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Climate Adaptation Needs to Reduce Water Scarcity Vulnerability in the Tagus River Basin

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Abstract: In southern Europe, climate change is expected to aggravate water scarcity conditions and challenge current water management practices. The present paper evaluates the impacts of climate change in the highly regulated Tagus River basin and assesses various adaptation options, quantifying the effort needed to maintain the ability to sustain current water uses. A water management and allocation model covering surface and groundwater resources is used to evaluate available and renewable water resources for different climate scenarios. Additionally, the Water Exploitation Index Plus (WEI+) and water supply reliability criteria are used to quantify water scarcity and the ability to satisfy water demands, respectively. The results show that climate change will significantly change the stream flow regime and reduce water availability in the Tagus River basin, but the existing reservoir infrastructure will alleviate some of these impacts, especially in the dry half-year. Until the end of the century, water scarcity levels, measured by annual WEI+, are expected to increase in the Tagus River basin from 0.46 to 0.52 or 0.62, respectively under two Representative Concentration Pathways (RCP 4.5 or RCP 8.5). The benefits of streamflow regulation vary with the hydrological regimen, the current degree of water use and the role of groundwater resources to meet demand. The benefits of streamflow regulation are also dependent on the environmental flow requirements that will be adopted in the future. A reduction of water consumption for irrigation by 25% to 40% will significantly improve the Tagus River system performance and maintain the current scarcity situation in the future, under the expected scenarios of climate change.

Keywords: climate change; adaptation measures; water availability; water demand reduction; transboundary river basin

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1. Introduction

Over the last decades, significant hydrological alterations have been occurring worldwide due to changes in precipitation and temperature patterns and to the intensification of the frequency and severity of extreme climatological conditions (floods and droughts) [1–5]. In Southern Europe, climate projections indicate increasing drier conditions and a higher frequency of droughts which will add further challenges to a region already exposed to water scarcity and frequent drought events [6–8]. Associated with increasing human-induced pressures, such as increasing water demands and land-use changes, these climate trends raise serious concerns about the ability to sustain current water uses. In some southern European river basins, where water constrains socio-economic development and the ecological integrity of environmental systems, current climate change projections have serious implications for major policy decisions, quite beyond the sectoral policies for water planning and management, and resource allocation and use [8,9].

To address climate change impacts on water resources and to alleviate the effects of expected water shortages, water management policies must be modified and adapted to future climate conditions, as the adopted global mitigation efforts to control greenhouse gas emissions to the atmosphere are insufficient to completely reverse current climate trends.

The water sector may contribute to the international efforts to significantly reduce and, ultimately, eliminate net greenhouse gas emissions, but its role in this domain is limited, although relevant [10,11].

Climate adaptation is the core instrument to minimize climate change impacts on water use and water-related risks and should constitute the priority of action at the river basin level [12]. The need for adaptation measures in water policies to address water scarcity and drought is also highlighted by the European Commission [13,14].

The definition of an adaptation programme requires creative and innovative thinking to design a comprehensive and integrated strategy that reduces society's vulnerability to climate change and provides the needed flexibility to deal with uncertainty. Each potential adaptation measure to be included in the strategy should be subject to a careful evaluation of its positive and negative environmental and socio-economic impacts to identify cost-benefit relationships and the course of actions worth pursuing. From this evaluation, an adaptation plan for water resources management will arise, which will necessarily include supply-side measures and demand-side measures.

Supply-side approaches to increase fresh water supply generally involve increasing the size or number of hydraulic infrastructures, reservoirs or water transfers, tapping ground water resources or adding other types of water sources, such as seawater desalination plants, wastewater reuse and rainwater harvesting [15,16]. Demand-side approaches include measures to restrict water consumption or to improve water-use efficiency, by controlling physical losses and reducing waste. In the agricultural sector, upgrading irrigation systems and changing cropping patterns and planting dates are possible measures to reduce water consumption [17,18]. In both cases, adjustments in the operation of existing hydraulic infrastructure may be needed to respond to changes in the water resources system [12,19,20].

The definition of a concrete climate and water scarcity adaptation strategy for a specific river basin is not an easy task for decision-makers, especially in transboundary river basins, where a plan must be agreed upon across borders, as well as among policy sectors and government levels. The final adaptation approach must evaluate the opportunities and constraints of each potential measure according to the hydrological and geological specificities of the river basin system, as well as the complexity and operation purposes of the reservoir network [21]. Water allocation models can help to overcome challenges in water management and climate adaptation by integrating climate change and hydrological modelling with water management and allocation and providing information to support the effective planning and management of water resources in regulated systems under future hydrological scenarios. This is a great advantage, especially in scarce regions where climate change and human-induced pressures represent the main drivers of streamflow reduction [18,22].

In Southern Europe, future climate change projections suggest significant reductions in water availability from surface and groundwater resources, as well as an increase in the frequency and severity of low flows [23,24]. Estimations suggest that more than a third of the population will be exposed to water scarcity at a 2 °C global warming level [25].

Climate change in the Tagus River transboundary basin of the Iberian Peninsula follows this decreasing trend in annual precipitation amounts and changes in seasonal patterns, leading to reductions in water availability [26–29]. Consequently, existing water uses may not be maintained with the current infrastructures and management policies and action is needed to control the socio-economic and environmental impacts that will arise in the future.

Despite the current understanding of major water management challenges in the Tagus River basin, there is still a lack of studies that focus on climate change impacts on the performance of water resource exploitation systems of the entire Tagus River basin and/or evaluate potential water management adaptation strategies to overcome those impacts and manage water scarcity situations. Most studies analyzed the water management challenges of particular sub-basins within the Tagus River basin and did not deal with the transboundary nature of the watershed. Lobanova et al. [30] and Pellicer-Martínez et al. [28] evaluated different water management strategies under climate change to assess their implications on water resource allocation in the Tagus headwaters. Lobanova et al. [31] considered the entire river basin but focused their appraisal on the impacts of climate change on the river basin hydrology and hydropower production capability. Sondermann and Oliveira [32,33] studied the entire river basin and evaluated the basin's ability to satisfy current and future water demands on both sides of the border, assuming the historical water availability records and not considering climate change impacts. To quantify water scarcity and the basin ability to satisfy water demands, indicators such as the Water Exploitation Index Plus (WEI+) and water supply reliability, vulnerability, resilience, and sustainability were used.

This paper evaluates the impacts of climate change in the Tagus River transboundary basin and assesses various adaptation options, quantifying the effort needed to maintain the ability to sustain current main water uses. A hydrological model is used to evaluate the main climate change impacts on water availability for three different time horizons, under two greenhouse gases emission scenarios (RCP 4.5 and RCP 8.5). A water management and allocation model covering surface and groundwater resources is used to simulate the highly regulated system of the Tagus River basin and to assess the performance of the basin's water infrastructure to satisfy current water demands. Different water management strategies are simulated to understand how climate change impacts can be abated and current water uses maintained in the Tagus River basin and its sub-basins. The mid-term horizon (2040–2070) was chosen to be the target of adaptation studies assuming that impacts are unavoidable in the short to mid-term period and that expected damages will be more severe for the mid-term horizon, when compared to the short-term horizon. To the best of our knowledge, this is the first integrated and quantified prospective of climate change impacts and adaptation needs for the Tagus River basin, covering both Portugal and Spain. The proposed methodology can be adopted in other case studies.

The paper does not assess the broad range of possible supply-side measures that may be implemented in the Tagus River basin, such as wastewater reuse, desalination, and the increase of storage capacity. The viability of these measures is strongly dependent on local opportunities and on the results of specific economic analyses. In addition, new storage infrastructures do not alleviate the expected reduction of average stream flows and lead to larger pressures on the vulnerable aquatic environment, which is already facing water stress [34]. Given the already significant regulation of the Tagus River basin, possible locations to build new infrastructures that increase water security on a river basin scale are scarce. This does not mean that opportunities to increase reservoir storage and attenuate the expected increase of the inter-annual and intra-annual variability of stream flow are non-existent in the Tagus River basin.

The paper concentrates on investigating the potential demand-side adaptation measures for controlling water abstractions that avoid future increases or even achieve some reduction. Although all water use sectors should contribute to this effort, the focus is set on the agricultural sector, as it is the major water consumer and the most directly affected by climate change impacts on seasonal water availability. To evaluate the potential of this approach in the Tagus River basin, two options are assessed:

(1) Reduction of water allocation to the agricultural areas of the Tagus River basin: Various reductions in water demand for the agriculture sector are assumed and the reductions are equally applied to all sub-basins and water demand units.
(2) Reduction of water allocation to the Tagus-Segura aqueduct, a major infrastructure that deviates water from the Tagus River headwater to southern Spain: The monthly volume assigned to the Tagus-Segura aqueduct is reduced by 30%, 60% or totally eliminated.

The paper examines the adaptation response to previous water management options by measuring two different indicators that are used to quantify the systems' performance in satisfying water demand (Reliability for urban and agriculture uses [35]) and to diagnose water scarcity conditions (the Water Exploitation Index Plus, WEI+ [36]).

2. Data and Methods

2.1. The Water Allocation Model

Climate change impacts on regulated water resources and reservoir operation performance are evaluated using a water management and allocation model. The existing network of hydraulic infrastructure, current water uses, and management practices is simulated in the AQUATOOL model for the historical hydrological record (1960/61–2015/16) and different future hydrologic scenarios. Each scenario considers one of the three-time horizons (near future (2011–2040), mid-century (2041–2070) and far-future (2071–2100)) and one of two Representative Concentration Pathways Scenarios, representing increasing radiative forcing conditions (RCP 4.5 and RCP 8.5).

AQUATOOL is a user-friendly decision-support system developed at the Universidad Politécnica de Valencia (UPV) and widely applied to simulate Spanish river basins. It is designed to represent the conjunctive usage of surface and groundwater sources to satisfy water demand, with the degree of detail selected by the user [37]. The model's setup for the Tagus River basin includes 87 entry points of inflow (surface runoff and recharge infiltration), 43 nodes representing the largest reservoirs, 22 hydropower plants, 12 aquifers, 72 nodes of consumptive demand for municipal, agriculture and industrial uses and 22 points of return flow. Detailed information about the scheme in AQUATOOL, as well as the reservoir operating rules and water allocations, can be found in Sondermann and Oliveira [33]. The paper describes an earlier application of AQUATOOL to simulate the operation of the existing man-made system of hydraulic infrastructure and groundwater exploitation in the Tagus River basin.

The model validation was carried out by adjusting the reservoir operating rules and the water allocation policies to the historical records of inflow, outflow and stored volume in reservoirs and the historical streamflow in monitoring sites while ensuring high-reliability levels of water supply. As the management policies implemented in the model simplify a complex decision-making process, the results are associated with some uncertainty [32,33].

2.2. Assessment of Climate Change Impacts on Water Resources and Reservoir Performance

Consider a cross-section i of the river network, where $Q_{i,t}^{nat}$ flows under natural or pristine conditions in period t. As water use, water transfers and reservoir regulation change the hydrological regime, the regulated or modified streamflow at cross-section i is $Q_{i,t}^{mod}$. If a hydrometric station exists at cross-section i, it will measure $Q_{i,t}^{mod}$.

The total available water resources in sub-basin i, located upstream of cross-section i and downstream of cross-section *i-1* are the renewable water resources, $RWR_{i,t}$. This value is different from $Q_{i,t}^{mod}$ because it does not consider existing water uses in sub-basin i. If $A_{i,t}$ is the sum of water abstractions to urban, industrial and agricultural uses from surface and groundwater sources within the sub-basin i, and $R_{i,t}$ represents the corresponding return flows, $RWR_{i,t}$ can be determined by

$$RWR_{i,t} = Q_{i,t}^{mod} + (A_{i,t} - R_{i,t}) \tag{1}$$

The climate change impacts on natural flows and renewable water resources may be determined by comparing the average of $Q_{i,t}^{nat}$ and $RWR_{i,t}$ for a climate scenario with the corresponding average of the historical record. If $\overline{Q_{i,s}^{nat}}$ and $\overline{RWR_{i,s}}$ are, respectively, the average natural flows and renewable water resources in sub-basin i in a year, season or month s, then

$$\Delta Q_{i,s}^{nat} = \frac{\overline{Q_{i,s}^{nat}}^{Scen} - \overline{Q_{i,s}^{nat}}^{Hist}}{\overline{Q_{i,s}^{nat}}^{Hist}} \times 100 \tag{2}$$

$$\Delta RWR_{i,s} = \frac{\overline{RWR}_{i,s}^{Scen} - \overline{RWR}_{i,s}^{Hist}}{\overline{RWR}_{i,s}^{Hist}} \times 100 \quad (3)$$

Note that $\Delta Q_{i,s}^{nat}$ measures the impact of climate change on flows under natural or pristine conditions, while $\Delta RWR_{i,s}$ measures the impact of climate change on available renewable water resources, which considers the regulating capacity of reservoirs. It is therefore interesting to assess the role of reservoirs in mitigating the impacts of climate change.

Ehsani et al. [38] proposed the Effective Degree of Regulation, EDR, as the ratio of the volume of water that is displaced (stored or released) by the operation of a dam or a cluster of dams, to the river's naturalized flow (without dams). This ratio can be used to quantify the contribution of the reservoir in increasing water availability, for each climate scenario, including the historical record.

$$EDR_{i,s}^{Scen} = \frac{\left| \overline{Q_{i,s}^{mod}}^{Scen} - \overline{Q_{i,s}^{nat}}^{Scen} \right|}{\overline{Q_{i,s}^{nat}}^{Scen}} \quad (4)$$

In Equation (4), the superscript *Scen* stands for historical data (1960-61–2015-16) or any future climate scenarios which assume a representative concentration pathway (RCP 4.5 or RCP 8.8) and one of the three time horizons (2011–2040, 2041–2070, 2071–2100). The subscript s stands for a year, over which the average may be computed. Although $EDR_{i,s}^{Scen}$ may be computed for a month or a season, its most interesting results are for the year. As the numerator of Equation (4) is a positive value resulting from the module function, $EDR_{i,s}^{Scen}$ is always positive and measures the total deviation of the regulated flow from the natural flow over period s.

The information provided by $EDR_{i,year}^{Scen}$ is similar to the one provided by the regulation coefficient (or storage coefficient) RC_i^{Scen}, defined as the ratio between storage capacity, K_i, and average annual stream flow, $\overline{Q_{i,year}^{nat}}^{Scen}$.

$$RC_i^{Scen} = \frac{K_i}{\overline{Q_{i,year}^{nat}}^{Scen}} \quad (5)$$

When comparing $EDR_{i,s}^{Scen}$ and RC_i^{Scen}, one may highlight that RC_i^{Scen} emphasizes the causes of the regulation (i.e., storage capacity), while $EDR_{i,year}^{Scen}$ draws attention to the consequences of the regulation (i.e., the deviation of $\overline{Q_{i,s}^{mod}}^{Scen}$ from $\overline{Q_{i,s}^{nat}}^{Scen}$). Both $EDR_{i,year}^{Scen}$ and RC_i^{Scen} are dependent on the streamflow scenario. In the Tagus River basin, the correlation between the current EDR_{year} and the regulation coefficient of each sub-basin is always higher than 0.93, for all streamflow scenarios.

The stream flows under natural conditions, $Q_{i,t}^{nat}$, for both historical records and future scenarios were obtained from the technical report entitled Assessment of current and future water availability in Portugal, developed by Nemus, Bluefocus and Hidromod for the Portuguese Environmental Agency [39], while the time series of $RWR_{i,t}$ were determined by the water allocation model.

To evaluate the basin's ability to satisfy its consumptive uses under different climate scenarios, the reliability indicator was used [35,40]. Reliability is determined by the percentage of years when the entire demand of a given use is met in all 12 months.

To quantify water scarcity conditions with spatial and temporal coverage, the Water Exploitation Index Plus (WEI+) was used [33,36]. WEI+ varies from 0 to 1, with values close to 0 meaning pristine conditions and values close to 1 representing a situation where all available water resources are being used to satisfy water demands. WEI+ is determined in monthly time intervals and statistics of WEI+ are computed from the monthly time series, such as the average value or the average value in each month, quarter or year. Equation (6) is used to determine the value of WEI+ at sub-basin i, in month t.

$$WEI+^{Scen}_{i,t} = \frac{A_{i,t} - R_{i,t}}{RWR^{Scen}_{i,t} - Q^{env}_{i,t}} \quad (6)$$

WEI+ considers net consumption for consumptive uses, determined by deduction return flows, $R_{i,t}$, from water abstractions, $A_{i,t}$. In addition, environmental flow requirements, $Q^{env}_{i,t}$, are deducted from the renewable water resources, $RWR^{Scen}_{i,t}$, as this volume is not available for consumptive uses.

2.3. Case Study

The Tagus River transboundary basin lies in the central part of the Iberian Peninsula and is shared between Spain and Portugal. The river runs from east to west, with two-thirds of its basin lying in Spain (55.781 km^2), the upstream country, and one-third in Portugal (24.845 km^2), the downstream country. In Spain, the basin is managed by the Confederación Hidrográfica del Tajo (CHT) and in Portugal by the Administração de Região Hidrográfica do Tejo, a regional office of the Agência Portuguesa do Ambiente (APA). The Albufeira Convention, signed in 1998 and revised in 2008, defines the rules for governing and protecting the shared river basins of the Iberian Peninsula.

The rainfall regime in both countries is highly variable with influences by both the Mediterranean climate, mainly on the eastern side of the basin and the Atlantic climate on the western side. Consequently, the basin is characterized by a significant inter-annual and inter-season variability of flows, with high flows usually occurring in the winter, especially from November to March (around 75% of mean annual flow) and low flows from June to September (around 7% of mean annual flow) [39].

In the past, the challenges arising from the highly variable meteorological conditions and the growing water demand have been met by building large reservoirs and using the basin groundwater resources intensely. The current storage capacity in reservoirs, in both countries, reaches almost 14,000 hm^3. The total water demand of around 4400 hm^3/year is satisfied by surface water sources (76%) and groundwater sources (24%).

During the most recent decades, a significant decrease in annual and seasonal flows has been recorded in the Tagus River basin and future climate scenarios suggest deeper decreases in precipitation, increases in temperature and evaporation, and strengthening of seasonal and interannual variability [26–29]. These trends towards drier conditions and more severe drought periods highlight a growing vulnerability of both upstream and downstream riparian countries to water scarcity [39,41].

Figure 1 shows the Tagus River basin with its major sub-basins, reservoirs and water uses. The metropolitan areas of Madrid and Lisbon are located in the Jarama-Guadarrama (Spain) and Tagus Valley (Portugal) sub-basins, respectively. The significant water demands for the urban sector in Spain and Portugal are mainly supplied by large reservoirs located in the Jarama-Guadarrama and Zêzere sub-basins, respectively. The agricultural sector is the main water user, with irrigation hubs existing in the entire Tagus River basin, but especially in the Alagón sub-basin, Spain, where water is supplied by reservoir regulation, and in the Tagus Valley, Portugal, where the main source of groundwater supply (the Tagus-Sado aquifers) is located. The basin also supports external uses, up to 650 hm^3/year, in Southern Spain, through the Tagus-Segura transfer scheme. In Portugal, it receives water from the Douro (up to 82 hm^3/year) and Mondego (up to 44 hm^3/year) river basins.

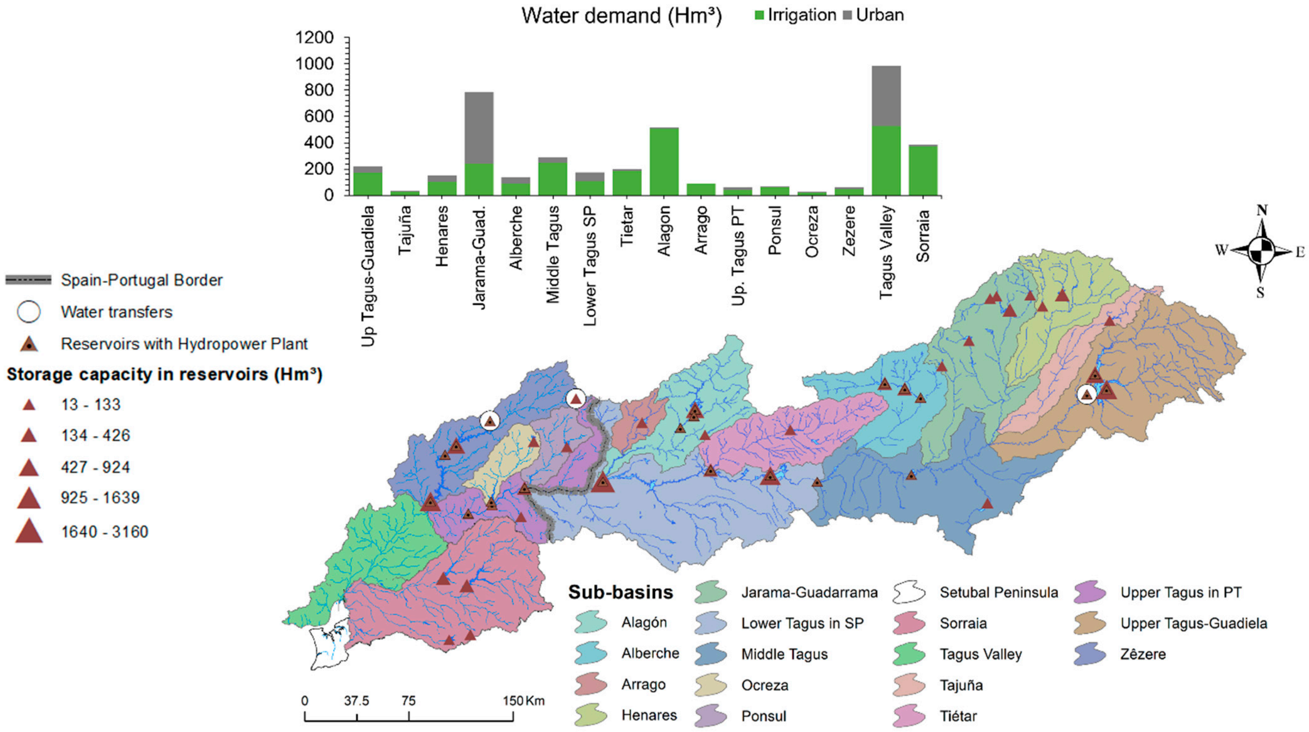


Figure 1. Tagus River basin and its human-induced pressures (hydraulic infrastructure and water demand) within sub-basins.

2.4. Data Sources

The physical characteristics of each hydraulic infrastructure included in the water allocation model were collected from Spanish and Portuguese national databases, such as the Centro de Estudios y Experimentación de Obras Públicas (CEDEX) and the Sistema Nacional de Informação de Recursos Hídricos (SNIRH). The same sources provided records of observed flows and stored volumes in reservoirs, which were used to validate the model.

The monthly hydrological records for the period from 1960/61 to 2015/16 were estimated using a distributed rainfall-runoff model, developed by Nemus, Bluefocus and Hidromod for the Portuguese Environmental Agency [39,42]. The same study also provides evapotranspiration and streamflow projections for the Iberian Peninsula, obtained from the precipitation and temperature scenarios provided by the EURO-CORDEX downscaling exercise [43]. An ensemble of 13 models was adopted to represent two emission scenarios (RCP 4.5 and RCP 8.5). RCP 4.5 refers to a global increase in temperature from 1.7 to 3.2 °C until the end of the century (2100), while RCP 8.5 refers to an extreme increase in temperature from 3.2 to 8 °C until 2100.

3. Results

3.1. Climate Change Impacts on Renewable Water Resources

Figure 2 compares the average monthly available water resources $\overline{RWR}_{i,s}$ for three future horizons (2011–2040, 2041–2070, 2071–2100) under two emissions pathways (RCP4.5 and RCP8.5) with the corresponding average of the historical record (1960/61–2015/16) and the estimated streamflow under natural or pristine conditions $Q^{nat}_{i,t}$. Results are presented for sub-basins, national parts (Portugal and Spain) and the entire Tagus River basin.

The results make clear the significant regulation of natural flows enforced by the existing reservoirs, with a negative deviation of renewable water resources (regulated flow) from natural flow from October to May and a positive deviation from June to September. Concentrating solely on renewable water resources, water availability is expected to decrease in all regions, under RCP 4.5 and 8.5, but especially in 2071–2100 under RCP 8.5.

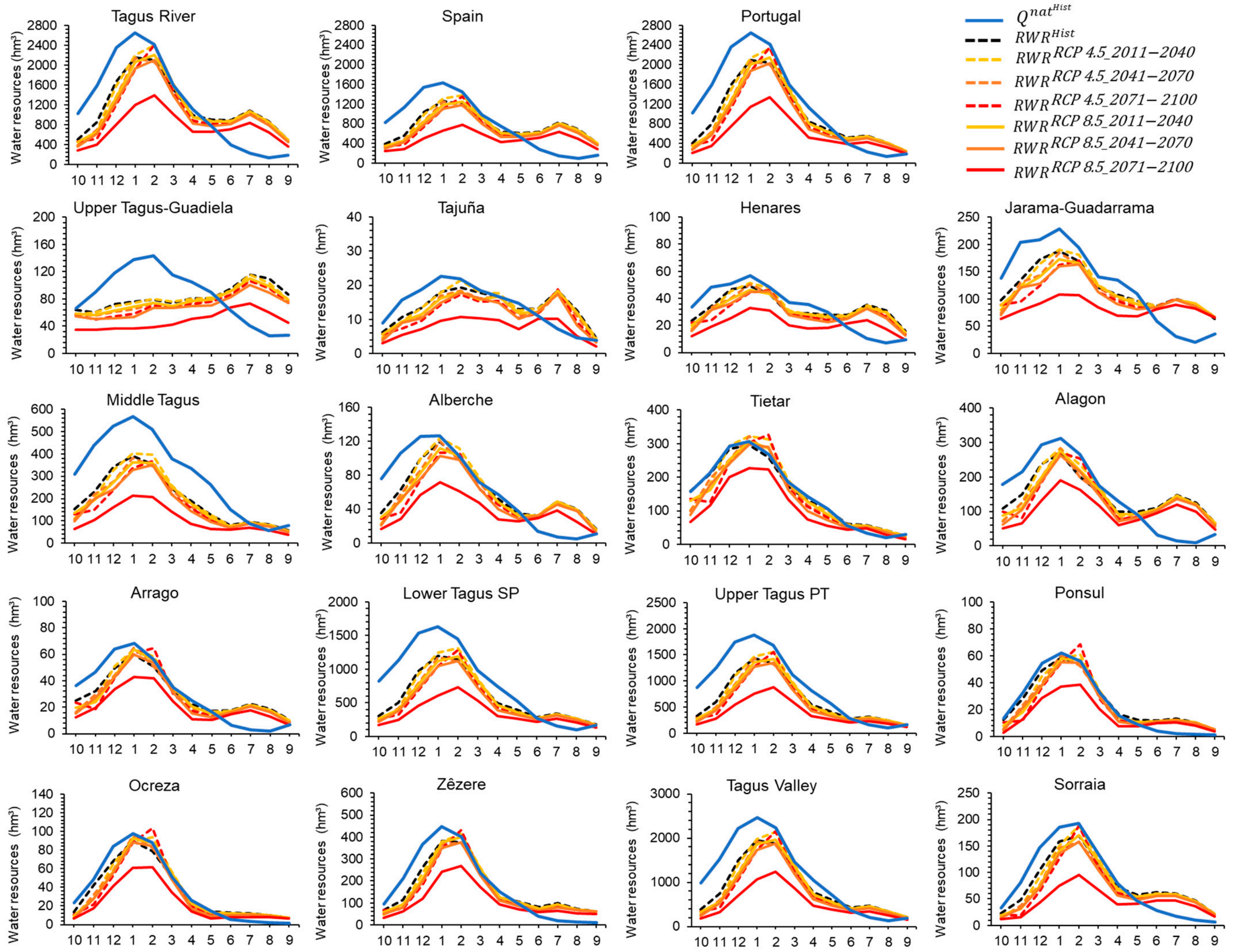
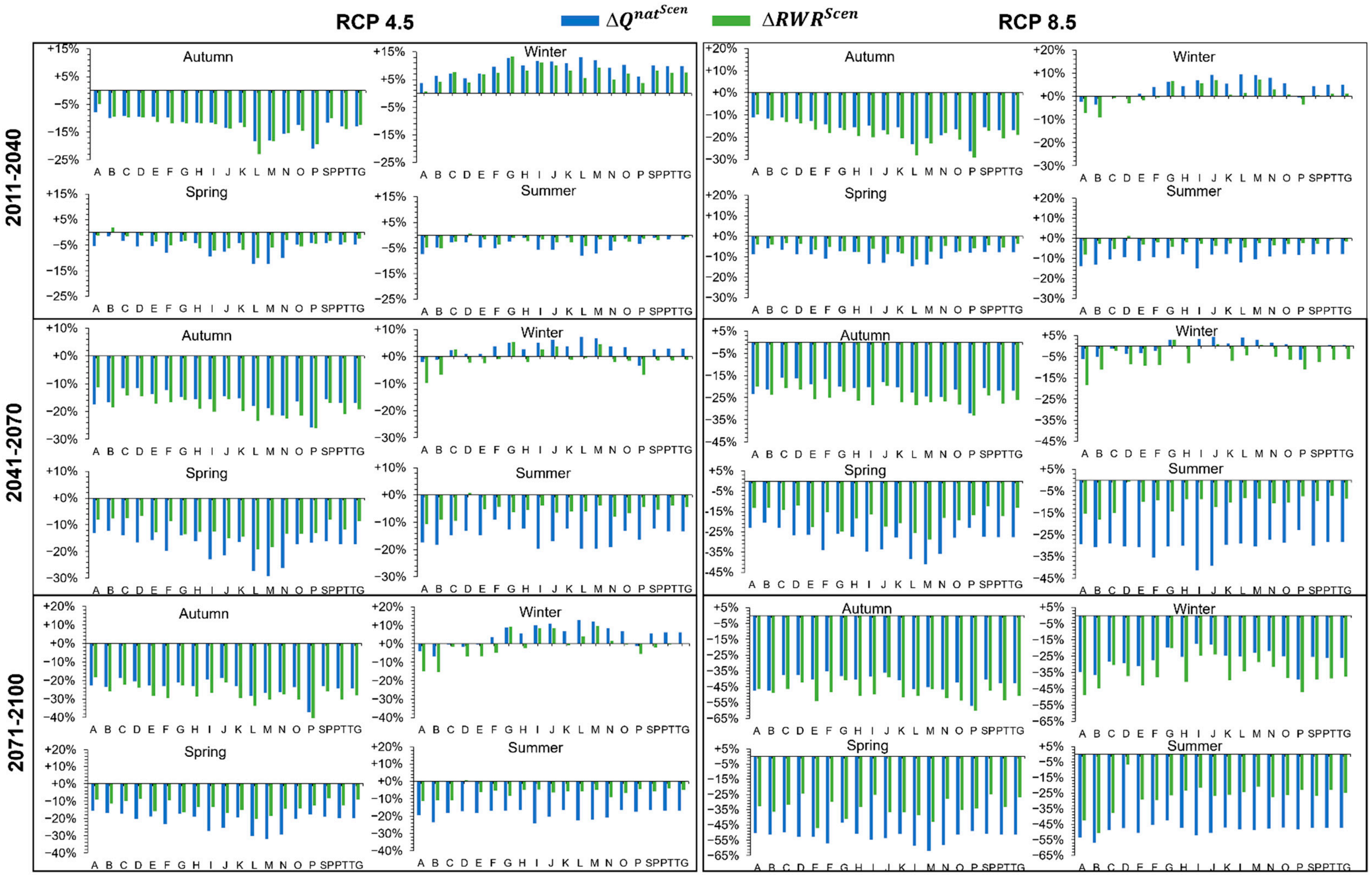


Figure 2. The average monthly streamflow under historical records (blue line) and the average monthly available water resources of sub-basins, Spain and Portugal, and the entire Tagus River basin for near, mid and far-future horizons under RCP 4.5 and 8.5.

Figure 3 illustrates the seasonal change of streamflow in natural conditions $\Delta Q_{i,s}^{nat}$ and renewable water resources $\Delta RWR_{i,s}$ for the three time horizons under RCP 4.5 and 8.5. A negative value indicates a reduction in natural flows or renewable water resources induced by climate change. Overall, climate change will lead to a reduction of water availability in all seasons in almost all scenarios, except in the winter when a small increase may be expected in some regions under RCP 4.5 or in the first half of the century under RCP 8.5. The comparison between ΔRWR_i and ΔQ_i^{nat} shows that existing hydraulic infrastructure alleviates climate change impacts on the Tagus River sub-basins under all future scenarios. The differences between ΔRWR_i and ΔQ_i^{nat} are considerably significant during the summer, when reservoir regulation is higher to support seasonal water demand. As the maintenance of flows during the dry half-year is made at the expense of flow during the wet half-year, if ΔRWR_i is lower than ΔQ_i^{nat} during the former period, the existing hydraulic infrastructure contributes to alleviating climate change impacts.



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	SP	PT	TG
Upper Tagus-Guadiela	Tajuña	Henares	Jarama-Guadarrama	Middle Tagus	Alberche	Tietar	Lower Tagus SP	Alagon	Arrago	Upper Tagus PT	Ponsul	Ocreza	Zezere	Tagus Valley	Sorraia	Spain	Portugal	Tagus River basin

Figure 3. The comparison of $\Delta RWR_{\ i,t}$ (green bars) and $\Delta Q^{nat}_{i,t}$ (blue bars) for three future horizons under RCP 4.5 and RCP 8.5.

3.2. Reservoir Performance under Different Hydrological Scenarios

The Tagus River basin is one of the most regulated rivers in Europe. Figure 4 shows the regulation coefficient, RC_i, and the average annual Effective Degree of Regulation, $EDR_{i,\text{year}}$, in each sub-basin for the historical record (1960/61–2015/2016). High RC_i and $EDR_{i,\text{year}}$ values occur in river basins where storage capacity is significant when compared to stream flow. Consequently, Figure 4 depicts higher EDR values in the Spanish part of the basin due to its largest installed storage capacity (11,150 hm^3 versus 2450 hm^3 in Portugal), and lower streamflow values. The Upper Tagus-Guadiela, in the basin headwaters and where the Entrepeñas-Buendia system is built and the Tagus-Segura aqueduct starts, holds the highest value of 0.69. It is followed by the Middle Tagus, with 0.43, and Lower Tagus with 0.35. In the Portuguese territory, the Upper Tagus sub-basin has the highest *EDR* value of 0.33, followed by the Tagus Valley, with an EDR value of 0.31. With only two run-of-river reservoirs (Fratel and Belver), the regulation of the main course of the Tagus River in Portugal arises mostly from the installed capacity in Spain. The Zêzere and Sorraia basins, with larger reservoirs, hold EDR values of 0.27 and 0.29, respectively.

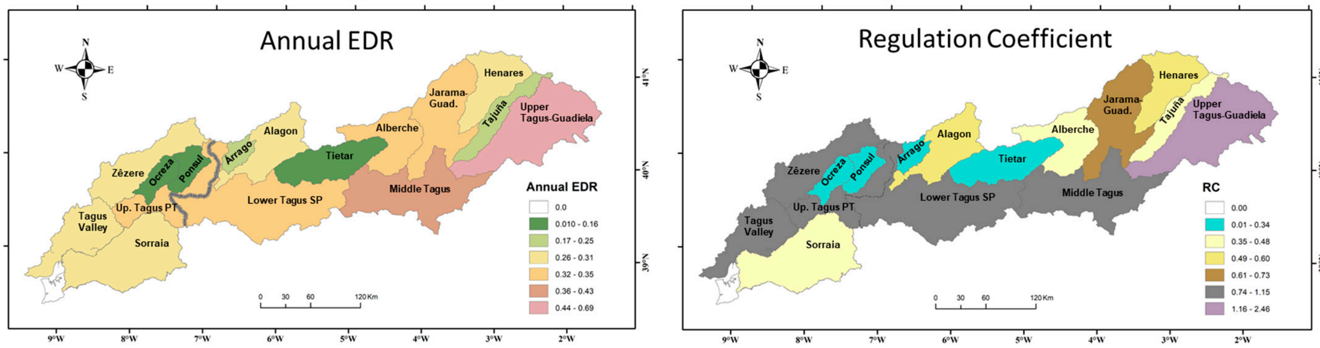


Figure 4. The regulation coefficient values and the average annual EDR values for the historical scenario of streamflows and existing infrastructure.

The comparison of EDR values and RC values in the Tagus River sub-basins highlights a difference in scale between those regulation coefficients. EDR reflects the regulation of reservoir networks dictated by water management and operating rules, and RC induces a potential regulation based on the total storage capacity, neglecting operating rules driven by the water allocation. The Upper Tagus-Guadiela sub-basin, currently with an EDR of 0.69 and a storage coefficient of 2.46, is a good example of this difference. A storage capacity of 2.46 times the average annual streamflow under natural conditions leads to a decrease of the average annual streamflow to 69% of the natural conditions.

Figure 5 presents the relationship between the regulation coefficient, RC_i, and the average annual Effective Degree of Regulation, $EDR_{i,\text{year}}$, for the different climate scenarios. The results show a non-linear positive relationship between R and EDR, with overlapping regression curves for the different scenarios. The concavity of the curve indicates that as storage capacity and RC increase, EDR increases with diminishing increments, which means that the impacts on the streamflow regime do not grow linearly with the increase of storage capacity. The points in the figure, representing each sub-basin, are clustered in groups and the increase of both RC and EDR, as climate change deepens, is quite visible.

Figure 6 illustrates the changes in EDR for three time horizons and two emission scenarios. The results show that EDR values increase as climate change impacts on the hydrological regimen strengthen. This means that the currently existing infrastructure will induce an increasing deviation of regulated flows from natural expected flows for each climate scenario. The deviation of regulated flows from the historical natural flows is much larger. In the entire Tagus River basin, EDR values vary from 7.2% to 47.4 % for the mid and far horizons under RCP 4.5 and RCP 8.5, reaching the higher value under the high-end scenario.

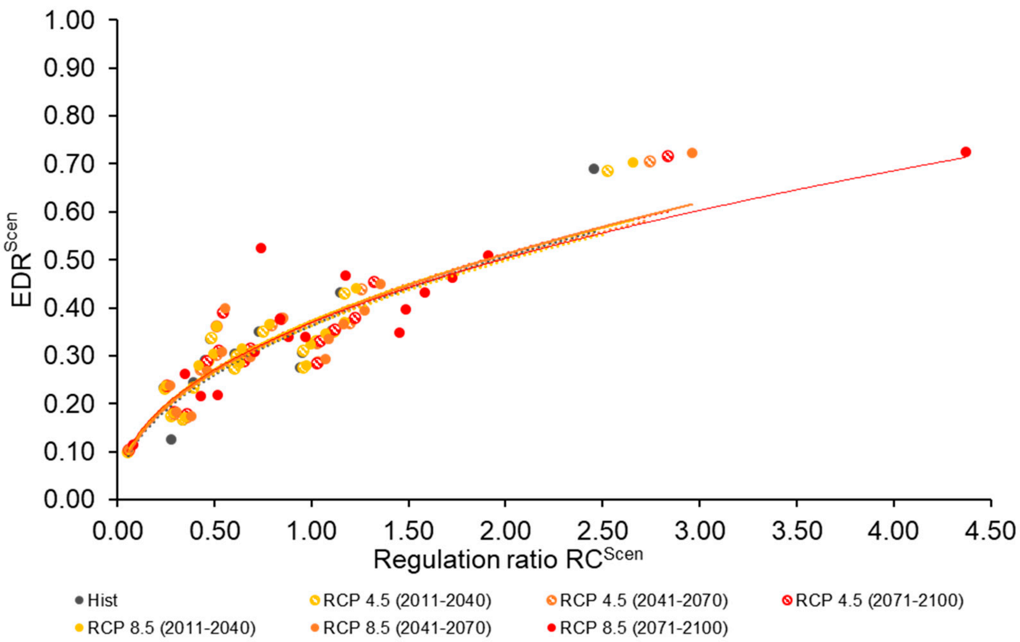


Figure 5. Relationship between the regulation coefficient RC and annual EDR for the various climate scenarios.

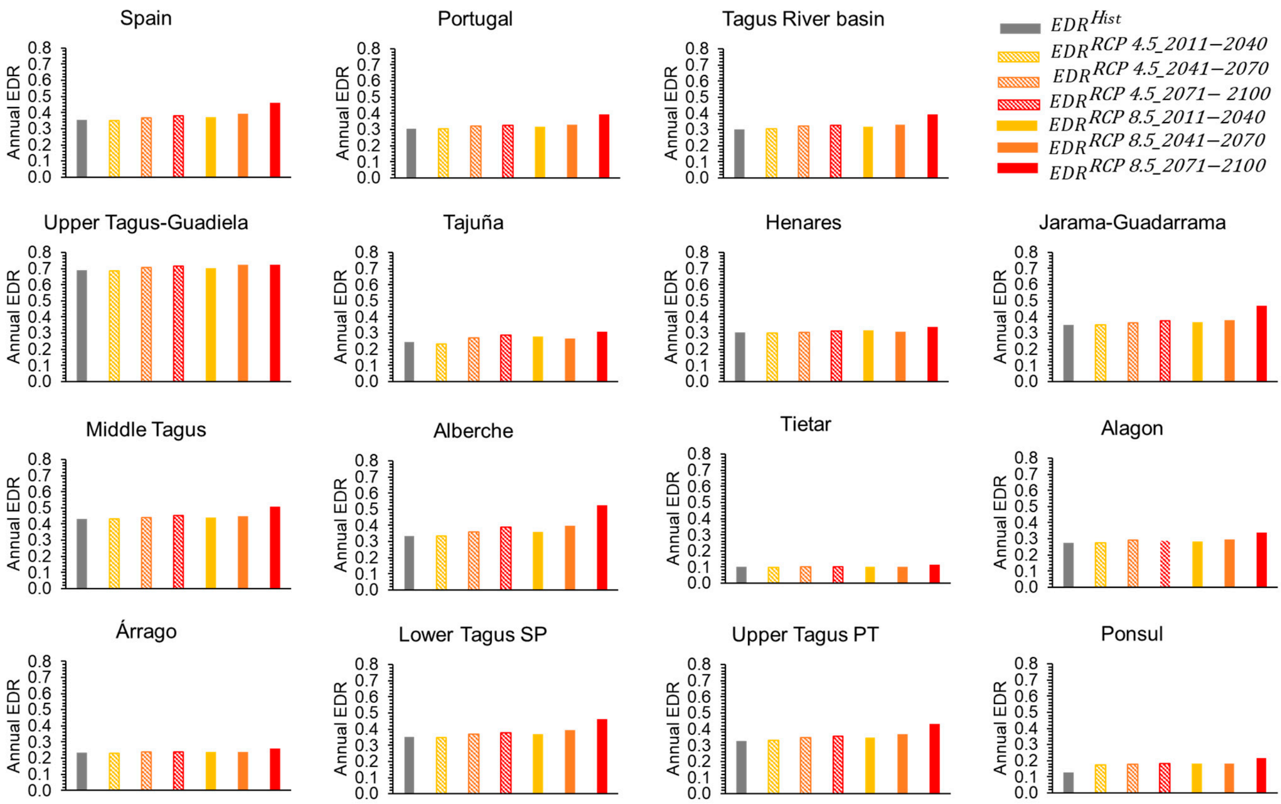


Figure 6. The comparison of annual EDR for historical records and annual EDR for near, mid and far future horizons under RCP 4.5 and RCP 8.5.

The increase of EDR values results from water management and allocation to consumptive and non-consumptive uses, environmental flow requirements and the consequent change of stream flows, namely during the high-flow period when reservoirs are filling to supply seasonal water demand in the low-flow period. This situation produces higher values of EDR, especially in regions with a strong dependence on reservoir operation to satisfy water needs. The Alberche sub-basin, in Spain, and the Ponsul sub-basin, in Portugal, are good examples, with respective increases in EDR for the end of the century of 16% and 46% under RCP 4.5, and 56% and 72% under RCP 8.5.

3.3. Climate Change Impacts on Water Allocation and Use

Tables 1 and 2 present urban and agricultural reliabilities for three future horizons (2011–2040, 2041–2070, 2071–2100) and under two emissions pathways (RCP4.5 and RCP8.5). The Tagus River basin will have a lower ability to satisfy water uses under future scenarios of climate change, with reliability values decreasing with time and with the intensification of climate change impacts. As urban uses have a higher allocation priority, urban reliability will decrease less than agricultural reliability. The expected decrease in urban reliability, which directly affects the population's well-being, will probably be avoided by corrective action.

Table 1. Reliability of urban supply under future scenarios.

Reliability for Urban Uses	Hist	RCP 4.5			RCP 8.5		
		2011–2040	2041–2070	2071–2100	2011–2040	2041–2070	2071–2100
Up Tagus-Guadiela	0.93	0.89	0.89	0.87	0.89	0.86	0.64
Tajuña	0.64	0.52	0.50	0.39	0.57	0.43	0.13
Henares	0.90	0.79	0.76	0.79	0.82	0.73	0.38
Jarama-Guadarrama	0.98	0.96	0.94	0.94	0.96	0.90	0.67
Alberche	0.72	0.65	0.52	0.52	0.62	0.43	0.20
Middle Tagus	0.92	0.84	0.84	0.82	0.85	0.76	0.49
Tietar	0.91	0.82	0.82	0.84	0.84	0.79	0.59
Alagon	0.99	0.99	0.99	0.98	0.99	0.93	0.87
Arrago	0.77	0.70	0.66	0.66	0.70	0.57	0.36
Lower Tagus SP	0.98	0.98	0.96	0.97	0.98	0.96	0.93
Up Tagus PT	0.99	0.98	0.96	0.96	0.98	0.94	0.80
Ponsul	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Ocreza	0.86	0.79	0.73	0.79	0.80	0.63	0.50
Zêzere	0.98	0.91	0.86	0.93	0.97	0.81	0.77
Tagus Valley	0.98	0.98	0.98	0.98	0.98	0.97	0.64
Sorraia	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Spain	**0.95**	**0.92**	**0.90**	**0.90**	**0.92**	**0.86**	**0.64**
Portugal	**0.98**	**0.98**	**0.98**	**0.98**	**0.98**	**0.96**	**0.66**
Tagus River basin	**0.96**	**0.94**	**0.93**	**0.93**	**0.94**	**0.90**	**0.64**

Overall, the Spanish territory is expected to suffer a larger decrease in agricultural reliability than the Portuguese territory, reaching reliability values of 0.67 and 0.38 for the mid and far future under RCP 8.5. This can be explained by a higher dependence on river regulation and dam operation in Spain, where most water demands are satisfied by water withdrawals from the surface system. In Portugal, water demand satisfaction is partly dependent on the exploitation of aquifers, mostly in the Tagus Valley and Sorraia sub-basins where the Tagus-Sado aquifer lies.

Sub-basins on the right bank of the Tagus River in Spain, where major agricultural exploitation is located, are expected to experience the worst decrease. The maintenance of environmental flow requirements at the outlet of each sub-basin also contributes to reductions in the ability to satisfy consumptive water demands with lower priority allocation, namely in the agricultural sector.

Table 2. Reliability of agricultural supply under future scenarios.

Reliability for Agriculture Uses	Hist	RCP 4.5			RCP 8.5		
		2011–2040	2041–2070	2071–2100	2011–2040	2041–2070	2071–2100
Up Tagus-Guadiela	0.87	0.80	0.78	0.75	0.78	0.72	0.45
Tajuña	0.52	0.50	0.39	0.38	0.48	0.32	0.13
Henares	0.78	0.71	0.66	0.57	0.71	0.51	0.22
Jarama-Guadarrama	0.84	0.75	0.70	0.66	0.75	0.55	0.31
Alberche	0.77	0.67	0.59	0.53	0.65	0.48	0.26
Middle Tagus	0.75	0.88	0.67	0.84	0.85	0.62	0.48
Tietar	0.39	0.38	0.27	0.29	0.32	0.14	0.04
Alagon	0.80	0.80	0.75	0.71	0.80	0.63	0.43
Arrago	0.59	0.57	0.52	0.54	0.52	0.45	0.29
Lower Tagus SP	1.00	1.00	1.00	1.00	1.00	0.99	0.97
Up Tagus PT	1.00	1.00	0.99	1.00	1.00	0.99	0.96
Ponsul	0.65	0.61	0.58	0.58	0.59	0.56	0.41
Ocreza	0.98	0.97	0.97	0.98	0.97	0.96	0.94
Zêzere	0.97	0.96	0.93	0.93	0.96	0.91	0.87
Tagus Valley	1.00	1.00	0.99	0.99	1.00	0.99	0.93
Sorraia	0.53	0.53	0.50	0.50	0.51	0.49	0.36
Spain	**0.76**	**0.75**	**0.67**	**0.67**	**0.73**	**0.57**	**0.38**
Portugal	**0.81**	**0.81**	**0.79**	**0.80**	**0.80**	**0.79**	**0.70**
Tagus River basin	**0.78**	**0.77**	**0.72**	**0.72**	**0.76**	**0.65**	**0.50**

It is worth mentioning that the environmental flows were defined as a percentage of the annual historical flow under natural conditions, which means that under the projected future scenarios, environmental flows will represent a higher percentage of average monthly flows, especially during the summer months. The criteria to define environmental flows for future streamflow scenarios is a critical issue and an ongoing debate.

Table 3 presents the expected evolution of average annual WEI+ values for each sub-basin, national parts and the entire Tagus River basin. The increasing trend in WEI+ values shows a worsening of water scarcity conditions in all simulated future scenarios. Under RCP 4.5, the overall WEI+ value for the Tagus River basin will increase, respectively, from 46% to 52% until mid-century, maintaining that value during the second half of the century. Under RCP 8.5, WEI+ will increase to 54% until the mid-century and will reach the highest value of 63% at the end of the century.

Table 3. Average annual WEI+ values under future scenarios.

Average Annual WEI+	Hist	RCP 4.5			RCP 8.5		
		2011–2040	2041–2070	2071–2100	2011–2040	2041–2070	2071–2100
Up Tagus-Guadiela	0.79	0.80	0.80	0.81	0.80	0.80	0.84
Tajuña	0.39	0.39	0.40	0.40	0.39	0.40	0.42
Henares	0.57	0.57	0.59	0.59	0.58	0.60	0.63
Jarama-Guadarrama	0.56	0.57	0.59	0.60	0.58	0.61	0.72
Alberche	0.55	0.58	0.60	0.61	0.58	0.63	0.75
Middle Tagus	0.41	0.42	0.44	0.44	0.43	0.46	0.56

Table 3. *Cont.*

Average Annual WEI+	Hist	RCP 4.5			RCP 8.5		
		2011–2040	2041–2070	2071–2100	2011–2040	2041–2070	2071–2100
Tietar	0.43	0.44	0.46	0.47	0.46	0.50	0.55
Alagon	0.52	0.55	0.56	0.56	0.55	0.58	0.62
Arrago	0.56	0.58	0.60	0.59	0.58	0.61	0.66
Lower Tagus SP	0.07	0.07	0.09	0.08	0.08	0.10	0.16
Up Tagus PT	0.04	0.04	0.05	0.05	0.04	0.07	0.15
Ponsul	0.69	0.73	0.73	0.73	0.72	0.75	0.79
Ocreza	0.45	0.48	0.50	0.50	0.48	0.53	0.60
Zêzere	0.57	0.59	0.61	0.61	0.59	0.62	0.69
Tagus Valley	0.30	0.34	0.37	0.37	0.34	0.40	0.55
Sorraia	0.73	0.76	0.77	0.77	0.76	0.78	0.84
Spain	**0.40**	**0.42**	**0.44**	**0.43**	**0.42**	**0.45**	**0.51**
Portugal	**0.31**	**0.35**	**0.37**	**0.37**	**0.35**	**0.40**	**0.51**
Tagus River basin	**0.46**	**0.50**	**0.52**	**0.52**	**0.50**	**0.54**	**0.63**

The Portuguese territory is expected to endure a higher increase of WEI+, although Spain, starting from a larger value, will go on suffering a higher degree of scarcity. The most significant change in WEI+ values will be felt in the Ocreza and Tagus Valley sub-basins, Portugal. In Spain, higher changes in WEI+ values are also observed in the Alberche sub-basin. There seems to be a slight trend towards higher increases of WEI+ in areas where WEI+ is already large.

3.4. Adaptation Measures for Water Resources Management

Climate change impacts on water supply and reservoirs performance will require a re-evaluation of water resource policies and reservoir operating rules, as existing water uses may not be maintained in the future with the current infrastructures and management practices. Climate adaptation efforts must pursue new water management strategies to attenuate potential climate change impacts on water resource systems, enhance the reliability of water supply for different uses and contribute to the restoration of the river basin's environmental and social well-being.

Figure 7 evaluates the results of an adaptation alternative which reduces water allocation to agricultural areas. The graphs show how the reliability and average annual WEI+ values change with increasing reductions for the mid-term horizon under RCP 4.5 and RCP 8.5. The x-axis value of 100% corresponds to the current water demand values and the value of 60% a reduction of 40% from the current water demand values. As expected, the results show that reductions in water use increase water supply reliability and decrease the annual WEI+ values along the Tagus River basin. The increase of urban and agricultural reliability with water demand reduction is more evident in Spain than in Portugal, as the starting expected reliability with no-adaptation effort is significantly lower.

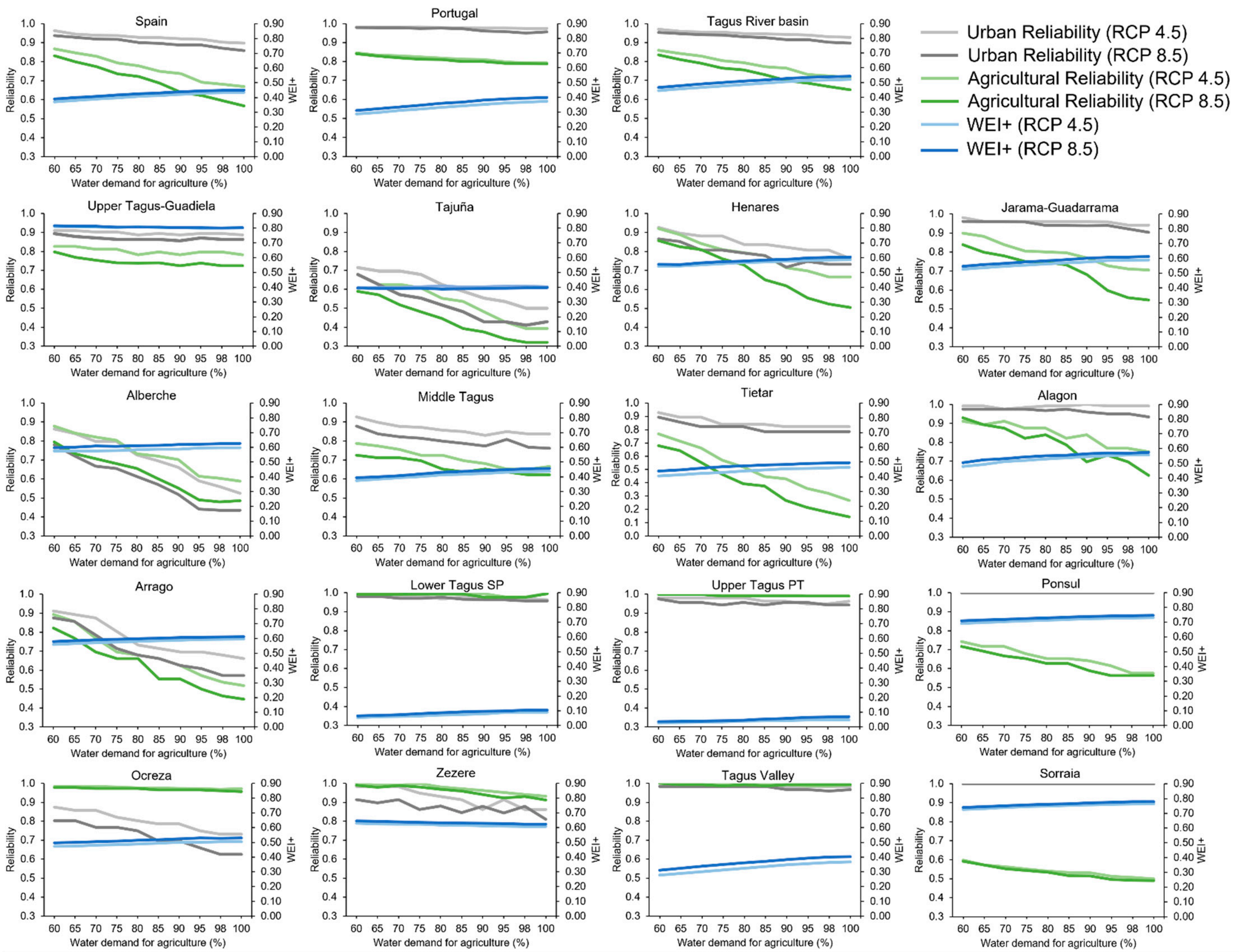


Figure 7. Alternative 1 of reductions in water demand in sub-basins, Spain, Portugal, as well as in the entire Tagus River basin, for mid-term horizon (2040 – 2070) under RCP 4.5 and RCP 8.5.

Table 4 presents the results of a more detailed analysis of what is needed to maintain a reliability of 90% for urban and industrial supply, a reliability of 80% for agricultural supply and the current levels of water scarcity (average annual WEI+), in mid-century under the two emission pathways (RCP 4.5 and RCP 8.5). The depicted values are water demand reduction requirements, as a percentage of current demands for irrigation. The requirements for maintaining water use reliability may be different from the ones needed to maintain the current WEI+ values since the two indices quantify distinct conditions. Water use reliability evaluates the system capacity to satisfy water demand, while WEI+ offers an overview of the water scarcity situation, reproducing the balance between renewable water resources and water use, without necessarily valuing the satisfaction of water allocation targets.

Table 4. Water demand reduction needs (%) to achieve urban and industrial reliability of 90%, agricultural reliability of 80% and the current level of WEI+.

Water Demand Reduction (%)	RCP 4.5 (2040–2070)			RCP 8.5 (2040–2070)		
	Reliability for Urban Uses	Reliability for Agriculture Uses	Average Annual WEI+	Reliability for Urban Uses	Reliability for Agriculture Uses	Average Annual WEI+
Upper Tagus-Guadiela	25	25	>40	>40	40	>40
Tajuña	>40	>40	> 40	>40	>40	>40
Henares	35	35	20	> 40	30	30
Jarama-Guadarrama	0	20	20	0	35	35
Alberche	>40	25	>40	>40	>40	>40
Middle Tagus	35	>40	20	>40	>40	30
Tietar	40	>40	25	>40	>40	>40
Alagon	0	10	25	0	20	35
Arrago	40	35	40	>40	40	>40
Lower Tagus Spain	0	0	25	0	0	40
Upper Tagus Portugal	0	0	25	30	0	>40
Ponsul	0	>40	40	0	>40	>40
Ocreza	>40	0	>40	>40	0	>40
Zêzere	15	0	>40	30	0	>40
Tagus Valley	0	0	30	0	0	>40
Sorraia	0	>40	35	0	>40	>40
Spain	**0**	**30**	**30**	**15**	**35**	**40**
Portugal	**0**	**5**	**30**	**0**	**10**	**40**
Tagus River basin	**0**	**25**	**35**	**0**	**35**	**40**

In most cases, the reduction requirements to maintain the reliability levels of urban and industrial supply are smaller than the ones needed to maintain the reliability levels of agricultural supply. Under RCP 4.5, the agricultural demand will have to be reduced to 70% of its current value to maintain the threshold levels of urban/industrial and agricultural reliability in Spain. The results are different for the two RCPs, with RCP 8.5 requiring larger reductions than RCP 4.5. In Portugal, the expected impacts of climate change on reliability are lower than in Spain. However, a reduction to 95% and 90% of the current value is needed to maintain the threshold levels of agricultural reliability, respectively, for RCP 4.5 and RCP 8.5. In most of the Spanish sub-basins, the increase of agricultural reliability to threshold values requires a reduction of water use to more than 90% under RCP 4.5 and more than 80% under RCP 8.5. In the Portuguese sub-basins, a reduction to more than 60%

in water demand is needed to increase the agricultural reliability in Ponsul and Sorraia under RCP 4.5 and RCP 8.5.

In both Spain and Portugal, the maintenance of current WEI+ values requires a reduction to 70% and 60% of agricultural water demand values under future RCP 4.5 and RCP 8.5, respectively. Within sub-basins, the preservation of current WEI+ values requires similar water demand reductions under both RCP 4.5 and RCP 8.5, but higher reductions are needed in the Portuguese sub-basins than in the Spanish sub-basins.

Figure 8 evaluates the results of the second adaptation alternative, which reduces water transfers to southern Spain. The graph shows how water supply reliability and WEI+ change in the Upper Tagus-Guadiela, Middle Tagus, Portugal and Spain, as well as the entire river basin. Results are only presented for those regions as the impacts of the transfer are not felt in all sub-basins.

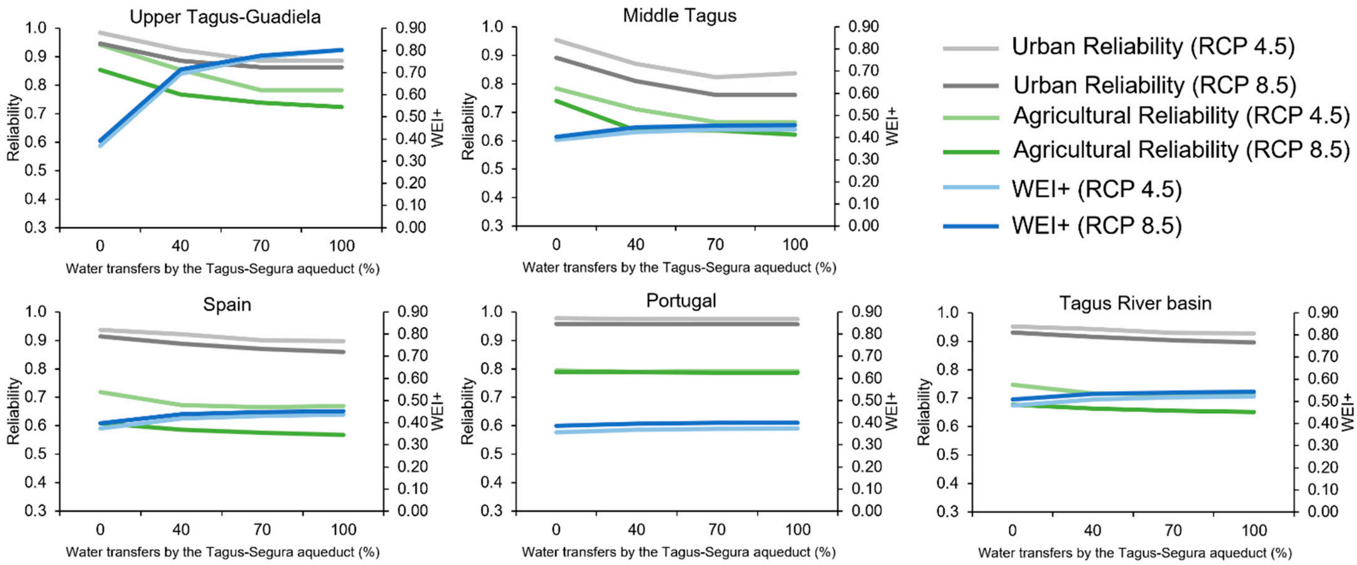


Figure 8. Alternative 2 for reductions in water demand at a local and transboundary level for the mid-term horizon (2040–2070) under RCP 4.5 and RCP 8.5.

The results show small changes in reliability values and water scarcity levels in all regions, when a reduction to 70% and 40% of the current volume assigned to the Tagus-Segura aqueduct is simulated. By removing the water transfer completely, significant improvements are observed in the Upper Tagus-Guadiela sub-basin and smaller changes occur in other regions.

Urban reliability values are the least affected as these uses have a higher priority, but still, small improvements are observed in the Upper Tagus-Guadiela and Middle Tagus sub-basins, as well as in the entire river basin, when the Tagus-Segura aqueduct is completely removed. Under RCP 4.5, the reliability level reaches the present value in all regions, and under RCP 8.5, it reaches the current value in the Upper Tagus-Guadiela sub-basin.

In the Upper Tagus Guadiela, and under RCP 4.5, agricultural reliability values vary from 0.78, when no adaptation is implemented, to 0.85 when a reduction to 40% of the water transfer is implemented, and finally to 0.94, when the transfer is completely removed. Scenario RCP 8.5 requires a larger transfer reduction to maintain current agricultural reliability levels.

The WEI+ is the most affected indicator by the reductions in water transfers to southern Spain, especially in the Upper Tagus-Guadiela. Under RCP 4.5, the WEI+ values vary from 0.80, with no adaptation, to 0.37, when the water transfer is eliminated.

The removal of the Tagus-Segura aqueduct does not seem to produce significant alterations in the future scenario conditions in Portugal, as the potential benefits are strongly conditioned by the operational policies of downstream reservoirs, particularly the Alcantara reservoir. The operating rules of this large reservoir need to be modified to use the additional reservoir inflow in fostering downstream ecological conditions. A more detailed simulation of the Alcantara reservoir operation is needed to quantify the potential ecological benefits of reducing the Tagus-Segura transfers.

4. Discussion

The results show that climate change will significantly change the stream flow regime and reduce water availability in the Tagus River basin. Under RCP 4.5, the average annual natural stream flow and the average natural stream flow in the dry half-year are expected to decrease by 9.3% and 19.3%, respectively, until the end of the century. RCP 8.5 offers a much more worrying scenario, with decreases of 36.6% and 50.5%, until the end of the century. The expected annual changes in streamflow are in line with those provided by Kilsby et al. [27], who estimated reductions at the end of the century varying from 20% to 49%, and by Guerreiro et al. [29], who projected changes in annual streamflow varying from +32% to −60% and reaching up to −65% in spring and −49% in summer. Until the end of the century, the WEI+ value for the Tagus River basin is expected to increase from 0.46 to 0.52 or 0.62, respectively, for RCP 4.5 or RCP 8.5.

The existing reservoir infrastructure will alleviate some of these impacts, especially in the dry half-year. Until the end of the century, the average annual RWR is expected to decrease by 8.8%, under RCP 4.5, and 36.1%, under RCP 8.5. The RWR of the dry half-year is expected to decrease 7.1% under RCP 4.5 and 26% under RCP 8.5, in the same period.

The role of regulation in alleviating climate change impacts may be measured by the difference in water availability between regulated and natural flows (ΔRWR and ΔQ^{nat}). This difference is larger in sub-basins with higher EDR and increases as climate change impacts intensify. It is also dependent on water allocation for consumptive purposes (urban, agriculture and industrial sectors), as most reservoir operating rules are dictated by annual or seasonal water abstractions. The Jarama-Guadarrama sub-basin, with average annual streamflow of 1500 hm^3 and a reservoir storage capacity of 800 hm^3, is a good example. The differences between ΔRWR and ΔQ^{nat} are higher than 50% during the summer for the mid and far century, under both RCP 4.5 and RCP 8.5. This result suggests that reservoir regulation and operating rules have a role in abating climate change impacts, but detailed studies must be performed at specific locations to evaluate the potential expected benefits of each project and weigh them against the negative environmental effects. Other supply-side adaptation measures, such as seawater desalination plants and wastewater reuse, must also be evaluated, as they may constitute better choices.

The benefits of streamflow regulation in Tagus River sub-basins vary with the hydrological regimen, the current degree of water use and the role of groundwater resources in meeting demand. The results obtained in this research showed the utility of water management and allocation models to estimate climate change impacts on water availability, water use and water scarcity conditions and to evaluate the benefits offered by different adaptation strategies. However, a more detailed and accurate model is needed to accurately assess how flow regulation benefits depend on the sub-basin hydrology and water use pattern. As groundwater may have an important role in satisfying water needs, the model's ability to reproduce the interactions between surface and groundwater systems is particularly important in this analysis, namely for evaluating climate change impacts on groundwater availability.

The contribution of streamflow regulation to water demand satisfaction is also dependent on environmental flow requirements. A critical issue is their possible adjustment to streamflow reduction arising from climate change. Quite often, environmental flow requirements are determined from a statistical analysis of the natural stream flow record, as opposed to a more detailed physical and biological evaluation of ecosystem water needs. If climate change induces a stream flow reduction, should environmental flow requirements be lowered? In this research, it was decided to maintain the current environmental flow requirements, but this option significantly constrains water allocation under the more extreme climate change scenarios.

The potential of water demand control actions, as an alternative adaptation approach, was also studied. As agriculture is the main water user, the focus was on irrigation demand reduction, which can be achieved by an improvement of irrigation methods, a change to crops with lower water needs or by a decrease in irrigated areas and the eradication of less valuable crops.

On a basin scale, a reduction of water consumption for irrigation by 25% to 40% will significantly improve the Tagus River system performance and maintain the current scarcity situation in the future, under the expected scenarios of climate change. On a local scale, a strong reduction of water consumption for irrigation will be needed to maintain threshold levels of water supply reliability and scarcity conditions, namely in the Upper Tagus-Guadiela, Tajuña and Middle Tagus sub-basins, in Spain, and the Ponsul and Sorraia sub-basins, in Portugal.

The results obtained for the Upper Tagus-Guadiela sub-basin show that significant reductions in the volume assigned to the Tagus-Segura aqueduct are needed to maintain current water supply reliability levels and water scarcity conditions in the region. If the assigned volume is reduced by 30%, it is possible to maintain the current levels of water scarcity in the region. Additionally, if the assigned volume is reduced by 60%, it is possible to achieve current water supply reliability levels under RCP 4.5, but additional reductions are needed to achieve the same levels under RCP 8.5.

These results are generally in line with those obtained in previous studies. Pellicer-Martínez et al. [28] suggest average decreases around 70–79% in water transfer to alleviate losses in available water resources within the Tagus River headwaters under RCP 4.5 and RCP 8.5. Lobanova et al. [30] suggested a reduction of 20% in water transfers when environmental flows are defined as a priority over the Tagus-Segura aqueduct for the period 2041–2070 under RCP 4.5 and a reduction of 40% for the same period under RCP 8.5.

Additional measures, such as the re-evaluation of reservoir operating rules and water allocation priorities and the substitution of part of the abstracted volume from rivers and aquifers with desalinated water and treated wastewater, may decrease the reduction effort of water consumption by the irrigation sector.

Climate change impacts and the required adaptation measures in the Tagus River Basin are substantial and are not achievable without changes in water management policies and major investments in irrigation infrastructures and methods. These changes also carry large socioeconomic impacts that will be felt by various sectors of society, which must be evaluated and addressed by national and regional policies.

5. Conclusions

In southern Europe, especially in the Mediterranean region, streamflow and aquifer recharge are expected to decrease under climate change, aggravating the already severe water scarcity conditions. This prospect affects the social, economic, and environmental development perspectives of southern European countries and challenges current water management policies and practices. Decisive action is needed to evaluate those impacts in detail and to design a comprehensive and integrated plan of action that reduces society's vulnerability to climate change and provides the needed flexibility to deal with uncertainty. This plan must include a variety of adaptation measures aiming to increase water use efficiency, reduce water demands and improve water availability. The costs and benefits of such measures must be evaluated *a priori*, before the selected measures are implemented.

In transboundary river basins, such as the Tagus River basin, the non-existence of a common water governance framework and the lack of studies covering the whole river basin complicate these adaptation efforts. The joint analysis of possible adaptation measures to address water scarcity in both countries enlarges the set of options suitable to address the climate threat, increases the efficacy and efficiency of the programme of measures and avoids transferring vulnerabilities from one part of the basin to the other.

The basin is subject to highly variable meteorological conditions and to significant water demands that are satisfied by a complex system of large reservoirs and aquifers.

The results show that climate change will significantly change the streamflow regime and reduce water availability in the Tagus River basin. Until the end of the century, the WEI+ value for the Tagus River basin is expected to increase from 0.46 to 0.52 or 0.62, respectively, for RCP 4.5 and RCP 8.5. The existing reservoir infrastructure will alleviate some of these impacts, especially in the dry half-year. The benefits of streamflow regulation vary with the hydrological regimen, the current degree of water use and the role of groundwater resources in meeting demand.

The contribution of streamflow regulation to water demand satisfaction is also dependent on the environmental flow requirements that will be adopted in the future in response to reductions in natural streamflow arising from climate change.

The assessment of potential demand-side adaptation measures for controlling water abstractions that avoid future increases or even achieve some reductions showed that a reduction of water consumption for irrigation by 25% to 40% will significantly improve the Tagus River transboundary system performance and maintain the current scarcity situation in the future, under the expected scenarios of climate change.

Climate change impacts and the required adaptation measures in the Tagus River Basin are substantial and are not achievable without changes in water management policies and major investments to simultaneously control water demand and diversify water supply. These changes also carry large socioeconomic impacts that will be felt by various sectors of society, which must be evaluated and addressed by national and regional policies.

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