**26**

Table A4.3 Water exchanges among sectors under the water markets policy by climate scenario.

Climate scenarios	**CC-2070**	**CC-2100**
Water exports (+) and imports (-) by irrigation districts (Mm^3)		
Bardenas	195	208
A&C	90	100
Imperial	22	25
Jalon	27	21
Lodosa	-8	-25
Navarra	48	45
Tauste	2	2
Urgel	140	121
Delta	37	64
Rioja	12	6
RAA	173	225
Zadorra	4	2
Exports irrigation districts	750	819
Imports irrigation districts	8	25
Imports urban centers	53	107
Imports CHE (water for the river)	689	687
Water shadow prices (Euro/m^3)	**0.03**	**0.06**
Costs of purchases by CHE (million Euro)	**19**	**42**

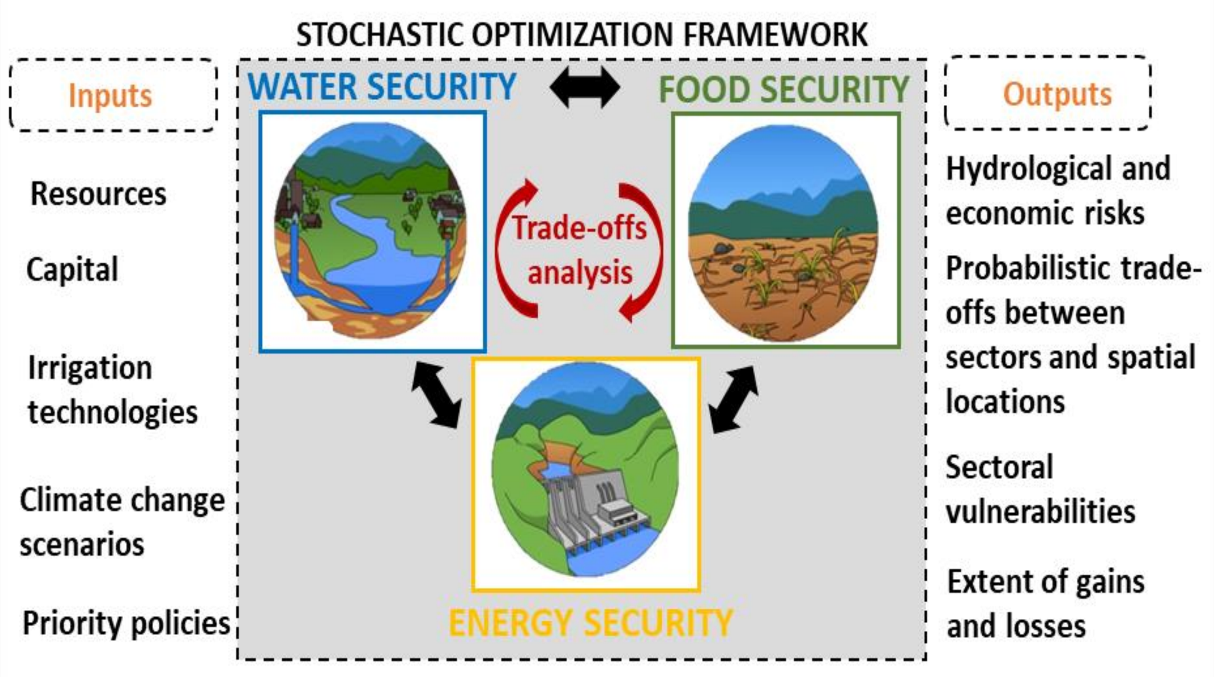
CHAPTER 5

PROBABILISTIC CROSS-SECTORAL TRADE-OFFS ASSESSEMENT UNDER CLIMATE STRESS FOR SUSTAINABLE AND EQUITABLE WATER PLANNING

Chapter 5 Probabilistic cross-sectoral trade-offs assessments under climate stress for sustainable and equitable water planning

Abstract

Pressures on water resources are fueling conflicts between sectors. This trend will likely worsen under future climate-induced water stress, jeopardizing food, energy and human water security in most arid and semi-arid regions. Probabilistic analysis using stochastic optimization modeling can characterize vulnerabilities and risks associated with future water stress. The original contribution of this study is to make headway on filling these gaps, identifying the probabilistic trade-offs between agricultural, urban and energy sectors in the Ebro Basin (Spain). Two intervention policies are examined and compared, agricultural priority and energy priority, for two planning horizons 2040-2070 (CC-2070) and 2070-2100 (CC-2100). The analysis gives insights on the extent and distribution of welfare gains and losses from alternative intervention objectives. Our paper provides evidence to support science-based policy reform for efficient, flexible, and equitable water planning. Results show that the human water security goal is achieved under both intervention policies. However, the accomplishment of food and energy security goals depends on the policy objectives and the spatial location of irrigation schemes and hydropower plants, changing basin stream flows and impacting water user withdrawals. Agricultural priority advances food security, but increases the vulnerability of downstream hydropower where the main hydropower plants are located. On the other hand, energy priority increases the vulnerability of upstream irrigation districts. The policy choice results in substantially different benefit gains and losses by sector and therefore by location. Moreover, neither priority policy provides an equitable sharing of benefits among all sectors and locations under climate change. This is an important issue, because the success or failure of policy interventions would depend on the distribution of the gains and losses of benefits across the basin. Policy uptake by stakeholders would depend on reaching win-win outcomes delivering acceptable levels of food, energy and human water security in large river basins. Information on the probabilistic trade-offs contributes to the design of water management strategies capable of handling the challenges of larger water vulnerability by implementing appropriate benefit-sharing schemes.



Key words: Trade-off analysis, Risk assessment, Stochastic optimization, Water allocation policies, Climate water stress

5.1 Introduction

Water resources are essential for food, energy and human water security. Water scarcity and uneven spatial water distribution threaten sustainable development (Cheng et al., 2019). The sharp rise of water withdrawals during the last century, well above the rate of population growth, has created massive pressures, severe degradation problems (Greve et al., 2018), and major management challenges in many river basins worldwide. Driven by socioeconomic and climate developments, these challenges are expected to become more crucial in the coming decades. Management policies in arid and vulnerable river basins must be adapted to a changing climate. The development of successful policies requires knowing the trade-offs across sectors, such as agricultural production, energy supply, and ecosystem health, as well as across space and time (Cai et al., 2018). At present, drought damages and economic losses in Europe are estimated at € 9 billion per year, mostly affecting Spain (1.5 b.), Italy (1.4 b.) and France (1.2 b.), with damages concentrating in the agriculture (50%) and energy sectors (35%). Future damages could increase up to five times for a +3°C scenario (Cammalleri et al., 2020; Feyen et al., 2020). A critical policy task is to understand and identify the tradeoffs between competing uses, by finding the gains and losses for alternative water allocation policies under climate change. Then, the scope of policymaking negotiation can go beyond outdated water allocations, and seek creative and sustainable policies (Tilmant et al., 2020). Hajkowicz and Collins (2007) indicate that an ex-ante assessment of trade-offs between competing uses could become an instrumental for mitigating burgeoning conflicts.

Water system models can be used to discover trade-offs in complex water resource systems involving multiple, inter-dependent, water uses. More specifically, optimization modeling is an efficient tool for optimal water allocation and for discovering tradeoffs between sectors and spatial locations (Wu et al., 2022). Several nonlinear and stochastic optimization models have been applied to identify the interaction between sectors and to inform policy debates (Cai et al., 2018; Crespo et al., 2019; Jalilov et al., 2018; Jalilov et al., 2016; Tilmant et al., 2020). Mendes et al. (2015) develop a nonlinear multiobjective optimization model to assess the tradeoff among multiple water uses in a hydropower system in the São Francisco River Basin in Brazil. Tradeoffs among environmental flows, hydropower, and inter-basin water diversion projects have been analyzed in the Datong River basin using a nonlinear multiobjective programming (Yin et al., 2022). Tilmant and Kelman (2007) developed a stochastic multiobjective optimization to analyze tradeoffs between energy generation and irrigated agriculture under hydrologic uncertainty in the Euphrates River basin. Also, probabilistic trade-offs between agriculture, floodplain, hydropower, navigation and fisheries are analyzed in the Senegal River basin, identifying their vulnerability with respect to natural and anthropogenic factors (Tilmant et al., 2020). Another study considers the trade-offs between spatial locations for the management of inter-basin water diversions (Wu et al., 2022).

Addressing future climate vulnerability in water sectors is a growing topic that is critical for drought risk research and for the design and implementation of adaptation strategies (Vargas and Paneque, 2017). Vulnerabilities in water resources are defined as the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor (Turner et al., 2003). Zhang et al. (2023) emphasize the need to assess water resources vulnerability and identify spatiotemporal patterns for policymaking. Several studies develop a bottom-up approach based on stress tests in order to identify conditions under which water systems require adaptation policies (Brown et al., 2012; Turner et al., 2014).

This study contributes to the growing body of literature on adapting the management of water resources systems to climate change. More specifically, this study focuses on assessing the spatial distribution of water uses' risks and vulnerabilities, as well as the corresponding trade-offs in heavily committed river basins. A novel integrated hydroeconomic model is developed using stochastic dual dynamic programming (SDDP) to identify suitable mechanisms for sustainable and equitable water and benefit-sharing arrangements (Grey and Sadoff, 2007). The SDDP has been successfully employed to solve optimization problems with stochastic inflows. Several studies used the SDDP to assess the economic value of coordination in a multiuser and multi-reservoir, determine the costs and benefits related to the multi-reservoir operation, and to evaluate the probabilistic trade-offs between competing sectors (Goor et al., 2010; Marques and Tilmant, 2013; Tilmant et al., 2020).

This paper addresses the water challenges and sectoral vulnerabilities under uncertainty and future climate water stress by providing information on the hydrologic and economic risks associated with each water allocation policy. The spatial distribution of benefit gains and losses from water stress scenarios analyzed aims to contribute to the debate on sustainable basin management, which includes stakeholder participation and equitable benefit sharing in strategic planning (Wilson, 2019). As indicated by Dinar et al. (2015), benefit-sharing arrangements are relevant for ensuring resilient and adaptive communities. Sustainable management needs to be based on scientific knowledge and appropriate governance to balance human water withdrawals and environmental flows, and information on trade-offs would contribute to the design of mechanisms leading to stakeholders' cooperation for better governance.

5.2 Study area

The Ebro River Basin is one of the main European Mediterranean basins located in the north-east of the Iberian Peninsula. The Ebro is the largest river in Spain, covering 85,600 km^2 and being home to 3.2 million inhabitants (Figure 5.1). Renewable water resources amount to 15,000 (million cubic meters (Mm^3) per year (15 km^3), with 8,500 Mm^3 (8.5 km^3) of water withdrawals of which 7,680 for irrigation, 630 for urban networks and 150 for direct industry abstractions. An intense development of water infrastructures took place during the twentieth century due to the large expansion of irrigation and a surge in economic development and industrialization. The consequence has been the growing pressure on water resources and the ensuing problems of water scarcity that has been aggravated by periodic droughts, especially in the middle basin.

Water resources in the Ebro are managed by the Ebro water authority (Confederación Hidrográfica del Ebro). A special characteristic of the water authority is the crucial role played by user groups, which maintains the traditional culture of stakeholders' cooperation. Users from every sector (irrigation, urban, industrial and hydropower), central and state governments, municipalities, farmers' unions, environmental associations, business associations and workers unions are represented in the water authority taking and enforcing decisions.

The pressures on water resources in the Ebro Basin are going to be aggravated by the impacts of climate change with reductions and increased variability of water availability (CHE, 2022). As indicated, severe droughts occur about every 10 years in recent decades. The resulting damage costs are considerable, reaching 400 million euro in 2005 (0.5% of GDP) (Hernández et al., 2013; Lines et al., 2017), although the average yearly drought damages could be estimated at below 0.1% of GDP (Feyen et al., 2020).

Interactions between climate and land use drivers, water availability and water withdrawals have led to an increased level of conflicts among the Ebro basin sectors and locations, including farmers, cities, industries, environmental flow protection, as well as between the federal water authority, states in the basin, and local administrations (Crespo et al., 2019). 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. The worsening of future extreme events further threatens sustainable outcomes, and call for a reconsideration of the current water management, institutions and policies not only in the Ebro but in all Mediterranean basins.

So, a key issue for dealing with hydroclimate-driven risks in a warmer world is the successful implementation of enhanced management policies and strategies that bring about resilience and adaptation to more extreme droughts. This governance framework can only be based on the collective action of stakeholders.

5.3 The SDDP model for optimal allocation

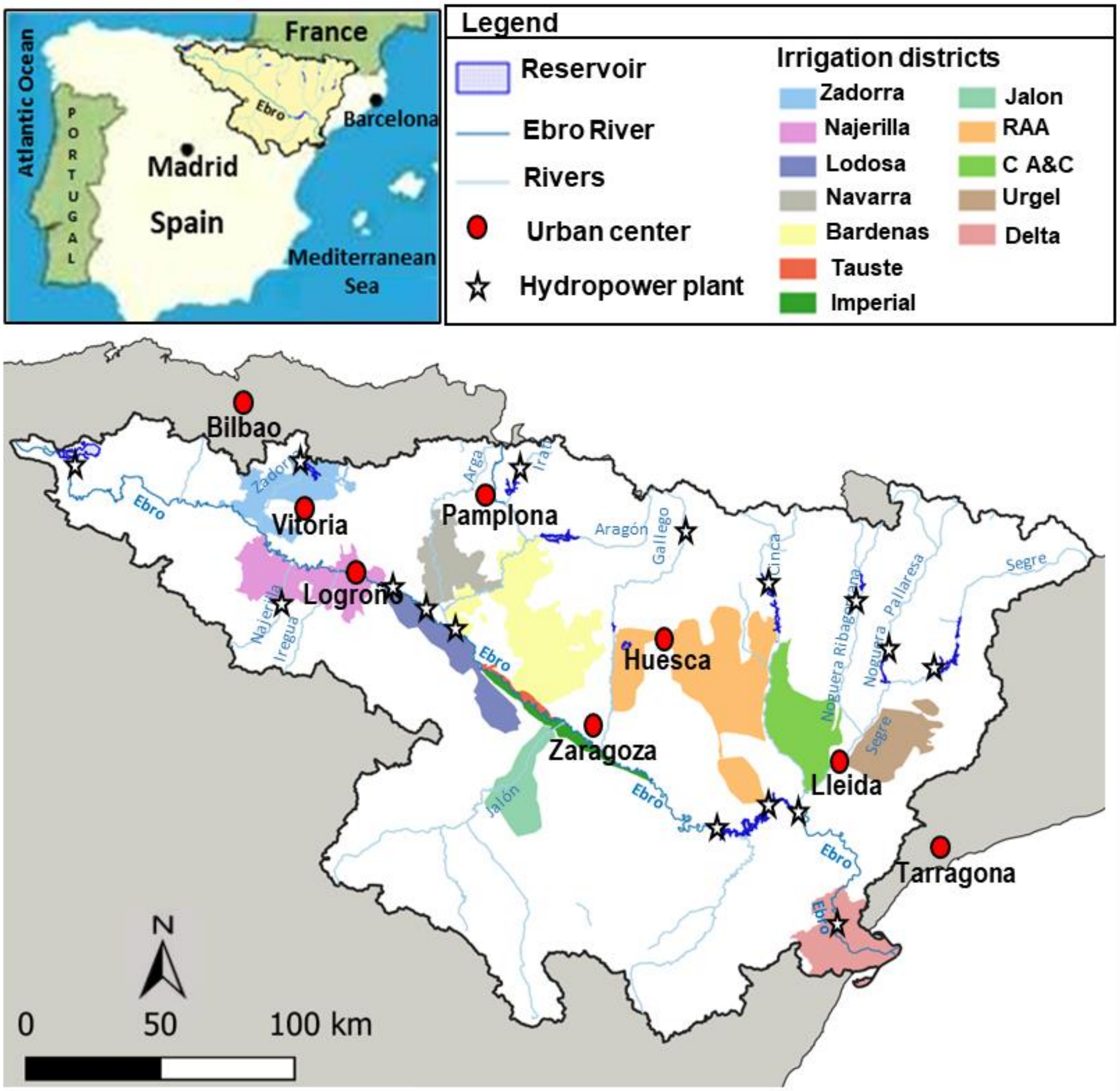
A stochastic hydroeconomic model of the Ebro basin is developed in order to assess cross-sectoral probabilistic trade-offs, and hydrological and economic risks under climate change. The model is solved with the SDDP algorithm that could deal with complex multi-stage and stochastic problems, applying the Bellman's principle of optimality (Bellman, 1957). The model integrates the economic activities and the hydrologic system, and it is used to analyze different water allocation policies for water sector withdrawals and reservoir releases. Figure 5.2 shows the schematic representation of the Ebro basin, which includes 52 nodes, 13 reservoirs, 16 hydropower plants, 8 urban centers, and 12 irrigation districts growing 27 crops under different irrigation technologies (flood, sprinkler, drip). The optimal allocation decision is determined for monthly time steps over a period of 30 years.

A periodic autoregressive model of order p - PAR(p) is used to generate the stochastic inflow at stage t, whose parameters are derived from historical inflows. For the sake of notational simplicity, the description of the SDDP algorithm is restricted to cases where inflows can be modeled by an autoregressive model of order one PAR(1). The one-stage SDDP optimization problem at stage t during the Lth iteration has the following objective function:

$$F_t\ (\boldsymbol{s}_t, \boldsymbol{q}_{t-1}) = \max_{x_t}\{b_t\ (\boldsymbol{s}_t\ , \boldsymbol{q}_t, \boldsymbol{x}_{t+1}) + \propto_{t+1}\ F_{t+1}\} \tag{5.1}$$

where F_t represents the benefit-to-go function, $\boldsymbol{s}_t$ is the volume of reservoir storage at the beginning of stage t, and $\boldsymbol{q}_t$ is the inflows at stage t. $\boldsymbol{x}_t$ is the vector of allocation decision variables (release, spillage and losses, end of period storage, and water withdrawal). $b_t(.)$ is the net benefit function at stage t, $\propto_{t+1}$ is the discount rate, and F_{t+1} is the future benefits variable.

Figure 5. 1 The Ebro River basin in Spain.

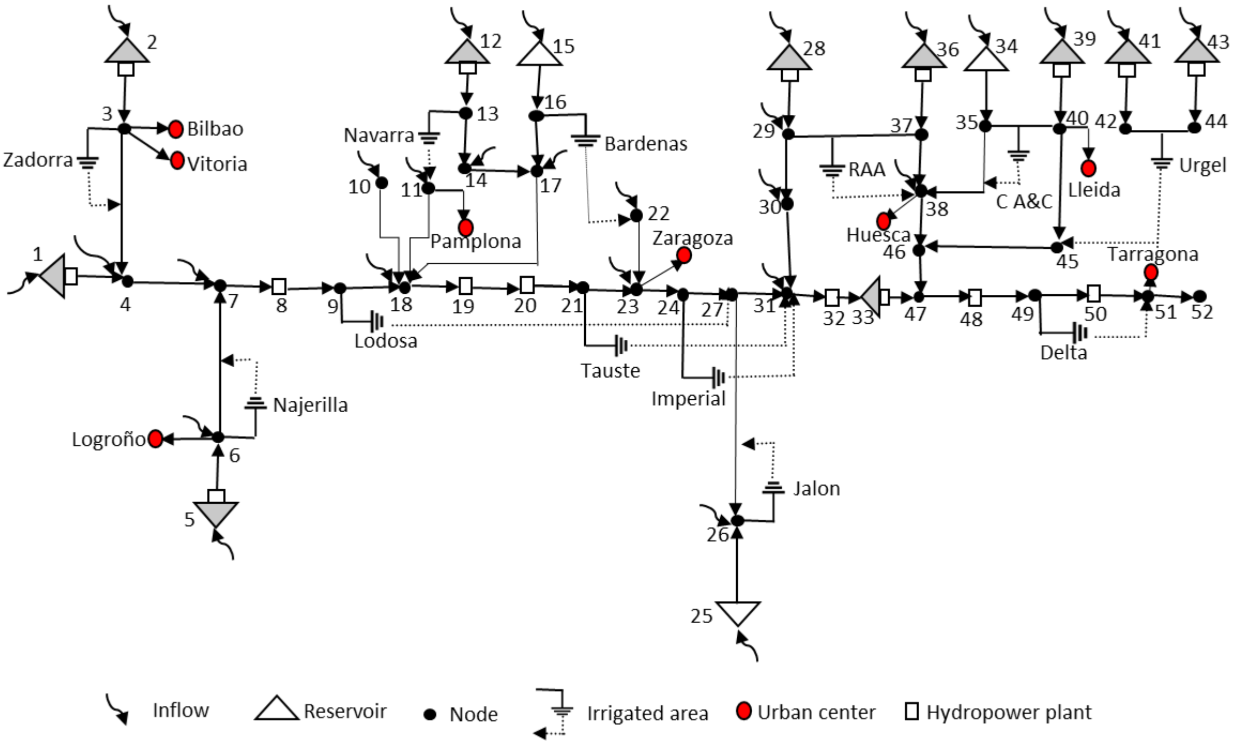


The optimization problem includes several constraints such as lower and upper bounds on storages (Equation (5.2)), reservoirs releases (Equation (5.3)), water withdrawals (Equation (5.4)), water balance (Equation (5.5)), and the outer approximation of the future benefits (Equation (5.6)). The different constraints are represented as follows:

- Lower and upper bounds on storages:

$$\underline{\boldsymbol{s}}_{t+1} \leq \boldsymbol{s}_{t+1} \leq \overline{\boldsymbol{s}}_{t+1} \tag{5.2}$$

Figure 5. 2 Schematic representation of the Ebro River basin.



- Lower and upper bounds on reservoir releases:

$$\underline{\boldsymbol{r}}_t \leq \boldsymbol{r}_t \leq \overline{\boldsymbol{r}}_t \qquad (5.3)$$

- Lower and upper bounds on water withdrawals:

$$\underline{\boldsymbol{i}}_t \leq \boldsymbol{i}_t \leq \overline{\boldsymbol{i}}_t \qquad (5.4)$$

- Water balance:

$$\boldsymbol{s}_{t+1} - C^R(\boldsymbol{r}_t + \boldsymbol{l}_t) - C^I(\boldsymbol{i}_t) + \boldsymbol{e}_t(\boldsymbol{s}_t, \boldsymbol{s}_{t+1}) = \boldsymbol{s}_t + \boldsymbol{q}_t(\boldsymbol{q}_{t-1}, \xi_t) \qquad (5.5)$$

where the topology of the system is represented using the connectivity matrices C^R and C^I. $\boldsymbol{e}_t$ and $\boldsymbol{l}_t$ represent the vector of reservoirs evaporation and the vector of spillage and losses, respectively. $\boldsymbol{q}_t(\boldsymbol{q}_{t-1}, \xi_t)$ is the inflow generated using the PAR(1).

- The outer approximation of the future benefits:

$$F_{t+1} - \boldsymbol{\varphi}_{t+1,l}^{\tau}\, \boldsymbol{s}_{t+1} \leq \boldsymbol{\gamma}_{t+1,l}^{\tau}\, \boldsymbol{q}_t + \beta_{t+1,l} \qquad (L = 1, 2, \dots, L-1) \qquad (5.6)$$

where $\boldsymbol{\varphi}_{t+1,l}$ and $\boldsymbol{\gamma}_{t+1,l}$ are the gradients of F_{t+1} regarding the state variables $(\boldsymbol{s}_{t+1}, \boldsymbol{q}_t)$, $\beta_{t+1,l}$ is the intercept, and L-1 is the total number of iterations already completed. More details are available in (Tilmant et al., 2020).

- The Convex hull approximation of the hydropower production functions can be found in Goor et al. (2011).

The simulation of optimal allocation policy decision is determined from the SDDP results based on the re-optimization procedure described by Tejada-Guibert et al. (1993) with SDP and applied by Tilmant et al. (2020) with the SDDP. The approach is based in using the twelve monthly piecewise linear functions determined from the intermediate year in simulation over the entire streamflow record. The re-optimization problem at time t (year y and month m) is:

$$Z = \max_{x_t} \{b_m\, (\boldsymbol{s}_t\, ,\, \boldsymbol{q}_{y,m}, \boldsymbol{x}_t) + \; F_{m+1} \tag{5.7}$$

Subject to

$$\boldsymbol{s}_{t+1} - \; C^R(\boldsymbol{r}_t \; + \boldsymbol{l}_t) - C^I(\boldsymbol{i}_t\,) + \boldsymbol{e}_t(\boldsymbol{s}_t\,, \boldsymbol{s}_{t+1}\,) = \; \boldsymbol{s}_t \; + \; \boldsymbol{q}_{y,m} \tag{5.8}$$

$$F_{m+1} - \boldsymbol{\varphi}^{\tau}_{m+1,l}\, \boldsymbol{s}_{t+1} \;\; \leq \boldsymbol{\gamma}^{\tau}_{m+1,l}\, \boldsymbol{q}_{y,m} + \; \beta_{m+1,l} \qquad\qquad (l = 1,2, \ldots., L-1) \tag{5.9}$$

Those constraints and the other constraints stated in the one-stage optimization problem are both applicable. Once the re-optimization problem is solved, the system moves to time t + 1 using the mass balance (Equation (5.8)) and solving a new re-optimization problem, and so forth until the end of the streamflow record is reached.

The simulated allocation decisions are used to obtain the performance indicators for the probabilistic trade-offs between economic sectors and between spatial locations. The analysis of trade-offs between economic sectors includes five performance indicators (field crops, fruits, vegetables, hydropower generation, and urban centers). The performance indicator for each group of crops (field crops, fruits, vegetables) is irrigated land, which is the number of hectares (ha) irrigated during the simulation period (30 years). The performance indicator for hydropower generation is the annual energy production, while the performance indicator for urban centers is the volume of water supplied to cities.

The analysis of trade-offs by spatial location includes six performance indicators (upstream irrigated agriculture, downstream irrigated agriculture, upstream hydropower generation, downstream hydropower generation, upstream urban centers, and downstream urban centers). The three indicators for upstream economic activities are irrigated land, energy production, and urban water use in upstream areas, and the three indicators for downstream economic activities are irrigated land, energy production, and urban water use in downstream areas.

In this study, the re-optimization procedure is performed for both historical (baseline) and future climate stream flows. This procedure is critical for assessing the performance of the system under historical and future drought conditions in hydrologic sequences that show the effects of extreme drought events.

5.4 Procedure to identify trade-offs

The optimization-reoptimization process is applied for baseline and for future climate scenarios (CC-2070; CC-2100) under the alternative water allocation policies of agricultural priority or energy priority (see more details in section 4). The re-optimization procedure for each climate scenario and each policy over 30 years delivers vectors for each performance indicator (30×1). These vectors are used for comparisons between sectors and spatial locations described above.

A variety of visualization techniques can be used to discover trade-offs between multiple elements and dimensions, such as Parallel Coordinate Plots and Radar Charts. These interactive visualization frameworks facilitate the discovery of the Pareto optimal solution, especially in high dimensional systems that need sophisticated representations of properties such as color, shape, etc. (Giuliani et al., 2014; Hurford et al., 2014; Tilmant et al., 2020). In this study, Parallel Coordinate Plots are used to discover trade-offs between sectors and spatial locations for each climate scenario and policy. The performance indicators are represented on the X-axis, while the increasing preferences are on the Y-axis. The average of the performance indicator over the simulation period (30 years) is represented by a dotted line. The distribution of the performance indicator is characterized by colored areas associated with quantiles. These areas explain the response of performance indicators to changing water stress conditions under each policy. The orange area represents the first quartile (25%), with the lowest values of performance preference. The green area is the interquartile range between the 25th and 75th percentile; and the blue area includes the highest values, above the 75th percentile. The comparison of plots shows the change in trade-offs between climate scenarios and policies, showing the impacts of priority policies and hydrologic uncertainty.

5.5 Policies and climate scenarios

The analysis investigates the two allocation policies between competing uses under climate scenarios (baseline, CC-2070, CC-2100). The energy priority policy ranks first hydropower generation, whereas the agricultural priority policy ranks agriculture first. In this study, the urban sector is given priority under both intervention policies based on the current water management of the Ebro water authority that prioritizes water allocation for the urban sector. The main reservoirs are operated to maximize their energy production under the energy priority policy, while the agriculture sector maximizes its benefits to the extent possible. For the agricultural priority, the model is optimized so that the total irrigated agriculture benefits are maximized.

The selected policies enhance three important challenging goals: human water security, food security, and energy security. Given escalating trends in human population, climate stress, water use, and development pressures, human water security will remain under threat into the future (Vorosmarty et al., 2010). Safe drinking water and access to fresh water are basic human rights and are prerequisite to achieving many dimensions of sustainable development including health and food security. The challenge of meeting future water needs in a sustainable manner requires the implementation of integrated water resources management and efficient water planning (UN, 2018). Food security and agricultural sustainability are particularly challenging during droughts, requiring urgent action in both developing and developed countries (Gil et al., 2019). Ensuring food security is an important target of the sustainable development goals (SDG) for reducing hunger and extreme poverty, and achieve good health and wellbeing. Energy security is a key issue in Europe and beyond for adaptation and mitigation of climate change. In Spain, the Integrated National Plan of Energy and Climate 2021-2030 and the Energy Security Enhancement Plan regulate the measures and investments for the development of renewable energies, including the target of 74% of renewable energies in electricity generation by 2030 (MITECO, 2020; 2022).

The model is used to assess three climate water stress scenarios for each priority policy in the Ebro basin: Baseline, CC-2070, CC-2100. The future climate water stress scenarios are based on the combination of historical drought patterns and projected future declines in stream flows under climate change. There have been four severe droughts during the last three decades in the Ebro with reductions close to 40% in basin inflows (in years 1989, 2002, 2005 and 2012). This will be combined with the negative trend of stream flows from climate change. The trend of stream flows in the Ebro have been calculated by CEDEX (2017) by downscaling six leading general circulation models. Under scenario RCP 4.5 the fall in streamflow is 11% in 2040-2070, and 12% in 2070-2100. Under scenario RCP 8.5 the fall in streamflow is 13% in 2040-2070, and 26% in 2070-2100.

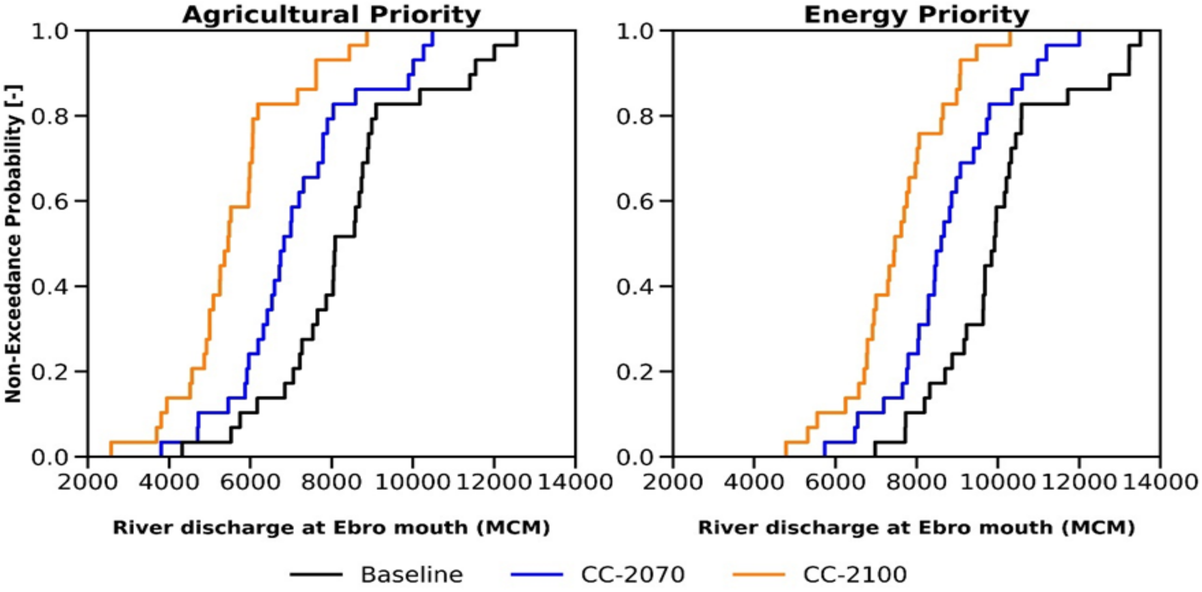
5.6 Results

5.6 1 Hydroeconomic risk assessment under future climate water stress

The empirical cumulative distribution of annual outflow at the Ebro River mouth under climate water stress scenarios (CC-2070 and CC-2100) and priority policies are shown in figure 5.3. Based on the SDDP simulations under historical climate conditions, the optimal annual outflow for 50% non-exceedance probability is estimated to be 8080 and 9910 Mm^3 under agriculture and energy priority, respectively. Not surprisingly, the energy priority policy involves higher stream flows at the Ebro River mouth because of the larger reservoir releases from hydroelectric generation. The rise of stream flows in rivers under the energy priority enhance water security. Overall, under future climate water stress scenarios, the annual outflow at Ebro River mouth is projected to be smaller for both priority policies in comparison with the historical outflow. For agricultural priority, the annual outflow at the Ebro River mouth with a 50% exceedance probability is estimated at 6830 Mm^3 under CC-2070 climate scenario, but only 5450 Mm^3 under CC-2100 climate scenario. However, for energy priority, the annual outflow will exceed 8600 and 7470 Mm^3 for 2070 and 2100, respectively, for a 50% exceedance probability.

The projected annual hydropower production, irrigated cropland, and urban water use in the Ebro River basin for baseline, CC-2070 and CC-2100 climate scenarios under agriculture and energy priority policies are shown in figure 5.4. The urban sector takes priority over all other water uses and the annual urban water withdrawals are maintained in both policies and future climate scenarios, promoting the human water security goal. The annual hydropower production for current climate conditions and 50% non-exceedance probability is estimated at 4030 GWh under agricultural priority, which is considerably smaller than under energy priority (-13%; 4640 GWh). The hydropower production is expected to decrease under future climate water stress scenarios because of the falling stream flows in the basin. The hydropower production decreases by almost 30% (at 2930 GWh) under agricultural priority, while it decreases only close to 20% (3610 GWh) under energy priority for the CC-2100 scenario, compared to the baseline. The drop in hydropower generation is substantial under agricultural priority compared to the energy priority policy. The projected irrigated land for current climate conditions under agricultural priority is 538,000 ha for an exceedance probability of 50%, while under energy priority, the irrigated land with a 50% exceedance probability is only 311,000 ha. In both future climate scenarios, the fall in irrigated land is below 10% under agricultural priority. However, under energy priority irrigated cropland falls by 20% (249,000 ha) and 34% (206,000 ha) for the CC-2070 and CC-2100 scenarios, respectively.

Figure 5. 3 Empirical cumulative probability distribution functions of projected annual outflows at the Ebro River mouth for baseline, CC-2070, and CC-2100 periods under energy and agricultural priority.



5.6 2 Probabilistic trade-offs between competing water users and spatial locations

Figures 5.5 and 5.6 show the trade-offs between economic activities and between spatial locations in the basin, by priority policy and climate scenario. The results show the trade-offs among economic sectors, agricultural subsectors, and upstream-downstream spatial locations. The magnitude of trade-offs reveals their sensitivity to hydrologic stress from climate conditions.

Under future climate scenarios, the policy of agricultural priority reduces energy generation considerably, while maintains the irrigated acreage of field crops, fruits and vegetables. This priority damages the energy sector, with lower production and higher vulnerability to climate conditions. The reason is the reduced basin stream flows because of larger irrigation withdrawals. Water is used for energy production only to the extent permitted by irrigation oriented reservoir releases and by the diminished river flows.

In contrast, for all climate scenarios the energy priority policy increases hydroelectric production, decreases the performance of agriculture, and maintains urban water use. There is a large drop in production of field crops, fruits and vegetables, compared to agricultural priority (Figure 5.5). This reveals the trade-offs between energy and agriculture, which are an important consideration for decision making. Water use in urban centers is met with a reliability of 100% under both agricultural and energy priority policies for all climate scenarios, achieving human water security.

Figure 5. 4 Empirical cumulative probability distribution functions of projected annual hydropower, irrigated land, and urban water use for baseline, CC-2070 and CC-2100 periods under energy and agricultural priority.

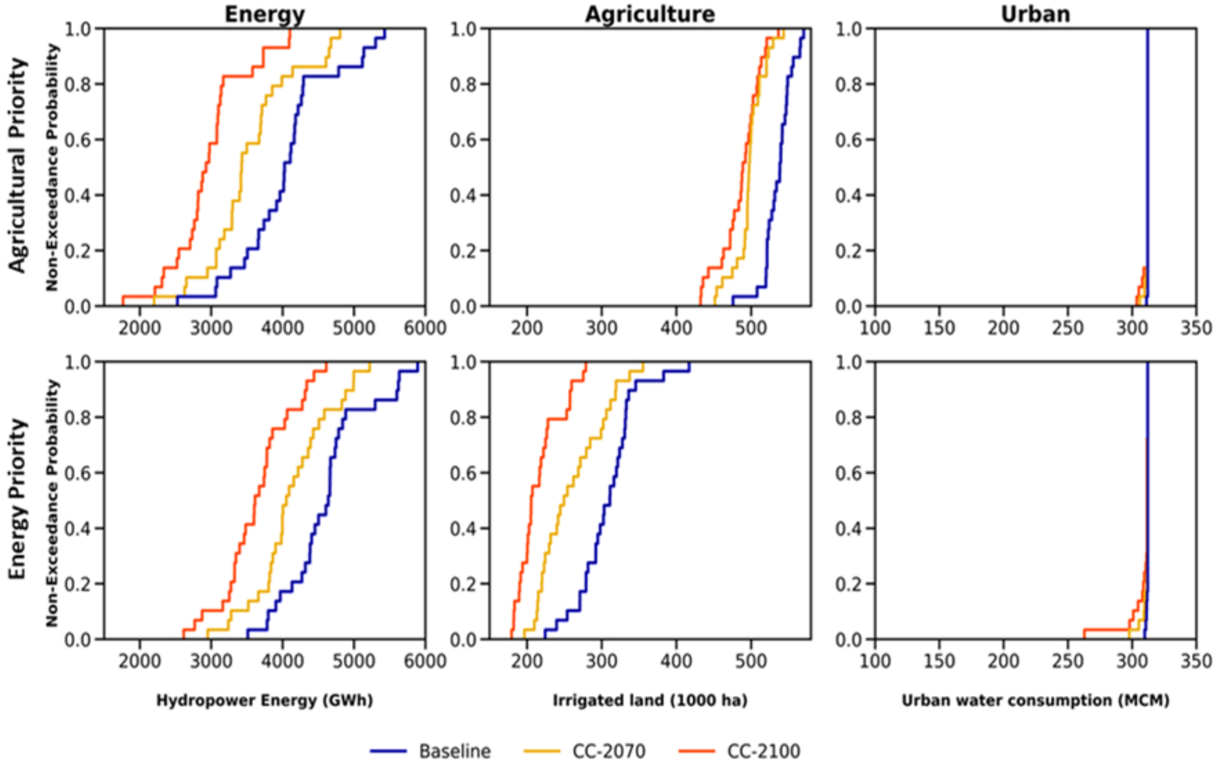
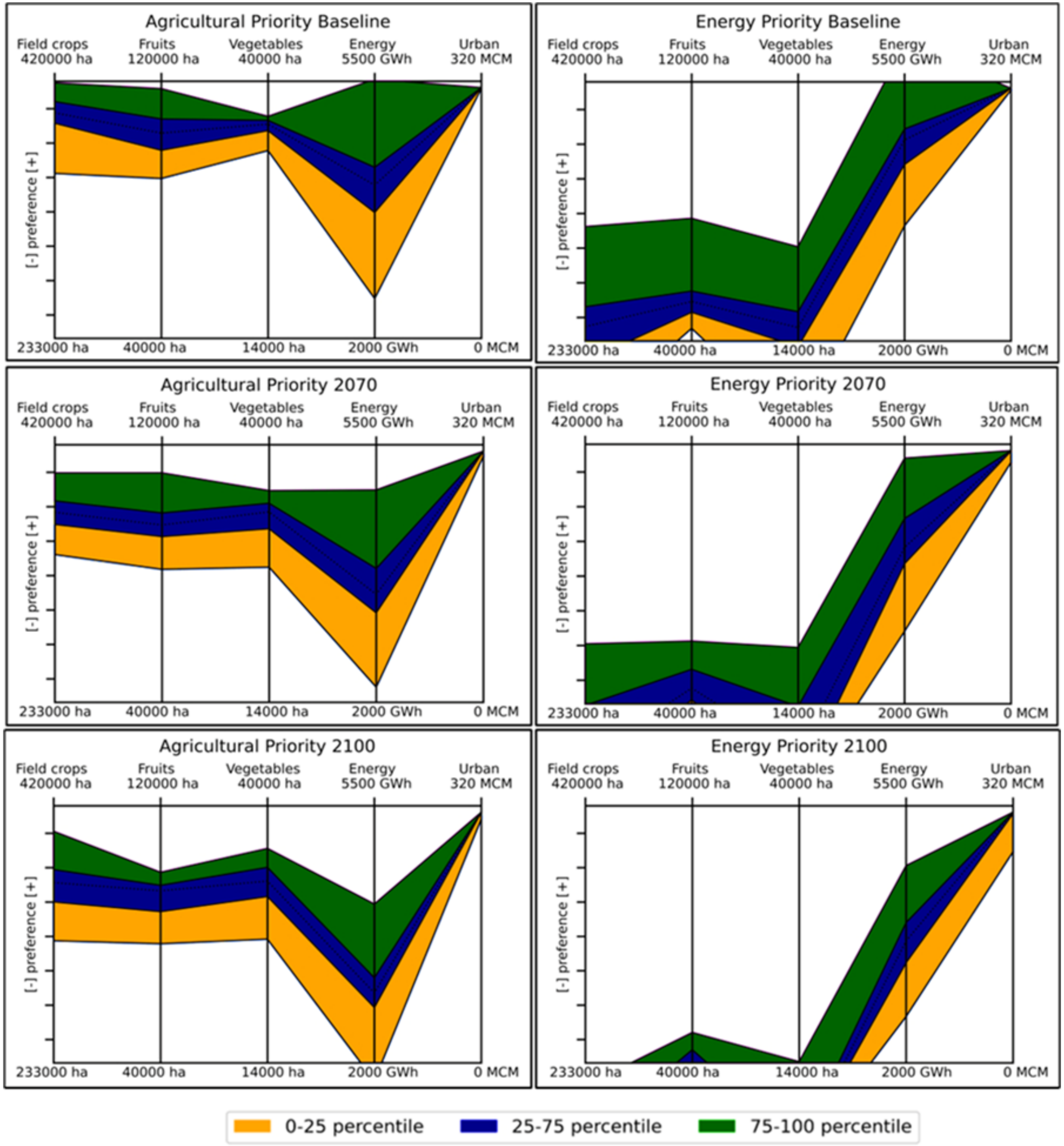


Figure 5.5 shows also the intra-sectoral trade-offs between agricultural subsectors, especially damaging under energy priority. The agricultural priority slightly reduces the acreage of field crops (-7%), fruits (-9%) and vegetables (-8%) for a 50% exceedance probability in 2070 and 2100. However, a considerable reduction of vegetables (-42% in 2070; -67% in 2100), and field crops (-21% in 2070; -31% in 2100) is sustained under energy priority when water scarcity intensifies. The reason for the considerable fall in irrigated area is the lack of water to cover crop requirements in all irrigation districts under climate water stress conditions. For the energy priority policy, the probability of the acreage of field crops and vegetables falling below 233,000 ha and 14,000 ha, respectively, is close to 25% in the baseline. This probability rises to 75% in 2070 and 100% in 2100, highlighting the vulnerability of field crops and vegetables to climate water stress. The probability of the acreage of fruits being below 40,000 ha is 0% in the baseline, and around 25% in 2070 and 50% in 2100, showing that fruits are less vulnerable to climate water stress than field crops and vegetables. The substantial decrease in field crops and vegetables under energy priority is due to the low profitability and high water requirement linked to outdated irrigation technology (flood).

Figure 5. 5 Trade-offs between sectors for baseline, CC-2070 and CC-2100 periods under energy and agricultural priority.



As mentioned above, agricultural priority results in low performance and high vulnerability of hydroelectric production under water stress conditions. However, the vulnerability level depends on the spatial location of hydropower plants. Figure 5.6 shows that under agricultural priority, downstream hydropower generation decreases by 15% in 2070 and 28% in 2100 for a 50% non-exceedance probability, while upstream hydropower generation declines only by 7% in 2070 and 20% in 2100. This indicates that downstream hydropower production is more vulnerable than upstream hydropower production.

Despite the slight vulnerability of the agriculture sector under agricultural priority, agriculture downstream is more impacted (-6% in 2070 and -10% in 2100) than agriculture upstream under future climate scenarios for a 75% non-exceedance probability. This indicates that agriculture downstream is more vulnerable than agriculture upstream. The reason is the advantage of upstream areas to use water from inflows and reservoir releases, while water withdrawals in downstream areas are limited by more scarce downstream flows.

The energy priority policy decreases upstream irrigated acreage by 57% and 100% for 2070 and 2100, respectively, for a 50% non-exceedance probability. However, irrigated acreage downstream decreases only by 8% and 16% for 2070 and 2100, respectively. This highlights the low performance and high vulnerability of agriculture upstream to water stress. The low vulnerability of downstream irrigation is explained by high hydroelectric production downstream, which delivers large reservoir releases to irrigation downstream.

Benefits from hydropower, irrigation and urban supply decrease under future climate scenarios (CC-2070 and CC-2100) for both priority policies. For the CC-2100 scenario, average annual agricultural benefit falls by 8% and 23% under agricultural and energy priorities, and average annual energy benefit falls by 27% and 21% under agricultural and energy priorities, respectively. The implication is that agricultural priority promotes food security and energy priority promotes energy security. However, agricultural priority worsens the performance and increases the vulnerability of hydropower, and energy priority has the same negative effect on agriculture. Results on basin-wide benefits indicate the trade-offs of shifting from agricultural to energy priority: agriculture benefit losses would be close to 50% (43% in baseline, 46% in 2070, and 52% in 2100), while energy benefit gains would be close to 20% (14% in baseline, 17% in 2070, and 23% in 2100).

The costs of climate change for irrigation districts and hydropower plants by spatial location are presented in Figure 5.7. This information provides a better understanding of the vulnerability of sectors across locations in the basin. Under energy priority, upstream irrigation districts would lose 57% of their benefits for CC-2070 and 95% for CC-2100 climate scenarios. This demonstrates how climate water stress coupled with energy priority, increases the likelihood of irrigation losses up to the point of threatening the sustainability of upstream irrigation. Benefits of downstream irrigation districts are less affected by future water scarcity coupled with energy priority, because they take advantage of large reservoir releases that maximize downstream hydropower production.

Figure 5. 6 Trade-offs between sectors by spatial location (upstream-downstream) for baseline, CC-2070 and CC-2100 periods under energy and agricultural priority.

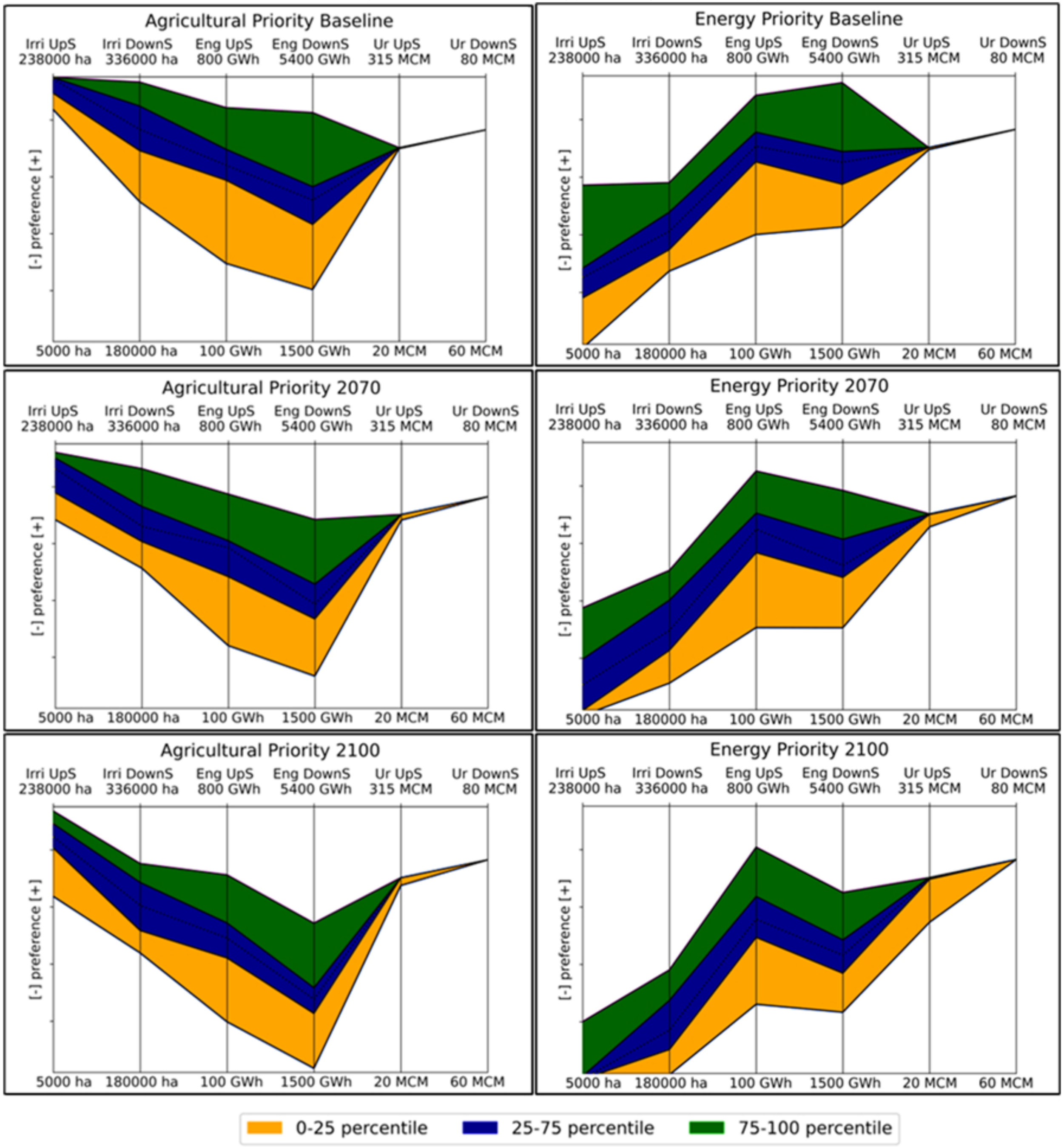
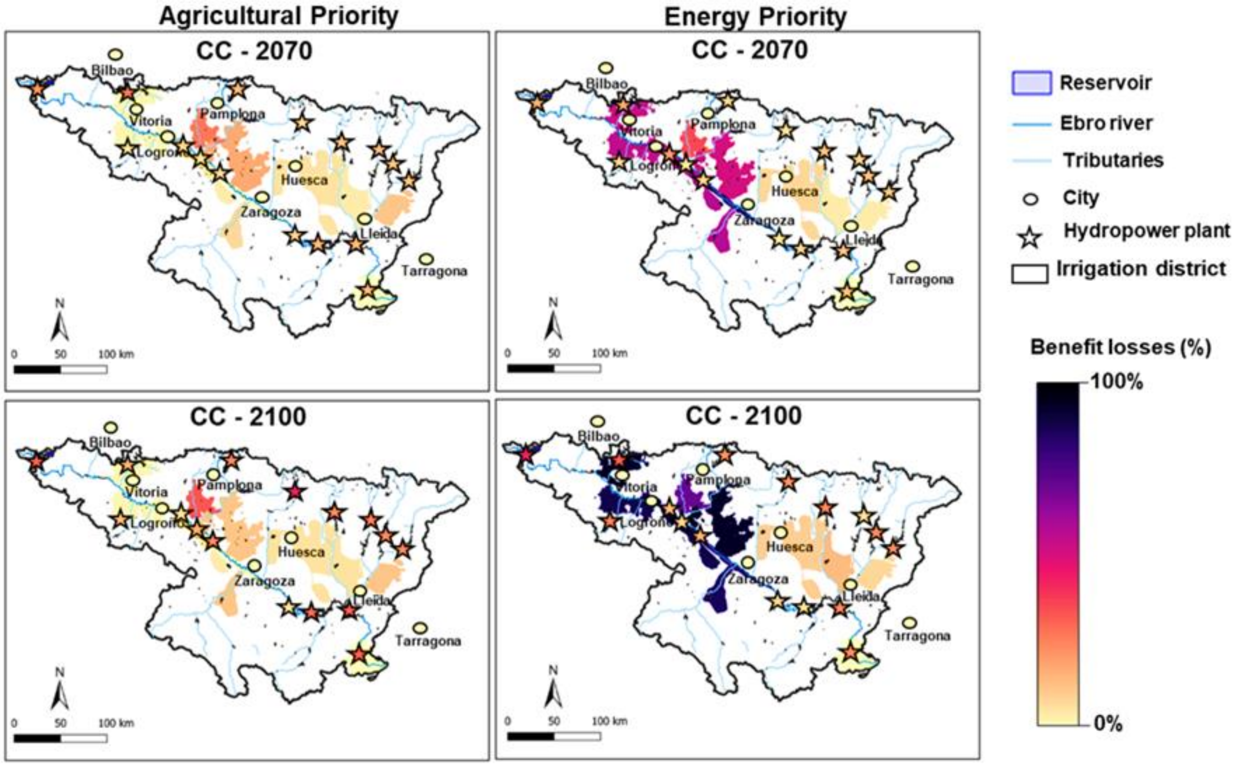


Figure 5. 7 Benefit losses by sector under future climate scenarios.



Under agricultural priority, benefit losses of downstream hydropower could reach 45% for the CC-2100 climate scenario, while benefits of upstream hydropower plants would be only slightly reduced. This is explained by the advantage of hydropower in upstream areas that can use water from headwaters and reservoir releases, whereas hydropower downstream is faced with depleted stream flows since more water is consumed by irrigation districts under agricultural priority.

5.7 Discussion and policy implications

This paper contributes to the literature by analyzing alternative water allocation policies that can be adopted to share water resources under future climate water stress conditions. The study deals with the hydrologic and economic impacts in the Ebro River, a large and complex basin. The research investigates the probabilistic trade-offs between agriculture, urban supply, and energy under water allocation policies and future climate scenarios. Furthermore, the study provides information on the gains and losses by sector from selecting alternative management objectives. Results can inform a nexus dialogue between sectors in order to improve cross-sectoral planning and achieve equitable trade-offs. This is in line with the ongoing international interest in protecting water resources, and preparing for global warming and future drought conditions.

Findings are based on the assessment of hydrological and sectoral risks from climate water stress. They call for decisive policy interventions by local, state and federal stakeholders in reducing the vulnerability of economic sectors. The results for climate change scenarios are consistent with other studies that find streamflow reductions: Pulido-Velazquez et al. (2021) indicate that there would be substantial streamflow reductions in Spain's northern basins, and Lopez-Moreno et al. (2014) estimate a 14% decrease in stream flows in the Pyrenees from the projected trend of warming for the period 2021-2050.

The relationships between hydropower and irrigation can be better understood by considering the impacts of climate water stress, which affects both water demand and supply by sector and location. Under climate change, there is competition between food security, energy security and human water security in urban centers. Our results indicate that the human water security is achieved under both priority policies and climate scenarios. Findings demonstrate that choosing a policy of agricultural priority worsens the performance and increases the vulnerability of hydropower. Conversely, selecting a policy of energy priority increases the vulnerability of irrigated agriculture. Tilmant et al. (2020) indicate that traditional food production is much more vulnerable to changes in hydro climatic conditions and allocation policies in the Senegal basin, emphasizing the importance of factoring this vulnerability into schemes for water and benefit sharing negotiations.

Enhancing energy security would come at the expense of irrigated agriculture. Findings show that the energy priority policy reduces water supply to upstream irrigation schemes, with substantial benefit losses in upstream agriculture. Conversely, the agricultural priority policy would damage hydropower generation downstream, where the bigger hydropower plants are located, because upstream withdrawals by irrigation districts deplete downstream river flows used for hydropower.

Although hydropower production does not consume water, the seasonality of releases and the spatial location of plants may have strong impacts on river flows. These flow changes could lead to conflicts between large hydropower plants downstream and upstream irrigation districts. The same dilemma is found by Jalilov et al. (2016) in the Amu Darya River Basin in the assessment of alternative priority policies. They indicate that energy priority ensures more energy production by Tajikistan but dwindling agricultural benefits in downstream countries, while agricultural priority brings more agricultural benefits to Tajikistan and Uzbekistan. They stress the importance of seasonality and timing in reservoir releases for the performance of energy production and irrigated agriculture.

Our study is novel in two aspects: first, a stochastic optimization model is used to assess the probabilistic trade-offs between sectors and spatial locations in the basin, under future climate scenarios and alternative water allocation policies. The trade-offs could inform a nexus dialogue between sectors for supporting the science-informed design of efficient, flexible, and equitable cross-sectoral water planning and promoting sustainable development. Identifying those trade-offs is a prerequisite towards the development of adapted, socially-acceptable allocation policies between sectors and spatial locations, and the collective action of stakeholders and decision-makers to advance sustainable water management coupled with food, energy, and human water security. Second, the evaluation of hydroeconomic risks under future climate conditions reveals the achievable goals and means for efficient water allocation among sectors, and the reduction of future uncertainties by promoting politically feasible planning.

A certain number of simplified assumptions have been undertaken in the modeling approach. The stochastic optimization model presents ongoing debates only between irrigated agriculture, urban supply and energy sectors. The inclusion of other important competing water users such as ecosystems could improve the assessment of the probabilistic trade-offs between sectors. This will guide a broader sectoral scope for efficient water allocation under future climate water stress. The projection of future hydrologic data that are used in this study is based on reductions in historic inflows for each spatial location based on the information provided by CEDEX (2017) for the Ebro basin. Future studies should improve hydrologic projections by using sophisticated methodologies for more accurate climate projections that could address spatial and temporal variabilities, and better deal with uncertainties. Despite these limitations, our modeling approach generates useful insights for improving cross-sectoral planning, achieve equitable trade-offs with the support of stakeholders, adapt to future climate water stress, and provide policymakers with inspiring messages for the design and implementation of efficient and feasible water allocation policies.

5.8 Conclusions

The contribution of the study focuses on investigating the probabilistic cross-sectoral trade-offs and risks associated with future climate water stress. The purpose is to understand the water-food-energy nexus under future uncertainties of climate variability. To meet this challenge, a stochastic optimization model (SDDP) is developed for the Ebro basin. This model is used to identify the vulnerability of the economic sectors to hydrological risks, and the response through alternative priority policies that result in gains and losses among sectors and spatial locations.

The take home message from our findings is that the analysis of probabilistic trade-offs shows the ranges of vulnerability for agriculture and hydropower depending on the goals embodied in the policy priorities of decision makers. The policies of agricultural or energy priority coupled with the spatial locations of irrigation schemes and hydropower plants, determine stream flows across the basin and water withdrawals to competing sectors. This results in dramatically different benefit gains and losses by sector. However, neither priority policy provides an equitable sharing of benefits among all sectors and spatial locations under climate change. This fact emphasizes the difficulties of reaching win-win outcomes that would enhance food, energy and human water security in large river basins. However, the information on probabilistic trade-offs contributes to the design of water management policies that could handle the challenges posed by climate water stress, by reducing economic losses and achieving acceptable levels of energy, agricultural and human water security.

References

Bellman R. Dynamic Programming, 1 ed. Princeton University Press, Princeton, NJ, USA. 1957.

Brown C, Ghile Y, Laverty M, Li K. Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. Water Resources Research 2012; 48: 12.

Cai XM, Wallington K, Shafiee-Jood M, Marston L. Understanding and managing the food-energy-water nexus - opportunities for water resources research. Advances in Water Resources 2018; 111: 259-273.

Cammalleri C, Naumann G, Mentaschi L, Formetta G, Forzieri G, Gosling S, et al. Global warming and drought impacts in the EU : JRC PESETA IV project : Task 7. Publications Office. https://doi.org/doi/10.2760/597045. 2020.

CEDEX. (Centro de Estudios Hidrográficos). Evaluación del Impacto del Cambio Climático en los Recursos Hídricos y Sequías en España. Informe final. Julio de 2017. Centro de Estudios Hidrográficos. CEDEX. Madrid. 2017.

Crespo D, Albiac J, Kahil T, Esteban E, Baccour S. Tradeoffs between Water Uses and Environmental Flows: A Hydroeconomic Analysis in the Ebro Basin. Water Resources Management 2019; 33: 2301-2317.

CHE. (Confederación Hidrográfica del Ebro). Plan de Gestión del Riesgo de Inundación (2º Ciclo). Memoria. Confederación Hidrográfica del Ebro. Zaragoza. . 2022.

Cheng B, Li HE, Yue SY, Huang K. A conceptual decision-making for the ecological base flow of rivers considering the economic value of ecosystem services of rivers in water shortage area of Northwest China. Journal of Hydrology 2019; 578: 7.

Dinar S, Katz D, De Stefano L, Blankespoor B. Climate change, conflict, and cooperation: Global analysis of the effectiveness of international river treaties in addressing water variability. Political Geography 2015; 45: 55-66.

Feyen L, Gosling S, Ciscar J, Ibarreta D, Soria A. Climate change impacts and adaptation in Europe. JRC PESETA IV final report. Publications Office of the European Union, Luxembourg. Doi: 10.2760/171121. 2020.

Gil JDB, Reidsma P, Giller K, Todman L, Whitmore A, van Ittersum M. Sustainable development goal 2: Improved targets and indicators for agriculture and food security. Ambio 2019; 48: 685-698.

Giuliani M, Herman JD, Castelletti A, Reed P. Many- objective reservoir policy identification and refinement to reduce policy inertia and myopia in water management. Water Resources Research 2014; 50: 3355-3377.

Goor Q, Halleux C, Mohamed Y, Tilmant A. Optimal operation of a multipurpose multireservoir system in the Eastern Nile River Basin. Hydrology and Earth System Sciences 2010; 14: 1895-1908.

Goor Q, Kelman R, Tilmant A. Optimal Multipurpose-Multireservoir Operation Model with Variable Productivity of Hydropower Plants. Journal of Water Resources Planning and Management 2011; 137: 258-267.

Greve P, Kahil T, Mochizuki J, Schinko T, Satoh Y, Burek P, et al. Global assessment of water challenges under uncertainty in water scarcity projections. Nature Sustainability 2018; 1: 486-494.

Grey D, Sadoff CW. Sink or Swim? Water security for growth and development. Water Policy 2007; 9: 545-571.

Hajkowicz S, Collins K. A review of multiple criteria analysis for water resource planning and management. Water Resources Management 2007; 21: 1553-1566.

Hernández N, Gil M, Garrido A, Rodríguez R. La sequía 2005-2008 en la Cuenca del Ebro: Vulnerabilidad, impactos y medidas de gestión. UPM-CEIGRAM, Madrid. 2013.

Hurford AP, Huskova I, Harou JJ. Using many-objective trade-off analysis to help dams promote economic development, protect the poor and enhance ecological health. Environmental Science & Policy 2014; 38: 72-86.

Jalilov SM, Amer SA, Ward FA. Managing the water-energy-food nexus: Opportunities in Central Asia. Journal of Hydrology 2018; 557: 407-425.

Jalilov SM, Keskinen M, Varis O, Amer S, Ward FA. Managing the water-energy-food nexus: Gains and losses from new water development in Amu Darya River Basin. Journal of Hydrology 2016; 539: 648-661.

Lines C, Werner M, Bastiaanssen W. The predictability of reported drought events and impacts in the Ebro Basin using six different remote sensing data sets. Hydrology and Earth System Sciences 2017; 21: 4747-4765.

Lopez-Moreno JI, Zabalza J, Vicente-Serrano SM, Revuelto J, Gilaberte M, Azorin-Molina C, et al. Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragon River, Spanish Pyrenees. Science of the Total Environment 2014; 493: 1222-1231.

Marques GF, Tilmant A. The economic value of coordination in large-scale multireservoir systems: The Parana River case. Water Resources Research 2013; 49: 7546-7557.

Mendes LA, de Barros MTL, Zambon RC, Yeh WWG. Trade-Off Analysis among Multiple Water Uses in a Hydropower System: Case of Sao Francisco River Basin, Brazil. Journal of Water Resources Planning and Management 2015; 141: 10.

MITECO. (Ministerio para la Transición Ecológica). Plan Nacional Integrado de Energía y Clima 2021-2030. MITECO. Madrid. 2020.

MITECO. (Ministerio para la Transición Ecológica). Plan Más Seguridad Energética. MITECO. Madrid. 2022.

Pulido-Velazquez D, Collados-Lara AJ, Perez-Sanchez J, Segura-Mendez FJ, Senent-Aparicio J. Climate change impacts on the streamflow in Spanish basins monitored under near-natural conditions. Journal of Hydrology-Regional Studies 2021; 38: 21.

Tejada-Guibert JA, Johnson SA, Stedinger JR. COMPARISON OF 2 APPROACHES FOR IMPLEMENTING MULTIRESERVOIR OPERATING POLICIES DERIVED USING STOCHASTIC DYNAMIC-PROGRAMMING. Water Resources Research 1993; 29: 3969-3980.

Tilmant A, Kelman R. A stochastic approach to analyze trade-offs and risks associated with large-scale water resources systems. Water Resources Research 2007; 43: 11.

Tilmant A, Pina J, Salman M, Casarotto C, Ledbi F, Pek E. Probabilistic trade-off assessment between competing and vulnerable water users - The case of the Senegal River basin. Journal of Hydrology 2020; 587: 15.

Turner BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, et al. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences of the United States of America 2003; 100: 8074-8079.

Turner SWD, Marlow D, Ekstrom M, Rhodes BG, Kularathna U, Jeffrey PJ. Linking climate projections to performance: A yield- based decision scaling assessment of a large urban water resources system. Water Resources Research 2014; 50: 3553-3567.

UN. (United Nations), High level political forum goals in focus: Goal 6: Ensure availability and sustainable management of water and sanitation for all. United Nations Statistics Division (UNSD), a division of the Department of Economic and Social Affairs (DESA). https://unstats.un.org/sdgs/report/2018/goal-06/. 2018.

Vargas J, Paneque P. Methodology for the analysis of causes of drought vulnerability on the River Basin scale. Natural Hazards 2017; 89: 609-621.

Vorosmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, et al. Global threats to human water security and river biodiversity. Nature 2010; 467: 555-561.

Wilson E. What is Benefit Sharing? Respecting Indigenous Rights and Addressing Inequities in Arctic Resource Projects. Resources-Basel 2019; 8: 23.

Wu JY, Luo JA, Du XZ, Zhang H, Qin S. Optimizing water allocation in an inter-basin water diversion project with equity-efficiency tradeoff: A bi-level multiobjective programming model under uncertainty. Journal of Cleaner Production 2022; 371: 13.

Yin DQ, Li X, Wang F, Liu Y, Croke B, Jakeman A. Water-energy-ecosystem nexus modeling using multi-objective, non-linear programming in a regulated river: Exploring tradeoffs among environmental flows, cascaded small hydropower, and inter-basin water diversion projects. Journal of Environmental Management 2022; 308: 19.

Zhang X, Tian Y, Dong N, Wu H, Li S. The projected futures of water resources vulnerability under climate and socioeconomic change in the Yangtze River Basin, China. Ecological Indicators 2023; 147.

Appendix

Table A5.1. Optimized energy production by hydropower plant, policy, and climate scenario, Averaged over 30 years (Gwh)

Policies	**Agriculture priority**			**Energy priority**		
Hydropower plants (Nodes)	**Baseline**	**CC-2070**	**CC-2100**	**Baseline**	**CC-2070**	**CC-2100**
Node 1	11.95	9.37	7.95	11.33	9.44	6.03
Node 2	49.97	36.42	41.76	44.14	36.15	29.39
Node 5	87.93	82.84	74.86	81.07	72.83	59.95
Node 8	152.92	140.19	122.73	159.27	147.79	135.64
Node 12	52.57	45.55	39.50	51.45	45.88	40.01
Node 19	104.90	98.39	87.11	131.88	125.92	121.99
Node 20	113.08	103.04	85.66	142.25	130.45	117.15
Node 28	6.77	6.28	3.71	6.91	6.47	5.37
Node 32	203.10	187.38	161.38	272.32	259.71	249.05
Node 33	950.56	824.14	656.42	1235.12	1115.12	981.66
Node 36	570.44	497.99	433.35	574.28	503.90	431.98
Node 39	330.16	285.04	244.43	325.53	289.90	258.16
Node 41	308.87	273.21	235.52	308.65	273.07	235.50
Node 43	209.70	184.20	158.57	208.45	183.20	160.30
Node 48	827.19	708.39	567.26	982.67	864.28	748.90
Node 50	63.27	54.22	42.84	75.91	66.93	57.68
Total Ebro	**4043.36**	**3536.66**	**2963.06**	**4611.23**	**4131.05**	**3638.78**

The spatial location of each node is represented in Figure 5.2.

Table A5.2. Optimized land in production by irrigation scheme, policy, and climate scenario, Averaged over 30 years (1000 ha)

Policies	**Agriculture priority**			**Energy priority**		
Irrigation schemes	**Baseline**	**CC-2070**	**CC-2100**	**Baseline**	**CC-2070**	**CC-2100**
Zadorra	6.18	5.99	6.02	0.66	0.30	0.04
Najerilla	27.78	27.07	27.31	8.33	3.72	0.88
Lodosa	56.58	54.65	54.43	16.01	6.94	1.83
Navarra	20.51	14.34	11.70	5.86	4.04	1.64
Bardenas	67.83	54.74	56.85	13.93	7.12	0.80
Tauste	8.84	8.84	8.84	3.18	1.66	0.49
Imperial	43.33	43.22	43.33	13.13	6.68	1.82
Jalón	12.31	11.31	9.63	2.88	1.22	0.38
RAA	107.31	102.84	103.98	67.74	59.13	51.85
C A&C	85.96	82.91	81.61	85.39	81.53	72.39
Urgel	70.06	62.47	53.10	61.07	58.30	54.15
Delta	29.34	29.34	29.34	29.34	29.34	29.34
Total Ebro	**536.02**	**497.72**	**486.11**	**307.53**	**259.97**	**215.61**

Table A5.3. Optimized land in production by crop type, policy, and climate scenario, Averaged over 30 years (1000 ha)

Policies	**Agriculture priority**			**Energy priority**		
Irrigation scheme	**Baseline**	**CC-2070**	**CC-2100**	**Baseline**	**CC-2070**	**CC-2100**
Field	396.5	369.9	362.5	239.4	204.0	173.0
Vegetables	35.4	32.7	32.0	14.9	9.9	6.3
Fruit	104.1	95.2	91.5	53.2	46.0	36.3
Total	**536.0**	**497.7**	**486.1**	**307.5**	**260.0**	**215.6**

Table A5.4. Optimized water use by sector, policy, and climate scenario, Averaged over 30 years (Mm^3)

Policies		**Agriculture priority**			**Energy priority**		
Climate scenarios	**sector**	**Baseline**	**CC-2070**	**CC-2100**	**Baseline**	**CC-2070**	**CC-2100**
Zadorra	A	25.1	24.3	24.4	2.4	1.1	0.1
Najerilla	A	82.9	80.9	81.5	21.7	9.7	2.2
Lodosa	A	185.1	178.0	177.9	42.1	18.3	4.4
Navarra	A	79.4	57.6	48.0	17.4	11.5	4.4
Bardenas	A	266.8	219.9	234.3	40.0	19.0	2.2
Tauste	A	38.4	38.4	38.4	10.0	5.3	1.3
Imperial	A	201.1	200.5	201.1	45.5	23.8	5.6
Jalón	A	48.7	44.8	38.9	9.4	4.0	1.1
RAA	A	479.2	454.7	466.5	286.1	261.5	230.6
C A&C	A	367.7	352.9	347.4	366.0	352.1	312.5
Urgel	A	311.7	275.9	244.9	269.6	259.6	248.0
Delta	A	205.8	205.8	205.8	205.8	205.8	205.8
Total	**A**	**2292.0**	**2133.9**	**2109.2**	**1316.1**	**1171.7**	**1018.5**
Vitoria	U	6.3	6.2	6.2	6.2	6.1	6.1
Bilbao	U	195.0	194.7	194.3	195.0	194.2	192.4
Logroño	U	6.0	6.0	6.0	5.9	5.9	5.4
Lérida	U	4.2	4.2	4.2	4.2	4.2	4.2
Pamplona	U	11.1	11.1	11.1	11.1	11.1	11.0
Zaragoza	U	17.7	17.7	17.7	17.7	17.7	17.7
Huesca	U	1.8	1.8	1.8	1.8	1.8	1.8
Tarragona	U	70.0	70.0	70.0	70.0	70.0	70.0
Total	**U**	**312.1**	**311.7**	**311.3**	**311.9**	**311.0**	**308.6**
Node 1	E	79.8	63.5	54.2	76.6	63.8	67.9
Node 2	E	361.9	338.4	323.1	349.8	346.1	310.4
Node 5	E	136.8	127.6	116.4	126.7	121.7	118.9
Node 8	E	1264.7	1144.7	1002.1	1300.4	1206.8	1107.5
Node 12	E	104.6	89.9	78.0	101.6	90.6	79.0
Node 19	E	1442.7	1306.0	1156.4	1750.7	1671.6	1619.3
Node 20	E	1993.0	1785.5	1484.3	2465.0	2260.6	2030.1
Node 28	E	63.2	53.8	41.8	60.6	55.5	46.0
Node 32	E	1876.8	1680.8	1447.6	2442.7	2329.7	2234.0
Node 33	E	2461.2	2114.4	1684.0	3169.0	2860.7	2518.3
Node 36	E	548.7	489.9	421.1	556.4	492.0	417.8
Node 39	E	289.8	245.5	210.6	280.4	249.7	222.4
Node 41	E	539.8	476.3	410.3	538.8	476.0	410.2
Node 43	E	296.4	261.4	224.5	295.1	259.3	226.9
Node 48	E	3978.2	3386.3	2711.7	4697.5	4131.6	3580.0
Node 50	E	3726.7	3171.7	2505.9	4440.9	3915.1	3374.2
Total	**E**	**19164.1**	**16735.9**	**13871.8**	**22652.2**	**20530.7**	**18363.0**

CHAPTER 6

SUMMARY AND GENERAL CONCLUSIONS

Chapter 6 Summary and general conclusions

This thesis addresses several challenges confronting water resources in most arid and semi-arid basins, proposing cost-effective management options to adapt to climate stress. The main outstanding challenges are water scarcity, water quality deterioration, climate stress impacts, water conflicts among sectors and spatial locations, and sectoral vulnerability. The four key chapters of this research present the development of various integrated and dynamic optimization frameworks, taking the Ebro River basin in Spain as a case study. Those different hydroeconomic modeling include hydrologic, economic, institutional, environmental, and climate aspects, with each model tailored to a specific goal. This integrated management approach provides a better understanding of the impacts of climate change, and identifies the potential of hydroeconomic modeling in informing equitable water planning for climate adaptation. The empirical findings of the different integrated modeling approaches provide useful insights into policy making for sustainable development. The modeling approaches developed are flexible, and could be adaptable to many river basins with similar climate conditions.

Facing increasing climate and human challenges that threaten water and atmosphere quality, this thesis analyzes various agricultural management practices that reduce nutrient water pollution and GHG emissions for climate mitigation and adaptation. Another contribution quite significant is the information presented on sectoral responses and competition under several water management strategies and future climate conditions. This information enables to find the best allocation strategies that are efficient, equitable, and sustainable for sharing the burden of dwindling resources and for protecting river flows. Such allocation strategies would minimize economic losses while adapting to hydrologic, economic, and institutional features in basins. The study contains several methodological modeling advances such as non-linear and stochastic optimization, the inclusion of both water quantity and quality in modeling, multi-sector assessment, and integration of different components of water systems (hydrology, economy, environment, and institutions). A limited number of studies in the literature address jointly these modeling advances for evaluating climate adaptation and mitigation policies. This research contributes to more sustainable water planning, and to advance water policy modeling.

The findings of this thesis have a wide range of policy implications since they highlight the variety of challenges that preclude sustainable water management in arid and semi-arid climate conditions. The key challenge is "How to deal with climate risks and uncertainty that threaten economic activities and ecosystems in river basins". Decision makers and governance bodies could design and implement several policies, such as institutional water allocation, water conservation, and reservoir management to combat the negative impacts of water scarcity and climate stress, and to encourage cooperative water management among sectors and locations. Those decisions must be supported by scientific information to prevent policy failure. Understanding the implications and the unintended consequences of policy interventions is an important step before policy implementation. Knowledge of sectoral responses and competition under various policies and climatic conditions, the economic analysis of gains and losses by group of stakeholders, and information on the costs and benefits of options could all help in finding affordable policies that can be successful. Providing cost-effective policy options will help achieve sustainable development goals, reduce financial burdens imposed by climate risks, and guide science-informed strategies for climate resilience. The conflicts between the goals of equity, environmental protection and water efficiency, coupled with the asymmetric distribution of power could jeopardize the effectiveness of interventions leading to policy failure.

MAIN CONCLUSIONS

The methodological advances and main conclusions of each chapter are presented as follows:

Chapter 2: Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain

A novel integrated hydroeconomic model for basin-scale optimal planning is developed in the Ebro River. The inclusion of water and air quality in the assessment is an important methodological advance considered in this model. The model includes water scarcity and nonpoint pollution and evaluates a series of climate change mitigation and adaptation policies. The assessment emphasizes the role that policies could play in abating nonpoint pollution in watercourses and the atmosphere, as well as identifies the tradeoffs between water quality and water scarcity. The analysis demonstrates the effectiveness of policies in the face of extreme droughts and the impacts on water use, pollution loads and environmental damages, and social benefit outcomes. The selected policies are: P1: Optimizing the amount of nitrogen fertilization; P2: Synthetic fertilization substitution for organic fertilization; P3: Irrigation modernization; and P4: Manure treatment plants. Results indicate that drought events increase nitrate concentrations by up to 63% while decreasing water availability by 42% at the mouth of the Ebro River, highlighting the tradeoffs between quantity and quality of water.

All mitigation and adaptation policies decrease the effects of climate change by improving water quality and lowering GHG emissions, which reduce environmental damages and improve social welfare.

Evaluating the selected policies with the model, provides clues on suitable combinations of mitigation and adaptation policies that enhance water and air quality. Irrigation modernization improves nitrogen and water efficiency, boosting social benefits by up to 90 million Euro while increasing stream flows at the river mouth. Manure treatment plants, on the other hand, reduce private and social benefits despite achieving the lowest nitrate concentrations and GHGs emission loads. Findings demonstrate that drought conditions reduce the effectiveness of policies and increase the tradeoffs between water availability and nitrate pollution. The policy implications of these findings highlight the importance of accounting for water quality in water management, and call for a reconsideration of ongoing water policies in most arid and semiarid regions. The assessment of different policies contributes to the discussion of designing cost-effective policies for the abatement of agricultural polluting emissions into water and the atmosphere.

Chapter 3: Climate adaptation guidance: new roles for hydroeconomic analysis

A state-of-the-art empirical dynamic hydroeconomic optimization model is developed to identify efficient water allocation plans for adapting to shortages under alternative water shortage sharing schemes, providing insight into important behavioral responses to climate water stress adaptation policies. The model uses innovative calibration methods (PMP) for urban and agricultural activities in order to ensure that the outcomes from the baseline optimized solution match the historically observed data on water use and economic welfare. The purpose is to find suitable climate adaptation measures that advance sustainable water management. Our model assesses two water sharing alternatives (Proportional sharing of shortages or else unrestricted water trading) for four levels of climate water stress (0%, 25%, 50%, 75%). These four climate water stress scenarios and their economic impacts represent selected levels of progressively higher water scarcity from drought events and diminishing inflow trends.

The model shows the potential of hydroeconomic modeling in promoting integrated water management under climate adaption policies, informing sustainable, equitable and affordable adaptation plans that could address climate water stress. Results indicate that climate water stress imposes a much large water adaption burden on agriculture when shortages are shared under a water market arrangement, effectively prioritizing the use of water for urban activities compared to irrigated farming. This highlights that a reduction in water availability exacerbates competition among sectors and spatial locations, allocating scarce water based on economic profitability and achieving allocative efficiency. Under proportional sharing of water, shadow prices of water in cities and irrigation districts are different and lower when water is abundant, but they increase when climate water stress becomes more intense. Under water markets shadow prices equalize among cities and irrigation districts, with gains in social welfare. Therefore, water markets seem to be the least cost way to adapt to climate water stress. The unrestricted water trading moves water from irrigation districts to cities until achieving an equal marginal value of an extra unit of water in all cities and irrigation districts. These shadow prices provide important information guiding the economic attractiveness of climate adaptation policies.

Chapter 4: Ecosystems in WEFE nexus planning enhance water security and biodiversity for climate resilience

The Water-Energy-Food-Ecosystems (WEFE) nexus offers promises as an innovative and comprehensive framework to guide science-based plans for sustainable development goals. In this chapter, a dynamic and integrated optimization framework is developed to spur more comprehensive cross-sectoral nexus dialogue among stakeholders. The model includes several water-using sectors including ecosystems for a significant river basin supporting livelihoods of large numbers of people. This study assesses synergies and tradeoffs among competing water uses that could be used to advance water, food, energy, and environmental security.

Findings provide a range of options that improve the hydrologic and economic performance of water management compared to the current policy (IC, *Institutional cooperation*) for addressing climate change. Policy interventions that account for the full range of benefits of environmental flows are more science-informed, furthering the strategies for climate resilience. They increase stream flows in rivers, enhance water security and biodiversity, and reduce the burdens imposed by climate risks. The *Irrigation modernization* policy could reduce agricultural water withdrawals by around 1000 Mm^3 and increase streamflow at Ebro mouth by 300 Mm^3, with large gains in social benefits between 120 and 150 million Euro for future climate scenarios. This policy supports farm income and social benefits, delivering water and food security and better ecosystem protection. The policy of *Enlarging dam storage* increases energy generation and provides a better ecosystem protection especially in mountain and delta watersheds, by delivering more water for the environment. It is a critical policy for climate resilience and adaptation by supplying more clean energy, protecting ecosystems, and improving water and energy security. The *Water markets* policy results in welfare gains by efficiently moving water among sectors and locations, reducing the economic impacts of future climate water stress. Water markets achieve the highest urban benefits which guarantee human water security, while providing also ecosystems protection. However, experience with fully developed markets in Australia and Chile shows that protection of environmental flows is not evident with water markets. These findings have important policy implications because they demonstrate the difficulties of achieving win-win outcomes that jointly ensure water, food, energy, and environmental security. A suitable mix of policy strategies could address scarcity and droughts in highly-stressed basins with the support of stakeholders, preventing the risks of policy failure.

Chapter 5: Probabilistic cross-sectoral trade-offs assessments under climate stress for sustainable and equitable water planning

A stochastic optimization model is developed to characterize vulnerabilities and risks associated with future water stress. This study identifies the probabilistic trade-offs between agricultural, urban and energy sectors, and examines water priority allocation policies for water sector withdrawals and reservoir releases for two planning horizon CC-2070 and CC-2100. Findings show that the spatial location of irrigation districts and hydropower plants is a key factor in the distribution of basin stream flows and the impacts on water user withdrawals, depending on the agricultural or the energy priority policies and the degree of climate stress. Results indicate that choosing a policy of agricultural priority improves food security, while worsening the performance and increasing the vulnerability of the hydropower sector. Agriculture priority would damage hydropower generation downstream, where the bigger hydropower plants are located, because upstream withdrawals by irrigation districts deplete downstream river flows used for hydropower. In contrast, selecting a policy of energy priority enhances energy security but increases the vulnerability of irrigated agriculture. Achieving win-win solutions that deliver acceptable levels of food, energy, and human water security in large river basins would be a prerequisite for stakeholders to uptake policies. The design of water management strategies that can handle the challenges of greater water vulnerability by implementing suitable benefit-sharing schemes is aided by knowledge about the probabilistic trade-offs.

RECOMMENDATIONS FOR FUTURE RESEARCH WORK

The findings in this thesis provide an inspiring message to policymakers, water authorities, farm managers, and stakeholders to design and implement sustainable and equitable water planning for climate adaptation. Future research-motivated works could investigate the detailed impacts of uncertainty and climate variability using Monte Carlo simulations and the Markov switching model within the hydroeconomic model. Agent-based modeling is also an innovative topic to address climate water stress adaptation and could be employed to determine the economic implications for the water users in our study area and beyond. Agent-based modeling could also examine the effectiveness of several pathways toward the adoption of water conservation technologies to combat water scarcity and solve water resource depletion. Additional research might be focused on linked hydroeconomic modeling to computable general equilibrium approaches to evaluate the economy-wide effects of policy interventions under future climate scenarios, accounting for the biophysical complexity of basins with the wide range of economic activities. A final direction of future research could be the improvement of ecosystem responses accounting for both water quantity and quality, based on more advanced modeling of ecosystems and better valuation of environmental goods and services.

Capítulo 6 Conclusiones generales

Esta tesis examina los distintos desafíos que amenazan la sostenibilidad de los recursos hídricos en la mayoría de las cuencas áridas y semiáridas, y propone opciones de gestión coste eficientes para la adaptación al estrés climático. Los principales desafíos a resolver son la escasez de agua, el deterioro de la calidad del agua, los impactos del estrés climático, los conflictos hídricos entre sectores y ubicaciones espaciales, y la vulnerabilidad de los sectores del agua. Los cuatro capítulos clave de esta investigación presentan el desarrollo de varios esquemas de optimización de modelos integrados y dinámicos, tomando como caso de estudio la cuenca del Ebro en España. Estos diferentes modelos hidroeconómicos incluyen aspectos hidrológicos, económicos, institucionales, ambientales y climáticos, y cada modelo se adecua a un objetivo específico. Este enfoque de gestión integrada proporciona una mejor comprensión de los impactos del cambio climático, e identifica el potencial de la modelización hidroeconómica para generar información de apoyo a planes de adaptación climática que sean equitativos. Los resultados empíricos de los diferentes enfoques de modelización integrada proporcionan información útil para la formulación de políticas de desarrollo sostenible. Los enfoques de modelización desarrollados son flexibles y pueden ser aplicados a otras cuencas fluviales con condiciones climáticas similares.

Frente a los crecientes desafíos climáticos y humanos que amenazan la calidad del agua y la atmósfera, esta tesis analiza varias prácticas de gestión agrícola que reducen la contaminación del agua por nutrientes y las emisiones de GEI para la mitigación y adaptación climática. Otra contribución importante es la información que se presenta sobre la competencia y respuesta de los sectores a distintas estrategias de gestión del agua bajo condiciones climáticas futuras. Esta información permite encontrar las mejores estrategias de asignación que sean eficientes, equitativas y sostenibles, y por tanto sirvan para compartir la carga de la disminución de recursos y para proteger los caudales de los ríos. Estas estrategias de asignación pueden minimizar las pérdidas económicas y pueden adaptarse a las características hidrológicas, económicas e institucionales de las cuencas. El estudio incorpora varios avances metodológicos de modelización, como la optimización no lineal y estocástica, la inclusión tanto de la cantidad como la calidad del agua, la evaluación multisectorial, y la integración de los diferentes componentes de los sistemas hídricos (hidrología, economía, medio ambiente e instituciones). Hay un número limitado de estudios en la literatura que abordan de forma conjunta estos avances en la modelización para evaluar políticas de adaptación y mitigación climática. Esta investigación contribuye a una planificación hídrica más sostenible y al avance en la modelización de las políticas del agua.

Los resultados de esta tesis tienen una amplia gama de implicaciones políticas, ya que ponen de manifiesto la variedad de desafíos que impiden la gestión sostenible del agua en condiciones climáticas áridas y semiáridas. El desafío clave es “Cómo afrontar los riesgos climáticos y la incertidumbre que amenazan las actividades económicas y los ecosistemas en las cuencas de los ríos”. Los responsables de la toma de decisiones y los órganos de gobierno pueden diseñar e implementar distintas políticas, como la asignación institucional de agua, la conservación del agua y la gestión de embalses, para combatir los impactos negativos de la escasez de agua y del estrés climático, y para fomentar la gestión cooperativa del agua entre sectores y ubicaciones. Estas decisiones deben estar respaldadas por información científica que evite el fracaso de las políticas. La comprensión de las implicaciones y consecuencias no deseadas de las políticas de intervención es un paso importante antes de llevar a cabo su implementación. El conocimiento de las respuestas sectoriales y la competencia entre sectores bajo distintas políticas y escenarios climáticos, el análisis económico de las ganancias y pérdidas de los grupos de interés, y la información sobre los costes y beneficios de las opciones pueden ayudar a encontrar políticas asequibles que puedan tener éxito. La propuesta de opciones de política que sean coste-eficientes contribuye a lograr los objetivos de desarrollo sostenible, a reducir las cargas financieras que imponen los riesgos climáticos, y a pilotar estrategias de resiliencia climática basadas en la ciencia. Los conflictos que existen entre distintos objetivos como son la equidad, la protección ambiental y el uso eficiente del agua, junto a la distribución asimétrica de poder de los agentes, pueden poner en peligro la validez de las intervenciones y conducir al fracaso de las políticas.

PRINCIPALES CONCLUSIONES

Los avances metodológicos y las principales conclusiones de cada capítulo se presentan a continuación:

Capítulo 2: Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain

Un novedoso modelo hidroeconómico integrado se ha elaborado para la planificación óptima a escala de cuenca en el río Ebro. La inclusión de la calidad del agua y de la atmósfera en la evaluación es un importante avance metodológico en este modelo. El modelo incluye la escasez de agua y la contaminación difusa, con el fin de evaluar una serie de políticas de mitigación y adaptación al cambio climático. En la evaluación se destaca la importancia que tienen las políticas de reducción de la contaminación difusa en los cursos de agua y en la atmósfera, e identifica las soluciones compromiso entre calidad del agua y escasez de agua. El análisis muestra la efectividad de políticas que aborden las sequías extremas y los impactos en el uso del agua, las cargas de contaminación y sus daños ambientales, y las consecuencias sobre los beneficios sociales. Las políticas seleccionadas son: P1: Optimización de la cantidad de fertilización nitrogenada; P2: Sustitución de fertilización sintética por fertilización orgánica; P3: Modernización del regadío; y P4: Plantas de tratamiento de estiércol. Los resultados indican que las sequías aumentan la concentración de nitratos hasta en un 63%, mientras que disminuyen la disponibilidad de agua en un 42% en la desembocadura del Ebro, lo que pone de relieve el balance en las soluciones compromiso entre cantidad y calidad del agua.

Todas las políticas de mitigación y adaptación aminoran los efectos del cambio climático al mejorar la calidad del agua y reducir las emisiones GEI, lo que reduce los daños ambientales e incrementa el bienestar social. La evaluación con el modelo de las políticas seleccionadas proporciona indicios sobre las combinaciones adecuadas de políticas de mitigación y adaptación que mejoran la calidad del agua y de la atmósfera. La modernización del regadío mejora la eficiencia del agua y del nitrógeno, lo que aumenta los beneficios sociales hasta en 90 millones de euros y también los caudales en la desembocadura del río. Las plantas de tratamiento de estiércol, por otro lado, reducen los beneficios privados y sociales, pero sin embargo consiguen la mayor reducción de concentraciones de nitrato y de carga de emisiones GEI. Los resultados muestran que las sequías reducen la eficacia de las políticas y aumentan el balance del compromiso (tradeoffs) entre disponibilidad de agua y contaminación por nitratos. Las implicaciones políticas de estos resultados destacan la importancia de considerar la calidad del agua en la gestión del recurso, y aconsejan reconsiderar las políticas de agua vigentes en la mayoría de las regiones áridas y semiáridas. La evaluación de las distintas políticas contribuye a la discusión sobre el diseño de políticas coste eficientes para reducir las emisiones contaminantes agrícolas del agua y la atmósfera.

Capítulo 3: Climate adaptation guidance: new roles for hydroeconomic analysis

El estudio desarrolla un modelo hidroeconómico de optimización dinámica de última generación, con el fin de identificar planes eficientes de asignación de agua ante la escasez, utilizando distintos esquemas de reparto de la escasez, y proporcionando información sobre las respuestas de comportamiento a las políticas de adaptación climática. El modelo utiliza métodos de calibración innovadores (PMP) para las actividades urbana y agrícola con el fin de garantizar que los resultados de la solución optimizada del escenario base coincidan con los datos observados históricamente sobre uso del agua y beneficio social. El propósito es encontrar medidas adecuadas de adaptación climática que promuevan la gestión sostenible del agua. El modelo evalúa dos alternativas para compartir agua (reparto proporcional de la escasez, o mercados de agua sin restricciones) para cuatro niveles de estrés hídrico climático (0%, 25%, 50%, 75%). Estos cuatro escenarios de estrés hídrico climático y sus impactos económicos representan niveles seleccionados de mayor escasez de agua por las sequías y por la tendencia decreciente de entradas de agua en cuenca.

El modelo muestra el potencial de la modelización hidroeconómica para promover la gestión integrada del agua bajo políticas de adaptación climática. Esto permite la elaboración de planes de adaptación sostenibles, equitativos y asequibles que sirvan para abordar el estrés hídrico climático. Los resultados indican que el estrés hídrico climático impone un coste de adaptación mucho mayor sobre la agricultura cuando la escasez se distribuye mediante mercados de agua, priorizando de hecho el uso del agua en actividades urbanas en comparación con el regadío. Esto refleja que la reducción de disponibilidad de agua exacerba la competencia entre sectores y ubicaciones espaciales, y que la asignación del agua escasa se realiza en función de la rentabilidad económica con criterios de eficiencia. Bajo una política de reparto proporcional del agua, los precios sombra del agua en las ciudades y los polígonos de riego son distintos y menores cuando el agua es abundante, pero los precios aumentan cuando el estrés hídrico climático es más intenso. Bajo la política de mercados de agua, los precios sombra se igualan entre ciudades y polígonos de riego, con ganancias en el bienestar social. Por lo tanto, los mercados del agua parecen ser la forma menos costosa de adaptarse al estrés hídrico climático. El comercio de agua sin restricciones mueve el agua de los polígonos de riego a las ciudades hasta lograr un valor marginal igual de unidades adicionales de agua en todas las ciudades y polígonos de riego. Estos precios sombra proporcionan información importante que determina el atractivo económico de las políticas de adaptación climática.

Capítulo 4: Ecosystems in WEFE nexus planning enhance water security and biodiversity for climate resilience

El nexo Agua-Energía-Alimentos-Ecosistemas (WEFE) ofrece propuestas como marco innovador e integral para orientar planes basados en la ciencia que persigan objetivos de desarrollo sostenible. En este capítulo, se desarrolla un marco de optimización dinámico e integrado para estimular un razonamiento de nexo intersectorial más completo entre los grupos de interés. El modelo abarca los distintos sectores que utilizan el agua incluidos los ecosistemas, de una importante cuenca con un gran número de habitantes. Este estudio evalúa las sinergias y los compromisos entre los usos del agua que compiten entre sí, para poder mejorar la seguridad del agua, de los alimentos y la energía y del medio ambiente.

Los resultados muestran una gama de opciones que mejoran la eficacia hidrológica y económica de la gestión del agua en comparación con la política actual (IC, Cooperación institucional) para abordar el cambio climático. Las intervenciones de política que tienen en cuenta todo el rango de beneficios de los caudales ecológicos incorporan más información científica, lo que promueve estrategias de resiliencia climática. Estas estrategias aumentan los caudales de los ríos, mejoran la seguridad hídrica y la biodiversidad, y reducen los costes que imponen los riesgos climáticos. La política de modernización del regadío puede reducir las extracciones de regadío en unos 1000 Mm^3 y aumentar el caudal de la desembocadura del Ebro en 300 Mm^3, con ganancias significativas en beneficios sociales de entre 120 y 150 millones de Euro para escenarios climáticos futuros. Esta política favorece las rentas agrícolas y los beneficios sociales, y proporciona seguridad de uso urbano y seguridad alimentaria a la vez que mejora la protección de los ecosistemas. La política de ampliación de la capacidad de almacenamiento de las presas aumenta la generación de energía y proporciona una mayor protección a los ecosistemas, especialmente en las cuencas de montaña y el delta, al incrementar los caudales ecológicos. Se trata de una política fundamental para la resiliencia y la adaptación al cambio climático, ya que suministra más energía limpia, protege los ecosistemas y mejora de la seguridad energética y de uso urbano. La política de mercados de agua proporciona ganancias de bienestar al mover el agua de manera eficiente entre sectores y ubicaciones, reduciendo los impactos económicos del estrés hídrico climático. Los mercados de agua logran los mayores beneficios urbanos y garantizan la seguridad hídrica de la población, y también proporcionan un caudal suficiente a los ecosistemas. Ahora bien, la experiencia empírica de los mercados de agua plenamente desarrollados en Australia y Chile indica que la protección de los caudales ecológicos no es evidente con mercados de agua. Estos resultados tienen implicaciones políticas importantes, ya que demuestran las dificultades para conseguir soluciones “win-win” que beneficien a todos, y que mejoren a la vez la seguridad hídrica humana, alimentaria, energética y medioambiental. Una combinación adecuada de estrategias de intervención política podría afrontar la escasez y las sequías en cuencas muy amenazadas con el apoyo activo de los grupos de interés, evitando el riesgo de que las políticas fracasen.

Capítulo 5: Probabilistic cross-sectoral trade-offs assessments under climate stress for sustainable and equitable water planning

En él trabaja se elabora un modelo de optimización estocástica para caracterizar las vulnerabilidades y los riesgos asociados con el estrés hídrico futuro. Este estudio identifica los compromisos (tradeoffs) probabilísticas entre los sectores agrícola, urbano y energético, y examina políticas de asignación prioritaria de uso de agua entre sectores y de desembalse de las presas para dos horizontes de planificación, CC-2070 y CC-2100. Los resultados muestran que la ubicación espacial de los polígonos de riego y de las centrales hidroeléctricas es un factor clave en la distribución de caudales en la cuenca y de los impactos en las extracciones de agua de los usuarios, en función de la política prioritaria agrícola o energética y del grado de estrés climático. Los resultados indican que la política de prioridad agrícola mejora la seguridad alimentaria, pero sin embargo empeora el rendimiento del sector hidroeléctrico y aumenta su vulnerabilidad. La prioridad agrícola daña la generación de energía hidroeléctrica en la cuenca baja donde se encuentran las centrales hidroeléctricas más grandes, ya que las extracciones en la cuenca alta y media de los polígonos de riego reducen los caudales aguas abajo que se utilizan para la generación hidroeléctrica. Por el contrario, una política de prioridad energética mejora la seguridad energética, pero incrementa la vulnerabilidad de la agricultura de regadío. Lograr soluciones “win-win” que sean beneficiosas para todos que proporcionen niveles aceptables de alimentos, energía y seguridad hídrica humana en grandes cuencas fluviales sería un requisito previo para que los grupos de interés apoyen las políticas de intervención. El conocimiento de los compromisos (tradeoffs) probabilísticos puede servir para diseñar estrategias de gestión del agua que puedan afrontar los desafíos de mayor vulnerabilidad del agua, y que implementen esquemas adecuados para compartir los beneficios y las pérdidas.

RECOMENDACIONES PARA FUTUROS TRABAJOS DE INVESTIGACIÓN

Los resultados de esta tesis proporcionan mensajes que pueden inspirar a los responsables políticos, autoridades del agua, agricultores, y demás grupos de interés, sobre la posibilidad de diseñar e implementar planes hidrológicos sostenibles y equitativos para la adaptación al cambio climático. Los trabajos futuros podrían investigar en mayor detalle los impactos de la incertidumbre y variabilidad climática, mediante la utilización de simulaciones Monte Carlo y modelos “Markov switching” en la modelización hidroeconómica. La modelización basada en agentes también es un tema innovador para abordar la adaptación al estrés hídrico climático y puede emplearse en el análisis de las implicaciones económicas para los usuarios del agua en esta área de estudio y en otras. La modelización basada en agentes también puede examinar la efectividad de distintas trayectorias para la adopción de tecnologías conservadoras de agua que contrarresten la escasez de agua y resuelvan la degradación de los recursos hídricos. Otra dirección de investigación consiste en la modelización hidroeconómica ligada a enfoques de equilibrio general computable. Esto permite evaluar los efectos directos e indirectos de las intervenciones políticas en toda la economía bajo escenarios climáticos futuros, teniendo en cuenta tanto la complejidad biofísica de las cuencas como todo el conjunto de actividades de la economía. Una dirección final de investigación futura consiste en mejorar el conocimiento de la respuesta de los ecosistemas a los caudales en cuenca, que tengan en cuenta tanto la cantidad como la calidad del agua, y que estén basados en una modelización mas avanzada de los ecosistemas y en valoraciones más precisas de los bienes y servicios que proveen los ecosistemas.

Publications

Baccour, S., Ward,F., Albiac,J., 2022. Climate Adaptation Guidance: New Roles for hydroeconomic Analysis. Journal of Science of the Total Environment, 155518. https://doi.org/10.1016/j.scitotenv.2022.155518

Baccour, S., Albiac, J., Kahil, T., Esteban, E., Crespo, D., Dinar, A., 2021. Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain. Journal of Cleaner Production, 129459. https://doi.org/10.1016/j.jclepro.2021.129459

Baccour, S., Albiac, J., Kahil, T., 2021. Cost-effective mitigation of greenhouse gas emissions in the agriculture of Aragon, Spain. International journal of environmental research and public health, 18(3), 1084. https://doi.org/10.3390/ijerph18031084

Crespo, D., Albiac, J., Kahil, T., Esteban, E., **Baccour, S**., 2019. Tradeoffs between water uses and environmental flows: a hydroeconomic analysis in the Ebro basin. Water Resources Management, 33(7), 2301-2317. http://doi.org/10.1007/s11269-019-02254-3

Other publications in process

Baccour, S., Goelema, G., Kahil, T., Albiac, J., van Vliet, MTH., Zhu, X, Strokal, M., 2023. Water quality management could cost-effectively halve future water scarcity. (Under review)

Baccour, S., Albiac, J., Ward, F., Kahil, T., Esteban, E., Uche, J., Calvo, E., Crespo, D., 2023. Managing climate risks: New evidence from integrated analysis at the basin scale. (Under review).

Baccour, S., Tilmant, A., Albiac, J., Espanmanesh, V., 2023. Probabilistic cross-sectoral trade-offs assessments under climate stress for sustainable and equitable water planning. (Under review).

GLOBECHO model (In process).