Managing climate risks: New evidence from integrated analysis at the basin scale

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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 integrated multi-sector water management strategies for climate resilience. The Water-Energy-Food-Ecosystems (WEFE) nexus offers promise as a comprehensive framework to guide science-based plans to achieve 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. 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 untested use of information to guide proposed water allocations among several economic sectors 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 reveal a range of policy choices that improve the hydrologic and economic performance of water management compared to the current policy for addressing climate change. Policy options that systematically account for the full range of benefits of environmental flows guide science-informed strategies for guiding climate resilience planning. They can increase stream flows in rivers, enhance water security and biodiversity, and reduce the economic burdens imposed by climate risks.

1. Introduction

Communities internationally face hard choices to sustain supplies of water, energy, land, and food, while protecting key ecological assets (Gupta et al. 2023). Pressure on these resources is driven by the growing global population, wealth, urbanization, and consumption (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. 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 et al. 2010). The Food and Agriculture Organization of the United Nations has investigated the potential gains from applying the nexus approach (FAO 2013), and the European Commission has included food-energy-water-climate linkages among challenges facing its Horizon research and innovation program (EC 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 has the potential to achieve sustainable development (Endo et al. 2017). The nexus approach can have the capacity to 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 the effects of energy taxes and prices (Sun et al. 2021), as well as links among energy, water and ecosystems (Amjath-Babu et al. 2019; Chen et al. 2020). Still others have implemented a nexus approach to advance Sustainable Development Goals (Yoon et al. 2021).

The integration of ecosystem services as an element of the nexus approach has been proposed recently for sustainable resource management, although environmental services have to date been weakly addressed in nexus studies (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; 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.

In spite of significant advances in nexus analysis 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. One recent work (Bekchanov et al. 2019) propose using the hydroeconomic modeling framework to address the water-food-energy-environment nexus at the basin scale. However, reviews of the peer-reviewed hydroeconomic literature conclude that feedbacks across nexus elements remain incomplete, 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 to guide selected climate adaptation policies.

The journal *Water Resources Management* has published a number of important works investigating nexus elements of water resources as connected to other strategically-important resources like food and energy (de Vito et al. 2019; Dong et al. 2019; El-Gafy et al. 2017; Hatamkhani and Moridi 2019; Karnib 2018; Molajou et al. 2021; Moore et al. 2015). Other scientific journals have also published some similarly motivated works (Herath et al. 2011; Karlberg et al. 2015; Pokhrel et al. 2018; Rasul 2014; Shumilova et al. 2018; Vanham 2016). Despite the high level of professional excellence of these contributions, we were unable to find any published work that conceptualizes, formulates, implements, and assesses an integrated framework in an important river basin to identify affordable and sustainable climate adaptation strategies.

This paper addresses these gaps by conceptualizing, formulating, applying, and assessing an integrated and unified hydroeconomic modeling framework addressing future climate risks to discover and empirically track and sustainable and affordable climate adaptation strategies. The framework systematically accounts for nexus elements among competing and complementary sectors (agriculture, energy, urban supply and ecosystems) for gaining a better understanding of a series of water management strategies under climate water stress scenarios in 2070 (CC-2070) and 2100 (CC-2100), taking Spain’s Ebro River Basin as a case study (online supplementary material section 1 [SM1]). A cross sectoral integration, after developing the conceptual framework, is applied to discover synergies among sectors and spatial locations, uncovering insights into connections among the elements. This analysis shows interactions and potential compensations among groups of stakeholders as well as workable interventions that could bring about improved resilience and adaptation to future climate change.

The potential of systematic science-informed water management strategies to achieve water, food, and energy security and ecosystem protection is assessed. Findings reveal affordable choices that have a measured potential to limit water sector vulnerability, reduce costs of water stress, and improve climate resilience (Rausser and Zilberman 2022). Results provide information on water reallocations among economic and environmental sectors, locations, and time periods and the associated distribution of benefits and cost of proposed polices for those same dimensions. Findings, used properly, can inform improved management to enhance water, food and energy security as well as ecosystems protection through improved environmental flows.

2. Modeling Framework

2.1. Model structure

Figure 1 depicts the main features of a novel integrated hydroeconomic modeling framework and the configuration among nexus elements, including input data and outputs. The WEFE (Water-Energy-Food-Ecosystems) nexus assessment is based on an empirical hydroeconomic model developed using the GAMS® (General Algebraic Modeling System) software. The GAMS code with the data can be accessed in online material GAMSNexusCode. The model is an extension and advancement of previous modeling work (Baccour et al. 2021; Baccour et al. 2022). The model is specified as a dynamic optimization problem with multisector benefits as the objective function, and with biophysical, technical, resource availability and institutional information embedded in the constraints. The objective function maximizes total economic benefits over time summed over economic sectors across basin locations, under current and future climate conditions for a series of proposed climate adaptation policies. There are three components in the model; the hydrological, economic, and environmental.

The hydrological component is a reduced form hydrological representation of the Ebro basin. It characterizes flows between supply and demand nodes, using the hydrological principles of water mass balance to protect flow continuity throughout the basin. The hydrological component shows the spatial distribution of water between economic sectors and environmental flows, and the model dynamics accounts for reservoir storage This component is calibrated introducing additional variables for river reaches, so that predicted gauged flows are consistent with observed flows at each river gauge.

The economic component consists of optimization problems for water allocated to irrigation districts, hydropower plants, and urban settlements. The optimization model accounts for agricultural activities in every irrigation district, based on the farm objective of income maximization from crop production subject to technical and resource constraints. The objective for urban water use maximizes economic surplus, the sum of consumer and producer surpluses in the basin's main cities. The objective of hydropower is revenue minus costs of electricity production. Positive Mathematical Programming (PMP) is used to calibrate agriculture and urban sectors at the baseline observed data of water allocations, extending methods originally developed in Baccour et al. (2022) .

The environmental component includes the ecosystem health levels and associated environmental benefits. The environmental benefits of ecosystem in the basin depend on the health status of ecosystems, where the relationship between the status of river habitat and stream flows is portrayed by the Weighted Usable Area (WUA). WUA is a measure of the habitat potential to host a specific species given the characteristics of the river streamflow (Tharme 2003). The WUA methodology accounts for the hydrological, hydraulic (physical and mechanical properties), and biological relationships in order to evaluate environmental flow requirements.

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 stakeholder group are important for assessing the efforts and related break-even compensations for social justice and acceptability of policy interventions. Several supply and demand water management strategies have been assessed for improving climate resilience and adaptive capacity of irrigated agriculture, energy production, urban use, and the environment (Arnold and Fohrer 2005; Elliott et al. 2014; Garcia-Ruiz et al. 2011; Green et al. 2011; Haddeland et al. 2014; Vorosmarty et al. 2000).

2.2. Mathematical formulation: Optimization of the Ebro model

The optimization problem in the hydro-economic model maximizes the discounted net present value of economic benefits summed over sectors and periods. Economic 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:

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

where $B^{Irr}_{k,t}$ is private benefit from irrigation district *k*, $B^{Urb}_{u,t}$ is urban economic surplus from urban center *u*, $B^{HP}_{HPplant,t}$ is hydropower benefit from hydropower plant *HPplant*, and $B^{ecos}_{e,t}$ is environmental benefit from river reach *e*. The discount rate r used in the analysis is 2%.

The optimization problem includes several constraints, including mass balance, supply-demand balance, reservoir capacity, land constraints, labor constraints, and hydropower plants capacities. More details about data, the mathematical formulation of each model component and the different constraints, and model calibration are described in online supplementary material section 2 and 3 [SM2; SM3].

2.3. Generation of future climate scenarios

Future climate scenarios through the year 2100 are developed based on the Ebro basin inflow projections under climate change estimated by CEDEX (2017). The basin's headwater flows are generated using the statistical delta change downscaling method (Escriva-Bou et al. 2017; Fowler et al. 2007) The CEDEX projections are derived from a set of Global Climate Models (GCM). These projections are arranged in four time periods between 1960 and 2100, including 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 for each headwater node covering a horizon of 30 years for periods 2040–2070 (CC-2070) and 2070–2100 (CC-2100). The procedure consists in randomizing the historically observed monthly series between 1986 and 2016, by using the CEDEX information to generate future basin inflows for climate water scenarios (online supplementary material section 4 [SM4]).

2.4. Water management options

Cross-sectoral water management and enhanced climate resilience plans are needed to limit 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 internationally 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 development and use of 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 is the current Ebro water management that is based on the effective involvement and cooperation of stakeholders. Under drought conditions, the basin authority reduces water allocations to irrigation districts in proportion to the fall in inflows. Selected water management policies are assessed, including alternative water allocation approaches, advanced irrigation technologies, and enlargement of the reservoir storage capacity (Table 1). A detailed description of these management strategies (IC, EIC, IM, EDS, WM) are presented in the online supplementary material section 5 [SM5].

Table 1
Description of water management options

Water management options	**Description**
Current management (Maximization of private benefits)	
Institutional cooperation (IC)	It is the present water management strategy of the Ebro basin authority, based on the involvement and cooperation of stakeholders. Under drought, water allocations are reduced in proportion to the fall of inflows first to irrigation districts and environmental flows, and if scarcity is severe to hydropower and urban supply. The model maximizes the private benefits of agriculture, urban supply and hydropower.
WEFE Nexus (Maximization of social benefits)	
Environmental institutional cooperation (EIC)	It is the IC policy combined with a stronger protection of ecosystems by accounting for the benefits of environmental flows. The basin authority increases stream flows acquiring water for the river. The procedure is to maximize social benefits, the sum of both private and environmental benefits.
Irrigation modernization (IM)	Investments in modernization involve upgrading irrigation technologies, with gains in irrigation efficiency. Investment costs used in the study are 250 €/ha/year (Guardia 2010). The basin authority buys water for the river.
Enlarging dam storage capacity (EDS)	The increase in water storage in the basin is set at a 50% increase in dam storage capacity, and an increase of 25% in hydropower production. The investment costs for additional storage are estimated at 0.5 €/m^3, based on the costs of the recent Yesa and Itoiz reservoirs. The amortization costs are included in the calculation of social benefits (42 M€ per year). Water for the river is acquired by the water authority.
Water markets (WM)	The reduced water allocations during droughts can be exchanged among sectors, creating market-motivated trading to efficiently move water to where it could minimize economic losses caused by water stress. Water trading takes place not only between economic activities, but also with the environment with purchases by the water authority

3. Results

3.1. Enhancing environmental flows with improved institutional cooperation

Adjusting the current *Institutional cooperation* (IC) in the Ebro basin augmented by *Environmental institutional cooperation* (EIC) is prescribed by more fully accounting for the benefits of environmental flows in river reaches. In this light, EIC achieves better ecosystem protection than the existing IC, delivering more environmental flows even with reduced cultivated land (-13%) and energy generation (-5%) (Fig. 2a). 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. That EIC policy reveals a significant improvement of ecosystem status across the full range of watersheds in the basin (Fig. 2c).

Water use in agriculture under EIC compared to IC is reduced by 14%, although impacts on agricultural economic benefits are modest (-2%) because farmers reduce cultivation of field crops, which have high water requirements and minimal income generating capacity. Economic benefit gains remarkably complement gains in environmental benefits of €170 million, for which some economic benefits are lost at a level of about €20 million both energy and agriculture (Fig. 2b). These results reveal trade-offs between the environment and the economic sectors, if decision makers implement 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 management policy to advance.

3.2. Sectoral responses and competition: Tradeoffs analysis under future climate scenarios

Understanding the complex relationship among water, energy, food and ecosystems provides essential insights for development of future sustainable water planning. Tradeoffs among competing water uses in the Ebro basin by policy and climate scenario (CC-2070 and CC-2100), for which results are presented in Fig. 3.

Information from the tradeoff analysis guides the design of water management strategies. These strategies have the capacity to address challenges of future elevated water vulnerability by identifying 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 with only modest economic losses, depending on the policy option. An unadjusted IC policy (status quo) is the weakest-performing strategy for adapting to climate change, for which there is a poor economic benefit outcome, largely explained by lower ecosystem benefits, driven by smaller environmental flows as a result of high irrigation withdrawals (Table 2).

Table 2

Land use, energy production, water use, and benefits by climate change scenario and management policy. Figures for climate change scenarios are yearly averages of 30 simulation runs over the 30 years periods 2040–2070 and 2070–2100.

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

IC: Institutional cooperation, EIC: Environmental institutional cooperation, IM: Irrigation modernization, EDS: Enlarging dam storage capacity, 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.

Under the EIC, IM, EDS, and WM policy options, the water authority would assign water for the environment to improve ecosystem status.[1] These policies deliver higher economic benefits than an unadjusted IC, reducing 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 2, Fig. 3a). The EDS policy increases energy production and environmental flows over any other policy, while reducing cultivated acreage compared to IC (Fig. 3). 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, a common challenge faced by scientists, stakeholders, and water managers in large and complex basins.

Differentiating IC and EIC with climate change conditions is similar to that without climate change. Compared to the IC policy, the EIC policy reallocates water among economic activities and the environment to maximize total economic welfare, while respecting relevant constraints, by reducing irrigation withdrawals and increasing environmental flows, augmenting streamflow at the Ebro system mouth by 300 and 200 Mm^3 for CC-2070 and CC-2100 scenarios, respectively. In both climate scenarios, an EIC program increases environmental benefits by about €170 million and overall economic benefits by about €100 million, compared to the base IC policy (Table 2). The water authority would also acquire 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 (online supplementary material section 6 [SM6]). The EIC policy requires implementing resource and benefit sharing that would advance ecosystem biodiversity, water security, and resilience and improve adaptation to climate change.

Achievement of 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 1000 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 (online supplementary material section 6 [SM6]), 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.

EDS is an essential policy for adapting to periods of water scarcity during droughts. As a risk management strategy, it buffers against fluctuations in water supply by permitting augmented water storage with greater reservoir storage capacity, with optimized reservoir releases covering economic and environmental demands in a controlled manner which dampen the economic costs of droughts when they occur. The EDS policy achieves improved results for economic benefits as well as producing top performing result for energy security, in both CC-2070 and CC-2100 scenarios. For both scenarios, EDS supplies about 1700–1800 GWh of additional energy generation and about €100 million of additional energy benefits based on the power prices we used. This policy also achieves better performing ecosystem protection, most noticeable in mountain and delta watersheds, by delivering more water for the environment. The water authority purchases about 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 system mouth between 30 and 330 Mm^3 in CC-2070, and between 100 and 420 Mm^3 in CC-2100. EDS performs well for supplying clean energy, protecting ecosystems, and augmenting both water and energy security. It is also a high-performing measure to build resilience and adaptation to climate change.

The WM policy reallocates the available water among sectors from lower to higher economic valued 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 economic welfare gains by moving water among sectors, locations, and time periods, mitigating economic impacts of future climate water stress. The WM policy enhances the economic performance of urban use, the highest economically valued sector for water use, 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 about 690 Mm^3, with costs at €20 million in CC-2070 and €40 million in CC-2100 (online supplementary material section 6 [SM6]). These efficient water reallocations between competing sectors achieve the highest economic returns in CC-2100 (€4741 million), and the second-highest economic returns in CC-2070 (€4931 million) only behind EDS. This policy achieves the top performing urban economic benefit, which improves the performance of human water security, while also providing ecosystems protection.

Policy choices for best adapting to future climate water stress depend on society's goals. If the priority is food production, then both unadjusted IC and IM deliver higher agricultural benefits, although IM secures higher stream flows across the basin and enhances 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 also reduces food production. If ecosystems are a priority, then all policies deliver high environmental benefits except the current unadjusted IC.

3.3. Climate risk management: resilience and adaptation

There remains considerable interest by policymakers in discovering measures to improve the climate resilience of water sectors, and to more effectively deal with shrinking water supplies in arid and semi-arid regions. A number of strategies can be undertaken for reducing 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 (Fig. 4). Improving the resilience of water resources to adapt to climate change involves more efficient use of water and larger environmental flows, while finding a workable balance between food, energy and human water security.

The economic analysis of strategies assesses costs and benefits of policies which are tracked by sector, stakeholder group, spatial location, and time period. The optimization model developed for this paper is a powerful framework for informing policy debates and guiding adaptation to the ongoing evidence of climate change. The success or failure of policy interventions will depend on the equitable sharing of costs and benefits among stakeholders (Segerson 2022), including compensations where needed for losers. Findings indicate that all alternatives assessed to the current policy (IC) increase net economic welfare (Table 2), despite the high investment and operating costs associated with some water management strategies, such as investments required for irrigation modernization (IM) or to augment dam storage capacity (EDS). These gains in social benefits could contribute to financing compensations to groups of stakeholders facing losses from policy changes. When the gains exceed the losses, the result is the well-known Potential Pareto Improvement (Baah-Kumi and Ward 2020; Goulder and Williams 2012; Habteyes et al. 2015; Zheng et al. 2021).

[1] In all policy and climate scenarios, most water trading comes from Bardenas, RAA, Urgel and A&C irrigation districts (online supplementary material section 1 [SM1], Fig. S1). These districts have low shadow prices of water (0.02–0.06 €/m3) and large water sales (between 100 and 200 Mm^3) (online supplementary material section 6 [SM6], Tables S1-S3).

4. Discussion

The relevance of our work comes from its capacity to inform the science and policy dialogue among water, energy, food, and ecosystems stakeholders to improve outcomes from multi-sectoral planning and to achieve equitable tradeoffs. Our results show that the current Institutional cooperation (IC, business as usual) is the lowest performing 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 costs adapting to climate stress. Therefore, integrated water management shows considerable gains to support the mission of coordinating groups of stakeholders and to build adaptive capacity to face climate change impacts (Jordan et al. 2022). 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 (Alexandra 2023) and maximize social benefits constrained by the need to avoid jeopardizing ecosystem sustainability.

The irrigation modernization policy has considerable 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). 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 in earlier works by water economists (Hartman and Seastone 1965; Ward and Pulido-Velazquez 2008). However, water authorities could impose water measuring and enforcement when designing irrigation modernization policies that usually involve public subsidies. More work is needed to uncover 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 (Ward 2022).

Enlarging dam storage capacity 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. Our work shows EDS is an economically viable measure to confront water shortages, and improve climate resilience and adaptation (Ward 2022). However, there is at present some opposition to building new dams from environmental NGOs. Setting up water markets enables trading between economic activities by moving water from low to high valued uses that generate welfare gains, and also reduce 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 protection of environmental flows faces implementation difficulties, both 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).

Future work can profitably focus on better hydrologic projections using sophisticated methodologies that could address spatial and temporal variabilities, and better deal with uncertainties. The work in this paper can be considerably advanced by including water quality in the analysis. Despite these limitations, our modeling approach presented the first step of a systematic framework for informing multi-sector planning to jointly deliver water, food, energy, and environmental security, while promoting climate resilience and adaptive capacity of sectors.

5. Conclusion

The Water-Energy-Food-Ecosystems (WEFE) nexus is implemented by using an innovative integrated hydroeconomic modeling framework, where water and its numerous services are 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, calling for an intensive use of data and advanced methods.

Results 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. Our study has important policy implications because it demonstrates the difficulties of water management options in 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.

Declarations

Ethical Approval

Not applicable

Consent to participate

All authors consent to participate

Consent to Publish

All authors consent to publish in the journal

Authors Contributions

S.B., J.A., and F.W. designed research; S.B., J.A., F.W., T.K., and E.E. performed research; S.B., J.A., F.W., T.K., E.E., J.U., E.C., and D.C. analyzed data; and S.B., J.A., F.W., T.K., E.E., J.U., and E.C wrote the paper.

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Data Availability

Data used for this work is available in the GAMS code provided in the supplementary material file GAMSNexusCode.gms.

Competing Interests Statement

The authors declare no conflict of interest.

Availability of data and materials

All data are included in the paper, the supplementary material, and the GAMS code file included as the attachment GAMSNexusCode.docx

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Figures

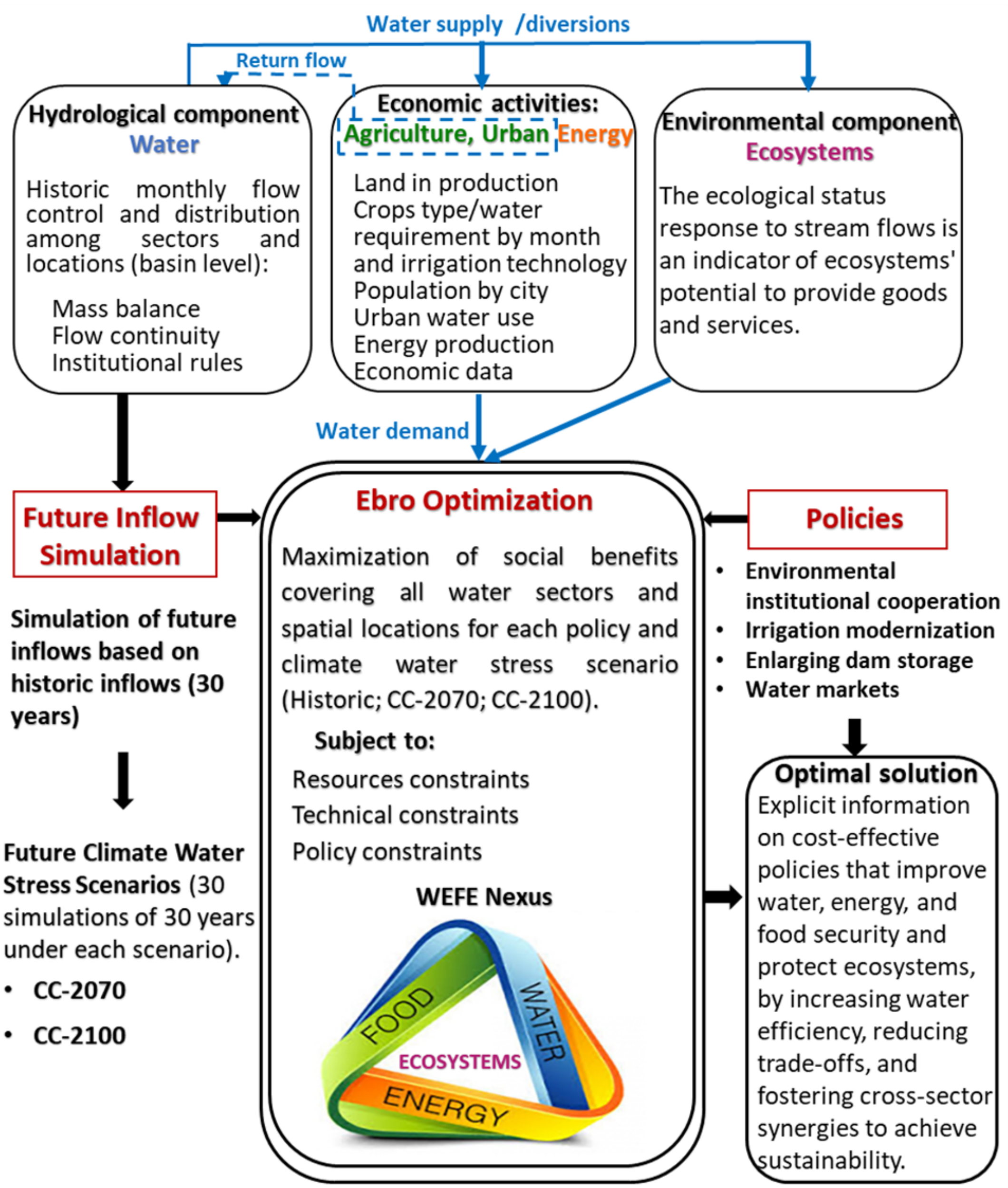
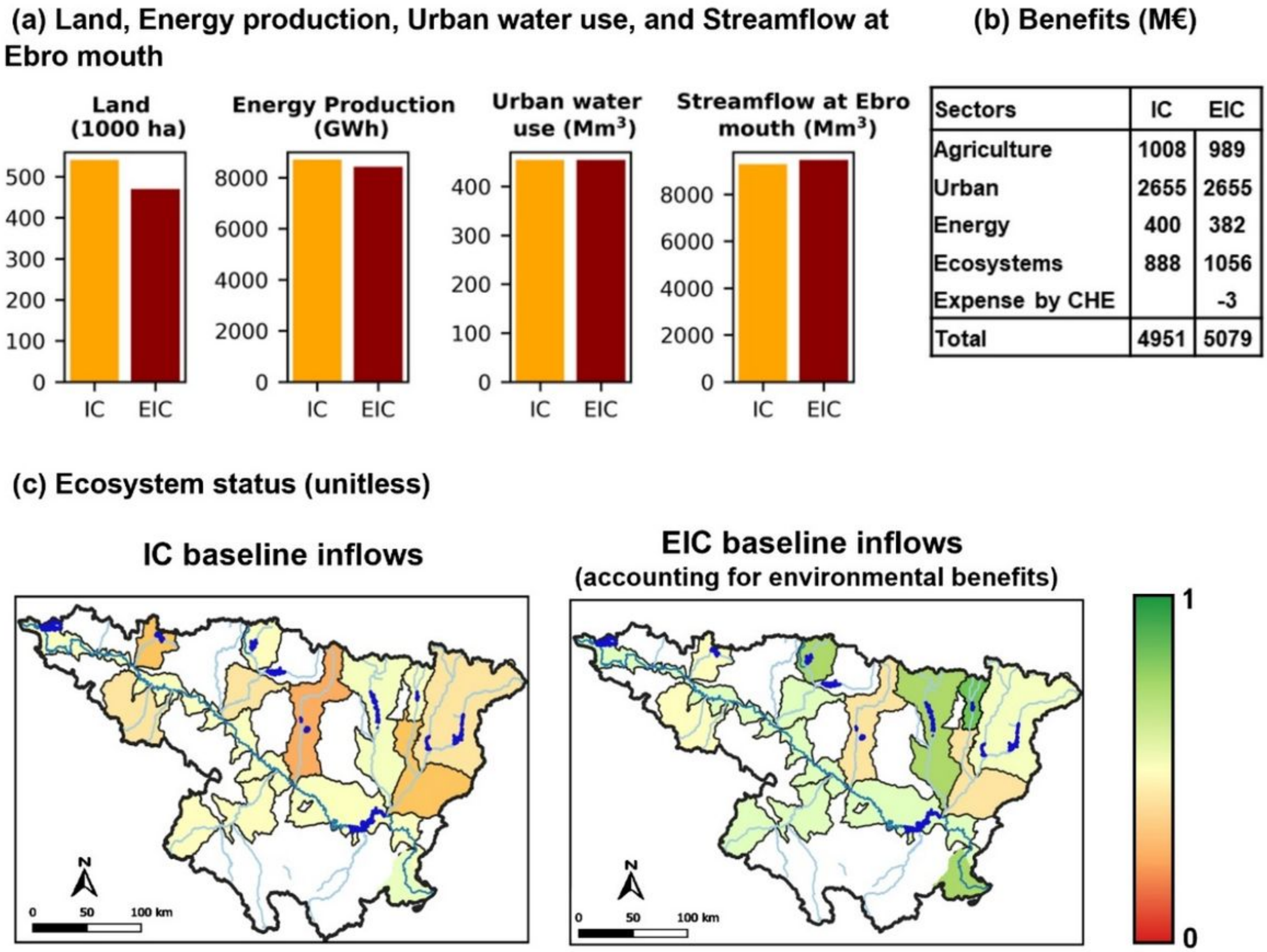


Figure 1

WEFE nexus modeling framework



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

Figure 2

IC and EIC under baseline inflows. (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.

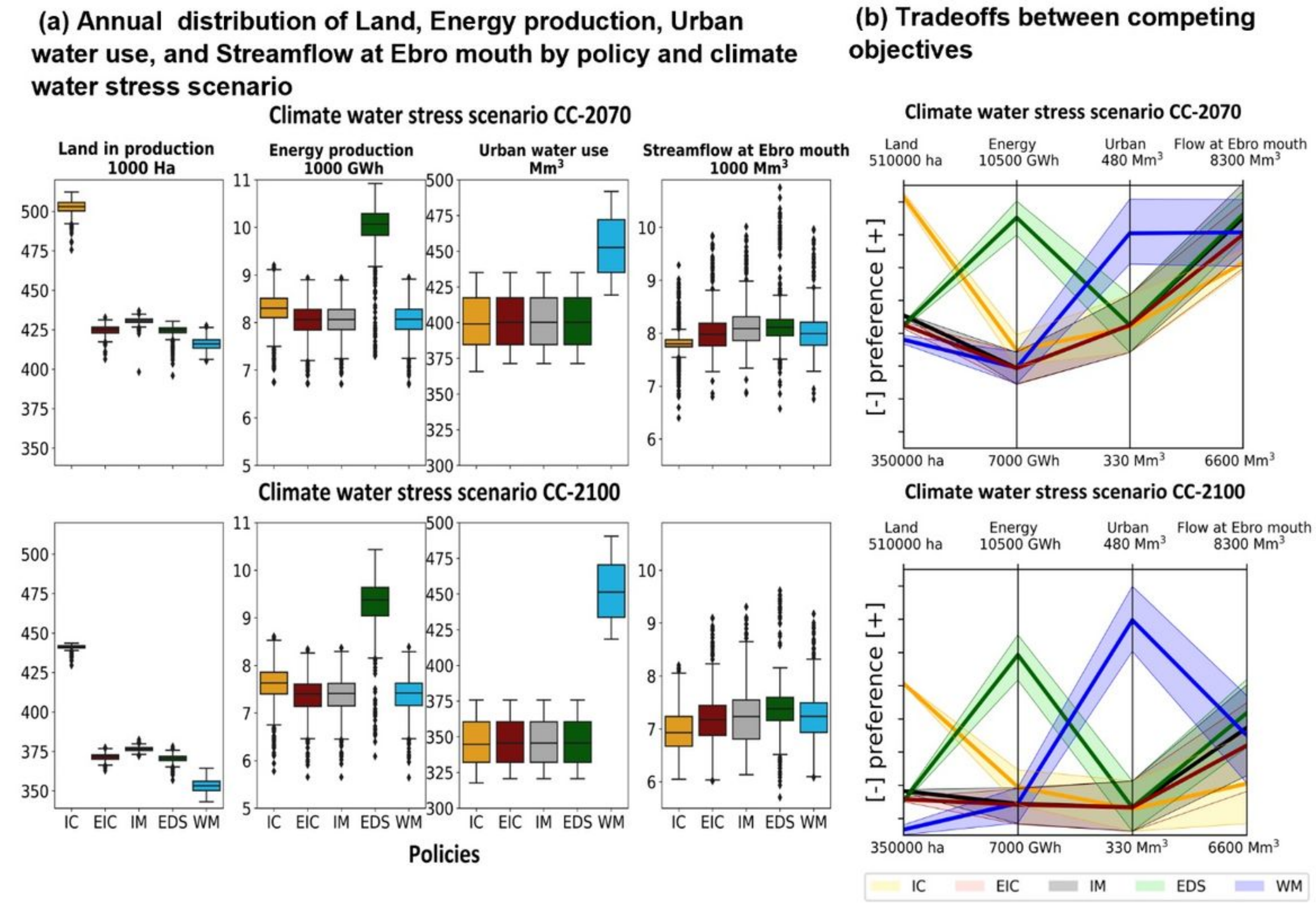
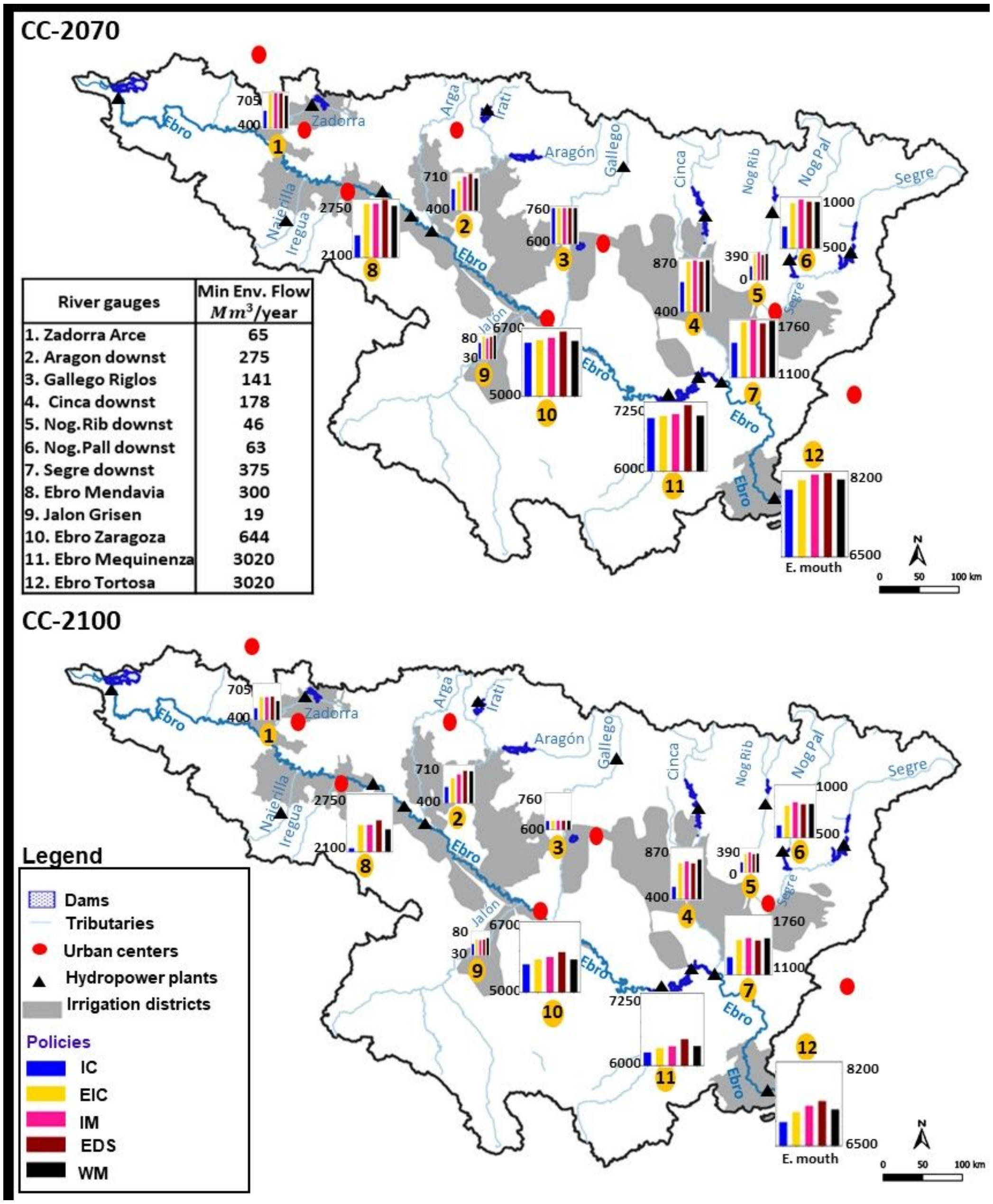


Figure 3

(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 capacity. WM: Water markets.



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

Figure 4

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

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

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- GAMSNexusCode.docx
- SupplementaryMaterial.docx