



High-resolution estimates of water availability for the Iberian Peninsula under climate scenarios

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Abstract

Water availability is of paramount importance for sustainable development and environmental planning, specifically in regions such as the Iberian Peninsula, renowned for diverse landscapes and varying climatic conditions. Due to climate change, understanding the potential impacts on water resources becomes essential for effective water management strategies. This research effort aims to assess future potential water availability for the Iberian Peninsula in different climate scenarios, employing cutting-edge water resource modelling techniques integrated within a geographic information system (GIS) framework. In this study, potential water availability is defined as the annual demand for water that can be satisfied at a specific point in the fluvial network with certain reliability. An ensemble of state-of-the-art climate models is utilised to project runoff for the Iberian Peninsula during the mid- and late-twenty-first century periods. These climate projections were subsequently processed using the GIS-based water resource management model, WAAPA, to derive potential water availability under a range of realistic hypotheses. The results indicate that anticipated shifts in precipitation patterns will lead to alterations in hydrological regimes across the region, significantly impacting future water availability. By using GIS-based methodologies, we can facilitate the identification of vulnerable areas susceptible to changes in water availability, offering spatially explicit information along the main rivers of the Iberian Peninsula for decision-makers and stakeholders. High-resolution spatial outputs from this research and detailed water availability estimates serve as valuable input for integrated water resource management and climate change adaptation planning. By combining advanced GIS-based hydrological modelling with climate scenarios, this research presents a robust framework for assessing water resources amidst a changing climate, applicable to other regions struggling with analogous challenges. Ultimately, our study provides vital insights for policymakers and stakeholders, empowering them to make informed decisions and devise adaptive measures to ensure sustainable use of water resources despite uncertain future climatic conditions.

Keywords Climate change · Water availability · Mediterranean region · Hydrology

Introduction

The Iberian Peninsula, an area with a vast diversity of ecosystems and a home of immense historical, social, and cultural significance throughout history, has faced enormous challenges in recent decades in terms of the management of its water resources. This region, which encompasses Spain and Portugal, with important transboundary river basins, plays a crucial role in maintaining both wildlife and human activities (Sordo-Ward et al. 2019b; Zapata-Sierra et al. 2022). However, the stability of the peninsula's water resources has been hindered by climate change, which has caused significant changes in precipitation patterns and temperatures in the last decades (Tejeda 2012; Garrote et al. 2016; Zhang et al. 2019). This will potentially exacerbate

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the vulnerability of the region, affecting not only the main hydrological characteristics of the region such as runoff, but also affecting the adequate supply of water for consumption, industry, agriculture, forestry, or even tourism, which in turn will affect the economy and well-being of the inhabitants of this region (López-Moreno et al. 2007; Ruiz-Ramos and Mínguez 2010; Lutz et al. 2016; Villar-Navascués and Pérez-Morales 2018; Teuling et al. 2019; Torres-Bagur et al. 2019). Although climate change may have some isolated positive effects, the overall picture highlights the urgent need to adopt and integrate a comprehensive approach to water resources management. The Iberian Peninsula is at a crossroad, where the decisions made today will determine the resilience and sustainability of the region for decades to come.

The Iberian Peninsula is characterised by a multitude of hydrological and climatological regimes, which have been the subject of numerous studies that sought to understand the complexity and dynamics of its water resources (Kilsby et al. 2007; Ruiz-Ramos and Mínguez 2010; Vicente-Serrano et al. 2011; Tejeda 2012; Navarro-Ortega et al. 2012; Versini et al. 2016; José Vidal-Macua et al. 2017; Villar-Navascués and Pérez-Morales 2018; Oliveira et al. 2022; Pardo-Loaiza et al. 2022). Throughout history, significant changes in water availability have been observed, influenced by natural and anthropogenic factors. Available research points to a worrying trend towards a decrease in rainfall and an increase in temperatures that directly impacts runoff and water availability in all of the Mediterranean region (Senatore et al. 2011; Lelieveld et al. 2012; Piras et al. 2014; Lutz et al. 2016; Bucak et al. 2017; Abrantes et al. 2017; Lobanova et al. 2018; Gorguner and Kavvas 2020). Critical basins of the southern Iberian Peninsula may be impacted by these effects, and certain semi-arid and arid areas of the western Mediterranean may be at increased risk of water scarcity (Miranda et al. 2011; Santos et al. 2019; Zapata-Sierra et al. 2022). In addition, in recent decades, the management of water resources in the Iberian Peninsula has faced several challenges related to climate variability, which has exacerbated conflicts over the use of water and has jeopardised the sustainability of various socioeconomic activities in the region (Kilsby et al. 2007; Tejeda 2012; Pascual et al. 2015). These concerns emphasise the need for adaptive management policies and models, capable of addressing the uncertainty and complexity of the current water landscape (Iglesias et al. 2011, 2018; Lobera et al. 2015; Marín-Comitre et al. 2020; Redondo-Orts and López-Ortiz 2020; van der Laan et al. 2023).

In addition to the effects that can be observed today, the potential future effects of climate change suggest potential unprecedented threats to the Iberian Peninsula, particularly in relation to the management of water resources (Nunes et al. 2017; van der Laan et al. 2023). Various studies have

suggested the potential future alteration of weather patterns for the region and have also suggested potential changes in water regimes in some areas (Mariotti et al. 2008; Vicente-Serrano et al. 2011; Mourato et al. 2015; Peñas et al. 2016). These future estimates, based on various climate change scenarios, suggest not only increased water stress but also significant changes in hydrological processes, such as runoff, aquifer recharge, and snow accumulation (Zhang et al. 2019; Zapata-Sierra et al. 2022). These alterations, added to the anticipated growing demand for water for agricultural use and human consumption, threaten to exacerbate the already tense water situation on the peninsula (Kilsby et al. 2007; Redondo-Orts and López-Ortiz 2020). Recent research has addressed the challenge of analysing and forecasting future water availability, using methodologies and models to generate more accurate and adaptive estimates in the context of this challenging situation (Rivas-Tabares et al. 2019; Oliveira et al. 2022; Nistor et al. 2022). The overlap of these studies highlights the need for mitigation and adaptation measures in the region, with an integrated and multi-disciplinary perspective (Garrote 2017; Iglesias et al. 2018).

The main purpose of this study lies in the in-depth analysis of water availability in the Iberian Peninsula, with a particular focus on how it is influenced by various factors, including climate change. To achieve this, the WAAPA (water availability and adaptation policy assessment) model has been utilised; this state-of-the-art model allows for a detailed hydrological evaluation, even considering the crucial role of dams and reservoirs in the supply of water (Garrote et al. 2011; Paredes-Beltran et al. 2021). The WAAPA model has proven its reliability and consistency in previous research (Garrote et al. 2015, 2018; Sordo-Ward et al. 2019b) by demonstrating its capacity to consider a number of water resource management policies in its analysis as well as its ability to evaluate the effects of various climate change scenarios (Sordo-Ward et al. 2019c, a, 2020a, b; Sordo-Ward et al. 2020a, b). Nevertheless, it is important to recognise the existence of additional proficient decision support system (DSS) models such as Aquatool (Andreu et al. 1996), WEAP (Raskina et al. 1992), and MODSIM (Labadie 2006), which also provide reliable outcomes. The WAAPA model was selected over other options due to its enhanced flexibility in analysing climate change projections, particularly due to its reliance on long-term consistent data. Furthermore, the WAAPA model provides a higher level of detail in terms of hydrographic basins and river networks representation compared to global models that are specifically developed for climate change, such as WaterGAP (Alcamo et al. 2003). This enables a realistic integration of each reservoir and their regulatory impacts, which is a crucial element in our analysis (Garrote et al. 2011). In addition, in this analysis, the HydroSHEDS (hydrological data and maps based on Shuttle elevation derivatives at multiple scales) dataset (Lehner

et al. 2008a) was used for the construction of the topological model. This dataset provides a thorough description of the topographical and hydrological features of the area, enabling us to work with a more accurate resolution than in previous research (Sordo-Ward et al. 2020a; Granados et al. 2021). Three time periods were considered for this analysis: the historical (1960–1990), short term (2020–2059), and long term (2060–2099). Likewise, for this analysis, the climate models were taken from the EURO-CORDEX (Coordinated Downscaling Experiment—European Domain) initiative, which has proved a solid and widely accepted basis for climate simulations and predictions. Also, to reduce the potential uncertainties in the estimated mean annual flow data, the SIMPA model (SIMulación Precipitación-Aportación), developed by CEDEX (Centro de Estudios y Experimentación de Obras Públicas) (Estrela and Quintas 1996) was used for bias correction, thus guaranteeing greater precision and reliability in our projections.

In this article, crucial findings are presented to understand the dynamics of water resources in the Iberian Peninsula in a future context of climate change. A clear and quantitative perspective of the present and future conditions is provided by the use of detailed information depicting the results along the studied rivers, which were generated by using the simulated hydrological model. Additionally, generated profile graphs of mean annual flow and potential water availability provide an in-depth overview of each of the selected rivers, allowing for a direct overview of their characteristics and variations. When the longitudinal profiles simulated for each scenario are contrasted, a revealing picture of how water bodies are expected to develop and change in future is revealed. These results, in addition to their obvious relevance as a whole, can be considered in the practice of water management in the region since they shed light on possible challenges and opportunities that could arise in the near and distant future. However, it is essential to recognise the inherent limitations of this type of study. Although the models and methods used are advanced and precise, all simulations have restrictions and are subject to uncertainties, especially when long-term scenarios are projected (Navarro-Ortega et al. 2012; Santos et al. 2019; Oliveira et al. 2022; Nistor et al. 2022). These potential deviations, however controlled and minimised, must be considered when interpreting the results and planning interventions based on them.

The conclusions derived from this study seek not only to contribute to the discussion of current and future water availability in the Iberian Peninsula, but also to shed light on decision-making processes regarding the management of water resources in the region. The findings detailed in this research will hopefully contribute to generating a robust platform for designing more informed policies and strategies, especially in the context of a changing climate in future. The results obtained in this study could

potentially contribute to the creation of policies for proactive adaptation, allowing authorities, and other stakeholders to anticipate challenges and capitalise on opportunities. This could contribute to the discussion of water resource management strategies at the local, regional, and national levels, with the firm belief that the management of water resources in the Iberian Peninsula can, over time, not only adapt to the challenges of climate change, but thrive in spite of them.

Materials and methods

In formulating the methodology for this study, our initial effort consisted of creating a high-resolution topological model that covers the entire Iberian Peninsula. This model, with a resolution of 15 arc seconds, represents a notable advancement, as it enables us to obtain more precise and detailed results (Sordo-Ward et al. 2019b; Granados et al. 2021). After completing this initial phase, we proceeded to choose particular hydrographic basins for further investigation. We conducted a thorough examination of all selected basins, including a detailed examination of the longest river sections within each basin, spanning from the source to the ocean. This approach ensures a better understanding of the hydrological dynamics throughout the basin, while also providing a comprehensive analysis of its most notable river sections. The subsequent stage entailed the identification and analysis of the hydrological characteristics within each selected basin. This study mainly examined crucial hydrological characteristics for our analysis, such as mean annual flow, basin area, reservoir capacity, length of each river segment, and the number of reservoirs that exist within each basin. The selection of these parameters was based on their substantial impact on hydrological dynamics and water resource management, as demonstrated in previous research (Granados et al. 2021; Paredes-Beltran et al. 2021). Although several hydrological factors, such as land use, soil characteristics, or human activities, may also impact the management of water resources, the parameters selected for this study are essential for the proper functioning of the WAAPA model. This model is specifically designed to provide long-term reliable estimates based on these essential hydrological components, making it an appropriate tool for assessing the consequences of climate change on water availability. Therefore, our approach is in line with the main objective of this research, which is to comprehend and forecast the effects of climate change on the hydrological characteristics of the Iberian Peninsula. After conducting a thorough analysis of the key hydrological components for each basin, we proceeded to evaluate the potential water availability for each basin, for both present and future time periods. Finally, we conducted an analysis of the mean annual flow

and potential water availability for each specific time period and climatic scenario. The following sections offer a more comprehensive examination of the features of our study area, the data sources used for the development of both topological and hydrological models, and the methodology used for the analysis of the potential availability of water.

Area of study

The Iberian Peninsula, which covers mainly Spain and Portugal, is a region of special interest given its climatic and topographic diversity. Characterised by a varied landscape, from the high mountains of the Pyrenees to the extensive plains of the centre, the Iberian Peninsula emerges as a diverse and challenging hydrological and meteorological mosaic (Lobera et al. 2015; José Vidal-Macua et al. 2017). In climatic terms, while the northwest is hit by constant Atlantic precipitation, the southeast is characterised by a more arid and Mediterranean climate. This variability gives rise to a diverse fluvial network, from mighty rivers that flow into the Atlantic to more intermittent currents that flow into the Mediterranean (Vicente-Serrano et al. 2011; Abrantes et al. 2017; Marín-Comitre et al. 2020).

This study focusses on a careful selection of eight transnational river basins located between Spain and Portugal, with the objective of conducting a comprehensive and thorough examination. The river basins included in this list are Miño-Sil/Minho-Sil (known as such in Portuguese), Duero/Douro, Tajo/Tejo, Guadiana, Guadalquivir, Segura, Júcar, and Ebro. To maintain narrative continuity, the river basins discussed in this article shall be consistently referred to by their Spanish names. These basins are considered very important on the Iberian Peninsula due to their particular hydrological characteristics and play a crucial role in the overall environmental and economic structure of the region. The Miño-Sil River basin, as an example, presents a combination of strategically important water reservoirs and ecological sanctuaries, effectively connecting the northwest region of Spain (Vicente-Serrano et al. 2011). The Duero River basin, which crosses a vast expanse of the northern plateau, is of great relevance for both its agricultural surroundings and urban centres (Sordo-Ward et al. 2020a). In the context of transnational significance, the Tajo River system serves as a prominent fluvial conduit that links the central region of Spain to the border of Portugal (Kilsby et al. 2007). In addition, the Guadiana, Guadalquivir, Segura, and Júcar rivers exemplify the delicate equilibrium between human activities and natural ecosystems, serving as a reminder of their hydrological importance and highlighting the challenges of managing water resources amidst varied climatic conditions and anthropogenic pressures (Kilsby et al. 2007; Miranda et al. 2011; Lobera et al. 2015; Marín-Comitre et al. 2020; Redondo-Orts and López-Ortiz 2020).

The Ebro River, which governs the catchment area in the northeastern region, has a varied role by supporting both extensive agrarian tracts and metropolitan conglomerates (Ibáñez and Prat 1996; Batalla and Go 2004). The selection of these basins represents the diverse hydrological landscape of the Iberian Peninsula, and their study provides essential knowledge on the dynamics of water and management strategies in the area.

To provide a precise representation of the hydrological characteristics of the Iberian Peninsula, our study used the HydroSHEDS dataset, which is a comprehensive collection of hydrological data and maps derived from Shuttle Elevation Derivatives on various scales (Lehner et al. 2008b; Paredes-Beltran et al. 2021). The HydroSHEDS data set provides a comprehensive hydrographic perspective with a resolution of 15 arc seconds, mostly obtained from the Shuttle Radar Topography Mission (SRTM). Given the regional scope of our study, we adjusted the HydroSHEDS dataset to incorporate the catchments associated with reservoirs and those exceeding an area of 5000 km². The modelling process involved the consolidation of smaller subcatchments without reservoirs with their adjacent downstream basins. The outcome of this process manifests itself as a 'drain-to' network, initiating from the headwater catchments and progressing through more extensive downstream catchments, eventually reaching the sea. Furthermore, for the purpose of our analysis, we used data on dams and reservoirs obtained from the ICOLD (International Commission on Large Dams) database (ICOLD 2020), which contains detailed records on the location and storage capacities of dams around the world. For this analysis, we selected dams used for nonhydroelectric purposes, each with a reservoir capacity exceeding 1 hm³. Each dam was georeferenced and linked to its corresponding river based on the HydroSHEDS data set. In total, the topological model developed for the entire Iberian Peninsula consists of a total of 1948 subcatchments. This includes more than 720 dam catchments with a reservoir capacity over 1 hm³. Finally, as mentioned previously, the derived subcatchments of the topological model were analysed and categorised according to the eight distinct basins, which are the focus of this study. The study area generated for the entire Iberian Peninsula for this study is presented in Fig. 1.

For the climate projection, the EURO-CORDEX model was used, which offers regionalised climate data for Europe. For this analysis, the following climate models were used: GFDL-ESM2NM (GFDL), HadGEM2-ES (HadGEM2), IPSL-CM5A-LR (IPSL), MIROC-ESM-CHEM (MIROC), and NorESM1-M (NorESM1). These models were evaluated under two representative concentration scenarios RCP4.5 and RCP8.5, which reflect different emission trajectories and atmospheric concentrations in future. This study outlines three time periods: The control scenario (1960–1999), short-term ST (2020–2059), and long-term LT (2060–2099). The

Fig. 1 *Area of study.* This figure depicts the eight basins considered in this study (delimited by the red lines), the river network (blue lines), and reservoirs (green triangles) considered in this study



rationale behind our choice of these time periods is twofold. First, the control scenario provides a historical baseline, allowing a comparative analysis with future projections. Our choice of the period 1960–1999, over a more recent time period, is based on the availability of comprehensive and validated climatic and hydrological data, ensuring robustness in our baseline assessment. Furthermore, the subsequent time periods, ST (short term) and LT (long term), were chosen to encompass the near-term and long-term consequences of climate change, respectively. This approach enables a comprehensive understanding of the development of hydrological patterns. Furthermore, these time intervals correspond to our prior investigations, establishing a continuum in our research endeavours and allowing us to evaluate temporal modifications using revised and more precise data. Due to possible biases in climate projections, it was necessary to correct runoff using data from the SIMPA model, which has been developed by CEDEX and is widely recognised in Spain (Centro de Estudios y Experimentación de Obras Públicas (CEDEX) 2021). The correction of these data followed the methodology proposed by González-Zéas (González-Zéas et al. 2012), which establishes monthly correction factors based on historical records. Furthermore, socioeconomic and demographic data were integrated, taking the GRUMP (Global Rural–Urban Mapping Project) database as a reference to obtain georeferenced information on population densities (Centre for International Earth Science Information Network CIESIN et al. 2011). For information related to irrigation areas, the GMIA (global map of irrigated areas) (Siebert et al. 2005) was used. Lastly, projections of gross

domestic product (GDP) were obtained from the World Bank database, information that is essential to understand possible changes in the use and demand for water resources based on economic growth (The World Bank 2020).

Water availability analysis

The Iberian Peninsula, mainly composed of Spain and Portugal, is facing significant challenges in terms of water management, due to its climate variability and the expected impact of climate change on the hydrological cycle. To adequately assess the availability of water resources in this changing context, it is imperative to have robust tools and models that capture the complexity of the hydrological system. This study is based on the evaluation of potential water availability (PWA) in various basins of the Iberian Peninsula, analysing the impact of climate change and how it is modified by available storage in reservoirs. For this analysis, the PWA is defined as the annual demand for water that can be satisfied at a specific point in the fluvial network with a certain reliability, this being a metric that depends on the average and variability of the flow series, the flow regulation capacity through storage, the monthly distribution of demand, and the reliability indicator used in the analysis.

For the estimation of the PWA, the WAAPA model (water availability and adaptation policy analysis) model was employed (Garrote et al. 2015). This model simulates the operation of a complex system of water resources with multiple reservoirs. The basic topological unit of the WAAPA model is the fluvial network, where the main

components are the tributaries, reservoirs, and demands, all linked to nodes in the network. WAAPA calculates the amount of water supplied to the demands of a reservoir system, considering ecological flows and evaporation losses in the reservoirs. The input data for the WAAPA include monthly stream flow information at the relevant points in the river network, monthly demand values, and reservoir data. The information for each reservoir includes the maximum and minimum monthly capacity, storage area ratio, monthly evaporation rates, and required monthly ecological flow.

The model applies an algorithm with simple operational rules, where all reservoirs in the basin are managed jointly to satisfy the set of demands, preferably extracting water from reservoirs located upstream. This algorithm is applied to the potential demands located at each node of the fluvial network and, in this way, the potential availability of water for the entire network is obtained. The main results offered by WAAPA are time series of monthly volumes supplied to each demand, monthly storage values and monthly values of flow through spillways, ecological flows, and evaporation losses in each reservoir. From these results, the reliability of the demand can be calculated according to the chosen criterion.

For the Iberian Peninsula, considering its geographic and climatic context, the PWA was estimated considering a single type of demand in the system with a constant monthly distribution. Ecological flows were specified as the 10% percentile of the monthly marginal distribution of natural flows. The effectiveness of the system is evaluated as the reliability of the gross volume. For this study, the PWA was obtained with a volume reliability of 92%. This level of reliability was chosen as an intermediate value, assuming an approximate distribution of 20% urban demand and 80% irrigation demand, typical of the Iberian Peninsula.

Results

The subcatchments within the specified eight hydrological basins considered for this study were combined, and the essential characteristics of each catchment were then determined. Variables considered in this study are mean annual flow (F), basin area (A), length of the examined river segment for each basin (L), reservoir capacity (V), and the number of dams in each catchment (D). When evaluating the mean annual flow in the selected river basins in this study, our analysis indicates a combined mean annual flow of 60.59 km³ per year across the selected regions. The Duero River basin exhibits the highest mean annual flow with 15.30 km³ per year. In contrast, it should be noted that the Guadalquivir River basin, despite its notable geographical importance, has the lowest mean annual flow with 6.78 km³ per year. In terms of surface area, we analysed a total of 446,066.44 km² across the eight studied basins. Significantly, the most extensive regions correspond to the Duero and Ebro River basins, encompassing 97,238.51 km² and 84,763.29 km², respectively. Regarding the analysis of river segments, it should be noted that the Tajo basin has the most extensive stretch, measuring a considerable length of 878.86 km. In relation to the examination of the reservoir capacity, the Guadiana River basin exhibits the highest storage volume with 14.32 km³ of water within its reservoirs. Collectively, the eight basins selected for this study have a combined storage capacity of 46.52 km³ as a result of their dam infrastructure. This study considered a total of 406 dams located in the eight river basins. The Tajo basin is particularly notable for its high density of dams, with a total of 90 dams in place. The results for the mean annual flow (F), the basin area (A), length of the examined river segment for each basin (L), reservoir capacity (V), and the number of dams in each basin (D) for all the river basins considered in this study are presented in Table 1.

Table 1 Hydrological characteristics of the river basins considered in this study

River	Area (A) × 1000 km ²	Volume (V) km ³	Length (L) km	Dams (D)	Mean annual flow (F) km ³ /year
Miño-Sil	16.65	0.43	254.40	7	8.77
Duero	97.24	4.88	841.41	46	15.30
Tajo	70.76	7.15	878.86	90	9.08
Guadiana	66.93	14.32	827.75	56	4.77
Guadalquivir	56.43	8.58	537.06	84	6.78
Segura	17.28	1.09	258.08	14	0.79
Júcar	36.02	3.08	392.53	26	2.47
Ebro	84.76	6.98	816.59	83	12.64
Total	446.07	46.52	4806.68	406	60.59

The simulation results for the mean annual flow under the two climatic scenarios RCP4.5 and RCP8.5 are shown in Table 2 for the eight river basins evaluated on the Iberian Peninsula over the two timeframes: Short-term ST (2020–2059) and long-term LT (2060–2099). The simulations carried out in our study reveal that the Duero River basin exhibits the highest mean annual flow for all scenarios, while the Segura River basin shows the lowest mean annual flow among the basins examined. However, it is important to recognise that relying solely on these mean annual flow values does not fully encompass the complex hydrological dynamics of each individual river basin. As a result, we also determined the Specific Runoff for each basin, which is obtained by the ratio of the mean annual flow to the surface area of each basin (F/A). This analysis shows that the Miño-Sil basin presents a specific runoff of more than 526 mm per year in the control scenario. This specific runoff reaches its highest point at 456 mm per year in the RCP8.5-ST scenario and decreases to a minimum of 361 mm per year in the RCP8.5-LT scenario. On the contrary, the specific runoff of the Segura River basin is estimated at 45 mm/year in the control scenario. It reaches its maximum value of 44 mm/year in the RCP4.5-LT scenario and decreases significantly to 25 mm/year in the RCP8.5-LT scenario. Table 2 presents a complete overview of the data obtained for all the river basins taken into account. Furthermore, Figs. 2 and 3 depict the mean annual flow of the eight river basins considered in this study both in the control scenario and as a variation in future scenarios. The variation (Δ) was determined by comparing the mean annual flow in the simulated scenarios with the control scenario using the following rationale:

$$\Delta = \frac{\text{Mean annual flow at future scenarios} - \text{Mean annual flow at control scenario}}{\text{Mean annual flow at control scenario}} \quad (1)$$

This study also examined the potential availability of water (PWA) in the Iberian Peninsula using the WAAPA model. The model was applied to analyse two climatic scenarios, RCP4.5 and RCP8.5, over two-time frames: Short-term (2020–2059) and long-term (2060–2099). Our analyses indicate that the Ebro River basin consistently exhibits the highest estimates of potential water availability in all defined scenarios. In the control scenario, it is observed that the Ebro River basin has been allocated a PWA of 3.88 km³ per year. Within the scope of this basin, the RCP8.5-ST scenario exhibits the highest point, characterised by an estimated PWA of 3.63 km³ per year. On the contrary, the RCP8.5-LT scenario represents the lowest point, with a recorded PWA of 2.82 km³ per year. On the other hand, the Segura River basin shows the lowest PWA among all assessed basins. The control scenario in this estimates a PWA of 0.24 km³ per year for this basin. The maximum PWA for this basin is estimated

at 0.19 km³ per year in the RCP4.5-LT scenario. On the contrary, the minimum PWA is observed in the RCP8.5-LT scenario, with a significantly lower value of 0.12 km³ per year. Table 3 provides a comprehensive analysis of the specific characteristics of each basin that was investigated in our research. Also, Figs. 4 and 5 depict the mean annual flow of the eight river basins considered in this study both in the control scenario and as a variation in future scenarios. The variation (Δ) was determined by comparing the potential availability of water in the simulated scenarios with the control scenario using the following rationale:

$$\Delta = \frac{\text{PWA for future scenarios} - \text{PWA for control scenario}}{\text{PWA for control scenario}} \quad (2)$$

Following the first assessments and employing the detailed high-resolution model developed at a resolution of 15 arc seconds, we also present an analysis of the longitudinal profiles for both the mean annual flow (F) and the potential water availability (PWA) of each river basin. The improved resolution not only increased the precision of our findings, but also increased the quality of our subsequent analyses. The rationale for determining each river basin longitudinal profile is based on its ability to accurately depict spatial and temporal fluctuations along the river's course. This delineation allows us to comprehend the fundamental aspects of the hydrological dynamics, enhancing our understanding of these river systems. A detailed evaluation was conducted to identify the longest river segment within each of the selected hydrological basins in this study. In this evaluation, longitudinal profiles calculations were performed

for mean annual flow (F) and the potential water availability (PWA) at each significant node along these rivers, in both the control scenario and the simulated scenarios of RCP4.5 and RCP8.5, in short-term (ST) and long-term (LT) timeframes. It is worth mentioning that the Tajo River holds the distinction of having the longest stretch, measuring a total length of 878.86 km. In contrast, the Mino River has the shortest trajectory, spanning only 254.40 km. Figures 6, 7, 8, and 9 depict the longitudinal profiles of mean annual flow and potential water availability for the eight selected river basins considered in this study.

In addition, a detailed examination was conducted of fluctuations in the mean annual flow within the simulated climatic situations. Calculating this variation (Δ) was determined by comparing the mean annual flow in simulated scenarios with the control scenario. These identified variations suggest that within the scope of this investigation, the most

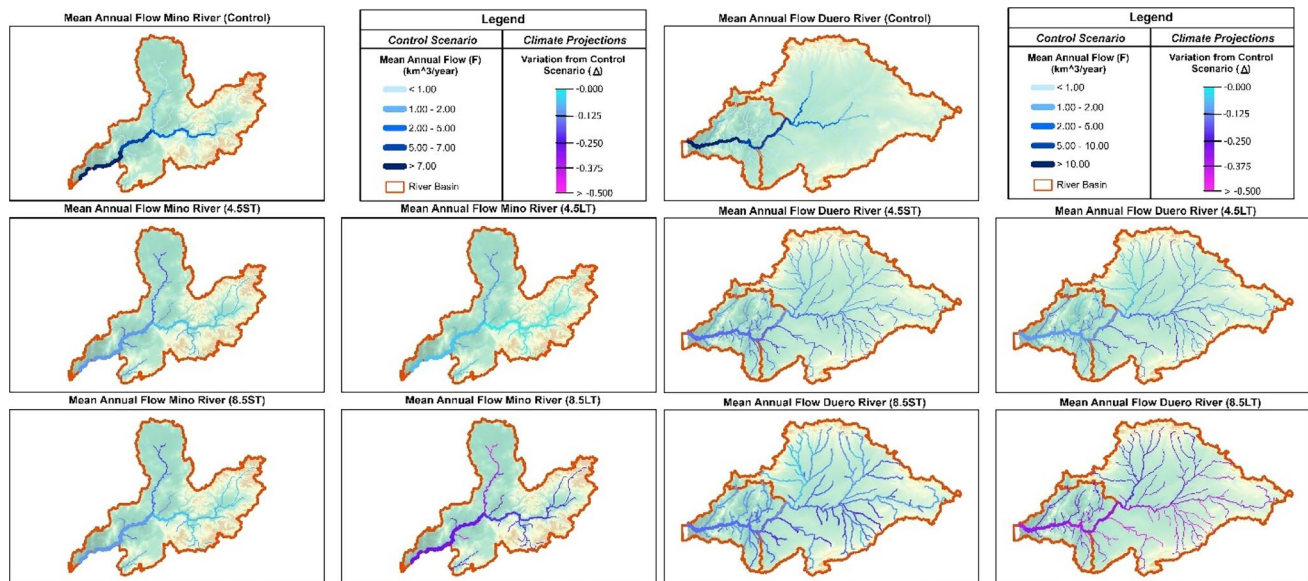


Fig. 2 Mean annual flow in Miño and Duero River basins for all considered scenarios. The control scenario shows the mean annual flow in km^3 per year, and the projected scenarios depict the mean annual flow as a variation from the control scenario

flows ($0.79 \text{ km}^3/\text{year}$ in the control scenario). Using a high-resolution model, we were able to accurately depict these subtle distinctions, highlighting the diverse levels of potential vulnerability to climate change throughout the basins. In addition, the specific runoff calculations presented in Table 2 offered a deeper understanding of the intrinsic hydrological properties of each basin. It was observed that the Miño-Sil basin exhibited the highest specific runoff ($526 \text{ mm}/\text{year}$ in the control scenario). The Duero River watershed shows the most significant mean yearly flow, particularly in the RCP4.5-LT scenario. However, the significance of our analysis lies in the fluctuations induced by climate influences. The RCP8.5-LT scenario predicted a significant reduction of more than 40% in the mean annual flow, compared to the control scenario. The decrease was most noticeable in the Guadiana and Guadalquivir basins, with projected potential losses exceeding 50%. Additionally, our study explored the complexities of the correlation between mean annual flow and the size of each basin by precisely determining its specific runoff. This facilitated a more thorough understanding of the intrinsic attributes of each basin. In all scenarios, the Mino River basin has the highest specific runoff, measuring 526 mm per year in the control scenario. On the contrary, the basins of Guadiana, Segura, and Jucar demonstrate reduced specific runoff, measuring less than $100 \text{ mm}/\text{year}$ in all scenarios. Furthermore, based on the observed patterns in mean annual flow, climatic predictions indicate a substantial reduction in specific runoff, with an average decrease of almost 40% under the RCP8.5-LT scenario. The Guadiana and Guadalquivir basins see considerable impact, with a notable reduction of more than 50%

in specific runoff. Similarly, our examinations of potential water availability (PWA) using the water availability and adaptation policy analysis (WAAPA) model have indicated that in the RCP8.5-LT scenario, the Guadiana, Guadalquivir, and Segura basins could experience a decrease of more than 50% in their annual PWA. On the contrary, basins such as Ebro, Mino, and Duero exhibited a significant level of resilience, as their reductions in PWA were comparatively less severe. Understanding the relationship between geographical and climatic factors on hydrological parameters improves our understanding of the diverse and important impacts of climate change on the water resources of the Iberian Peninsula. Therefore, it is crucial to design cautious and proactive strategies to address the challenges that are anticipated from these outcomes (Iglesias and Garrote 2015; Garrote et al. 2016; Garrote 2017).

This comparison highlights the unique and original contributions of our research, specifically in relation to the water dynamics of the Iberian Peninsula. Our research, using a high-resolution topological model and complete hydrological analysis, provides a more detailed knowledge of how certain river basins are expected to react to future climatic scenarios, which differs from earlier studies. As shown in Table 3 and Figs. 4 and 5, the Guadiana, Guadalquivir, and Segura basins are projected to have a decrease of over 50% in potential water availability (PWA) under the RCP8.5-LT scenario. This indicates that these basins are particularly vulnerable to water scarcity. The significant disparity between the resilience witnessed in the Ebro and Duero basins exemplifies the diversity of the effects of climate change in the region. Furthermore, the use of the WAAPA

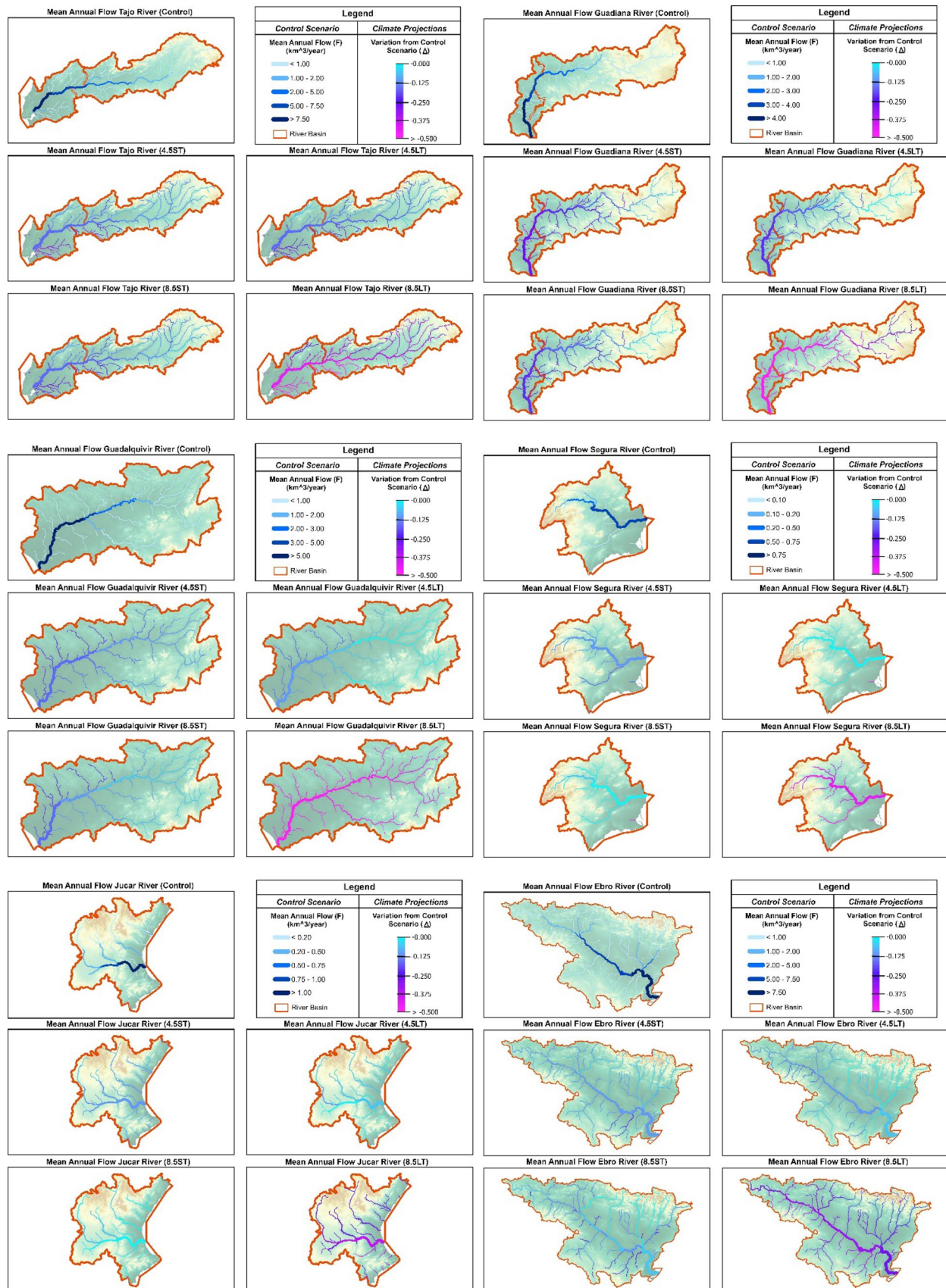


Fig. 3. Mean annual flow in Tajo, Guadiana, Guadalquivir, Segura, Júcar, and Ebro River basins for all considered scenarios. The control scenario shows the mean annual flow in km³ per year, and the projected scenarios depict the mean annual flow as a variation from the control scenario.

model has for a more comprehensive evaluation of PWA compared to earlier models, providing significant perspectives for the management of water resources in the face of climate change (García-Ruiz et al. 2011; Garrote et al. 2015, 2016; Mourato et al. 2015; Villar-Navascués and Pérez-Morales 2018). Additionally, and consistent with previous research, our results further highlight the significant variation in mean annual river flow between different river basins. However, there are possible discrepancies between our study and previous research on the magnitude of flow variability in specific basins, particularly when considering the climatic scenarios RCP4.5 and RCP8.5. A possible reason for these

inconsistencies may be the diversity of methodology used in different investigations. Our study used a novel approach by integrating many variables, namely mean annual flow, basin size, river segment length, reservoir capacity and dam count, to assess watershed characteristics. This approach distinguishes our research from previous studies that may not have considered these factors collectively. Furthermore, the implementation of the WAAPA model, despite being acknowledged for its effectiveness, can produce divergent outcomes compared to other models as a result of its distinct characteristics and configurations (Navarro-Ortega et al. 2012; Santos et al. 2019; Nistor et al. 2022). Differences in outcomes can be further influenced by variability in data sets, temporal scope, and the level of detail in the analysis, such as our comprehensive assessment of longitudinal profiles. Furthermore, it is essential to note the notable decrease in potential water availability (PWA) within the studied basins. The hydrological responses to climate

Table 3 Potential water availability results for the eight considered river basins in this study

Basin	Potential water availability (PWA) (km ³ /year)				
	CONTROL	RCP4.5-ST	RCP8.5-ST	RCP4.5-LT	RCP8.5-LT
Miño-Sil	0.40	0.38	0.36	0.34	0.33
Duero	2.54	2.35	2.24	2.24	1.96
Tajo	2.53	2.17	2.14	2.19	1.52
Guadiana	2.10	1.44	1.43	1.48	0.73
Guadalquivir	2.22	1.55	1.50	1.62	0.90
Segura	0.24	0.18	0.18	0.19	0.12
Júcar	0.68	0.50	0.54	0.56	0.41
Ebro	3.88	3.58	3.63	3.37	2.82

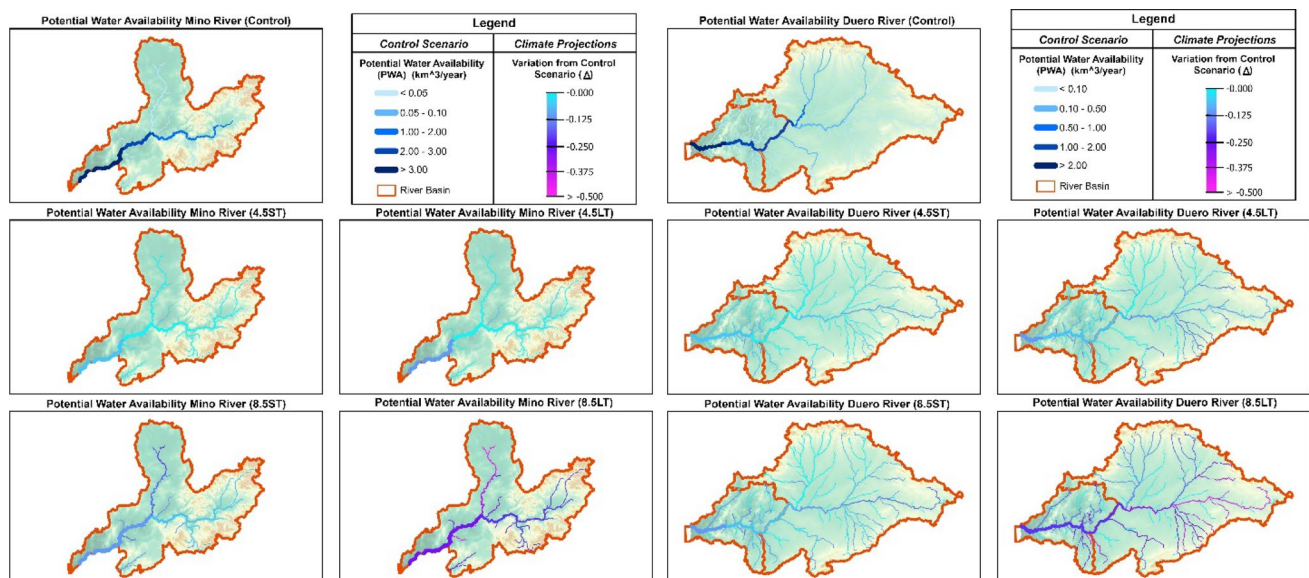


Fig. 4. Potential water availability (PWA) in Mino and Duero River basins for all considered scenarios. The control scenario shows the PWA in km³ per year, and the projected scenarios depict the PWA as a variation from the control scenario.

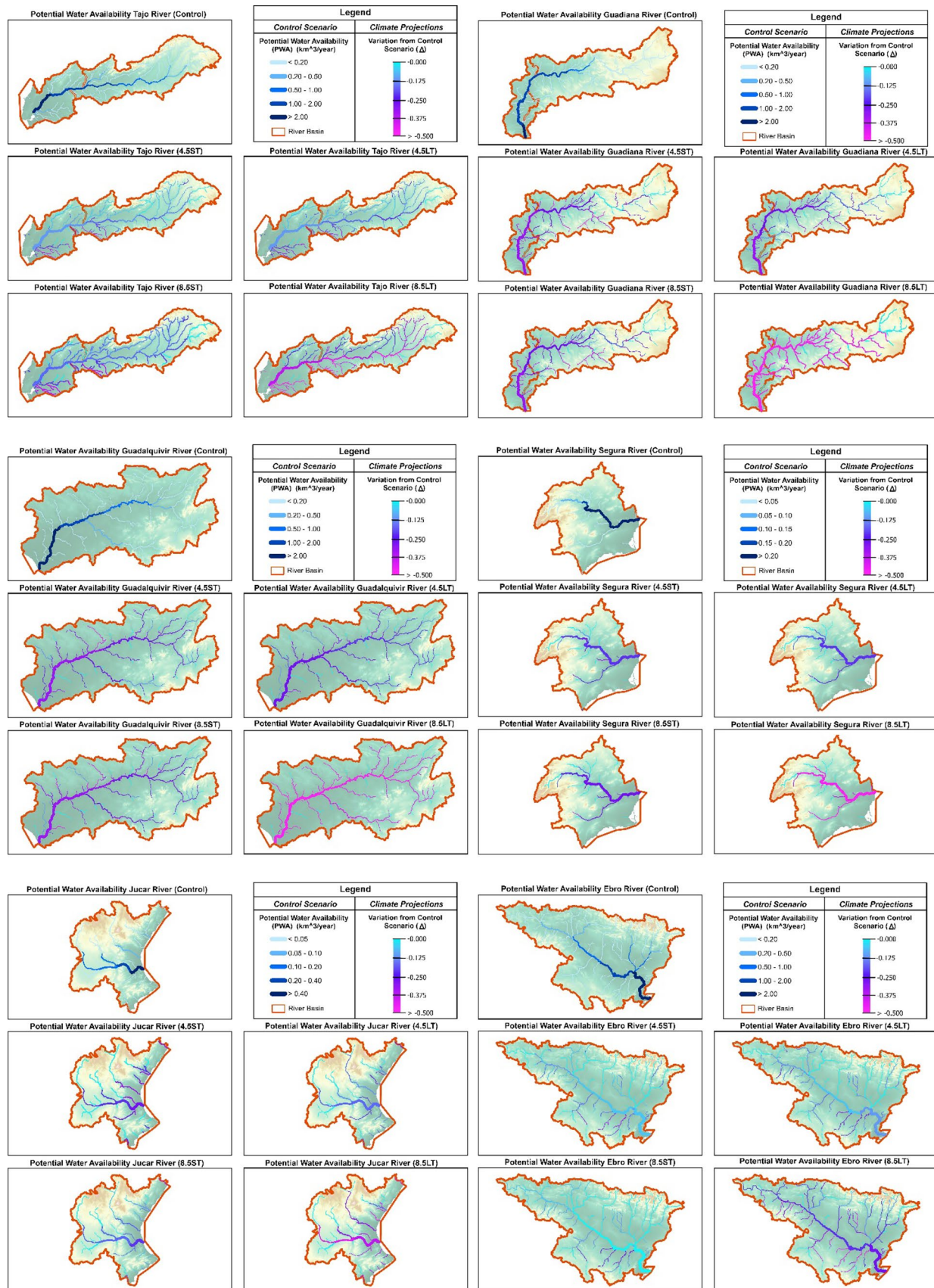


Fig. 5 Potential water availability (PWA) in Tajo, Guadiana, Guadalquivir, Segura, Jucar, and Ebro River basins for all considered scenarios. The control scenario shows the PWA in km³ per year, and the projected scenarios depict the PWA as a variation from the control scenario

change in the region are characterised by a notable disparity between the various basins. Specifically, the Guadiana, Guadalquivir, and Segura basins exhibit substantial reductions, while the Ebro, Mino, and Duero basins experience comparatively lesser impacts. This disparity highlights the intricate nature of the hydrological dynamics in response to climate change, which in turn suggests the need for further research, which may require the incorporation of additional or multidisciplinary methodologies.

The observed decrease, as specified in Tables 2 and 4 and Figs. 6 and 7, not only underscores the anticipated decrease in mean annual flow but also underscores the variation between various river basins. For example, the Guadiana and Guadalquivir basins are expected to experience a significant reduction in both mean annual flow and specific runoff, exceeding 50% in the RCP8.5-LT scenario. This indicates the increased susceptibility to hydrological vulnerabilities that these locations are expected to encounter. In contrast, the Duero basin, although also experiencing declines, has a certain level of resilience, as its mean annual flow remains at the highest levels among all climate scenarios. The implications of these findings are significant, encompassing not just ecological concerns but also social and economic aspects, as water scarcity can have a major impact on agricultural production, industrial operations, and home water supplies. The varying effects found in different basins highlight the necessity of implementing water management techniques that are tailored to each unique basin and may be adjusted to accommodate the diverse hydrological responses. The alteration of hydrological patterns, as indicated by the significant reduction in PWA in prominent basins such as the Guadiana, Guadalquivir, and Segura, poses a threat to the ecological balance, potentially affecting plant and animal species that depend on consistent water patterns for their survival. Furthermore, the decrease in PWA poses substantial challenges for human society, particularly in sectors such as agriculture, industry, and domestic consumption. This situation has the capacity to exacerbate preexisting water scarcity issues and incite socioeconomic disruptions in regions that are already vulnerable to water-related pressures (Ruiz-Ramos and Mínguez 2010; Vicente-Serrano et al. 2011; Miranda et al. 2011; Navarro-Ortega et al. 2012; José Vidal-Macua et al. 2017; Marín-Comitre et al. 2020). The complex nature of hydrological dynamics, as evidenced by the longitudinal profiles of individual river basins, highlights the significant contribution of rivers to regional water equilibrium and underscores the need for effective water management

techniques. Effective management of these water regimes requires a comprehensive approach that integrates infrastructure, policy, and conservation initiatives to achieve sustainable water use and maintain ecological well-being (Iglesias and Garrote 2015; Garrote et al. 2016, 2018; Iglesias et al. 2018; Sordo-Ward et al. 2019b). Given the increasing severity of climate change-induced consequences, it is important for policymakers and water managers to incorporate research findings such as ours into their adaptive plans. Significant fluctuations observed in the RCP8.5-LT scenario, characterised by substantial decreases exceeding 50% in average annual flow, specific runoff, and potential water supply in specific basins, underscore the critical necessity of reevaluating existing strategies for managing water resources. This re-assessment is essential to ensure the resilience of these practices in the light of ongoing climate change.

The variability in PWA, as indicated by the findings in Table 3 and Figs. 4, 5, 8, and 9, illustrates the heterogeneous influence of climatic scenarios on various river basins. The Guadiana, Guadalquivir, and Segura basins are particularly susceptible to increased vulnerability, with the anticipated decrease in PWA significant, especially under the RCP8.5-LT scenario. The findings stated in Table 4 provide additional evidence, as they show considerable reductions in the average variance of the mean annual flow in this scenario. However, the Duero and Ebro basins, although not completely unaffected by these changes, demonstrate a more resilient hydrological reaction, suggesting a distinct level of adaptation to climate fluctuations. The differences in the specific runoff, as described in Table 2, further support this observation, where the Duero basin consistently shows higher values in all scenarios. Variations in PWA and flow dynamics among basins require a sophisticated approach to managing water resources, one that is specifically designed to address the distinct characteristics and difficulties of each basin. An essential strategy is necessary to guarantee sustainable management of water resources in the light of these significant climatic alterations. On the contrary, the Duero River basin constantly has the highest mean annual flow, regardless of climatic circumstances, showcasing its ability to withstand a changing climate, but with notable reductions under some conditions. The observed variation in different regions, specifically the ability of the Duero and Ebro basins to withstand challenges compared to the susceptibility of the Guadiana and Guadalquivir basins, emphasises the urgent need for tailored water management strategies specific to each basin. Regional strategies are essential to deal with anticipated changes in geography and time, particularly with regard to prospective water resources. The proposed methodology should prioritise regions that exhibit increased vulnerability and establish adaptive strategies to facilitate sustainable management

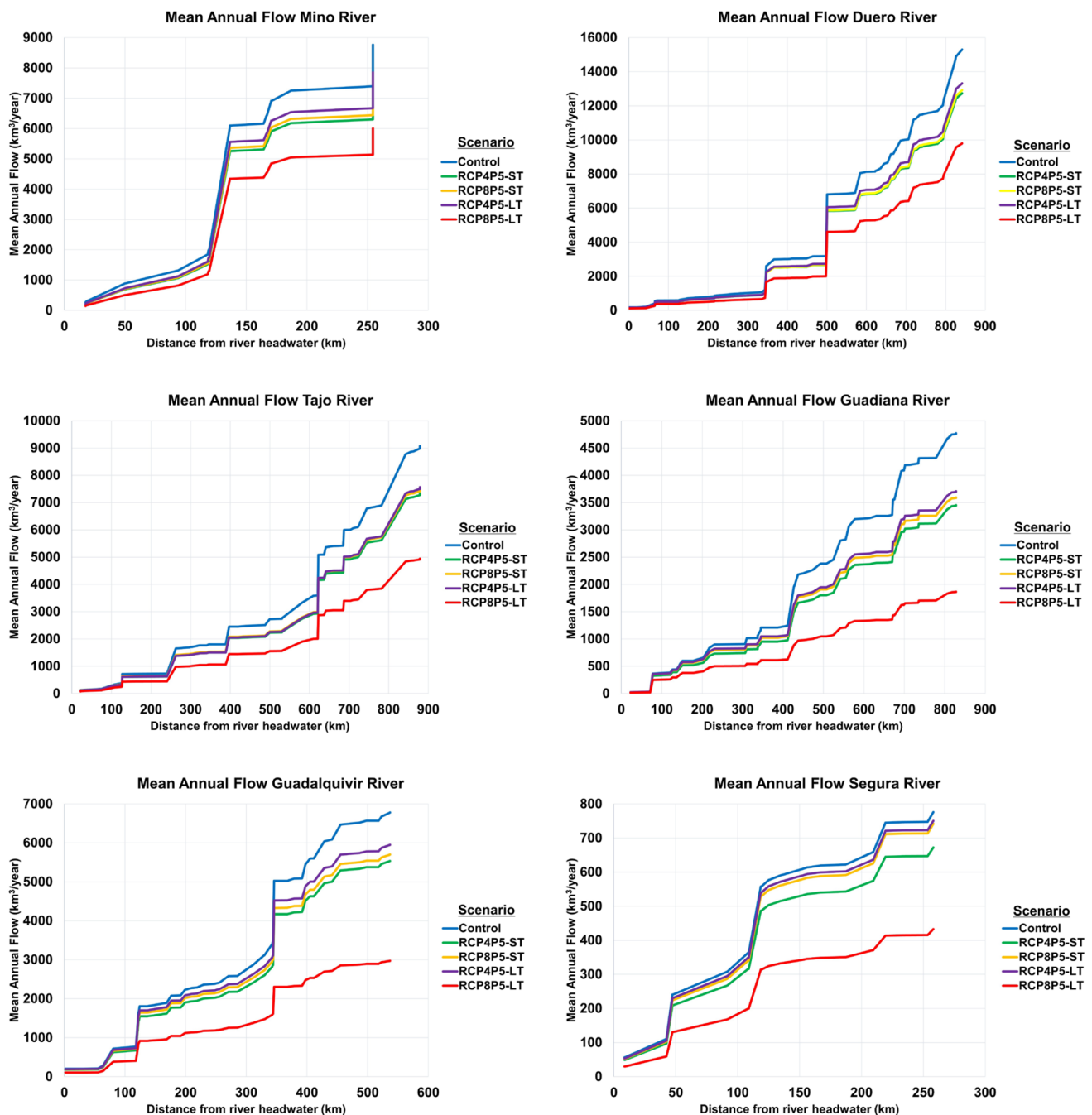


Fig. 6 Longitudinal profiles of mean annual flow for all scenarios and for the Mino, Duero, Tajo, Guadiana, Guadalquivir, and Segura River Basins

of water resources (Iglesias et al. 2011; Martin-Carrasco et al. 2013; Garrote et al. 2015; Sordo-Ward et al. 2019c; Sordo-Ward et al. 2020). Furthermore, the longitudinal profiles' insights, delineating fluctuations along the river courses, provide invaluable data for discerning potential 'hotspots' of water stress or surplus, further aiding in the precision of localised intervention strategies. This, in turn, improves the precision of targeted intervention approaches

at the local level. The aforementioned discoveries are of significant importance, particularly when considering their possible effects on nearby communities, agricultural practices, and ecological systems.

The complexity of this vulnerability is underscored by the findings presented in Tables 2 and 3 and Figs. 2, 3, 4, and 5, which illustrate the stark differences in water availability and runoff across the basins. For example, the Duero Basin,

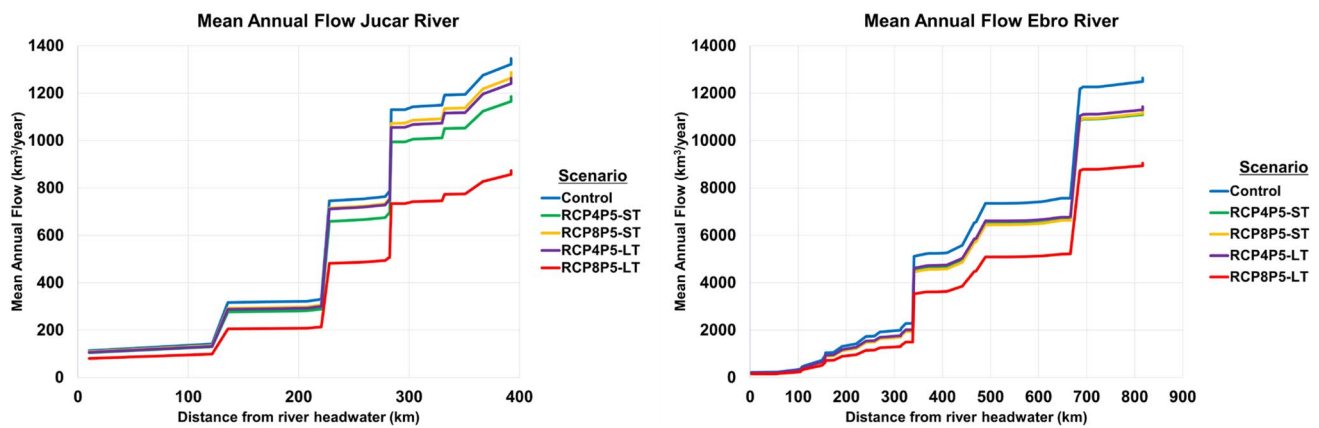


Fig. 7 Longitudinal profiles of mean annual flow for all scenarios and for the Jucar and Ebro River Basins

characterised by its higher mean annual flow and specific runoff, indicates a greater ability to withstand hydrological changes compared to basins such as the Guadalquivir, Jucar, or Segura, which have lower values in these measurements. The heterogeneity in specific runoff, as emphasised in Table 2, indicates that several basins can exhibit distinct responses to comparable climatic conditions. In addition, the analysis of longitudinal profiles, as mentioned in our methodology, offers a comprehensive understanding of the hydrological dynamics. It provides a complete picture of how the geographical and topographical characteristics of each basin contribute to its overall hydrological behaviour. It is crucial to acknowledge these inherent disparities in order to create customised approaches that can improve the ability of these basins to withstand and adapt to current and future climate changes. The size of the basin and the length of the river section can intrinsically influence the likelihood that particular basins, such as the Duero and Ebro, have larger water flows. However, it is crucial to consider the repercussions of human activity, as evidenced by the substantial number of dams in the Tajo basin. Dams have the capacity to improve resilience in response to varying water flow, although they also present ecological and socioeconomic concerns (Paredes-Beltran et al. 2021). The fragility of the basins is further emphasised by climate fluctuation, as indicated by future climatic predictions.

This multifaceted strategy is supported by the data presented in our results, notably in Tables 1 and 4 and Figs. 2 and 3. Table 1 presents essential information about the many attributes of each basin, such as its size, capacity, and the number of dams it contains. These data are crucial for customising targeted strategies for managing watersheds. Table 4 provides information about the variation in the mean annual flow in various climate scenarios. This emphasises the importance of adaptive management strategies that can address the distinct and evolving conditions of each basin

(Mourato et al. 2015; Rivas-Tabares et al. 2019). Subsequently, the implementation of adaptive management strategies is crucial to effectively respond to dynamic climatic data and model outputs, thus guaranteeing the resilience of the basins in the context of evolving climate impacts (Iglesias and Garrote 2015; Sanchez-Plaza et al. 2019). Finally, the imperative for effective collaboration among hydrological, climate and social scientists, in conjunction with policymakers, cannot be overstated to develop comprehensive solutions that effectively address the complex issues arising from changes in water availability in the Iberian Peninsula.

In addition to these general findings, the comprehensive data reported in Tables 2 and 3 and Figs. 2, 3, 4, and 5 offer a deep insight into the unique effects of climate change scenarios on each basin. Table 2 provides a complete analysis of the variations in mean annual flow and specific runoff in different scenarios for each basin. This demonstrates the significant disparities in water availability that can arise. Table 3 improves this comprehension by illustrating the possible availability of water under each climate scenario, revealing notable fluctuations that could have substantial consequences for the administration of water resources. The figures highlight the importance of adopting a detailed and sophisticated strategy for managing the water resources of the Iberian Peninsula. This approach should consider not only the overall hydrological patterns, but also the specific effects on each local basin. Precise information at this level is essential to develop efficient adaptation and resilience plans in response to climate change. It enables the implementation of more focused and effective measures to address the specific issues encountered in each basin. Furthermore, the use of the WAAPA model provides a comprehensive understanding of the potential water availability (PWA) within the basins analysed. The results of our research indicate that particular basins are highly vulnerable to climatic circumstances. Furthermore, the analysis of the longitudinal

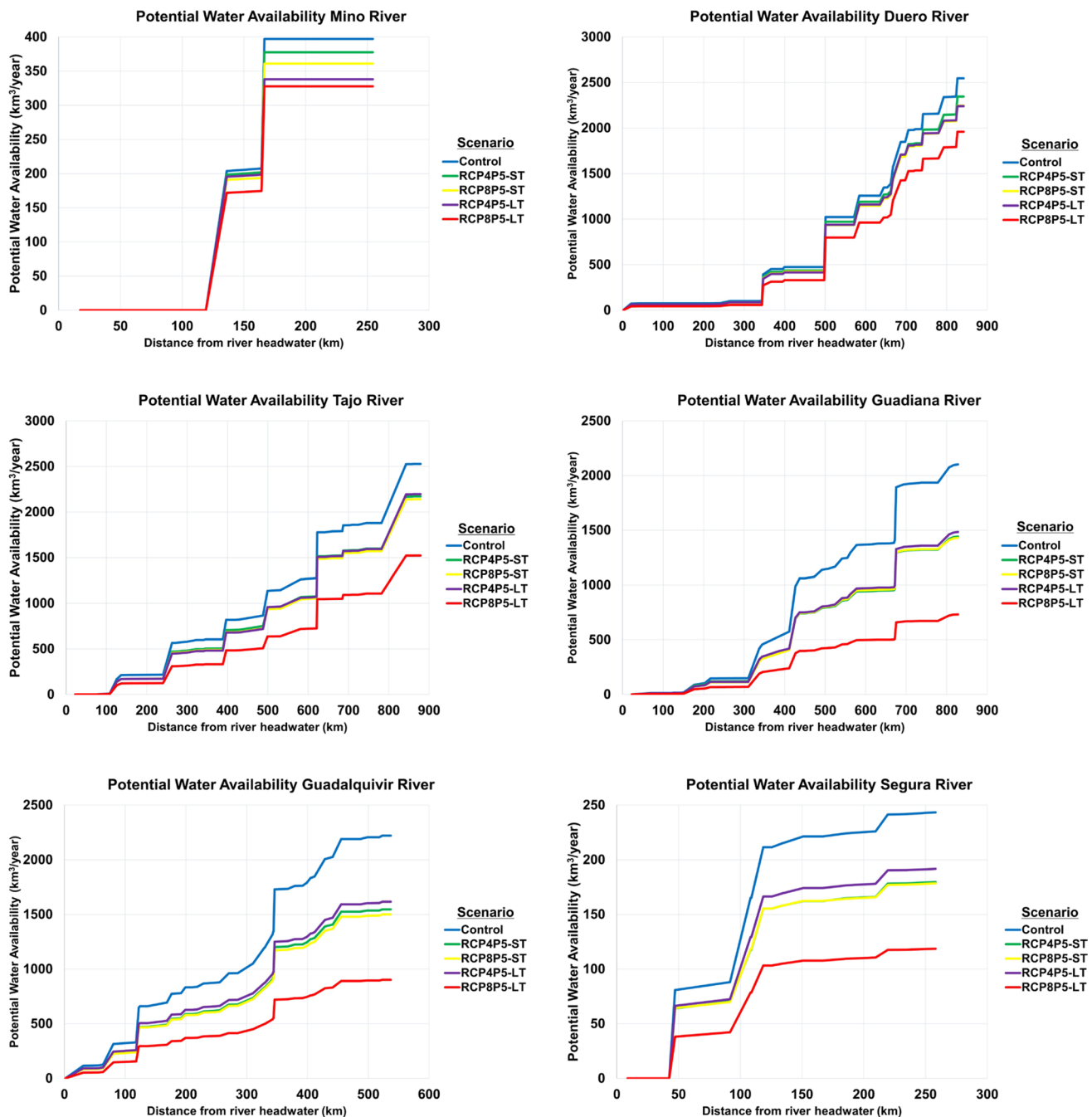


Fig. 8 Longitudinal profiles of potential water availability (PWA) for all considered scenarios and for the Jucar, Ebro, Mino, Duero, Tajo, Guadiana, Guadalquivir, and Segura River Basins

characteristics of each basin reveals the spatial and temporal changes along the river courses, illustrating the dynamic nature of these river systems. As climate change continues its inexorable pace, our findings underscore the urgent need for robust data-driven water management strategies in the Iberian Peninsula.

Within the scope of this research into the hydrological dynamics of the Iberian Peninsula, we have integrated

innovative methodologies that emphasise the novelty of our study. An essential aspect of this innovation is the use of a high-resolution topological model that encompasses the entire Iberian Peninsula with a precision of 15 arc seconds. This has enabled a more detailed and precise evaluation of hydrographic dynamics, surpassing the resolution limitations of previous studies (Sordo-Ward et al. 2019b, a; Sordo-Ward et al. 2020a, b). Furthermore, the choice and detailed

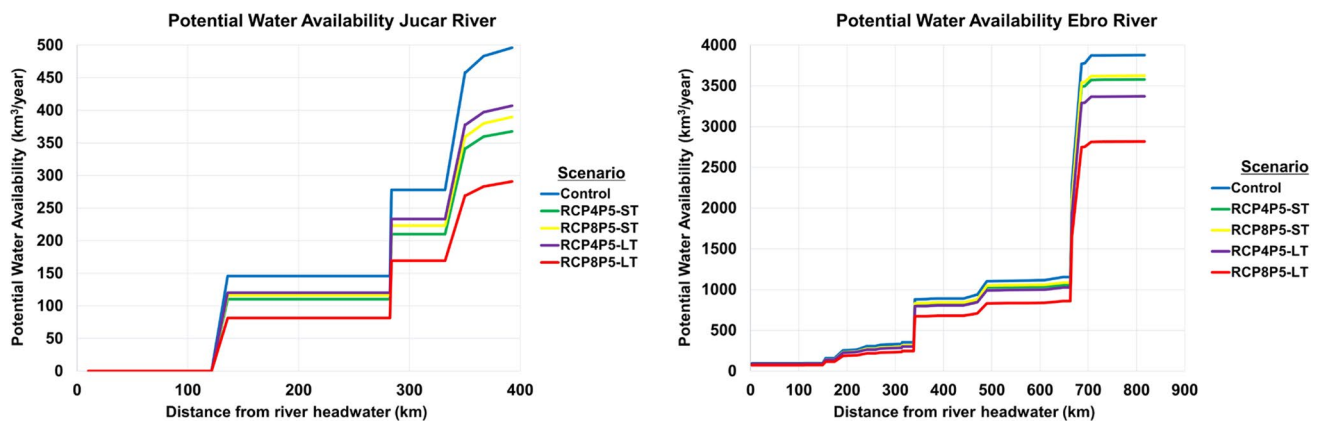


Fig. 9 Longitudinal profiles of potential water availability (PWA) for all considered scenarios and for the Júcar and Ebro River Basins

Table 4 Average variance (Δ) in mean annual flow for each basin in this study

Basin	RCP4.5-ST		RCP8.5-ST		RCP4.5-LT		RCP8.5-LT	
	Δ	SD	Δ	SD	Δ	SD	Δ	SD
Miño-Sil	− 0.154	0.034	− 0.134	0.037	− 0.104	0.039	− 0.315	0.060
Duero	− 0.167	0.010	− 0.156	0.009	− 0.129	0.009	− 0.360	0.014
Tajo	− 0.192	0.022	− 0.176	0.028	− 0.166	0.019	− 0.455	0.033
Guadiana	− 0.276	0.057	− 0.247	0.076	− 0.223	0.075	− 0.609	0.094
Guadalquivir	− 0.184	0.019	− 0.160	0.028	− 0.122	0.025	− 0.562	0.030
Segura	− 0.138	0.003	− 0.049	0.010	− 0.037	0.006	− 0.445	0.010
Júcar	− 0.124	0.010	− 0.038	0.013	− 0.072	0.016	− 0.350	0.016
Ebro	− 0.112	0.008	− 0.107	0.012	− 0.095	0.008	− 0.285	0.018

Table 5 Average variance (Δ) in potential water availability for each basin in this study

Basin	RCP4.5-ST		RCP8.5-ST		RCP4.5-LT		RCP8.5-LT	
	Δ	SD	Δ	SD	Δ	SD	Δ	SD
Miño-Sil	− 0.049	0.022	− 0.091	0.042	− 0.149	0.069	− 0.174	0.086
Duero	− 0.079	0.024	− 0.118	0.029	− 0.120	0.027	− 0.230	0.085
Tajo	− 0.141	0.035	− 0.153	0.041	− 0.132	0.041	− 0.398	0.085
Guadiana	− 0.314	0.064	− 0.320	0.044	− 0.294	0.049	− 0.652	0.083
Guadalquivir	− 0.304	0.038	− 0.324	0.041	− 0.273	0.038	− 0.594	0.071
Segura	− 0.262	0.080	− 0.267	0.081	− 0.212	0.064	− 0.513	0.155
Júcar	− 0.256	0.067	− 0.201	0.056	− 0.175	0.047	− 0.392	0.117
Ebro	− 0.077	0.021	− 0.065	0.021	− 0.130	0.027	− 0.274	0.022

examination of transnational hydrographic basins between Spain and Portugal offers a distinct point of view, especially relevant in the context of climate change and the joint management of water resources. The need to comprehend hydrological interactions within a wider and collaborative framework is emphasised by this cross-border approach. In addition, our research stands out for its thorough examination of the longitudinal river profiles in the studied basins. This methodology has enabled a more comprehensive understanding of regional and temporal fluctuations in flow and water availability, providing a more holistic understanding

of how river systems respond to climate change. The methodological advances that we have implemented in this study demonstrate our commitment to achieving a precise and comprehensive analysis.

Finally, it is necessary to highlight certain limitations within this study. Although we used a high-resolution topological model, the precision of our findings may be affected by limitations in the resolution and availability of hydrological and meteorological data. Furthermore, our dependence on projected climatic scenarios necessarily involves uncertainties that may impact the accuracy of future estimates

regarding water availability, even though they are derived from sophisticated climate models. Furthermore, although long-term climate change dynamics has been thoroughly examined, they may not fully account for unforeseen or sudden changes in climatic patterns or human activities that could unexpectedly affect the region's hydrology. Finally, although we mainly concentrated on the physical and climatic elements, we did not extensively incorporate the interaction with socioeconomic and political issues, which also exert a substantial influence on water management. These limitations highlight not only the areas that require improvement in our future research, but also the complexity associated with comprehensive water resource management in the context of climate change.

Conclusions

This study focused on assessing the mean annual flow and the potential availability of water in different river basins to better understand the hydrological complexities of the Iberian Peninsula in the context of a changing climate. By using a high-resolution topological model, we have successfully obtained a comprehensive and accurate representation of these hydrological systems. This approach has not only enhanced our comprehension but also strengthened our ability for robust analysis in the context of changing environmental conditions. The valuable knowledge obtained from this extensive investigation is crucial in influencing future plans for managing water resources, particularly in adapting to the unpredictable consequences of climate change.

Our analysis examined the hydrological dynamics of the Iberian Peninsula, which provided valuable information on mean annual flow and potential water availability under various climatic conditions. This comprehensive examination of eight river basins reveals significant potential consequences of climate change on hydrological patterns. Specifically, projections such as the high-emission RCP8.5-LT scenario anticipate severe decreases in river flows, particularly in basins such as Guadiana, Guadalquivir, and Segura, where declines could exceed 50%. On the other hand, the Duero and Ebro basins exhibit resilience, despite encountering problems. These findings emphasise the immediate requirement for flexible water management systems, customised to the distinct features of each basin, to lessen potential socio-ecological consequences and guarantee sustainable water resource management in response to climate change.

The results highlight the urgent need for adaptive management of water resources in the Iberian Peninsula due to the substantial variations in potential water availability that we have observed. Our research supports the use of adaptable and customised approaches that consider the distinct hydrological and climatic attributes of individual basins,

going beyond conventional management methods. These measures should include ongoing surveillance, prompt response capabilities, and the establishment of strong infrastructure. In addition, it is essential to promote interdisciplinary cooperation between hydrologists, policymakers, and community stakeholders. Together, these policies will improve the water systems in the region and prepare the Iberian Peninsula to successfully address the difficulties posed by climate change. This will ensure sustainable management of water resources for future generations.

This study represents a notable advancement in understanding the complex interaction between hydrological processes, the effects of climate change, and the availability of water resources in the Iberian Peninsula. Through the examination of different susceptibilities and adaptability of basins in diverse climate scenarios, we have improved our understanding of localised hydrological reactions to climatic pressures. Utilising advanced approaches, such as the WAAPA model, establishes a higher standard for future study, improving our ability to forecast water availability in changing climatic circumstances. Although our findings provide significant insights, they also present opportunities for additional investigation, such as evaluating the socio-economic effects of changes in water supply and examining more comprehensive climatic scenarios to obtain a more precise projection of these basins in future. This research is a significant achievement in advancing our knowledge of water supplies in response to global climate change.

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Author contributions Conceptualisation was performed by L.G., B.P.-B., and A.S.-W.; methodology was carried out by L.G., B.P.-B., and A.S.-W.; data processing was processed by B.P.-B. and F.M.-C.; software was developed by L.G. and B.P.-B.; validation was provided by F.M.-C. and A.S.-W.; writing—original draft preparation was revised by B.P.-B.; writing—review and editing was prepared by B.P.-B., L.G., F.M.-C., and A.S.-W.; visualisation was analysed by L.G. and B.P.-B.; supervision conducted by A.S.-W. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest The authors declare no conflict of interest.

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