Wiley Interdisciplinary Reviews: Water

WILEY

WIREs WATER

SYSTEMATIC REVIEW

Severe Impacts on Water Resources Projected for the Mediterranean Basin

J. P. C. Eekhout[1] | J. P. Nunes[2] | Y. Tramblay[3] | J. de Vente[1]

[1]Soil and Water Conservation Research Group, CEBAS-CSIC, Spanish Research Council, Murcia, Spain | [2]Soil Physics and Land Management Group, Wageningen University, Wageningen, the Netherlands | [3]Espace Dev, Université De Montpellier-IRD, Montpellier, France

Correspondence: J. P. C. Eekhout (joriseekhout@gmail.com)

Received: 5 November 2024 | **Revised:** 22 January 2025 | **Accepted:** 6 February 2025

Associate Editor: Anna Lintern | **Editor-in-Chief:** Wendy Jepson

Funding: This work was supported by Juan de la Cierva—Incorporación fellowship (IJC2020-044636-I) and by the LandEX project (PCI2024-153454), which has received funding from the Ministry of Science Innovation and Universities (MCIU) and the Spanish Research Agency (AEI 10.13039/501100011033/EU) and the European Union's Horizon Europe Programme under the 2022 Joint Transnational Call of the European Partnership Water4All (Grant Agreement n°101060874).

Keywords: climate change | drought | floods | Mediterranean | water quality

ABSTRACT

Water resources are becoming increasingly scarce in the Mediterranean Basin due to climate change. Through a systematic review of 262 catchment-based Mediterranean studies, we provide improved and detailed indications that runoff is projected to decrease by 19%, with increasing severity towards the end of the century and with increasing emission scenarios (up to −39%). We also show negative consequences for other water resources (soil moisture, aquifer recharge, irrigation demand), hydrological extremes (low flows), and water and soil quality (nutrient concentration, soil salinity, soil erosion), with negative impacts on rainfed and irrigated agriculture in the Mediterranean Basin. To protect water security, climate change adaptation aiming at more efficient water use and water retention in soils will be needed. While these adaptation measures have the potential to reverse the impacts of climate change, they may reduce downstream water availability and may be insufficient under extreme climate conditions.

1 | Introduction

The Mediterranean Basin has been identified as one of the global hot-spots of climate change (Giorgi 2006; IPCC 2023), most notably because of the projected decrease in precipitation (Nohara et al. 2006; Orlowsky and Seneviratne 2012), which may decrease by up to 30%–40% over the southern Iberian Peninsula and northwestern Africa at the end of the century, in the most extreme emission scenario (RCP8.5; Carvalho et al. 2022). Moreover, an increase in interannual variability and climate extremes is projected, including an increase in dry spells, extreme precipitation, and heatwaves (Orlowsky and Seneviratne 2012; Cramer et al. 2018; Tramblay and Somot 2018; Raymond et al. 2019; Lionello and Scarascia 2020; Molina et al. 2020; Zittis et al. 2021; IPCC 2023). As a consequence, climate change will have a significant impact on water resources availability in the Mediterranean Basin (García-Ruiz et al. 2011; Noto, Cipolla, Francipane, et al. 2023). Several large-scale climate change impact assessments have been performed in the Mediterranean Basin, which include studies that obtained projected changes in water resources directly from General Circulation Model (GCM) outputs, and by the application of integrated assessment models and global hydrological models (Table S1). These large-scale impact assessments project a 20% decrease in the net freshwater flux from the atmosphere to the surface (i.e., precipitation—actual evapotranspiration; Byrne and O'Gorman 2015) at the end of the century (Mariotti et al. 2008; Arjdal et al. 2023). Pan-Mediterranean runoff projections, that is, impact studies that give projections for the entire Mediterranean Basin, indicate a decrease of 10%–16% for the mid-century (Ludwig et al. 2010), toward 15%–38% for the end-century (Milano et al. 2013; Mariotti et al. 2015). Soil moisture is projected to decrease by 5%–9% (Mariotti et al. 2015; Arjdal et al. 2023), as a result of the projected increase in atmospheric demand and decrease in precipitation (Tramblay et al. 2018; Mimeau et al. 2021). Moreover, global-scale studies highlight a projected decrease in low flows (Wanders et al. 2015) and aquifer recharge (Reinecke et al. 2021; Berghuijs et al. 2024) for the Mediterranean Basin. These results show a general tendency of decreasing water resources in the Mediterranean Basin in the 21st century, aggravating the hydrological conditions for natural vegetation and rainfed crops, while increasing the irrigation water requirements for irrigated crops (Rodríguez-Díaz and Topcu 2010; Fader et al. 2016; Mairech et al. 2021). This stresses the need for the implementation of climate change adaptation to safeguard water security and future crop production (Cramer et al. 2018).

While global and pan-Mediterranean impact studies indicate severe impacts on water resources in the Mediterranean Basin, they also involve much uncertainty because of the lack of model calibration and the use of coarse-scale datasets. Catchment-scale studies, on the other hand, are often better tailored to local conditions, which make them also better suited to identify local differences and assess the potential of adaptation strategies. Catchment-scale impact assessments, for example, indicated more severe impacts on water resources in the Mediterranean Basin as compared to Central and Northern European areas (Hesse et al. 2015; Papadimitriou et al. 2016; Lobanova et al. 2018; Jorda-Capdevila et al. 2019; Hunink et al. 2019; Pastén-Zapata et al. 2022), which emphasizes the potential of catchment-scale studies to demonstrate contrasting impacts also at large spatial scales. Catchment-scale climate change impact assessments first appeared in the beginning of the 1990s using hypothetical climate change scenarios (Mimikou et al. 1991; Panagoulia 1991). The IS92 scenarios (IPCC Scenarios 1992; Leggett et al. 1992) were the first climate change scenarios that were adopted by the hydrological community. These scenarios were superseded by the SRES (Special Report Emission Scenarios; IPCC 2000) and RCP scenarios (Representative Concentration Pathways; Moss et al. 2008), gradually improving the spatial and temporal resolution of the climate change projections and the range of considered emission scenarios.

Pan-Mediterranean impact assessments have improved our understanding of how climate change may impact water resources in the Mediterranean Basin; however, in most cases, the projections are either directly obtained from the General Circulation Models (Mariotti et al. 2008, 2015; Arjdal et al. 2023) or from large-scale water balance models, without model calibration (Ludwig et al. 2010; Milano et al. 2013), leading to relatively little spatial detail and high uncertainty. Catchment-scale assessments provide a more detailed local perspective on these climate change impacts and may be more robust because of the use of local input data and model calibration with local observations (Hattermann et al. 2017; Kundzewicz et al. 2018). Here, we capitalize on the wealth of catchment-scale impact assessments performed in the Mediterranean Basin to project the change in water resources in the 21st century. To this end, we performed a systematic review of impact studies that apply a hydrological model forced with established climate change scenarios in the Mediterranean Basin. We obtained 1233 future projections from 262 studies for six water resources indicators, while accounting for emission scenarios and future periods. To obtain further insights, we also performed an informative review of the 262 selected studies, considering additional water security issues, including projections of hydrological extremes, water quality and soil quality, as well as the potential of climate change adaptation strategies.

2 | Material and Methods

2.1 | Systematic Review

We performed the systematic review process according to the SALSA framework (Search, AppraisaL, Synthesis, and Analysis; Grant and Booth 2009). The SALSA framework is a structured and contextual approach to perform systematic literature reviews and defines research questions and scope (Table S3), the search term, inclusion and exclusion criteria (Table S4), the extracted variables, and the postprocessing of the data. The application of the SALSA framework is further detailed in Data S1. The search term consisted of three main parts that focus on (1) water resources (including runoff, reservoir/lake inflow, soil moisture, aquifer recharge, and irrigation demand), (2) climate change, and (3) the Mediterranean Basin. Regarding the definition of the Mediterranean Basin, we focused on the area surrounding the Mediterranean Sea that is covered by the Mediterranean ecoregion (Figure 2), which describes the approximate extent of representative Mediterranean natural communities (Olson et al. 2001). The Mediterranean ecoregion covers all of the Mediterranean Sea coastline, except for some parts in Tunisia, Libya, and Egypt. The study area covers an area of 2.4 million km^2 across 32 countries. We only included those studies of which at least 50% of the study area intersects with the Mediterranean ecoregion. We also included only those studies that were performed in river catchments or groundwater aquifers, excluding small-scale (e.g., plot and hillslope scale studies) and large-scale studies (e.g., global, continental, and pan-Mediterranean studies).

The variables that were obtained from the selected studies were subdivided over five main themes, including bibliographic information, study area, climate models, hydrological model, and water resources projections (see Table S5 for the definition of the variables and Table S1 for the obtained variables per publication). The change in water resources was subdivided between six main water resources indicators, that is, runoff, reservoir/lake inflow, soil moisture, aquifer recharge, irrigation demand, and other water resources. The latter indicator (other water resources) includes studies that could not with enough certainty be included in any of the other five water resources indicators and includes studies that report water yield, water availability, and blue water (i.e., water stored as surface water). The runoff indicator is more specific and includes studies that report runoff or discharge. The reservoir/lake inflow indicator is even more specific and includes mostly studies that report reservoir inflow. The large number of runoff projections, as compared to

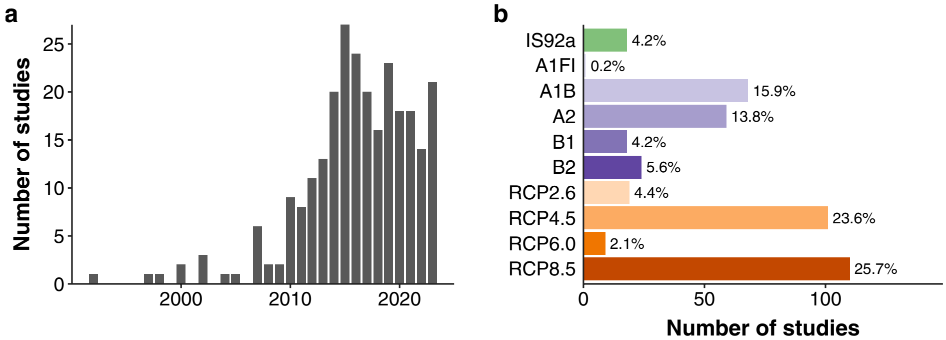

FIGURE 1 | (a) Number of studies published per year and (b) number of studies per emission scenarios.

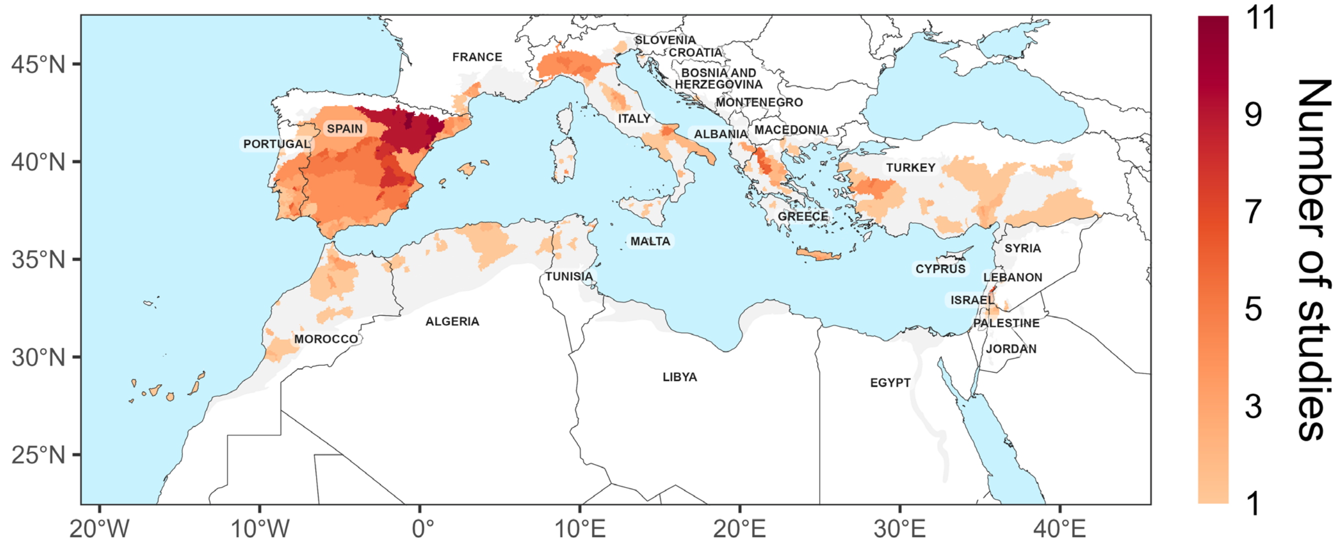

FIGURE 2 | Location of the study areas within the Mediterranean Basin. The boundary of the Mediterranean Basin is indicated in gray and the study areas in red, where darker colors indicate an increasing number of studies. The catchment boundaries were in most cases obtained from the HydroSHEDS database (Lehner et al. 2008).

the other five water resources indicators, allowed us to perform more detailed analysis, including a spatial representation of the results and a subdivision between emission scenarios and future periods.

The study mainly reports relative changes in water resources (Table S2), which were determined by dividing the projected changes in water resources by the values obtained in the reference/baseline period of each study. Data were extracted from the reported text, tables, and graphs, using image analysis software (WebPlotDigitizer) when necessary. The ensemble average was determined in cases where the water resources values were reported per individual climate model.

Climate change impact assessments involve the application of a model chain, including emissions scenarios, climate models, downscaling (i.e., the transformation from coarse scale GCM output to the spatial scale most appropriate for model assessments), bias correction (i.e., the correction applied to remove the bias between the historical model output and observations) and, ultimately, hydrological model application. Each of these components involves uncertainty, which has been quantified in the past in uncertainty decomposition studies. While there are some exceptions (Tian et al. 2016; Mandal and Simonovic 2017; Chegwidden et al. 2019), most studies suggest that climate models contribute most to the overall uncertainty of the model chain (Chen et al. 2011; Bosshard et al. 2013; Vetter et al. 2017; Kim et al. 2019; Ohn et al. 2021; Senatore et al. 2022). Several studies assessed the performance of individual climate models in the Mediterranean Basin (e.g., McSweeney et al. 2015; Cos et al. 2022), which could be used as a robustness metric in our analysis. However, not enough data were available in each of the selected studies to use the climate model performance to account for uncertainty. Therefore, we accounted for uncertainty by assigning a weight to each study based on the number of climate models used. Studies with 10 or more climate models (Wang et al. 2020) were assigned a weight of 1. Studies with fewer climate models were assigned a weight equal to the number of climate models divided by 10, that is, a weight of 0.1 for 1 climate model, a weight of 0.2 for 2 climate models, etc. The weights were subsequently used to plot weighted boxplots obtained from weighted quantiles, for quantiles 0.1, 0.25, 0.5, 0.75, and 0.9. The weighted quantiles were determined with the Hmisc R-package (v5.1.2; Harrell 2025). All analyses were performed using the R Statistical Software (v4.4.0; R Core Team 2024).

2.2 | Informative Review

Most of the selected studies also analyzed other water security issues. Through an informative review, we searched the selected articles for relevant keywords (Table S9) and annotated the projected changes for water security indicators relevant to hydrological extremes, water and soil quality, and climate change adaptation strategies. The projected changes were annotated in a semi-quantitative way, indicating strong increase (++; all scenarios project increase), increase (+; more than half of scenarios project increase), neutral (0; no change or equal number of scenarios with increase or decrease), decrease (–; more than half of the scenarios project decrease), and strong decrease (– –; all scenarios project decrease).

3 | Description of the Dataset

Our study includes 262 studies, from which the first was published in 1992, that is, Panagoulia (1992) (Figure 1a). It was not until 2007 that the number of studies per year started to increase, with a maximum in 2015 (27 studies). From 2014 onward, the publication rate remained around an average of 20 articles per year. The majority of the studies were published as journal articles (230 out of 262 studies), from which the most common journals are listed in Table S7. Other studies were published as conference papers (22 studies) or as book chapters (10 studies).

The studies were performed in 346 catchments located in 23 countries, most notably in Spain (114 catchments, including cross-bordering catchments), Italy (52), Greece (44), Portugal (39), France (28), Turkey (24), and Morocco (24) (Figure 2). Most studies were performed in the Iberian Peninsula, followed by France and Italy (Figure S1). The first studies were mainly performed in the Balkans, in particular in Greece. The 346 catchments cover a total area corresponding to 42.6% of the Mediterranean Basin. Most studies were performed in small (100–1000 km^2) and medium-sized catchments (1000–10,000 km^2), without a clear trend towards smaller or larger scale assessments (Figure S2). Most large-scale catchments are located in the Iberian Peninsula, such as the Duero (e.g., Sordo-Ward et al. 2019), Tagus (e.g., Lobanova et al. 2018), Guadiana (e.g., Papadimitriou et al. 2016), and Ebro catchments (e.g., Jorda-Capdevila et al. 2019), which all have a catchment size > 60,000 km^2. The Ebro River catchment (Spain) is also one of the most studied catchments with nine studies (e.g., González-Zeas et al. 2015). Other catchments are the Tagus in Spain and Portugal (eight times; e.g., Lobanova et al. 2016), Júcar in Spain (seven times; e.g., Hunink et al. 2019), Upper Jordan in Lebanon, Syria and Israel (seven times; e.g., Givati et al. 2019), Pinios in Greece (seven times; e.g., Mimikou et al. 2000), Segura in Spain (six times; e.g., Estrela et al. 2012), Po in Italy (four times; e.g., Pedro-Monzonís et al. 2016) and Gediz catchment in Turkey (four times; e.g., Gorguner and Kavvas 2020).

The first few studies (1992–2005) applied the IS92a scenario (Leggett et al. 1992) (Figure S3). With the introduction of the SRES scenarios (IPCC 2000), the number of studies started to increase from 2007 onward. The A1B (15.9%) and A2 (13.8%) scenarios are the most applied SRES scenarios (Figure 1b). The first studies that applied the RCP scenarios (Moss et al. 2008) appeared in 2015 and are the most applied scenarios from 2017 onward. The RCP4.5 and RCP8.5 are the most applied scenarios, amounting to 23.6% and 25.7% of all applied scenarios, respectively. Most studies adopt high emission scenarios (A2, A1FI, RCP8.5) (Figure S4). With the introduction of the RCP scenarios, there has been a shift from intermediate emission scenarios (IS92a, B2, A1B, RCP6.0) toward lower emissions scenarios (B1, RCP2.6, RCP4.5).

Most studies apply only a single climate model (36.9%), while the majority (78.7%) of the studies apply five climate models or less (Figures 3a and S5). With the introduction of the RCP scenarios in 2015, the share of studies applying six or more climate models increased. However, still in 2023, several studies apply only a single climate model. About half of the studies apply dynamical downscaling through the use of Regional Climate Model (RCM) output (Figure S6). The other half uses General Circulation Model (GCM) outputs, of which half applies statistical downscaling methods. Stochastic weather generators are the most popular statistical downscaling methods (Figure S7). About a quarter of the studies apply GCM output directly, without downscaling. The share of studies that apply RCM output is increasing, which is likely related to the free availability and application of RCM data through the PRUDENCE (Christensen and Christensen 2007), ENSEMBLES (van der Linden and Mitchell 2009), and EURO-CORDEX initiatives (Jacob et al. 2014).

A large portion of the studies apply both downscaling and bias correction (41.2%) (Figures 3b and S8). About half of the studies

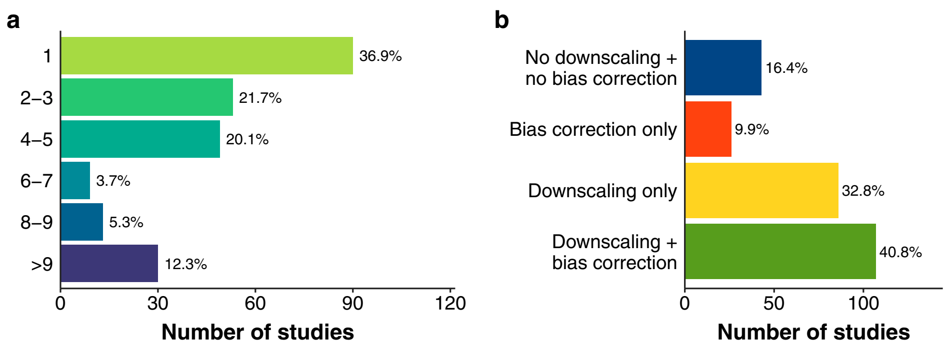

FIGURE 3 | (a) Number of studies per climate model ensemble size class and (b) number of studies that apply downscaling and/or bias correction.

apply bias correction only, from which the majority apply the change factor (51.9%) and quantile mapping methods (33.1%) (Figure S9).

On average, the reference periods are centered around the year 1990, with a mean period of 25 years. Most studies focus on mid-century assessments (45.5%), followed by end-century (35.5%), and early-century (19.0%) (Figure S10). The future periods have a mean length of 23 years.

The most used hydrological model is SWAT (Arnold et al. 2012) with 57 applications (21.8%), followed by GR2M (18 studies Mouelhi et al. 2006) and HEC-HMS (10 studies Scharffenberg 2013) (Table S8). The majority of the studies apply a hydrological model that runs on a daily time step (64.0%; Figure S11), followed by models with a monthly time step (27.9%). We obtained a total of 1233 water resources projections, divided over the six water resources indicators, emission scenarios, and future periods. Most projections were obtained for runoff (741 projections), followed by aquifer recharge (150), irrigation demand (111), reservoir/lake inflow (93), other water resources (82), and soil moisture (56).

4 | Water Resources Projections in the Mediterranean Basin

The selected catchment studies show that climate change is projected to cause a decrease in all of the main water resources in the Mediterranean Basin, that is, runoff, reservoir/lake inflow, soil moisture, and aquifer recharge (Figure 4). Runoff is projected to decrease by −19.1% (weighted median). While the results indicate a fair amount of variation among the different studies, the majority of the studies project a decrease in runoff. The projected decrease in runoff is in the range of most previous pan-Mediterranean assessments (−15% to −21%; Mariotti et al. 2008; Ludwig et al. 2010; Mariotti et al. 2015; Arjdal et al. 2023), except for the projections by Milano et al. (2013), who project a more severe decrease, ranging from −25% to −50%, based on the high emission scenario A2 (Table S6).

Reservoir/lake inflow is projected to decrease slightly (−2.6%), with the projections spread equally among positive and negative values. Hence, a more moderate decrease in reservoir/lake inflow is projected as compared with runoff. The relatively small number of studies (23) that considered reservoir/lake inflow might affect the results. An increase in reservoir/lake inflow was projected in studies where (extreme) precipitation is projected to increase (Eekhout et al. 2018; Rocha et al. 2020; Beça et al. 2023; Okkan et al. 2023; Savino et al. 2023). These studies had a relatively high contribution to the resulting weighted median. Moreover, the reservoir/lake inflow projections seem more diverse as compared to other indicators with fewer studies, such as soil moisture and aquifer recharge, which suggests more uncertain results.

All other indicators are projected to change more consistently. This is in particular the case for soil moisture, where the majority of the studies project a decrease, with a weighted median decrease of −13.7%. These soil moisture estimates are more severe than previously projected by pan-Mediterranean studies, which projected decreasing soil moisture from −5% to −9% (Mariotti et al. 2015; Arjdal et al. 2023; see also Table S6).

Aquifer recharge is projected to decrease most among the different output variables, with a weighted median of −21.0%. This is consistent with aquifer recharge projections for the Mediterranean Basin based on the global assessment by Reinecke et al. (2021), which range from −17% to −34%, depending on the global temperature increase (Table S6). Irrigation demand is projected to increase by +8.3%, with projections reaching up to 284.4% (Figure S12). The weighted median increase of +8.3% is in the range of the pan-Mediterranean irrigation water demand projections by Fader et al. (2016), which range between +4% and +18%, depending on the emission scenarios. The other water resources (i.e., water yield, water availability, and blue water) show similar results as runoff, with a weighted median decrease of −20.0%.

The large number of runoff projections allowed for a spatial analysis of the results. We mapped the average change in

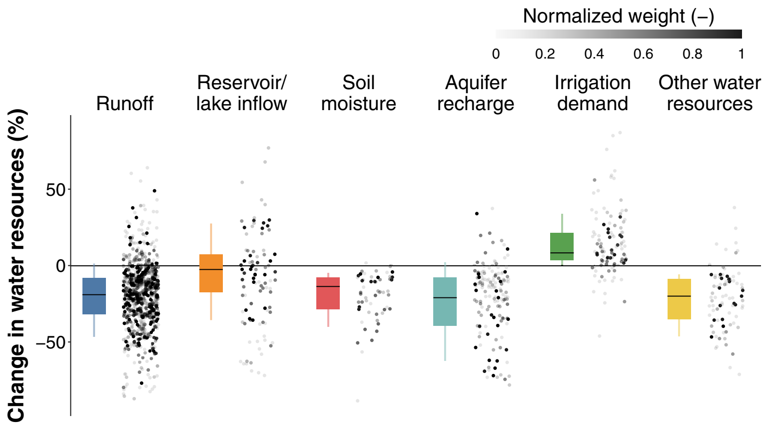

FIGURE 4 | Projected change per water resource category (%). The colored boxes indicate the weighted interquartile range (25th and 75th percentiles), the black horizontal line the weighted median (50th percentile), and the whiskers extend to the weighted 10th and 90th percentiles. The jitter plot shows the projected change in water resources per study, considering the different study areas, periods and emission scenarios. The gray shades indicate the robustness of the studies, as defined by the number of climate models used and quantified with the normalized weight. For clarity, the figure is truncated at ±90%, the full dataset is shown in Figure S12.

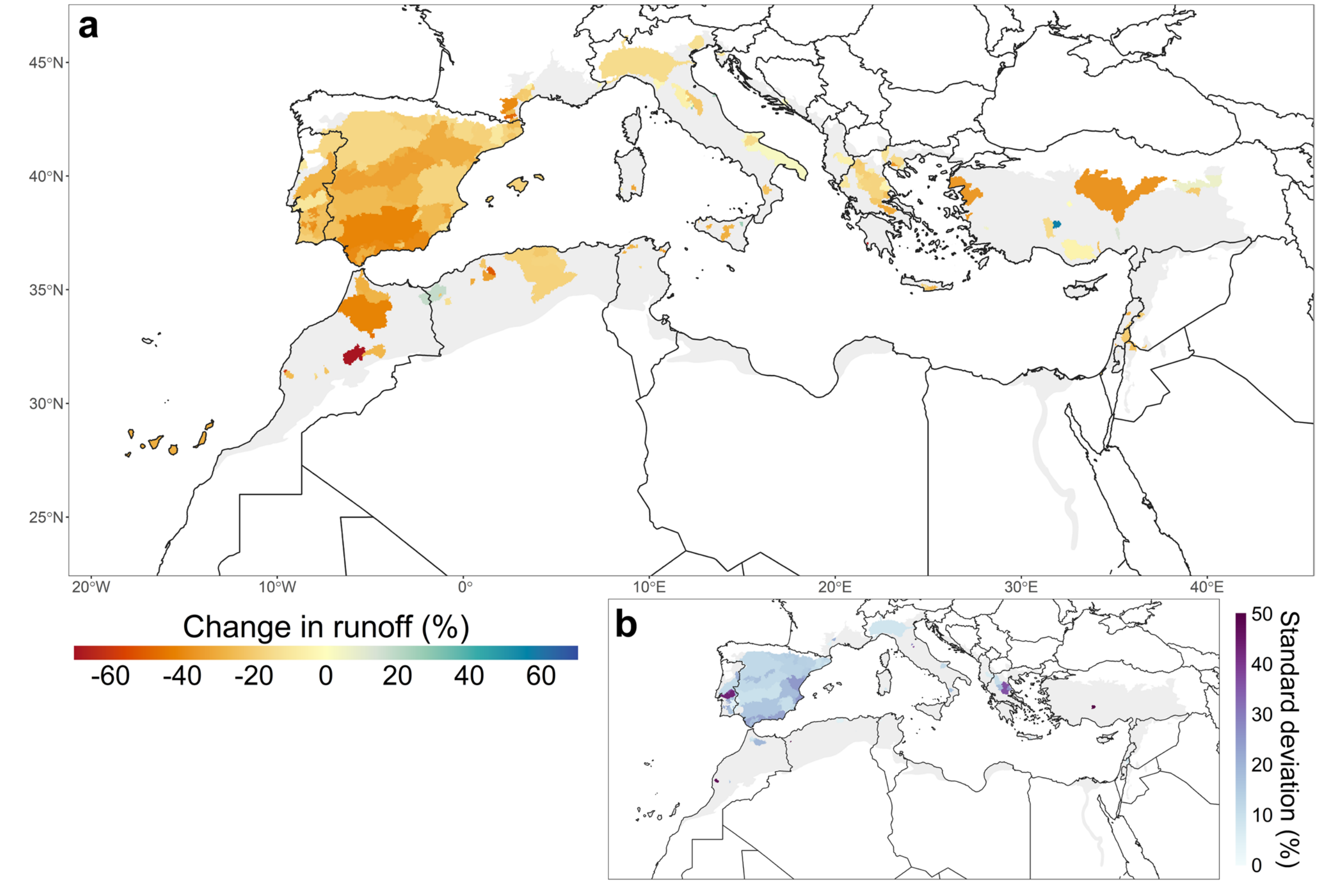

FIGURE 5 | Projected change in runoff (%) and standard deviation of the change in runoff (%) among the different studies (right bottom corner). First, we determined the average change in runoff per study, considering the different periods and emission scenarios, and projected this onto a raster with a 0.05° grid size using the catchment boundaries. Next, we determined the average and standard deviation among the different studies. The standard deviation was determined only for grid cells with at least two overlapping studies.

runoff per catchment using the catchment perimeters we obtained for all study areas (Figure 5a). The spatial distribution of the runoff projections reveals a north–south gradient in the Iberian Peninsula, with increasing severity toward the south of the peninsula. These results confirm several studies in the Iberian Peninsula that showed a similar gradient in severity (Da Cunha et al. 2007; Estrela et al. 2012; Nunes et al. 2013; Rasilla et al. 2013; González-Zeas et al. 2015; Lastrada et al. 2021). However, there also seems to be increasing uncertainty from the northwest to the southeast of the Iberian Peninsula, quantified by an increasing standard deviation (Figure 5b). The results also seem to suggest more extreme decreasing projections for the southern part of Italy, including the island of Sicily (e.g., Viola et al. 2016), and several regions in Turkey (e.g., Avcı et al. 2023), Morocco (e.g., El Khalki et al. 2021), and Algeria (e.g., Hadour et al. 2020). However, these results were mostly obtained from single studies, which make them more uncertain. The standard deviation map reveals some regions and catchments with relatively high uncertainties, most notably in central Portugal, central Greece, and some isolated catchments in Turkey, Morocco, and Algeria.

The north–south gradient in severity in the Iberian Peninsula and more extreme decreasing projections for southern Italy and several regions in Turkey, Morocco, and Algeria (Figure 5) correspond with the spatial distribution of the runoff projections of the pan-Mediterranean climate change assessment by Milano et al. (2013). However, most other pan-Mediterranean water balance projections (i.e., precipitation—actual evapotranspiration) obtained from General Circulation Models lack clear spatial differences within the Mediterranean Basin (Mariotti et al. 2008, 2015; Carvalho et al. 2022; Arjdal et al. 2023). This is in contrast to several climate change studies showing more pronounced spatial differences in temperature (Molina et al. 2020) and precipitation projections (Tramblay and Somot 2018; Raymond et al. 2019; Lionello and Scarascia 2020; Zittis et al. 2021; Carvalho et al. 2022) within the Mediterranean Basin. It is, therefore, likely that spatial differences in runoff are expected under future climate change.

While Figure 5 gives an overview of all runoff studies, it also shows that there is a lot of uncertainty, which may originate from differences in applied methodology, including the size of the climate model ensemble, postprocessing of climate model data, and hydrological models (Clark et al. 2016; Noto, Cipolla, Pumo, et al. 2023). Our results include several multi-catchment studies spanning two countries, in which the same methodology was used and can, therefore, better highlight spatial differences. These studies showed an increasing impact from the Po (Italy) to the Ebro and Guadalquivir catchments (Spain) (Alpert et al. 2014; Sordo-Ward et al. 2019), from the Herault (France) to the Loukkos catchment (Morocco) (Ruelland et al. 2015) and from the Thau (France) to the Chiba catchment (Tunisia) (Sellami et al. 2016). This highlights the increasing severity from the north toward the south of the Mediterranean Basin. Similarly, an increase in severity is shown from the Devoll (Albania) to the Kizilirmak catchment (Turkey) (Bakken et al. 2016), highlighting the increasing severity from the Central Mediterranean toward the Eastern Mediterranean. These studies highlight some spatial differences in runoff projections; however, because of the lack of extended spatial coverage, it is hard to draw solid conclusions from these results that are representative for the entire Mediterranean Basin. Hence, to detect further spatial differences, more catchment studies are required throughout the Mediterranean Basin, ideally using state-of-the-art emission scenarios, downscaling and bias-correction techniques, and hydrological models. Apart from the Iberian Peninsula, catchment studies are required in the entire Mediterranean Basin, especially in those areas where no catchment studies have been performed up to now (i.e., the gray areas in Figure 5), particularly in the southern and eastern Mediterranean Basin. Moreover, it would be useful to perform climate change assessments in areas with contrasting results (i.e., decreasing and increasing runoff projections), such as in Morocco/Algeria, Turkey, and Sicily (southern Italy).

The large number of runoff projections also allows us to differentiate the results between future periods and emission scenarios. The projected decrease in runoff will be more severe toward the end of the century and under high emission scenarios (Figure 6). All emission scenarios project a moderate decrease in runoff in the early century, with most decrease projected by the high emission scenarios (−8.7%). The differences between the emission scenarios increases in the mid-century. While the low and intermediate emission scenarios show similar projections around −11%, high emission scenarios project almost a double decrease of −19.3%. A similar difference between the three emission scenarios is projected for the end century, with comparable projections for low and intermediate emission scenarios around −20% and a doubling of those projections for the high emission scenarios with −38.7%.

The decreasing trend in runoff towards the end of the century and the increasing impact under higher emission scenarios has also been emphasized by pan-Mediterranean studies (Ludwig et al. 2010; Arjdal et al. 2023, see also Table S6). However, our results show more severe impacts for the end century under intermediate and high emission scenarios (−15% to −20%; Mariotti et al. 2015; Arjdal et al. 2023) and less severe impacts for the mid-century under a high emission scenario (−25% to −50%; Milano et al. 2013).

5 | Contrasting Impacts on Hydrological Extremes

Pan-Mediterranean studies showed that extreme precipitation is projected to increase in the Mediterranean Basin, most evidently in the Northern Mediterranean (Gao et al. 2006; Tramblay and Somot 2018; Lionello and Scarascia 2020; Zittis et al. 2021). Only a few catchment studies quantified the projected change in extreme precipitation, which provided a much more diverse result regarding the direction of change (Table S10). The projected change in flood magnitude and duration was quantified by 24 studies, but similarly showed contrasting results. Less than half of these studies project an increase in flood duration and magnitude (9 studies), while 10 studies project a decrease, and 5 studies project no change in floods. The differences in the direction of change seem unrelated to the location of the study sites, emission scenarios, or future periods used by the studies. Neither of these projections coincide with large-scale flood projections for the northern Mediterranean (Alfieri et al. 2015; Thober et al. 2018), which project decreasing flood magnitudes for the southern Iberian Peninsula and Greece and increasing flood magnitudes for Northern Italy. A projected increase in flood magnitude in the Mediterranean Basin is suggested to be caused by an increase in extreme precipitation

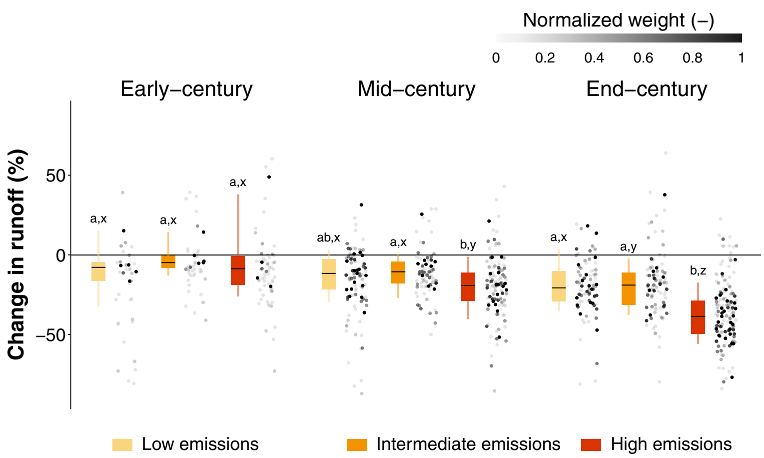

FIGURE 6 | Projected change in runoff (%), differentiated between the three future periods and the three emission scenario categories. The colored boxes indicate the weighted interquantile range (25th and 75th percentiles), the black horizontal line the weighted median (50th percentile) and the whiskers extend to the weighted 10th and 90th percentiles. The jitter plot shows the projected change in water resources per study. The gray shades indicate the robustness of the studies, as defined by the number of climate models used and quantified with the normalized weight. The boxplots followed by a common letter are not significantly different by the Wilcoxon rank-sum test at the 5% level of significance. Different combinations of letters were used to indicate significant differences within each of the three future periods (a, b, c) and within each emission scenario category (x, y, z).

(Cervi et al. 2018; Eekhout and de Vente 2019; Sirigu and Montaldo 2022) and a projected decrease in flood magnitude by a decrease in soil moisture content (Nunes et al. 2013; Sellami et al. 2016; Senatore et al. 2022). Decreasing soil moisture content has also been suggested to be one of the main drivers for decreasing flood magnitudes in Southern France over the past decades (Tramblay et al. 2019, 2023). Increasing extreme precipitation (Table S10) and decreasing soil moisture content (Figure 4) will likely occur simultaneously in some parts of the Mediterranean Basin and might counteract their impact on flood magnitudes, notably impacting the most frequent, but lower intensity, flood events (Wasko and Nathan 2019). More research will be needed on these contrasting impacts on flood magnitude, in particular for the most extreme events (Wasko et al. 2021), as well as their temporal and spatial differences within the Mediterranean Basin.

The observed historical increase in flood magnitude in the Mediterranean Basin is mostly associated with the increase in convective precipitation events (Llasat 2021; Tramblay et al. 2023). If the trend of increasing convective precipitation events continues into the future, it is unclear. Climate model outputs are mostly limited to daily time steps, while convective precipitation events are sub-daily phenomena (Fosser et al. 2024). Hence, most climate models do not yet simulate convective precipitation events. Currently, convection-permitting climate models are being developed, and the first studies show that an increase in floods due to convective precipitation events is projected for Mediterranean catchments (Poncet et al. 2024). To advance on this issue, there is a need to use high-resolution convection-permitting climate model outputs (Fosser et al. 2024) as input for hydrological models, which will allow detailed representation of (flash) flood processes in the Mediterranean Basin (Tramblay et al. 2020; Brunner et al. 2021).

Projections for drought-related indicators like dry spells and low flow duration and magnitude are more consistent than projections of floods in catchment studies. The duration of dry spells was quantified by two studies, which both project an increase (Table S10) in agreement with two pan-Mediterranean studies (Raymond et al. 2019; Lionello and Scarascia 2020). Pan-Mediterranean dry spell projections (obtained with the RCP4.5 and RCP8.5 scenarios) are most severe in southern Spain, Morocco, Algeria, and the Eastern Mediterranean (Raymond et al. 2019). These areas coincide with those where runoff is projected to decrease most (obtained from the A2 scenario) (Milano et al. 2013), which illustrates the predictive capability of dry spells in relation to runoff and likely low flows. The impact on low flow duration from the selected studies is very consistent, where all five studies project an increase. Similarly, the low flow magnitude is projected to decrease consistently according to eight out of nine studies. These results coincide with the low flow projections for the northern Mediterranean by Marx et al. (2018), who showed a consistent decrease in low flow magnitude, and a particularly severe decrease in low flow magnitude for the Iberian Peninsula and Greece. Despite these clear trends for drought-related indicators, there is a need to improve our knowledge on changes in low flows, most notably by accounting for the surface-groundwater interactions in karstic catchments (Sivelle et al. 2021).

6 | Negative Impacts on Water and Soil Quality

Climate change is not only affecting water quantity in rivers, reservoirs, and the soil, but also affects water and soil quality in the Mediterranean Basin. The impact of climate change on water quality has been assessed by quantifying concentrations and loads of different water quality indicators. Most studies project an increase in the concentration of phosphorus, nitrogen, ammonium, and chloride under climate change (Table S11). This is most likely due to decreasing runoff, while input from nutrient sources (i.e., agricultural fields) is projected to be constant or to increase, which ultimately leads to increasing concentrations. This is expected to lead to increasing water quality issues, including deteriorating impacts on aquatic ecology (Stefanidis et al. 2018; Vagheei et al. 2023). However, at the same time, total nutrient loads are projected to decrease due to decreasing runoff, including decreasing phosphorus and nitrate loads (Table S11). How this will affect water quality in reservoirs, lakes, deltas, and coastal zones is unclear because of the complex interplay between water quantity and water quality indicators.

Soil salinity is the most considered soil quality indicator in the reviewed literature, most likely because of its importance for agricultural soils (Corwin 2021; Mukhopadhyay et al. 2021). Increasing soil salinity is often projected in coastal zones, where decreasing aquifer recharge reduces groundwater flow towards the Mediterranean Sea (Colombani et al. 2016), which increases soil salinity caused by seawater intrusion, that may be further worsened due to sea level rise (Carneiro et al. 2010). Irrigation may also be responsible for soil salinization, where excessive irrigation may increase the water table, bringing up salts from the deeper soil layers toward the root zone (Singh 2021). An increase in soil salinity is projected for coastal study areas in Morocco and Spain (Table S11). Salinity levels may reach levels corresponding to saline soils (Haj-Amor and Bouri 2020), ultimately leading to the loss of arable land (Pisinaras et al. 2021). Moreover, an increase in soil salinity could affect drinking water quality (Romanazzi et al. 2015), worsening the impact on water security in the Mediterranean Basin.

Soil and water quality will also be affected by soil erosion because of the associated decrease in soil organic matter and increase in suspended sediment concentrations (Morgan 2005; Amundson et al. 2015). Apart from some exceptions, most evaluated studies project an increase in soil erosion in the Mediterranean Basin (Table S11), with increasing soil erosion rates up to 40% (Eekhout et al. 2018; Pastor et al. 2019). This general tendency coincides with the projected average increase in soil erosion (+7%) for Mediterranean climate zones (Eekhout and de Vente 2022). The projected increase in extreme precipitation is one of the main drivers for the projected increase in soil erosion and landslides (Ciabatta et al. 2016), even despite decreasing annual precipitation in some case studies (Eekhout et al. 2018; Mouris et al. 2023). The impact of climate change on sediment yield at the catchment outlet and sedimentation of reservoirs seems less problematic, where studies project a decrease or no changes with respect to the reference period (Table S11). Similar to the decrease in total nutrient load mentioned earlier, this is related to a decrease in river transport capacity due to decreasing runoff and river discharge (Eekhout et al. 2018). Land use change may have even more important impacts on soil erosion than climate change in the Mediterranean Basin (Raclot et al. 2018), with increasing erosion rates projected for agricultural intensification scenarios and decreasing rates for afforestation scenarios (Serpa et al. 2015; Pastor et al. 2019; Eekhout and de Vente 2022).

7 | Potential for Climate Change Adaptation

Climate change adaptation will be needed to mitigate the projected decrease in available water resources in the Mediterranean Basin. Most studies focus on climate change adaptation by more efficient water use in irrigated agriculture. This includes studies on the potential of large-scale implementation of drip irrigation and reduced deficit irrigation (Table S12), which have the potential to reduce irrigation water demand under climate change, even below reference conditions. These studies confirm the pan-Mediterranean irrigation projections by Fader et al. (2016), who showed that a conversion to drip irrigation would lead to a reduction of gross irrigation demand of about 30% with respect to reference conditions. This would more than counterbalance the increase in irrigation water demand caused by climate change. These results show that more efficient irrigation techniques have the potential to adapt irrigated agriculture to climate change in the Mediterranean Basin. Nevertheless, it is important to consider that more efficient water use in irrigation only alleviates stress on water resources if saved water in agriculture is not used for the expansion of irrigated agricultural land, as is often observed (Grafton et al. 2018).

Other on-site climate change adaptation measures focus on water retention through practices like reduced tillage and soil improvement by organic amendments and cover crops. These practices may lead to increased soil moisture (Table S12), thereby improving resilience to climate change for rainfed agriculture. However, such measures also lead to decreasing runoff and water yield, with potential negative impacts on off-site water resource availability, such as storage in reservoirs. Stakeholder consultation showed that adaptation measures applied in less productive rainfed agricultural areas are more likely to be implemented than those applied in high-productive areas (Naulleau et al. 2022). Moreover, land managers are often in favor of small-scale (least-regret) adaptation measures, such as improving water use and network efficiency, wastewater recycling, and modernization of agricultural operations (Girard et al. 2015; Dias et al. 2020). Large-scale adaptation measures that require significant policy support, such as the construction of desalination plants, are thought to be more effective but less likely to be implemented because of the high costs involved (Seif-Ennasr et al. 2016). Such large-scale measures also include managed aquifer recharge, which is shown to be effective in increasing groundwater volumes and could prevent seawater intrusion, with positive impacts on groundwater salinity (Table S12).

8 | Conclusions

Through a systematic review, we show that runoff in the Mediterranean is projected to decrease by −19.1% (weighted median), with increasing severity towards the end of the century and under higher emission scenarios (up to −38.7%). Similar trends were obtained for low and intermediate emission scenarios, which are in most cases about half the impact compared with the high emission scenarios. A gradient of increasing severity is projected from the north to the south of the Mediterranean Basin and in particular within the Iberian Peninsula. However, these projections involve much uncertainty, which suggests that there is a need for more catchment studies on the impact of climate change on runoff in the Mediterranean Basin, especially in the southern and eastern Mediterranean Basin. Our results confirm previous pan-Mediterranean runoff projections (Table S6), but provide more detailed spatial insights and highlight the differences between future periods and emission scenarios. The projected decrease in runoff, reservoir/lake inflow, and aquifer recharge (Figure 7) suggests that irrigation water supply from surface water and aquifers is projected to decrease in the Mediterranean Basin. In

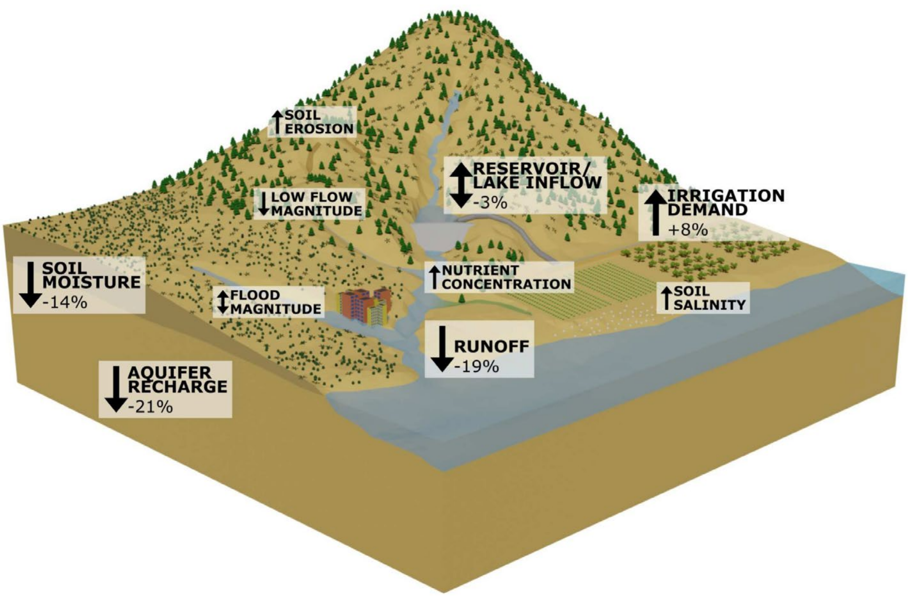

FIGURE 7 | Summary of the impact of climate change on water resources in the Mediterranean Basin. An upward arrow indicates increasing projections, a downward arrow indicates decreasing projections, and a combination indicates projections without a clear direction of change.

combination with the projected increase in irrigation water demand (+8.3%), this suggests increasing pressure on irrigated agriculture. Similarly, the projected decrease in soil moisture (−13.7%) will likely have negative consequences for natural vegetation and rainfed agriculture. Hence, these projections suggest a negative impact of climate change on both rainfed and irrigated agriculture in the Mediterranean Basin.

Our review of projected impacts on broader water security issues revealed a consistent increase in dry spells, with an equally consistent increase in low flow duration and a decrease in low flow magnitude. However, projections for extreme precipitation and floods give more contrasting results, without a clear increasing or decreasing trends at the scale of the Mediterranean Basin. The changes in water resources affect water quality, with mostly increasing trends in nutrient concentration, but decreasing trends in annual nutrient loads. This is most likely the result of the projected decrease in runoff, which allows fewer nutrients to be transported toward reservoirs and the Mediterranean Sea. A similar response is projected for sediment transport and sediment yield. However, soil erosion is projected to increase, which is often related to the projected increase in extreme precipitation. Agricultural soils will be affected by increasing soil salinity as a result of decreasing aquifer recharge, increasing seawater intrusion, and more intensive irrigated agriculture.

Climate change adaptation has the potential to mitigate the negative impact of climate change on water resources, hydrological extremes, and other water security risks in the Mediterranean Basin. A conversion from traditional irrigation techniques toward drip irrigation and reduced deficit irrigation can reduce the impact of climate change on irrigation water demand. Rainfed agriculture can be made more resilient to climate change by implementing sustainable land management to improve the water retention capacity of the soil (e.g., reduced tillage and cover crops). Although water retention can help decreasing the impacts of climate change on soil moisture, it may also cause trade-offs regarding off-site water resources availability. In rainfed agriculture, small-scale adaptation strategies, such as reduced tillage, are often found to be popular among stakeholders because of their efficiency and lower costs. However, it was also shown that additional adaptation strategies are needed under more extreme climate scenarios.

This study shows the invaluable contribution of catchment studies to assess the impacts and local differences of climate change on water resources and the potential for adaptation in the Mediterranean Basin. The catchment studies confirm general trends observed in several pan-Mediterranean studies but show a more severe decrease in soil moisture and add new projections regarding aquifer recharge and reservoir/lake inflow based on more robust climate change assessments. Moreover, these catchment-based studies provide insights with the detail needed to develop effective climate change adaptation strategies fit to local environmental and socioeconomic conditions. However, more catchment studies are needed that consider multiple water resources indicators to highlight the contrasting impacts of climate change on water security in the Mediterranean Basin.

Author Contributions

J. P. C. Eekhout: conceptualization (equal), data curation (lead), formal analysis (lead), funding acquisition (equal), investigation (lead), visualization (lead), writing – original draft (lead). **J. P. Nunes:** conceptualization (equal), writing – review and editing (equal). **Y. Tramblay:** conceptualization (equal), writing – review and editing (equal). **J. de Vente:** conceptualization (equal), funding acquisition (equal), supervision (lead), writing – review and editing (equal).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available in the Supporting Information.

Related WIREs Articles

Challenges in modeling and predicting floods and droughts: A review

Scientific evidence of the hydrological impacts of nature-based solutions at the catchment scale

References

Alfieri, L., P. Burek, L. Feyen, and G. Forzieri. 2015. "Global Warming Increases the Frequency of River Floods in Europe." *Hydrology and Earth System Sciences* 19, no. 5: 2247–2260.

Alpert, P., F. Jin, and A. Kitoh. 2014. "The Projected Death of the Fertile Crescent." In *A World After Climate Change and Culture-Shift*, edited by J. Norwine, 193–203. Springer Netherlands.

Amundson, R., A. A. Berhe, J. W. Hopmans, C. Olson, A. E. Sztein, and D. L. Sparks. 2015. "Soil and Human Security in the 21st Century." *Science* 348, no. 6235: 1261071.

Arjdal, K., F. Driouech, É. Vignon, et al. 2023. "Future of Land Surface Water Availability Over the Mediterranean Basin and North Africa: Analysis and Synthesis From the CMIP6 Exercise." *Atmospheric Science Letters* 24, no. 11: e1180.

Arnold, J. G., D. N. Moriasi, P. W. Gassman, et al. 2012. "Swat: Model Use, Calibration, and Validation." *Asabe* 55, no. 4: 1491–1508.

Avcı, B. C., E. Kesgin, M. Atam, R. I. Tan, and M. Abdelkader. 2023. "Short-Term Climate Change Influence on Surface Water Quality Impacts From Agricultural Activities." *Environmental Science and Pollution Research* 30, no. 38: 89581–89596.

Bakken, T., C. Almestad, J. Melhuus Rugelbak, M. Escobar, S. Micko, and K. Alfredsen. 2016. "Climate Change and Increased Irrigation Demands: What Is Left for Hydropower Generation? Results From Two Semi-Arid Basins." *Energies* 9, no. 3: 191.

Beça, P., A. C. Rodrigues, J. P. Nunes, P. Diogo, and B. Mujtaba. 2023. "Optimizing Reservoir Water Management in a Changing Climate." *Water Resources Management* 37, no. 9: 3423–3437.

Berghuijs, W. R., R. A. Collenteur, S. Jasechko, et al. 2024. "Groundwater Recharge Is Sensitive to Changing Long-Term Aridity." *Nature Climate Change* 14: 357–363.

Bosshard, T., M. Carambia, K. Goergen, et al. 2013. "Quantifying Uncertainty Sources in an Ensemble of Hydrological Climate-Impact Projections." *Water Resources Research* 49, no. 3: 1523–1536.

Brunner, M. I., L. Slater, L. M. Tallaksen, and M. Clark. 2021. "Challenges in Modeling and Predicting Floods and Droughts: A Review." *WIREs Water* 8, no. 3: e1520.

Byrne, M. P., and P. A. O'Gorman. 2015. "The Response of Precipitation Minus Evapotranspiration to Climate Warming: Why the "Wet-Get-Wetter, Dry-Get-Drier" Scaling Does Not Hold Over Land." *Journal of Climate* 28, no. 20: 8078–8092.

Carneiro, J. F., M. Boughriba, A. Correia, Y. Zarhloule, A. Rimi, and B. El Houadi. 2010. "Evaluation of Climate Change Effects in a Coastal Aquifer in Morocco Using a Density-Dependent Numerical Model." *Environmental Earth Sciences* 61, no. 2: 241–252.

Carvalho, D., S. C. Pereira, R. Silva, and A. Rocha. 2022. "Aridity and Desertification in the Mediterranean Under EURO-CORDEX Future Climate Change Scenarios." *Climatic Change* 174, no. 3–4: 28.

Cervi, F., F. Petronici, A. Castellarin, M. Marcaccio, A. Bertolini, and L. Borgatti. 2018. "Climate-Change Potential Effects on the Hydrological Regime of Freshwater Springs in the Italian Northern Apennines." *Science of the Total Environment* 622–623: 337–348.

Chegwidden, O. S., B. Nijssen, D. E. Rupp, et al. 2019. "How Do Modeling Decisions Affect the Spread Among Hydrologic Climate Change Projections? Exploring a Large Ensemble of Simulations Across a Diversity of Hydroclimates." *Earth's Future* 7, no. 6: 623–637.

Chen, J., F. P. Brissette, and R. Leconte. 2011. "Uncertainty of Downscaling Method in Quantifying the Impact of Climate Change on Hydrology." *Journal of Hydrology* 401, no. 3–4: 190–202.

Christensen, J. H., and O. B. Christensen. 2007. "A Summary of the PRUDENCE Model Projections of Changes in European Climate by the End of This Century." *Climatic Change* 81, no. 1: 7–30.

Ciabatta, L., S. Camici, L. Brocca, et al. 2016. "Assessing the Impact of Climate-Change Scenarios on Landslide Occurrence in Umbria Region, Italy." *Journal of Hydrology* 541: 285–295.

Clark, M. P., R. L. Wilby, E. D. Gutmann, et al. 2016. "Characterizing Uncertainty of the Hydrologic Impacts of Climate Change." *Current Climate Change Reports* 2, no. 2: 55–64.

Colombani, N., A. Osti, G. Volta, and M. Mastrocicco. 2016. "Impact of Climate Change on Salinization of Coastal Water Resources." *Water Resources Management* 30, no. 7: 2483–2496.

Corwin, D. L. 2021. "Climate Change Impacts on Soil Salinity in Agricultural Areas." *European Journal of Soil Science* 72, no. 2: 842–862.

Cos, J., F. Doblas-Reyes, M. Jury, R. Marcos, P.-A. Bretonnière, and M. Samsó. 2022. "The Mediterranean Climate Change Hotspot in the CMIP5 and CMIP6 Projections." *Earth System Dynamics* 13, no. 1: 321–340.

Cramer, W., J. Guiot, M. Fader, et al. 2018. "Climate Change and Interconnected Risks to Sustainable Development in the Mediterranean." *Nature Climate Change* 8, no. 11: 972–980.

Da Cunha, L., R. De Oliveira, J. Nascimento, and L. Ribeiro. 2007. *Impacts of Climate Change on Water Resources: A Case-Study for Portugal*. Vol. 310, 37–48. IAHS-AISH Publication.

Dias, L. F., B. A. Aparício, J. P. Nunes, et al. 2020. "Integrating a Hydrological Model Into Regional Water Policies: Co-Creation of Climate Change Dynamic Adaptive Policy Pathways for Water Resources in Southern Portugal." *Environmental Science & Policy* 114: 519–532.

Eekhout, J. P. C., and J. de Vente. 2019. "Assessing the Effectiveness of Sustainable Land Management for Large-Scale Climate Change Adaptation." *Science of the Total Environment* 654: 85–93.

Eekhout, J. P. C., and J. de Vente. 2022. "Global Impact of Climate Change on Soil Erosion and Potential for Adaptation Through Soil Conservation." *Earth-Science Reviews* 226: 103921.

Eekhout, J. P. C., J. E. Hunink, W. Terink, and J. de Vente. 2018. "Why Increased Extreme Precipitation Under Climate Change Negatively Affects Water Security." *Hydrology and Earth System Sciences* 22, no. 11: 5935–5946.

El Khalki, E. M., Y. Tramblay, L. Hanich, A. Marchane, A. Boudhar, and B. Hakkani. 2021. "Climate Change Impacts on Surface Water Resources in the Oued El Abid Basin, Morocco." *Hydrological Sciences Journal* 66, no. 15: 2132–2145.

Estrela, T., M. A. Pérez-Martin, and E. Vargas. 2012. "Impacts of Climate Change on Water Resources in Spain." *Hydrological Sciences Journal* 57, no. 6: 1154–1167.

Fader, M., S. Shi, W. Von Bloh, A. Bondeau, and W. Cramer. 2016. "Mediterranean Irrigation Under Climate Change: More Efficient Irrigation Needed to Compensate for Increases in Irrigation Water Requirements." *Hydrology and Earth System Sciences* 20, no. 2: 953–973.

Fosser, G., M. Gaetani, E. J. Kendon, et al. 2024. "Convection-Permitting Climate Models Offer More Certain Extreme Rainfall Projections." *npj Climate and Atmospheric Science* 7, no. 1: 1–10.

Gao, X., J. S. Pal, and F. Giorgi. 2006. "Projected Changes in Mean and Extreme Precipitation Over the Mediterranean Region From a High Resolution Double Nested RCM Simulation." *Geophysical Research Letters* 33, no. 3: 2005GL024954. https://doi.org/10.1029/2005GL024954.

García-Ruiz, J. M., J. I. López-Moreno, S. M. Vicente-Serrano, T. Lasanta–Martínez, and S. Beguería. 2011. "Mediterranean Water Resources in a Global Change Scenario." *Earth-Science Reviews* 105, no. 3–4: 121–139.

Giorgi, F. 2006. "Climate Change Hot-Spots." *Geophysical Research Letters* 33, no. 8: 1–4.

Girard, C., M. Pulido-Velazquez, J.-D. Rinaudo, C. Pagé, and Y. Caballero. 2015. "Integrating Top–Down and Bottom–Up Approaches to Design Global Change Adaptation at the River Basin Scale." *Global Environmental Change* 34: 132–146.

Givati, A., G. Thirel, D. Rosenfeld, and D. Paz. 2019. "Climate Change Impacts on Streamflow at the Upper Jordan River Based on an Ensemble of Regional Climate Models." *Journal of Hydrology: Regional Studies* 21: 92–109.

González-Zeas, D., L. Garrote, A. Iglesias, A. Granados, and A. Chávez-Jiménez. 2015. "Hydrologic Determinants of Climate Change Impacts on Regulated Water Resources Systems." *Water Resources Management* 29, no. 6: 1933–1947.

Gorguner, M., and M. L. Kavvas. 2020. "Modeling Impacts of Future Climate Change on Reservoir Storages and Irrigation Water Demands in a Mediterranean Basin." *Science of the Total Environment* 748: 141246.

Grafton, R. Q., J. Williams, C. J. Perry, et al. 2018. "The Paradox of Irrigation Efficiency." *Science* 361, no. 6404: 748–750.

Grant, M. J., and A. Booth. 2009. "A Typology of Reviews: An Analysis of 14 Review Types and Associated Methodologies." *Health Information and Libraries Journal* 26, no. 2: 91–108.

Hadour, A., G. Mahé, and M. Meddi. 2020. "Watershed Based Hydrological Evolution Under Climate Change Effect: An Example From North Western Algeria." *Journal of Hydrology: Regional Studies* 28: 100671.

Haj-Amor, Z., and S. Bouri. 2020. "Use of HYDRUS-1D–GIS Tool for Evaluating Effects of Climate Changes on Soil Salinization and Irrigation Management." *Archives of Agronomy and Soil Science* 66, no. 2: 193–207.

Harrell, F. E. 2025. "Hmisc: Harrell Miscellaneous."

Hattermann, F. F., V. Krysanova, S. N. Gosling, et al. 2017. "Cross-Scale Intercomparison of Climate Change Impacts Simulated by Regional and Global Hydrological Models in Eleven Large River Basins." *Climatic Change* 141, no. 3: 561–576.

Hesse, C., A. Stefanova, and V. Krysanova. 2015. "Comparison of Water Flows in Four European Lagoon Catchments Under a Set of Future Climate Scenarios." *Water* 7, no. 12: 716–746.

Hunink, J., G. Simons, S. Suárez-Almiñana, et al. 2019. "A Simplified Water Accounting Procedure to Assess Climate Change Impact on Water Resources for Agriculture Across Different European River Basins." *Water* 11, no. 10: 1976.

IPCC. 2000. *Special Report on Emissions Scenarios*. Cambridge University Press.

IPCC. 2023. *Climate Change 2022—Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 1st ed. Cambridge University Press.

Jacob, D., J. Petersen, B. Eggert, et al. 2014. "EURO-CORDEX: New High-Resolution Climate Change Projections for European Impact Research." *Regional Environmental Change* 14, no. 2: 563–578.

Jorda-Capdevila, D., D. Gampe, V. Huber García, et al. 2019. "Impact and Mitigation of Global Change on Freshwater-Related Ecosystem Services in Southern Europe." *Science of the Total Environment* 651: 895–908.

Kim, Y., I. Ohn, J.-K. Lee, and Y.-O. Kim. 2019. "Generalizing Uncertainty Decomposition Theory in Climate Change Impact Assessments." *Journal of Hydrology X* 3: 100024.

Kundzewicz, Z. W., V. Krysanova, R. E. Benestad, Ø. Hov, M. Piniewski, and I. M. Otto. 2018. "Uncertainty in Climate Change Impacts on Water Resources." *Environmental Science & Policy* 79: 1–8.

Lastrada, E., J. Garzón-Roca, G. Cobos, and F. J. Torrijo. 2021. "A Decrease in the Regulatory Effect of Snow-Related Phenomena in Spanish Mountain Areas due to Climate Change." *Water* 13, no. 11: 1550.

Leggett, J., W. J. Pepper, and R. J. Swart. 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*. Cambridge University Press.

Lehner, B., K. Verdin, and A. Jarvis. 2008. "New Global Hydrography Derived From Spaceborne Elevation Data." *Eos, Transactions American Geophysical Union* 89, no. 10: 93–94.

Lionello, P., and L. Scarascia. 2020. "The Relation of Climate Extremes With Global Warming in the Mediterranean Region and Its North Versus South Contrast." *Regional Environmental Change* 20, no. 1: 31.

Llasat, M. C. 2021. "Floods Evolution in the Mediterranean Region in a Context of Climate and Environmental Change." *Cuadernos de Investigación Geográfica* 47, no. 1: 13–32.

Lobanova, A., H. Koch, S. Liersch, F. F. Hattermann, and V. Krysanova. 2016. "Impacts of Changing Climate on the Hydrology and Hydropower Production of the Tagus River Basin." *Hydrological Processes* 30, no. 26: 5039–5052.

Lobanova, A., S. Liersch, J. P. Nunes, et al. 2018. "Hydrological Impacts of Moderate and High-End Climate Change Across European River Basins." *Journal of Hydrology: Regional Studies* 18: 15–30.

Ludwig, W., A. F. Bouwman, E. Dumont, and F. Lespinas. 2010. "Water and Nutrient Fluxes From Major Mediterranean and Black Sea Rivers: Past and Future Trends and Their Implications for the Basin-Scale Budgets: River Discharges to the Mediterranean." *Global Biogeochemical Cycles* 24, no. 4: GB0A13.

Mairech, H., Á. López-Bernal, M. Moriondo, et al. 2021. "Sustainability of Olive Growing in the Mediterranean Area Under Future Climate Scenarios: Exploring the Effects of Intensification and Deficit Irrigation." *European Journal of Agronomy* 129: 126319.

Mandal, S., and S. P. Simonovic. 2017. "Quantification of Uncertainty in the Assessment of Future Streamflow Under Changing Climate Conditions." *Hydrological Processes* 31, no. 11: 2076–2094.

Mariotti, A., Y. Pan, N. Zeng, and A. Alessandri. 2015. "Long-Term Climate Change in the Mediterranean Region in the Midst of Decadal Variability." *Climate Dynamics* 44, no. 5–6: 1437–1456.

Mariotti, A., N. Zeng, J.-H. Yoon, et al. 2008. "Mediterranean Water Cycle Changes: Transition to Drier 21st Century Conditions in Observations and CMIP3 Simulations." *Environmental Research Letters* 3, no. 4: 044001.

Marx, A., R. Kumar, S. Thober, et al. 2018. "Climate Change Alters Low Flows in Europe Under Global Warming of 1.5, 2, and 3°C." *Hydrology and Earth System Sciences* 22, no. 2: 1017–1032.

McSweeney, C. F., R. G. Jones, R. W. Lee, and D. P. Rowell. 2015. "Selecting CMIP5 GCMs for Downscaling Over Multiple Regions." *Climate Dynamics* 44, no. 11: 3237–3260.

Milano, M., D. Ruelland, S. Fernandez, et al. 2013. "Current State of Mediterranean Water Resources and Future Trends Under Climatic and Anthropogenic Changes." *Hydrological Sciences Journal* 58, no. 3: 498–518.

Mimeau, L., Y. Tramblay, L. Brocca, C. Massari, S. Camici, and P. Finaud-Guyot. 2021. "Modeling the Response of Soil Moisture to Climate Variability in the Mediterranean Region." *Hydrology and Earth System Sciences* 25, no. 2: 653–669.

Mimikou, M., E. Baltas, E. Varanou, and K. Pantazis. 2000. "Regional Impacts of Climate Change on Water Resources Quantity and Quality Indicators." *Journal of Hydrology* 234, no. 1–2: 95–109.

Mimikou, M., Y. Kouvopoulos, G. Cavadias, and N. Vayianos. 1991. "Regional Hydrological Effects of Climate Change." *Journal of Hydrology* 123, no. 1–2: 119–146.

Molina, M. O., E. Sánchez, and C. Gutiérrez. 2020. "Future Heat Waves Over the Mediterranean From an Euro-CORDEX Regional Climate Model Ensemble." *Scientific Reports* 10, no. 1: 8801.

Morgan, R. P. C. 2005. *Soil Erosion and Conservation*. 3rd ed. Blackwell Science Ltd.

Moss, R., M. Babiker, S. Brinkman, et al. 2008. "Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies: IPCC Expert Meeting Report: 19–21 September, 2007, Noordwijkerhout, the Netherlands." Intergovernmental Panel on Climate Change, Geneva, 132.

Mouelhi, S., C. Michel, C. Perrin, and V. Andréassian. 2006. "Stepwise Development of a Two-Parameter Monthly Water Balance Model." *Journal of Hydrology* 318, no. 1–4: 200–214.

Mouris, K., S. Schwindt, M. H. Pesci, S. Wieprecht, and S. Haun. 2023. "An Interdisciplinary Model Chain Quantifies the Footprint of Global Change on Reservoir Sedimentation." *Scientific Reports* 13, no. 1: 20160.

Mukhopadhyay, R., B. Sarkar, H. S. Jat, P. C. Sharma, and N. S. Bolan. 2021. "Soil Salinity Under Climate Change: Challenges for Sustainable Agriculture and Food Security." *Journal of Environmental Management* 280: 111736.

Naulleau, A., C. Gary, L. Prévot, F. Vinatier, and L. Hossard. 2022. "How Can Winegrowers Adapt to Climate Change? A Participatory Modeling Approach in Southern France." *Agricultural Systems* 203: 103514.

Nohara, D., A. Kitoh, M. Hosaka, and T. Oki. 2006. "Impact of Climate Change on River Discharge Projected by Multimodel Ensemble." *Journal of Hydrometeorology* 7, no. 5: 1076–1089.

Noto, L. V., G. Cipolla, A. Francipane, and D. Pumo. 2023. "Climate Change in the Mediterranean Basin (Part I): Induced Alterations on Climate Forcings and Hydrological Processes." *Water Resources Management* 37, no. 6: 2287–2305.

Noto, L. V., G. Cipolla, D. Pumo, and A. Francipane. 2023. "Climate Change in the Mediterranean Basin (Part II): A Review of Challenges and Uncertainties in Climate Change Modeling and Impact Analyses." *Water Resources Management* 37, no. 6: 2307–2323.

Nunes, J. P., J. Seixas, and J. J. Keizer. 2013. "Modeling the Response of Within-Storm Runoff and Erosion Dynamics to Climate Change in Two Mediterranean Watersheds: A Multi-Model, Multi-Scale Approach to Scenario Design and Analysis." *Catena* 102: 27–39.

Ohn, I., S. Kim, S. B. Seo, Y.-O. Kim, and Y. Kim. 2021. “Model-Wise Uncertainty Decomposition in Multi-Model Ensemble Hydrological Projections.” *Stochastic Environmental Research and Risk Assessment* 35, no. 12: 2549–2565.

Okkan, U., O. Fistikoglu, Z. B. Ersoy, and A. T. Noori. 2023. “Investigating Adaptive Hedging Policies for Reservoir Operation Under Climate Change Impacts.” *Journal of Hydrology* 619: 129286.

Olson, D. M., E. Dinerstein, E. D. Wikramanayake, et al. 2001. “Terrestrial Ecoregions of the World: A New Map of Life on Earth.” *Bioscience* 51, no. 11: 933.

Orlowsky, B., and S. I. Seneviratne. 2012. “Global Changes in Extreme Events: Regional and Seasonal Dimension.” *Climatic Change* 110, no. 3–4: 669–696.

Panagoulia, D. 1991. “Hydrological Response of a Medium-Sized Mountainous Catchment to Climate Changes.” *Hydrological Sciences Journal* 36, no. 6: 525–547.

Panagoulia, D. 1992. “Impacts of GISS-Modelled Climate Changes on Catchment Hydrology.” *Hydrological Sciences Journal* 37, no. 2: 141–163.

Papadimitriou, L. V., A. G. Koutroulis, M. G. Grillakis, and I. K. Tsanis. 2016. “High-End Climate Change Impact on European Runoff and Low Flows—Exploring the Effects of Forcing Biases.” *Hydrology and Earth System Sciences* 20, no. 5: 1785–1808.

Pastén-Zapata, E., R. Pimentel, P. Royer-Gaspard, et al. 2022. “The Effect of Weighting Hydrological Projections Based on the Robustness of Hydrological Models Under a Changing Climate.” *Journal of Hydrology: Regional Studies* 41: 101113.

Pastor, A. V., J. P. Nunes, R. Ciampalini, et al. 2019. “Projecting Future Impacts of Global Change Including Fires on Soil Erosion to Anticipate Better Land Management in the Forests of NW Portugal.” *Water* 11, no. 12: 2617.

Pedro-Monzonís, M., M. Del Longo, A. Solera, S. Pecora, and J. Andreu. 2016. “Water Accounting in the Po River Basin Applied to Climate Change Scenarios.” *Procedia Engineering* 162: 246–253.

Pisinaras, V., C. Paraskevas, and A. Panagopoulos. 2021. “Investigating the Effects of Agricultural Water Management in a Mediterranean Coastal Aquifer Under Current and Projected Climate Conditions.” *Water* 13, no. 1: 108.

Poncet, N., P. Lucas-Picher, Y. Tramblay, et al. 2024. “Does a Convection-Permitting Regional Climate Model Bring New Perspectives on the Projection of Mediterranean Floods?” *Natural Hazards and Earth System Sciences* 24, no. 4: 1163–1183.

R Core Team. 2024. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.

Raclot, D., Y. Le Bissonnais, M. Annabi, M. Sabir, and A. Smetanova. 2018. “Main Issues for Preserving Mediterranean Soil Resources From Water Erosion Under Global Change.” *Land Degradation & Development* 29, no. 3: 789–799.

Rasilla, D. F., C. Garmendia, and J. C. García-Codron. 2013. “Climate Change Projections of Streamflow in the Iberian Peninsula.” *International Journal of Water Resources Development* 29, no. 2: 184–200.

Raymond, F., A. Ullmann, Y. Tramblay, P. Drobinski, and P. Camberlin. 2019. “Evolution of Mediterranean Extreme Dry Spells During the Wet Season Under Climate Change.” *Regional Environmental Change* 19, no. 8: 2339–2351.

Reinecke, R., H. Müller Schmied, T. Trautmann, et al. 2021. “Uncertainty of Simulated Groundwater Recharge at Different Global Warming Levels: A Global-Scale Multi-Model Ensemble Study.” *Hydrology and Earth System Sciences* 25, no. 2: 787–810.

Rocha, J., C. Carvalho-Santos, P. Diogo, P. Beça, J. J. Keizer, and J. P. Nunes. 2020. “Impacts of Climate Change on Reservoir Water Availability, Quality and Irrigation Needs in a Water Scarce Mediterranean Region (Southern Portugal).” *Science of the Total Environment* 736: 139477.

Rodríguez-Díaz, J. A., and S. Topcu. 2010. “Sustaining Mediterranean Irrigated Agriculture Under a Changing Climate.” *Outlook on Agriculture* 39, no. 4: 269–275.

Romanazzi, A., F. Gentile, and M. Polemio. 2015. “Modelling and Management of a Mediterranean Karstic Coastal Aquifer Under the Effects of Seawater Intrusion and Climate Change.” *Environmental Earth Sciences* 74, no. 1: 115–128.

Ruelland, D., P. Hublart, and Y. Tramblay. 2015. “Assessing Uncertainties in Climate Change Impacts on Runoff in Western Mediterranean Basins.” *Proceedings of the International Association of Hydrological Sciences* 371: 75–81.

Savino, M., V. Todaro, A. Maranzoni, and M. D'Oria. 2023. “Combining Hydrological Modeling and Regional Climate Projections to Assess the Climate Change Impact on the Water Resources of Dam Reservoirs.” *Water* 15, no. 24: 4243.

Scharffenberg, W. 2013. *HEC-HMS User's Manual, Version 4.2. Technical Report*. U.S. Army Corps of Engineers: Hydrologic Engineering Center, HEC.

Seif-Ennasr, M., R. Zaaboul, A. Hirich, et al. 2016. “Climate Change and Adaptive Water Management Measures in Chtouka Aït Baha Region (Morocco).” *Science of the Total Environment* 573: 862–875.

Sellami, H., S. Benabdallah, I. La Jeunesse, and M. Vanclooster. 2016. “Quantifying Hydrological Responses of Small Mediterranean Catchments Under Climate Change Projections.” *Science of the Total Environment* 543: 924–936.

Senatore, A., D. Fuoco, M. Maiolo, G. Mendicino, G. Smiatek, and H. Kunstmann. 2022. “Evaluating the Uncertainty of Climate Model Structure and Bias Correction on the Hydrological Impact of Projected Climate Change in a Mediterranean Catchment.” *Journal of Hydrology: Regional Studies* 42: 101120.

Serpa, D., J. P. Nunes, J. Santos, et al. 2015. “Impacts of Climate and Land Use Changes on the Hydrological and Erosion Processes of Two Contrasting Mediterranean Catchments.” *Science of the Total Environment* 538: 64–77.

Singh, A. 2021. “Soil Salinization Management for Sustainable Development: A Review.” *Journal of Environmental Management* 277: 111383.

Sirigu, S., and N. Montaldo. 2022. “Climate Change Impacts on the Water Resources and Vegetation Dynamics of a Forested Sardinian Basin Through a Distributed Ecohydrological Model.” *Water* 14, no. 19: 3078.

Sivelle, V., H. Jourde, D. Bittner, N. Mazzilli, and Y. Tramblay. 2021. “Assessment of the Relative Impacts of Climate Changes and Anthropogenic Forcing on Spring Discharge of a Mediterranean Karst System.” *Journal of Hydrology* 598: 126396.

Sordo-Ward, A., A. Granados, A. Iglesias, L. Garrote, and M. Bejarano. 2019. “Adaptation Effort and Performance of Water Management Strategies to Face Climate Change Impacts in Six Representative Basins of Southern Europe.” *Water* 11, no. 5: 1078.

Stefanidis, K., Y. Panagopoulos, and M. Mimikou. 2018. “Response of a Multi-Stressed Mediterranean River to Future Climate and Socio-Economic Scenarios.” *Science of the Total Environment* 627: 756–769.

Thober, S., R. Kumar, N. Wanders, et al. 2018. “Multi-Model Ensemble Projections of European River Floods and High Flows at 1.5, 2, and 3 Degrees Global Warming.” *Environmental Research Letters* 13, no. 1: 014003.

Tian, Y., Y.-P. Xu, M. J. Booij, and L. Cao. 2016. “Impact Assessment of Multiple Uncertainty Sources on High Flows Under Climate Change.” *Hydrology Research* 47, no. 1: 61–74.

Tramblay, Y., P. Arnaud, G. Artigue, et al. 2023. "Changes in Mediterranean Flood Processes and Seasonality." *Hydrology and Earth System Sciences* 27, no. 15: 2973–2987.

Tramblay, Y., L. Jarlan, L. Hanich, and S. Somot. 2018. "Future Scenarios of Surface Water Resources Availability in North African Dams." *Water Resources Management* 32, no. 4: 1291–1306.

Tramblay, Y., M. C. Llasat, C. Randin, and E. Coppola. 2020. "Climate Change Impacts on Water Resources in the Mediterranean." *Regional Environmental Change* 20, no. 3: 83.

Tramblay, Y., L. Mimeau, L. Neppel, F. Vinet, and E. Sauquet. 2019. "Detection and Attribution of Flood Trends in Mediterranean Basins." *Hydrology and Earth System Sciences* 23, no. 11: 4419–4431.

Tramblay, Y., and S. Somot. 2018. "Future Evolution of Extreme Precipitation in the Mediterranean." *Climatic Change* 151, no. 2: 289–302.

Vagheei, H., A. Laini, P. Vezza, G. Palau-Salvador, and F. Boano. 2023. "Climate Change Impact on the Ecological Status of Rivers: The Case of Albaida Valley (SE Spain)." *Science of the Total Environment* 893: 164645.

van der Linden, P., and J. F. B. Mitchell. 2009. "ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results From the ENSEMBLES Project." Technical Report, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.

Vetter, T., J. Reinhardt, M. Flörke, et al. 2017. "Evaluation of Sources of Uncertainty in Projected Hydrological Changes Under Climate Change in 12 Large-Scale River Basins." *Climatic Change* 141, no. 3: 419–433.

Viola, F., A. Francipane, D. Caracciolo, D. Pumo, G. La Loggia, and L. V. Noto. 2016. "Co-Evolution of Hydrological Components Under Climate Change Scenarios in the Mediterranean Area." *Science of the Total Environment* 544: 515–524.

Wanders, N., Y. Wada, and H. a. J. Van Lanen. 2015. "Global Hydrological Droughts in the 21st Century Under a Changing Hydrological Regime." *Earth System Dynamics* 6, no. 1: 1–15.

Wang, H.-M., J. Chen, C.-Y. Xu, J. Zhang, and H. Chen. 2020. "A Framework to Quantify the Uncertainty Contribution of GCMs Over Multiple Sources in Hydrological Impacts of Climate Change." *Earth's Future* 8, no. 8: e2020EF001602.

Wasko, C., and R. Nathan. 2019. "Influence of Changes in Rainfall and Soil Moisture on Trends in Flooding." *Journal of Hydrology* 575: 432–441.

Wasko, C., R. Nathan, L. Stein, and D. O'Shea. 2021. "Evidence of Shorter More Extreme Rainfalls and Increased Flood Variability Under Climate Change." *Journal of Hydrology* 603: 126994.

Zittis, G., A. Bruggeman, and J. Lelieveld. 2021. "Revisiting Future Extreme Precipitation Trends in the Mediterranean." *Weather and Climate Extremes* 34: 100380.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.