Probabilistic trade-offs analysis for sustainable and equitable management of climate-induced water risks

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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 multi-sector vulnerabilities and risks associated with future water stress. This study identifies the probabilistic trade-offs between agricultural, urban and energy sectors in the Ebro Basin (Spain). Two intervention policies have been examined and compared: (i) agricultural priority, and (ii) energy priority, for two planning horizons 2040-2070 and 2070-2100. Results show that the human water security goal is achieved under both intervention policies. However, the achievement of the food and energy security goals depends on the policy objectives and on the spatial location of irrigation schemes and hydropower plants, which result in different stream flows across the basin. The policy choice results in substantially different benefit gains and losses by sector and therefore by location. Neither priority policy provides an equitable sharing of benefits among all sectors and locations under climate change, which 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 where losers are compensated, while 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 addressing the multi-sector vulnerability.
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Key Points:

- Stochastic optimization modeling for assessing probabilistic trade-offs among sectors and spatial locations.
- Equitable and efficient water planning is needed for sustainable development.
- Food, energy, and human water security goals are examined under climate uncertainty.
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 multi-sector vulnerabilities and risks associated with future water stress. This study identifies the probabilistic trade-offs between agricultural, urban and energy sectors in the Ebro Basin (Spain). Two intervention policies have been examined and compared: (i) agricultural priority, and (ii) energy priority, for two planning horizons 2040-2070 and 2070-2100. Results show that the human water security goal is achieved under both intervention policies. However, the achievement of the food and energy security goals depends on the policy objectives and on the spatial location of irrigation schemes and hydropower plants, which result in different stream flows across the basin. The policy choice results in substantially different benefit gains and losses by sector and therefore by location. Neither priority policy provides an equitable sharing of benefits among all sectors and locations under climate change, which 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 where losers are compensated, while 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 addressing the multi-sector vulnerability.

Keywords: Probabilistic trade-offs, stochastic optimization, water management, vulnerability

1 Introduction

Water resources are essential for food, energy and human water security (Cheng et al., 2019). The sharp rise of water withdrawals during the last century has created massive pressures on water resources and led to severe environmental degradation and major management challenges in many river basins worldwide (Greve et al., 2018). These challenges are expected to become more critical in the coming decades, driven by imminent socioeconomic and climate changes. 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). Management policies in arid and vulnerable river basins must thus be adapted to address the future water challenges. The development of adaptation policies requires the analysis of trade-offs across sectors, such as urban water supply, agricultural production, energy generation, and ecosystem health, as well as across space and time (Cai et al., 2018). 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).

Water system models can be used to identify trade-offs in complex water resource systems, involving multiple and inter-dependent water uses. More specifically, optimization modeling is an
efficient tool for optimal water allocation and for identifying trade-offs 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) developed a nonlinear multiobjective optimization model to assess the trade-offs among multiple water uses in a hydropower system in the São Francisco River Basin in Brazil. Trade-offs 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 trade-offs 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). In another study the trade-offs between spatial locations for the management of inter-basin water diversions are considered (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 & 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 spatio-temporal 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).

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 multi-sector risks and vulnerabilities, as well as the corresponding trade-offs among competing objectives in heavily committed river basins. A novel integrated hydro-economic model is developed using stochastic dual dynamic programming (SDDP) to identify suitable mechanisms for sustainable and equitable water and benefit-sharing arrangements (Grey & 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 multi-user and multi-reservoir, to 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 & Tilmant, 2013; Tilmant et al., 2020).

This paper addresses the water challenges and sectoral vulnerabilities under future climate uncertainty and water stress by providing information on the hydrologic and economic risks associated with different water allocation policies. The spatial distribution of benefit gains and losses from water stress scenarios are important aspects in the debate on sustainable basin management, which requires 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.
2 Materials and Methods

2.1 Case study: The Ebro River basin

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 km² and being home to 3.2 million inhabitants (Figure 1). Renewable water resources amount to 15,000 (15 billion m³, 15 km³) million cubic meters (Mm³) per year, with 8,500 Mm³ (8.5 km³) 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 euros 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 hydro-climatic 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.

2.2 The SDDP model for optimal allocation

A stochastic hydro-economic 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 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. Data were gathered from a variety of reliable sources to establish a basis for an integrated analysis. The Ebro basin Authority and CEDEX (CEDEX, 2016; CHE, 2016) provide monthly data on streamflow and reservoir storage for the entire 30 year period (1986-2016). Several sources of data on crop yields, prices, production costs, water requirements and land in production were secured from the Spanish Ministry of Agriculture and State Governments (DGA, 2016; GC, 2016; GN, 2016; MAPAMA, 2021).

A periodic autoregressive model of order p - PAR(p) is needed 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 \( L \)th iteration has the following objective function:

\[
F_t(s_t, q_{t-1}) = \max_{x_t} \{ b_t(s_t, q_t, x_{t+1}) + \alpha_{t+1} F_{t+1} \} 
\]

(1)

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

The optimization problem includes several constraints such as lower and upper bounds on storages (Eq. 2), reservoirs releases (Eq. 3), water withdrawals (Eq. 4), water balance (Eq. 5), and the outer approximation of the future benefits (Eq. 6). The different constraints are represented as follows:

- Lower and upper bounds on storages:
  \[
s_{t+1} \leq s_t \leq \bar{s}_{t+1} 
\]

(2)

- Lower and upper bounds on reservoir releases:
  \[
r_{t} \leq r_t \leq \bar{r}_t 
\]

(3)

- Lower and upper bounds on water withdrawals:
  \[
i_t \leq i_t \leq \bar{i}_t 
\]

(4)

- Water balance:
  \[
s_{t+1} - C^R(r_t + l_t) - C^I(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t(q_{t-1}, \xi_t) 
\]

(5)

where the topology of the system is represented using the connectivity matrices \( C^R \) and \( C^I \). \( e_t \) and \( l_t \) represent the vector of reservoirs evaporation and the vector of spillage and losses, respectively. \( q_t(q_{t-1}, \xi_t) \) is the inflow generated using the PAR (1).

- The outer approximation of the future benefits:
  \[
F_{t+1} - \varphi_{t+1,l}^T s_{t+1} \leq \gamma_{t+1,l}^T q_t + \beta_{t+1,l} \quad (l = 1, 2, ..., L - 1) 
\]

(6)

where \( \varphi_{t+1,l} \) and \( \gamma_{t+1,l} \) are the gradients of \( F_{t+1} \) regarding the state variables \( (s_{t+1}, q_t) \), \( \beta_{t+1,l} \) 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:

$$
Z = \max_{s_t} \{ b_m (s_t, q_{y,m}, x_t) + F_{m+1} \}
$$

subject to

$$
\begin{align*}
    s_{t+1} & - C^R (r_t + l_t) - C^I (i_t) + e_t (s_t, s_{t+1}) = s_t + q_{y,m} \\
    F_{m+1} & - \varphi^R_{m+1,l} s_{t+1} \leq \gamma^R_{m+1,l} q_{y,m} + \beta_{m+1,l} \\
    (l = 1, 2, \ldots, L - 1)
\end{align*}
$$

Eq. 2-6 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 (Eq. 8) and solving a new re-optimization problem, and so forth until the end of the simulation period is reached.

The simulated allocation decisions are used to obtain performance indicators for the probabilistic trade-offs between economic sectors and between spatial locations.

**Indicators for the trade-offs between economic sectors** are: field crops, fruits, vegetables, hydropower generation, and urban centers. The performance of field crops, fruits, and vegetables is the number of hectares (ha) irrigated during the simulation period (30 years). The annual energy production represents the performance indicator for hydropower generation, whereas the volume of water delivered to cities represents the performance indicator for urban centers.

**Indicators for the trade-offs between spatial locations** are the upstream and downstream variables for the different economic activities: irrigated area, energy production, and urban water use.

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.

### 2.3. Procedure to identify trade-offs

The optimization-reoptimization process is applied for baseline and for future climate scenarios (CC-2070; CC-2100) under two alternative water allocation policies: 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 ($30 \times 1$). These vectors are used for the comparisons between sectors and spatial locations described above.
A variety of visualization techniques can be used to identify trade-offs between multiple elements and dimensions, such as Parallel Coordinate Plots and Radar Charts. These interactive visualization frameworks facilitate the identification 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 identify 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.

2.4. Policies and climate scenarios

The analysis investigates the two allocation policies between competing uses under climate scenarios (baseline, CC-2070, CC-2100): Intermediate development with emphasis on food production (Agriculture priority) and intermediate development with priority given to energy generation (Energy priority). 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 optimizes agricultural benefits, while the energy sector maximizes its benefits to the extent possible.

The selected policies have an effect on three important challenging objectives: human water security, food security, and energy security. Human water security will remain under threat in the future because of the escalating trends in human population, climate stress, water use, and development pressures (Vorosmarty et al., 2010). Access to safe drinking water and sanitation 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 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, and 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 (Figure S1 in the SI). 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 general circulation models. Under the RCP4.5 scenario, the fall in streamflow is 11% in 2040-2070, and 12% in 2070-2100. Under the RCP8.5 scenario, the fall in streamflow is 13% in 2040-2070, and 26% in 2070-2100.

3 Results

3.1. Hydrologic and economic impacts of climate risks

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 is shown in Figure 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 the agriculture and energy priority policies, respectively. 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 alleviate water scarcity and reduce the competition for water by users in drought months. Therefore, water security is enhanced in the basin. 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, water use by irrigated agriculture is reduced by around 8% (-158 Mm$^3$ for CC-2070; -183 Mm$^3$ for CC-2100), water use for energy production decreases by up to 28% (-2430 Mm$^3$ for CC-2070; -5292 Mm$^3$ for CC-2100), and urban water use is maintained. The annual outflow at the Ebro River mouth falls to 6830 Mm$^3$ under CC-2070 climate scenario, and to only 5450 Mm$^3$ under CC-2100 climate scenario. However, for the energy priority, the annual outflow will exceed 8600 and 7470 Mm$^3$ for 2070 and 2100, respectively, with a 50% exceedance probability. The high outflow levels under energy priority are due to the increased reservoir releases (+1370 Mm$^3$ for CC-2070; +4491 Mm$^3$ for CC-2100) that maximize hydropower generation, compared to agriculture priority outflows.

Projected annual hydropower production, irrigated cropland, and urban water use in the Ebro River basin for baseline, CC-2070 and CC-2100 scenarios under the agriculture and energy priority policies are shown in Figure 4. The urban sector takes priority over all other water uses and the annual urban water withdrawals are maintained under both policies and future climate scenarios, promoting the human water security objective. 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 streamflow in the basin. Compared to the baseline, hydropower production decreases by almost 30% (at 2930 GWh) under agricultural priority, while decreasing only by 20% (3610 GWh) under energy priority for the CC-2100 scenario. The reduction 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 the energy priority, the irrigated land with a 50%
exceedance probability is only 311,000 ha. In both future climate scenarios, the reduction in irrigated land is below 10% under agricultural priority. However, irrigated cropland falls by 20% (to 249,000 ha) and 34% (to 206,000 ha) under the energy priority for the CC-2070 and CC-2100 scenarios, respectively.

3.2. Probabilistic trade-offs between competing water users and spatial locations

Figures 5 and 6 show the trade-offs between economic activities and between spatial locations in the basin, by priority policy and climate scenario (Table S1-S4 in the SI). 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 water stress from climate conditions.

Under future climate scenarios, the agricultural priority policy reduces energy generation considerably, while maintaining the irrigated area of field crops, fruits and vegetables. This prioritization of the agriculture sector leads to damages in the energy sector, with lower hydropower 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 the irrigation oriented reservoir releases and by the dwindling river flows.

In contrast, for all climate scenarios the energy priority policy increases hydropower production, reduces the performance of agriculture, and maintains urban water use. There is a large reduction in the production of field crops, fruits and vegetables, compared to agricultural priority (Figure 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 shows also the intra-sectoral trade-offs between agricultural subsectors, especially damaging under energy priority. The agricultural priority slightly reduces the area 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 water requirements in all irrigation districts under climate water stress conditions. For the energy priority policy, the probability of the area 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 area of fruits falling 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 (surface irrigation).

As mentioned above, the agricultural priority policy results in low performance and high vulnerability of hydropower production under water stress conditions. However, the vulnerability level depends on the spatial location of hydropower plants. Figure 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 the reduced flows coming from upstream areas.

The energy priority policy decreases upstream irrigated area by 57% and 100% for 2070 and 2100, respectively, for a 50% non-exceedance probability. However, the irrigated area 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 the high hydropower 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 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 continuation of upstream irrigation activities. Benefits of downstream irrigation districts are less affected by future water stress coupled with energy priority, because they take advantage of large reservoir releases that maximize downstream hydropower production.

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.
4 Discussion and policy implications

This paper develops a stochastic hydro-economic model in the Ebro basin. The purpose is to assess different water allocation policies to confront future climate water stress, considering the interaction between water, energy, and agricultural systems. Results of this study highlight the importance of selecting the adequate water policies for an equitable sharing of benefits among all sectors and spatial locations under future climate conditions. The analysis of hydrologic risks indicates reductions in stream flows under both climate change scenarios (CC-2070; CC-2100), which are consistent with the results of other studies. 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 in 14% the decrease in stream flows in the Pyrenees from the projected trend of warming for the period 2021-2050.

The study estimates the impacts of future climate water stress on 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. They also 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 food production is highly vulnerable to changes in hydro climatic conditions and allocation policies in the case of the Senegal basin, emphasizing the importance of factoring this vulnerability into schemes for water and benefit sharing negotiations.

Understanding the trade-offs among spatial locations by sector is indeed crucial for improving the knowledge required for strengthening the food, energy and human water security. 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 larger 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 several 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 model's capacity to provide optimized solutions for all sectors and locations under varied future climate conditions demonstrates the model's sensitivity to parameter changes and qualifies it for effective policy support. Second, the trade-offs analysis 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 for
supporting the collective action of stakeholders and decision-makers to advance sustainable water management coupled with food, energy, and human water security. Finally, the evaluation of hydro-economic 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 environmental flows for 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 the predictions of reduced inflows for each spatial location based on the study by CEDEX (2017) on 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 Conclusions

This study develops a stochastic optimization model (SDDP) for the Ebro basin 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 probabilistic trade-off analysis 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 combined 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 with possible compensations in order to achieve acceptable levels of energy, agricultural and human water security.

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Availability of data

All data are included in the paper and in the supplementary material. The data are available from the institutional repository of the CITA research center, at the data link xxx.xxx.xxx. Monthly streamflow data across the Ebro Basin are collected from CEDEX (Centro de Estudios y Experimentación de Obras Públicas, Ministerio para la Transición Ecológica). All streamflow data are available in the CEDEX webpage (https://ceh.cedex.es/anuarioaforos/default.asp) or in the Ministry webpage (https://www.miteco.gob.es/app/descargas/descargafichero.aspx?f=TablaAnuario2018-19.zip)
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Figure 1. The Ebro River basin in Spain.
Figure 2. Schematic representation of the Ebro River basin.
Figure 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.
Figure 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. Trade-offs between sectors for baseline, CC-2070 and CC-2100 periods under energy and agricultural priority.
Figure 6. Trade-offs between sectors by spatial location (upstream-downstream) for baseline, CC-2070 and CC-2100 periods under energy and agricultural priority.
Figure 7. Benefit losses by sector under future climate scenarios.
Probabilistic trade-offs analysis for sustainable and equitable management of climate-induced water risks

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Key Points:

- Stochastic optimization modeling for assessing probabilistic trade-offs among sectors and spatial locations.
- Equitable and efficient water planning is needed for sustainable development.
- Food, energy, and human water security goals are examined under climate uncertainty.
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 multi-sector vulnerabilities and risks associated with future water stress. This study identifies the probabilistic trade-offs between agricultural, urban and energy sectors in the Ebro Basin (Spain). Two intervention policies have been examined and compared: (i) agricultural priority, and (ii) energy priority, for two planning horizons 2040-2070 and 2070-2100. Results show that the human water security goal is achieved under both intervention policies. However, the achievement of the food and energy security goals depends on the policy objectives and on the spatial location of irrigation schemes and hydropower plants, which result in different stream flows across the basin. The policy choice results in substantially different benefit gains and losses by sector and therefore by location. Neither priority policy provides an equitable sharing of benefits among all sectors and locations under climate change, which 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 where losers are compensated, while 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 addressing the multi-sector vulnerability.

Keywords: Probabilistic trade-offs, stochastic optimization, water management, vulnerability

1 Introduction

Water resources are essential for food, energy and human water security (Cheng et al., 2019). The sharp rise of water withdrawals during the last century has created massive pressures on water resources and led to severe environmental degradation and major management challenges in many river basins worldwide (Greve et al., 2018). These challenges are expected to become more critical in the coming decades, driven by imminent socioeconomic and climate changes. 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). Management policies in arid and vulnerable river basins must thus be adapted to address the future water challenges. The development of adaptation policies requires the analysis of trade-offs across sectors, such as urban water supply, agricultural production, energy generation, and ecosystem health, as well as across space and time (Cai et al., 2018). 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).

Water system models can be used to identify trade-offs in complex water resource systems, involving multiple and inter-dependent water uses. More specifically, optimization modeling is an
efficient tool for optimal water allocation and for identifying trade-offs 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) developed a nonlinear multiobjective optimization model to assess the trade-offs among multiple water uses in a hydropower system in the São Francisco River Basin in Brazil. Trade-offs 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 trade-offs 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). In another study the trade-offs between spatial locations for the management of inter-basin water diversions are considered (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 & 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 spatio-temporal 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).

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 multi-sector risks and vulnerabilities, as well as the corresponding trade-offs among competing objectives in heavily committed river basins. A novel integrated hydro-economic model is developed using stochastic dual dynamic programming (SDDP) to identify suitable mechanisms for sustainable and equitable water and benefit-sharing arrangements (Grey & 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 multi-user and multi-reservoir, to 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 & Tilmant, 2013; Tilmant et al., 2020).

This paper addresses the water challenges and sectoral vulnerabilities under future climate uncertainty and water stress by providing information on the hydrologic and economic risks associated with different water allocation policies. The spatial distribution of benefit gains and losses from water stress scenarios are important aspects in the debate on sustainable basin management, which requires 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.
2 Materials and Methods

2.1 Case study: The Ebro River basin

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 km² and being home to 3.2 million inhabitants (Figure 1). Renewable water resources amount to 15,000 (15 billion m³, 15 km³) million cubic meters (Mm³) per year, with 8,500 Mm³ (8.5 km³) 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 euros in 2005 (0.5% of GDP) (Hernández et al., 2013; Líñez 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 hydro-climatic 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.

2.2 The SDDP model for optimal allocation

A stochastic hydro-economic 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 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. Data were gathered from a variety of reliable sources to establish a basis for an integrated analysis. The Ebro basin Authority and CEDEX (CEDEX, 2016; CHE, 2016) provide monthly data on streamflow and reservoir storage for the entire 30 year period (1986-2016). Several sources of data on crop yields, prices, production costs, water requirements and land in production were secured from the Spanish Ministry of Agriculture and State Governments (DGA, 2016; GC, 2016; GN, 2016; MAPAMA, 2021).

A periodic autoregressive model of order p - PAR(p) is needed 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:

$$F_t(s_t, q_{t-1}) = \max_{x_t} \left\{ b_t(s_t, q_t, x_{t+1}) + \alpha_{t+1} F_{t+1} \right\}$$

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

The optimization problem includes several constraints such as lower and upper bounds on storages (Eq. 2), reservoirs releases (Eq. 3), water withdrawals (Eq. 4), water balance (Eq. 5), and the outer approximation of the future benefits (Eq. 6). The different constraints are represented as follows:

- Lower and upper bounds on storages:
  $$s_{t+1} \leq s_t \leq \bar{s}_{t+1}$$

- Lower and upper bounds on reservoir releases:
  $$r_t \leq r_t \leq \bar{r}_t$$

- Lower and upper bounds on water withdrawals:
  $$i_t \leq i_t \leq \bar{i}_t$$

- Water balance:
  $$s_{t+1} - C^R(r_t + l_t) - C^I(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t(q_{t-1}, \xi_t)$$

where the topology of the system is represented using the connectivity matrices $C^R$ and $C^I$. $e_t$ and $l_t$ represent the vector of reservoirs evaporation and the vector of spillage and losses, respectively. $q_t(q_{t-1}, \xi_t)$ is the inflow generated using the PAR (1).

- The outer approximation of the future benefits:
  $$F_{t+1} - \varphi^T_{t+1,l} s_{t+1} \leq \gamma^T_{t+1,l} q_t + \beta_{t+1,l} (l = 1, 2, ..., L - 1)$$

where $\varphi_{t+1,l}$ and $\gamma_{t+1,l}$ are the gradients of $F_{t+1}$ regarding the state variables $(s_{t+1}, q_t)$, $\beta_{t+1,l}$ 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:

\[
Z = \max_{x_t} \{ b_m(s_t, q_{y,m}, x_t) + F_{m+1} \} \tag{7}
\]

Subject to

\[
s_{t+1} - C^R(r_t + l_t) - C^I(i_t) + e_t(s_t, s_{t+1}) = s_t + q_{y,m} \tag{8}
\]

\[
F_{m+1} - q_{m+1,l}^s s_{t+1} \leq y_{m+1,l}^s q_{y,m} + \beta_{m+1,l} \quad (l = 1, 2, \ldots, L - 1) \tag{9}
\]

Eq. 2-6 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 (Eq. 8) and solving a new re-optimization problem, and so forth until the end of the simulation period is reached.

The simulated allocation decisions are used to obtain performance indicators for the probabilistic trade-offs between economic sectors and between spatial locations.

**Indicators for the trade-offs between economic sectors** are: field crops, fruits, vegetables, hydropower generation, and urban centers. The performance of field crops, fruits, and vegetables is the number of hectares (ha) irrigated during the simulation period (30 years). The annual energy production represents the performance indicator for hydropower generation, whereas the volume of water delivered to cities represents the performance indicator for urban centers.

**Indicators for the trade-offs between spatial locations** are the upstream and downstream variables for the different economic activities: irrigated area, energy production, and urban water use.

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.

### 2.3. Procedure to identify trade-offs

The optimization-reoptimization process is applied for baseline and for future climate scenarios (CC-2070; CC-2100) under two alternative water allocation policies: 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 the comparisons between sectors and spatial locations described above.
A variety of visualization techniques can be used to identify trade-offs between multiple elements and dimensions, such as Parallel Coordinate Plots and Radar Charts. These interactive visualization frameworks facilitate the identification 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 identify 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.

2.4. Policies and climate scenarios

The analysis investigates the two allocation policies between competing uses under climate scenarios (baseline, CC-2070, CC-2100): Intermediate development with emphasis on food production (Agriculture priority) and intermediate development with priority given to energy generation (Energy priority). 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 optimizes agricultural benefits, while the energy sector maximizes its benefits to the extent possible.

The selected policies have an effect on three important challenging objectives: human water security, food security, and energy security. Human water security will remain under threat in the future because of the escalating trends in human population, climate stress, water use, and development pressures (Vorosmarty et al., 2010). Access to safe drinking water and sanitation 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 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, and CC-2100. The future climate water stress scenarios are...
based on the combination of historical drought patterns and projected future declines in streamflows under climate change (Figure S1 in the SI). 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 general circulation models. Under the RCP4.5 scenario, the fall in streamflow is 11% in 2040-2070, and 12% in 2070-2100. Under the RCP8.5 scenario, the fall in streamflow is 13% in 2040-2070, and 26% in 2070-2100.

3 Results

3.1. Hydrologic and economic impacts of climate risks

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 is shown in Figure 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 the agriculture and energy priority policies, respectively. 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 alleviate water scarcity and reduce the competition for water by users in drought months. Therefore, water security is enhanced in the basin. 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, water use by irrigated agriculture is reduced by around 8% (-158 Mm$^3$ for CC-2070; -183 Mm$^3$ for CC-2100), water use for energy production decreases by up to 28% (-2430 Mm$^3$ for CC-2070; -5292 Mm$^3$ for CC-2100), and urban water use is maintained. The annual outflow at the Ebro River mouth falls to 6830 Mm$^3$ under CC-2070 climate scenario, and to only 5450 Mm$^3$ under CC-2100 climate scenario. However, for the energy priority, the annual outflow will exceed 8600 and 7470 Mm$^3$ for 2070 and 2100, respectively, with a 50% exceedance probability. The high outflow levels under energy priority are due to the increased reservoir releases (+1370 Mm$^3$ for CC-2070; +4491 Mm$^3$ for CC-2100) that maximize hydropower generation, compared to agriculture priority outflows.

Projected annual hydropower production, irrigated cropland, and urban water use in the Ebro River basin for baseline, CC-2070 and CC-2100 scenarios under the agriculture and energy priority policies are shown in Figure 4. The urban sector takes priority over all other water uses and the annual urban water withdrawals are maintained under both policies and future climate scenarios, promoting the human water security objective. 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 streamflow in the basin. Compared to the baseline, hydropower production decreases by almost 30% (at 2930 GWh) under agricultural priority, while decreasing only by 20% (3610 GWh) under energy priority for the CC-2100 scenario. The reduction 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 the energy priority, the irrigated land with a 50%
exceedance probability is only 311,000 ha. In both future climate scenarios, the reduction in irrigated land is below 10% under agricultural priority. However, irrigated cropland falls by 20% (to 249,000 ha) and 34% (to 206,000 ha) under the energy priority for the CC-2070 and CC-2100 scenarios, respectively.

3.2. Probabilistic trade-offs between competing water users and spatial locations

Figures 5 and 6 show the trade-offs between economic activities and between spatial locations in the basin, by priority policy and climate scenario (Table S1-S4 in the SI). 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 water stress from climate conditions.

Under future climate scenarios, the agricultural priority policy reduces energy generation considerably, while maintaining the irrigated area of field crops, fruits and vegetables. This prioritization of the agriculture sector leads to damages in the energy sector, with lower hydropower 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 the irrigation oriented reservoir releases and by the dwindling river flows.

In contrast, for all climate scenarios the energy priority policy increases hydropower production, reduces the performance of agriculture, and maintains urban water use. There is a large reduction in the production of field crops, fruits and vegetables, compared to agricultural priority (Figure 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 shows also the intra-sectoral trade-offs between agricultural subsectors, especially damaging under energy priority. The agricultural priority slightly reduces the area 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 water requirements in all irrigation districts under climate water stress conditions. For the energy priority policy, the probability of the area 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 area of fruits falling 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 (surface irrigation).

As mentioned above, the agricultural priority policy results in low performance and high vulnerability of hydropower production under water stress conditions. However, the vulnerability level depends on the spatial location of hydropower plants. Figure 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 the reduced flows coming from upstream areas.

The energy priority policy decreases upstream irrigated area by 57% and 100% for 2070 and 2100, respectively, for a 50% non-exceedance probability. However, the irrigated area 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 the high hydropower 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 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 continuation of upstream irrigation activities. Benefits of downstream irrigation districts are less affected by future water stress coupled with energy priority, because they take advantage of large reservoir releases that maximize downstream hydropower production.

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.
4 Discussion and policy implications

This paper develops a stochastic hydro-economic model in the Ebro basin. The purpose is to assess different water allocation policies to confront future climate water stress, considering the interaction between water, energy, and agricultural systems. Results of this study highlight the importance of selecting the adequate water policies for an equitable sharing of benefits among all sectors and spatial locations under future climate conditions. The analysis of hydrologic risks indicates reductions in stream flows under both climate change scenarios (CC-2070; CC-2100), which are consistent with the results of other studies. 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 study estimates the impacts of future climate water stress on 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. They also 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 food production is highly vulnerable to changes in hydro-climatic conditions and allocation policies in the case of the Senegal basin, emphasizing the importance of factoring this vulnerability into schemes for water and benefit sharing negotiations.

Understanding the trade-offs among spatial locations by sector is indeed crucial for improving the knowledge required for strengthening the food, energy and human water security. 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 larger 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 several 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 model's capacity to provide optimized solutions for all sectors and locations under varied future climate conditions demonstrates the model's sensitivity to parameter changes and qualifies it for effective policy support. Second, the trade-offs analysis 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 for
supporting the collective action of stakeholders and decision-makers to advance sustainable water management coupled with food, energy, and human water security. Finally, the evaluation of hydro-economic 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 environmental flows for 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 the predictions of reduced inflows for each spatial location based on the study by CEDEX (2017) on 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 Conclusions

This study develops a stochastic optimization model (SDDP) for the Ebro basin 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 probabilistic trade-off analysis 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 combined 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 with possible compensations in order to achieve acceptable levels of energy, agricultural and human water security.

Acknowledgments

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Availability of data

All data are included in the paper and in the supplementary material. The data are available from the institutional repository of the CITA research center, at the data link xxx.xxx.xxx. Monthly streamflow data across the Ebro Basin are collected from CEDEX (Centro de Estudios y Experimentación de Obras Públicas, Ministerio para la Transición Ecológica). All streamflow data are available in the CEDEX webpage (https://ceh.cedex.es/anuarioaforos/default.asp) or in the Ministry webpage (https://www.miteco.gob.es/app/descargas/descargafichero.aspx?f=TablaAnuario2018-19.zip)


References


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GN. (2016). (Gobierno de Navarra), Base de datos IT de superficies de cultivos por término municipal 2009, Departamento de Desarrollo Rural. Medio Ambiente y Administración Local, Pamplona.


Figure 1. The Ebro River basin in Spain.
Figure 2. Schematic representation of the Ebro River basin.
Figure 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.
Figure 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. Trade-offs between sectors for baseline, CC-2070 and CC-2100 periods under energy and agricultural priority.
Figure 6. Trade-offs between sectors by spatial location (upstream-downstream) for baseline, CC-2070 and CC-2100 periods under energy and agricultural priority.
Figure 7. Benefit losses by sector under future climate scenarios.
Probabilistic trade-offs analysis for sustainable and equitable management of climate-induced water risks

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Introduction

Figure S1 provides monthly inflow data into the Ebro basin for each climate scenario.

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Table S2 provides optimized irrigated area in each irrigation schemes for the agriculture and energy priority policies and CC-2070 and CC-2100 climate scenarios.

Table S3 provides optimized irrigated area by crop type for the agriculture and energy priority policies and CC-2070 and CC-2100 climate scenarios.

Table S4 provides optimized water use by sector and spatial location for the agriculture and energy priority policies and CC-2070 and CC-2100 climate scenarios.
Future climate water stress scenarios are based on the combination of historical drought patterns and projected future declines in stream flows under climate change using CEDEX (2017). Figure shows monthly inflow data into the Ebro basin for each climate scenario.
Table S1. Optimized energy production by hydropower plant, policy, and climate scenario, Averaged over 30 years (Mm$^3$)

<table>
<thead>
<tr>
<th>Hydropower plants (Nodes)</th>
<th>Agriculture priority</th>
<th>Energy priority</th>
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<tr>
<td>Node 28</td>
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<td>6.28</td>
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</tr>
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<td>Node 48</td>
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<td>Node 50</td>
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The spatial location of each node is represented in Figure 2.
Table S2. Optimized land in production by irrigation scheme, policy, and climate scenario, Averaged over 30 years (1000 ha)

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Table S3. Optimized land in production by crop type, policy, and climate scenario, Averaged over 30 years (1000 ha)

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### Table S4. Optimized water use by sector, policy, and climate scenario, Averaged over 30 years (1000 ha)

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