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# Vegetation greening and reservoir construction as drivers of century-long discharge trends in the Mediterranean Basin

Joris P.C. Eekhout [a,b,*], Hamouda Boutaghane [c], Hamouda Dakhlaoui [d], El Mahdi El Khalki [e], Gökçen Uysal [f], Sergio M. Vicente Serrano [g], Yves Tramblay [h], Joris de Vente [b]

[a] Department of Geography, University of Murcia, Murcia, Spain
[b] Soil and Water Conservation Research Group, CEBAS-CSIC, Spanish National Research Council, Murcia, Spain
[c] Laboratory of Soil and Hydraulic, Badji Mokhtar Annaba University, Annaba, Algeria
[d] Laboratoire de Modélisation en Hydraulique et Environnement (LMHE), Ecole Nationale des Ingénieurs de Tunis (ENIT), Tunis, Tunisia
[e] International Water Research Institute, Mohammed VI Polytechnic University (UM6P), Benguerir, Morocco
[f] Department of Civil Engineering, Eskişehir Technical University, Eskişehir, Türkiye
[g] Instituto Pirenaico de Ecología, IPE-CSIC, Zaragoza, Spain
[h] Espace Dev, Université de Montpellier, IRD, Montpellier, France

## HIGHLIGHTS

- Century-long Mediterranean discharge trends analyzed using data from 654 stations.
- Focus on climate, greening-up and reservoir construction as drivers of change.
- Trends in mean discharge align mostly with precipitation trends from 1921–2000.
- Precipitation and vegetation greenness counteract their effects on runoff (1982–2022).
- Reservoir construction weakened the natural discharge regime.

## ARTICLE INFO

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## ABSTRACT

The Mediterranean Basin is typically classified as a region with decreasing streamflow trends since the 1960s, despite high variability in precipitation. Here we evaluated over a century of discharge trends (1914–2022) using data obtained from 654 discharge stations across the Mediterranean Basin from national and continental discharge databases. We assessed several drivers of discharge trends, including climate change, vegetation greening and reservoir construction. Trends in mean discharge align mostly with precipitation trends, showing distinct periods of statistically significant increasing (1941–1971) and decreasing discharge (1961–2000). Yet, mean discharge has been remarkably stable between 1981 and 2020, diverging from the significantly increasing precipitation trends during this period. Multiple linear regression confirmed that recent precipitation and vegetation greenness trends have an equally strong but counteracting effect on runoff trends. Reservoir construction caused a further consistent decrease in mean and maximum discharge, and weakened the natural discharge regime. Our study concludes that over the last century, discharge trends in the Mediterranean Basin can only partly be explained by precipitation variability. Reservoir construction and recent vegetation greening are identified as additional strong drivers of discharge trends.

## 1. Introduction

The Mediterranean Basin is typically classified as a region with consistent negative trends in streamflow since the 1960s (Kahya and Kalaycı, 2004; Hannaford et al., 2013; Martínez-Fernández et al., 2013; Masseroni et al., 2021), in contrast to mostly positive trends in northern Europe (Stahl et al., 2010; Teuling et al., 2019; Vicente-Serrano

* Corresponding author at: Department of Geography, University of Murcia, Murcia, Spain.
*Email address:* jeekhout@cebas.csic.es (J.P.C. Eekhout).

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et al., 2019). Long-term streamflow observations in the Mediterranean Basin show strong interdecadal variability during the 20th century. Also increasing trends are observed, for instance between 1940 and 1960 (Hannaford et al., 2013; Masseroni et al., 2021), which is consistent with increasing precipitation trends for this period (Vicente-Serrano et al., 2025b). However, observed trends in average streamflow are not always consistent with precipitation trends (López-Moreno et al., 2011; Sharma et al., 2018; De Girolamo et al., 2022). The influence of precipitation on streamflow variability and trends has been declining over time in the Iberian Peninsula (Lorenzo-Lacruz et al., 2012). Other environmental and human impacts have been suggested to affect the decreasing relationship between streamflow and precipitation, including an increase in forest cover, changes in vegetation greenness and reservoir construction (Ellison et al., 2017; Piao et al., 2020; Brunner, 2021; Slater et al., 2021; Zhang and Wei, 2021; Anderson et al., 2022), in particular for the Mediterranean Basin (López-Moreno et al., 2011; Piqué et al., 2016; Vicente-Serrano et al., 2019; Teuling et al., 2019; Collignan et al., 2025; Vicente-Serrano et al., 2025a).

Since the mid-20th century, land use change in the (northern) Mediterranean Basin mostly involved agricultural land abandonment and afforestation (García-Ruiz and Lana-Renault, 2011; Skulska et al., 2020; Quintas-Soriano et al., 2022). Afforestation was stimulated by afforestation programs, such as in Spain (Vallejo et al., 2012; Lasanta et al., 2015; van Leeuwen et al., 2019), but also resulted from secondary succession in abandoned farmland (Varela et al., 2020). Agricultural land abandonment occurred mostly in the headwaters, where mechanization was more difficult to implement, or in areas further away from the main distribution infrastructure, leading to an increase in natural vegetation (García-Ruiz and Lana-Renault, 2011; Nainggolan et al., 2012). Afforestation and agricultural abandonment are often associated with decreasing streamflow (Bosch and Hewlett, 1982; Farley et al., 2005; van Dijk and Keenan, 2007; García-Ruiz and Lana-Renault, 2011; Filoso et al., 2017; Khorchani et al., 2022), due to an increase in vegetation cover and subsequent increases in evapotranspiration and soil water retention capacity (Andréassian, 2004; López-Moreno et al., 2011; Sterling et al., 2013; Novara et al., 2017; Shao et al., 2019; Teuling et al., 2019; Khorchani et al., 2022; Molenaar et al., 2024). The impact of afforestation on streamflow is more pronounced in water-limited environments (Zhou et al., 2015; Zhang et al., 2017; Hou et al., 2023), like the Mediterranean Basin, and the decrease in streamflow after afforestation is most evident for low flows (Brown et al., 2005; Farley et al., 2005; Bathurst et al., 2020; Vicente-Serrano et al., 2021). However, surface runoff may also increase after agricultural land abandonment, due to crust development during the dry summer months, which reduces infiltration (Lasanta et al., 2000; Ries and Hirt, 2008; Nunes et al., 2010). The sparse tree cover of degraded lands may increase infiltration and aquifer recharge, which can further increase discharge (Bruijnzeel, 2004; Ilstedt et al., 2016). Afforestation may also have a mitigating effect on low to moderate flood events, potentially explained by drier antecedent soil moisture conditions causing a decreased impact of such events (Castillo et al., 2003; Bathurst et al., 2020; Massari et al., 2023; Tramblay et al., 2023). However, for more extreme floods, characterized by high intensity rain that exceeds the infiltration capacity of the soil, the increased forest cover was suggested to have a limited effect (Castillo et al., 2003; Nadal-Romero et al., 2016; Soulsby et al., 2017; Bathurst et al., 2020).

Vegetation greenness, often represented by the Normalized Difference Vegetation Index (NDVI), is frequently used to explain changes in streamflow (Huang and She, 2022; Wang et al., 2022b; Zhao et al., 2022), with the limitation that satellite-based data have only been available since the beginning of the 1980s (Pinzon et al., 2023). Vegetation greenness trends vary throughout the Mediterranean Basin, with increasing trends observed in the northern part of the Mediterranean Basin (2009–2018; Li et al., 2021), specifically in Türkiye (2001–2019; Rhif et al., 2022), Greece (2000–2017; Banti et al., 2019), and the Iberian Peninsula (1981–2015; Gouveia et al., 2016; Vicente-Serrano et al., 2020), and decreasing trends in the Maghreb and Levant subregions (2001–2019; Li et al., 2021; Rhif et al., 2022). Global vegetation greenness trends are found to be primarily explained by precipitation trends (Yang et al., 2019), however, this relationship is less evident for Spain (Vicente-Serrano et al., 2020). Land use change might better explain the increase in vegetation greenness in the Mediterranean Basin, especially considering agricultural land abandonment, afforestation, and expansion of irrigated agriculture. However, increasing vegetation greenness trends in semi-arid regions, like large parts of the Mediterranean Basin, are also associated with increased $CO_2$ fertilization (Donohue et al., 2013) and reduced water requirements by vegetation (Peñuelas et al., 2018). Moreover, vegetation greenness trends show marked differences between different land use classes, with forests and irrigated agriculture showing the highest positive trends, while rainfed agriculture shows more modest increases (Gouveia et al., 2016; Banti et al., 2019; Vicente-Serrano et al., 2020). An increase in vegetation greenness has been related to a decline in streamflow (Juez et al., 2023), however, evidence of the impact of changes in vegetation greenness on streamflow at the scale of the Mediterranean Basin is still lacking.

Dam construction represents another strong driver of discharge trends. Numerous large dams have been built throughout the Mediterranean Basin, especially in the Iberian Peninsula, Türkiye and the coastal zone of the southern Mediterranean (Mulligan et al., 2021; Wang et al., 2022a). Dam construction accelerated from the 1950s onward, with a peak in construction during the 1980s and 1990s (Mulligan et al., 2021). Close to 1300 large dams have been constructed in the Mediterranean Basin, with an average reservoir capacity of 176 $hm^3$ (Mulligan et al., 2021). Most reservoirs were built for hydropower and irrigation purposes, such as in the Southeastern Anatolia Project (GAP) in southeastern Türkiye (Yuksel, 2006). Reservoirs are found to have a larger impact on hydrological extremes than on mean streamflow (Batalla et al., 2004; Brunner, 2021) and may have even a larger impact than climate change (Yang et al., 2021). Reservoirs decrease the temporal runoff variability (Poff et al., 2007; Jaramillo and Destouni, 2015), which often translates to an increase in low flows (López-Moreno et al., 2009; Vicente-Serrano et al., 2017) and a decrease in high flows and flood severity (Batalla et al., 2004; Verbunt et al., 2005; FitzHugh and Vogel, 2011; Piqué et al., 2016; Brunner, 2021), affecting the hydrological regime (Magilligan and Nislow, 2005; Zahar et al., 2008; Peng et al., 2022). Reservoirs can also drive further land use change, for instance, by expansion of irrigated agriculture (Di Baldassarre et al., 2018; Eekhout et al., 2020), leading to increased water use and further reducing downstream water availability (López-Moreno et al., 2009).

Climate variability, land use change, increase in vegetation greenness and reservoir construction are all potential drivers of change in streamflow in the Mediterranean Basin. The objective of this study is to assess trends in annual mean, maximum and minimum discharge in 654 discharge stations across the Mediterranean Basin for the period 1914–2022 and to evaluate human impacts versus climate variability as drivers of discharge trends. Trends in streamflow and climate were analyzed for eight 30-year periods between 1921 and 2020. The additional impact of changes in vegetation greenness on streamflow was assessed between 1982 and 2022, based on available satellite-based NDVI images. Finally, the impact of reservoir construction was assessed for 35 discharge stations with sufficient data before and after reservoir construction.

## 2. Material & methods

### 2.1. Study area

This study focuses on the Mediterranean Basin, i.e., the area surrounding the Mediterranean Sea. We defined the Mediterranean Basin by the Mediterranean forests, woodlands and scrub Biome (Fig. 1), which describes the approximate extent of representative Mediterranean natural communities (Olson et al., 2001) and is, therefore, essentially defined by climate, rather than hydrological boundaries. The study area extends

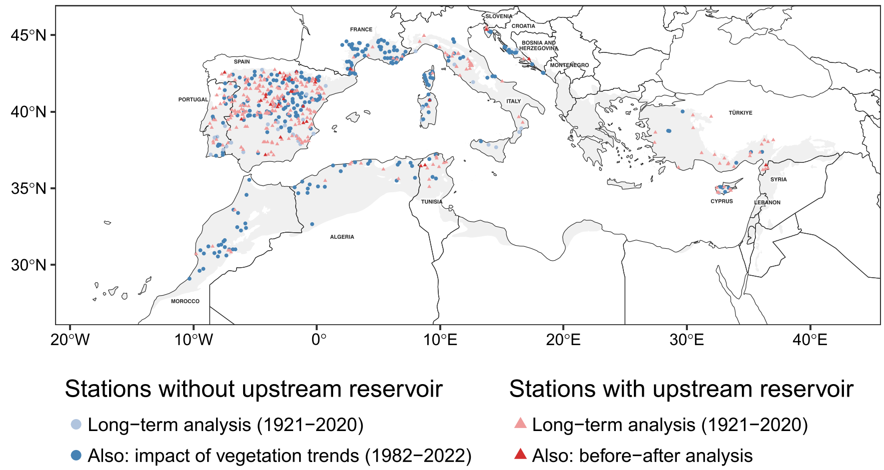


**Fig. 1.** Location of the discharge stations obtained from the six databases. The locations of the discharge stations without upstream reservoirs are indicated with blue circles, where light blue indicates the stations that were solely used in the long-term analysis and the dark blue indicates the stations which were, in addition, used to study the impact of vegetation greenness. The stations with reservoirs are indicated with red triangles, where light red indicates the stations used in the long-term analysis and dark red indicates the stations that were in addition used in the before-after analysis. The extent of the Mediterranean Basin is indicated in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to almost all of the Mediterranean Sea coastline. The Mediterranean Basin covers an area of 2.05 million $km^2$ across 31 countries. The average annual precipitation in the Mediterranean Basin amounts to 567 mm and the average temperature is 16.0 °C (1991–2020) (Harris et al., 2020). There is a clear gradient from more humid (average 720 mm) and colder conditions (13.8 °C) in the northern part of the Mediterranean Basin (Portugal to Greece), towards more arid (349 mm) and warmer conditions (18.1 °C) in the southern part (Morocco to Egypt). Land use is equally distributed among cropland (45%) and natural vegetation (51%), according to the ESA CCI Land Cover dataset (Harper et al., 2023).

### 2.2. Data

Discharge data for 654 stations within the boundaries of the Mediterranean Basin were obtained from six databases (Table 1). We selected only discharge stations with at least 50% of their upstream area located within the Mediterranean Basin. To ensure reliable discharge trend estimates, we selected discharge stations with at least 20 years of non-missing data. The analysis of trends in discharge was primarily performed for the period 1921–2020, while additional analyses of the impact of changes in vegetation greenness and reservoir construction were performed for the periods 1982–2022 and 1914–2022, respectively.

Daily discharge data for Algeria, France (except the island of Corsica), Morocco, Tunisia and Türkiye were obtained from national water resources agencies. Discharge data for the European part, except for mainland France and Türkiye, were obtained from the EStreams dataset (do Nascimento et al., 2024). From these datasets we obtained or determined the annual mean, maximum and minimum discharge (based on calendar years). The annual maximum discharge is defined by the absolute maximum daily discharge of a particular year. The minimum discharge is defined by the minimum 7-day mean discharge for a particular year.

We obtained catchment boundaries for each discharge station. Catchment boundaries were included in the EStreams dataset. For the remaining datasets we obtained the catchment boundaries using the GSIM delineation procedure (Do et al., 2018). These boundaries were used to obtain catchment-average annual precipitation, potential evapotranspiration and NDVI, and to determine the presence of reservoirs within the catchment.

**Table 1**
Characteristics of the six discharge databases used in the study.

| Source | Domain | Available period | Catchment polygons |
|---|---|---|---|
| EStreams | Europe | 1900–2022 | Provided by dataset |
| Agence Nationale des Ressources Hydriques (ANRH) | Algeria | 1960–2018 | Obtained using GSIM delineation procedure (Do et al., 2018) |
| Eaufrance | France | 1959–2021 | Obtained using GSIM delineation procedure (Do et al., 2018) |
| Hydraulic Basin Agencies | Morocco | 1960–2018 | Obtained using GSIM delineation procedure (Do et al., 2018) |
| Direction Générale des Ressources en Eau (DGRE) | Tunisia | 1960–2018 | Obtained using GSIM delineation procedure (Do et al., 2018) |
| State Hydraulic Works (DSI, 2024) | Türkiye | 1935–2011 | Obtained using GSIM delineation procedure (Do et al., 2018) |

Climate data were obtained from the CRU global dataset (v.4.08), with a 0.5° resolution (Harris et al., 2020). From the monthly climate data we determined the annual precipitation and annual potential evapotranspiration.

NDVI data were obtained from the GIMMS-3G + dataset (v1.1), with a 0.0833° resolution for the period 1982–2022 (Pinzon et al., 2023). We obtained the annual average NDVI from the 24 bi-monthly NDVI estimates.

Reservoir data were obtained from the Global Dam Watch (GDW) (Mulligan et al., 2021) and Georeferenced global Dams And Reservoirs (GeoDAR) (Wang et al., 2022a) datasets. The two datasets contain the reservoir perimeters of mostly large reservoirs. We first assessed which reservoirs are located within the catchment boundaries of the selected stations. On this subset we made an intersection between the GDW and GeoDAR databases and removed the overlapping reservoirs from the GeoDAR database, which do not contain the metadata needed for further analysis (i.e., construction years). The reservoir perimeters were subsequently used to divide the stations into a group with and a group without upstream reservoirs (Fig. 1). We excluded stations with a reservoir located at the catchment outlet, because it is unclear if the reservoir operations in those cases influence the discharge time series.

The construction year of each reservoir was used to determine whether a reservoir was built within the period of analysis. Construction years were available for most reservoirs in the GDW database, but were lacking in the GeoDAR database. Through internet search we obtained the construction years for 227 reservoirs for which the construction year was missing (Table S1). Because of the central role of the timing of reservoir construction in our analysis, we excluded stations with upstream reservoirs for which the construction year could not be determined.

### 2.3. Discharge station characteristics

Of the six considered discharge databases, 2043 discharge stations are located within the Mediterranean Basin. After considering the minimum number of years of non-missing data (>20 years), we selected 654 stations for analysis, which cover 31% of the surface area of the Mediterranean Basin.

We used data from 16 countries, most notably from Spain (342 stations), France (77), Italy (56), Portugal (40), Morocco (32), Türkiye (30) and Algeria (27) (Table S2). Catchment sizes range from 5 to 92,108 $km^2$, with an average of 3419 $km^2$ and a median of 549 $km^2$. The average catchment size is 485 $km^2$ for stations without upstream reservoirs and 6445 $km^2$ for those with reservoirs. The average length of the discharge time series is 57 years (SD = ±23 years). Stations are equally distributed between stations without upstream reservoirs (332 stations) and stations with upstream reservoirs (322 stations). Most stations with upstream reservoirs are located in Spain, Italy, Türkiye and Portugal.

### 2.4. Data analysis

Long-term changes in discharge and climate were obtained for the period 1921–2020. We subdivided the dataset into eight 30-year periods (i.e., 1921–1950, 1931–1960, etc.). For each 30-year period, the subset of included stations varied, depending on the data availability. A station was included in a certain 30-year period in case at least 20 years of non-missing data were available for that period. Within each period a distinction was made between stations with and without upstream reservoirs. A station was assigned to the reservoir category if a reservoir was constructed within or prior to the 30-year period. In all other cases (i.e., the reservoir was constructed after the 30-year period or for stations without upstream reservoirs), the station was assigned to the no reservoir category.

We analyzed the temporal trends of the three discharge indicators (mean, maximum and minimum discharge) and two climate indicators (precipitation and potential evapotranspiration) using Theil-Sen slopes, as implemented in the zyp R-package (v0.11-1) (Bronaugh and Schoeneberg, 2012). We divided the obtained Theil-Sen slope by the average of each indicator to obtain the relative annual trend. Given the substantial variability in sample size (ranging from 11 to 451 stations per 30-year period), relying exclusively on a single statistical test would fail to yield robust statistical inferences. Therefore, we used a dual-criterion approach to determine if the change in annual trends is significantly different from 0, requiring both statistical significance (Wilcoxon signed-rank test, $p < 0.05$) and a minimum effect magnitude (standardized effect size, $r > 0.2$).

We used the annual runoff (mm) instead of the mean discharge to make the absolute trends comparable between the stations for the analysis of the impact of changes in vegetation greenness and the before-after reservoir construction analysis. The annual runoff was obtained by multiplying the mean discharge by the number of seconds per year, which was divided by the catchment area (in $m^2$) and multiplied by 1000 to obtain annual runoff in mm. We assessed the accuracy of the obtained annual runoff estimates by calculating the annual mean runoff coefficient (i.e., runoff divided by precipitation). A number of stations had a runoff coefficient much larger than 1, which did not seem credible. We therefore decided to exclude from the analysis 77 stations with a runoff coefficient larger than 1.

The impact of changes in vegetation greenness on discharge was studied for the period 1982–2022 for stations without upstream reservoirs. We obtained the relative annual change in discharge, climate and NDVI for 294 stations. We applied multiple linear regression to assess the contributions of changes in precipitation, potential evapotranspiration and NDVI to changes in runoff. The multiple linear regression model consisted of the absolute change in runoff (mm $yr^{-1}$) as dependent variable and the absolute change in precipitation (mm $yr^{-1}$), potential evapotranspiration (mm $yr^{-1}$) and NDVI ($yr^{-1}$) as independent variables. We obtained the partial effects of the independent variables to assess their individual contributions to the multiple linear regression model, as implemented in the lm.beta R-package (v1.7-2) (Behrendt, 2014).

The impact of reservoir construction was assessed for 35 stations for which at least 20 years of discharge data were available, both before and after construction. Seven stations contained multiple upstream reservoirs, up to seven reservoirs for the Genil station (Spain). For stations with multiple upstream reservoirs, the two periods before the first and after the last constructed reservoir were considered. We determined the relative change in discharge and climate indicators by comparing the averages before and after reservoir construction. In addition, we plotted the annual runoff and precipitation for each station, differentiating between the before and after reservoir construction periods. We fitted a linear model through the two point clouds of each station to show changes in the response of the precipitation–runoff relationship as a result of reservoir construction.

## 3. Results & discussion

### 3.1. Long-term evolution of discharge

The number of stations considered in each 30-year period shows an increasing trend towards the last two periods (Figs. 2 and 3). The first two periods include 11 and 19 stations, respectively, mostly located in Portugal and Italy. From the period 1941–1970 onward, stations from other countries are included, particularly Spain, which remains the country with the highest number of stations considered up to the final period (1991–2020). A peak of 492 stations is reached in the period 1981–2010. From the period 1961–1990 onward, the stations seem well distributed across the Mediterranean Basin (Fig. 3), with notable exceptions for Albania and Greece, which are not represented in the dataset (Fig. 1).

Distinct periods of increasing and decreasing mean discharge are observed throughout the study period (Fig. 2). Increasing trends are observed primarily for the period 1941–1970 and decreasing trends for the periods 1961–1990 and 1971–2000, where the latter confirms previous studies from France, Italy and Spain (López-Moreno et al., 2011; Lutz et al., 2016; Piqué et al., 2016; De Girolamo et al., 2022). The increasing trends for the period 1941–1970 are mostly concentrated in the Iberian Peninsula (Fig. 3), which is also the only subregion with significant increasing trends in mean discharge for this period (Figure S1). In contrast, the decreasing trends during the period 1961–2000 are more widespread across the Mediterranean Basin, with decreasing trends in all subregions and with particularly strong declines in central Spain, Sardinia and Cyprus.

The precipitation trends for 1921–2020 are generally consistent with the large-scale precipitation analysis in the Mediterranean Basin by Vicente-Serrano et al. (2025b), including the observed increasing trends for the periods 1941–1970 and 1981–2010 and decreasing trends for the period 1961–1990. This suggests that the precipitation results obtained from the selected stations can be considered representative of the Mediterranean Basin. Trends in mean discharge align mostly with precipitation trends for the first six 30-year periods up to 1971–2000. However, the last two 30-year periods show some notable deviations between the mean discharge and precipitation trends (Fig. 2). Mean discharge has been particularly stable from 1981–2020, as previously shown for France and Spain (Folton et al., 2019; Córdoba-Ariza et al., 2024). However, precipitation shows significant increasing trends for 1981–2010 (0.43–0.46% $year^{-1}$) and significant decreasing trends for stations without upstream reservoirs for 1991–2020 (−0.30% $year^{-1}$).

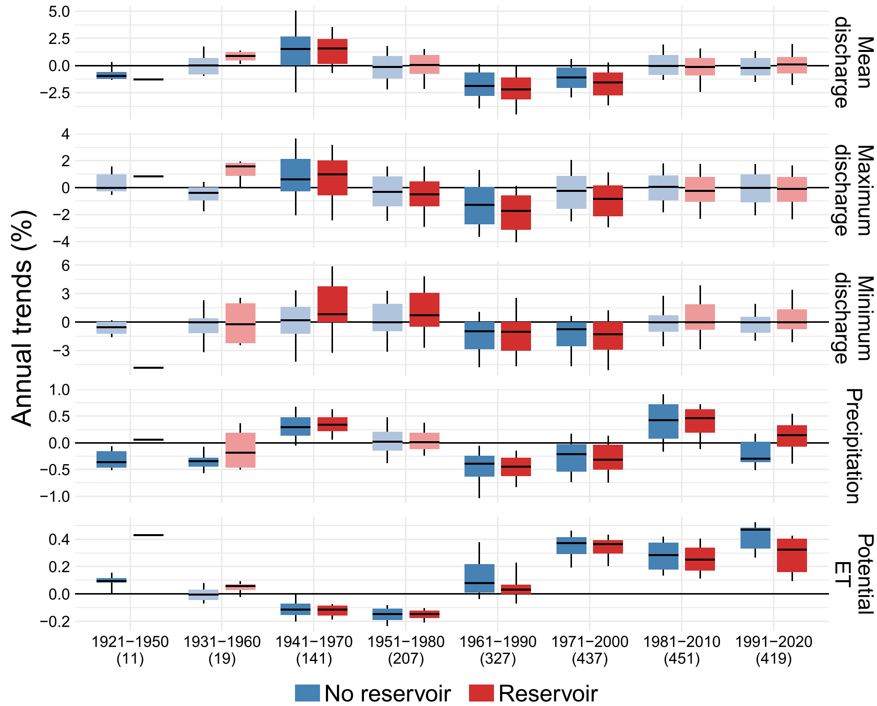


**Fig. 2.** Annual trends (Theil-Sen slopes; %) in discharge (mean, maximum and minimum) and climate indicators (precipitation and potential evapotranspiration) per 30-year period from 1921–2020, shown separately for stations without (blue) and with upstream reservoirs (red). The dark blue and red boxplots indicate annual trends that are significantly different from 0, obtained from the Wilcoxon signed-rank test ($p < 0.05$) and the standardized effect size ($r > 0.2$). The boxes indicate the interquartile range (25th and 75th percentiles), the black horizontal line indicates the median (50th percentile) and the whiskers extend to the 10th and 90th percentiles. The number of considered stations is shown in parentheses below the respective periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This suggests that the role of precipitation as a driver for mean discharge variability is decreasing, confirming previous observations of this phenomenon in the Iberian Peninsula (Lorenzo-Lacruz et al., 2012). The positive trends in potential evapotranspiration for the period 1971–2020 (Fig. 2) may have contributed to the decreasing role of precipitation on mean discharge trends, where an increase in evapotranspiration could have counteracted the increase in precipitation for the period 1981–2010. However, the contribution of the potential evapotranspiration to the mean discharge trends for the period 1991–2020 seems less obvious, especially for stations without upstream reservoirs, which in addition show decreasing precipitation trends. This suggests that it is likely that other environmental factors have contributed to the decreasing role of precipitation as a driver for mean discharge in the Mediterranean Basin.

The maximum discharge mostly follows the mean discharge trends, i.e. increasing trends for 1941–1970, decreasing trends for 1961–2000 and stable for 1981–2020 (Fig. 2), which is consistent with earlier studies (López-Moreno et al., 2006; Mediero et al., 2014, 2015; Lutz et al., 2016; Tramblay et al., 2019; De Girolamo et al., 2022; Tramblay et al., 2023; Córdoba-Ariza et al., 2024; Tramblay et al., 2024). When looking at regional differences, the maximum discharge trends for the Levant subregion are consistently decreasing for the period 1961–2020, while the other subregions show less persistent changes, especially for the period 1971–2020 (Figure S1). The trends obtained for maximum discharge show a similar pattern to the mean discharge trends, but seem less pronounced and are only significant for 1961–2000. Corresponding mean and maximum discharge trends were also observed in the Ebro River basin in Spain (Lutz et al., 2016) and in the Celone River basin in Italy (De Girolamo et al., 2022). While trends in mean discharge can largely be explained by trends in annual precipitation, explaining trends in maximum discharge requires more information on trends in extreme precipitation and antecedent soil moisture (Tramblay et al., 2023), which are currently not available at the temporal and spatial scale of this study. The minimum discharge does not show many differences among the considered periods, apart from a small but significant decrease between 1961 and 2000, with most trends close to 0 and little apparent relation with the climate trends. These results agree with previous Mediterranean studies, which additionally showed increasing trends in low flow duration, which was not assessed here (Belmar et al., 2010; Coch and Mediero, 2016; Lutz et al., 2016; Folton et al., 2019; De Girolamo et al., 2022).

Reservoirs seem to affect trends in mean discharge only slightly, most notably for the period 1971–2000, where stations with upstream reservoirs show a slightly more pronounced decrease in mean discharge (Fig. 2). However, this might also be explained by a slightly higher decreasing trend in precipitation. The differences are more obvious for maximum discharge, especially for the two 30-year periods between 1961 and 2000. In these periods, the stations with upstream reservoirs show a slightly more pronounced decrease in maximum discharge, which cannot entirely be explained by differences in climate trends. For minimum discharge the opposite response is obtained for the two 30-year periods between 1941–1980, where stations with upstream reservoirs show significant increasing trends in minimum discharge, while stations without upstream reservoirs lack a clear trend in minimum discharge.

### 3.2. Impact of greening-up

The three discharge indicators do not show any increasing or decreasing trends for the period 1982–2022 (Fig. 4), the period for which vegetation data from satellite imagery (i.e. NDVI) were available for the Mediterranean Basin, confirming the results shown in Fig. 2. There was a slight, but significant, increase in precipitation and a higher, more robust, increase in potential evapotranspiration and NDVI. We

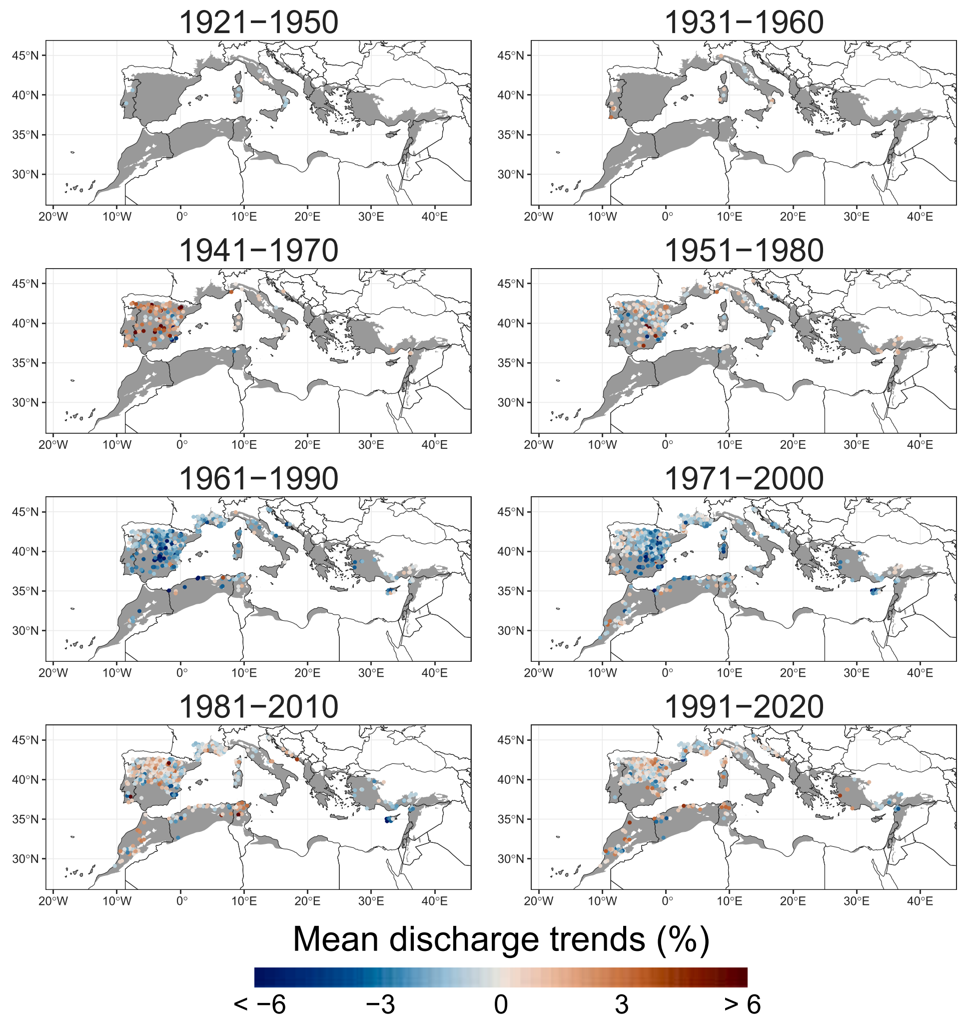


**Fig. 3.** Mean discharge trends (Theil-Sen slopes; %) per 30-year period from 1921–2020, where each point indicates the location of the discharge station. Negative trends are indicated in blue and positive trends are indicated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

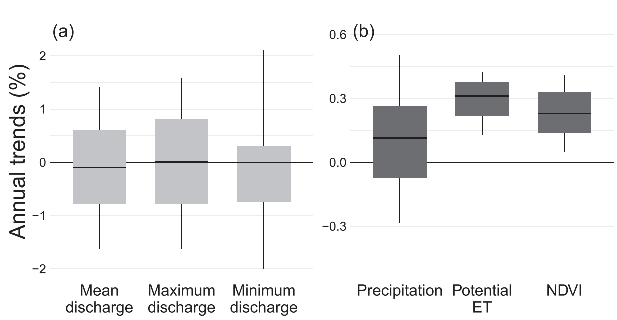


**Fig. 4.** Annual trends (Theil-Sen slopes; %) in (a) mean, maximum and minimum discharge and (b) precipitation, potential evapotranspiration and NDVI for stations without upstream reservoirs for the period 1982–2022. The dark grey boxplots indicate annual trends that are significantly different from 0, obtained from the Wilcoxon signed-rank test ($p < 0.05$) and the standardized effect size ($r > 0.2$). The boxes indicate the interquartile range (25th and 75th percentiles), the black horizontal line represents the median (50th percentile) and the whiskers extend to the 10th and 90th percentiles.

argue that the absence of discharge trends may be a result of the counteracting influence between increasing precipitation and increased evapotranspiration losses due to increasing potential evapotranspiration and vegetation greenness.

We assessed how much the climatic and vegetation indicators affect the mean discharge trends through multiple linear regression. We used the absolute trends in annual runoff, precipitation and potential evapotranspiration to make the trends comparable between the selected stations. Fig. 5 shows the partial effects of the three considered indices, which indicate the contribution of each of the indicators to annual runoff trends while keeping the other indicators constant. This figure shows a positive relationship between runoff trends and precipitation trends and a negative relationship with NDVI trends. More striking is that both trends have a similar, but opposite, contribution within the multiple regression model. This might confirm the suggestion of the counteracting influence of increasing precipitation vs. increasing vegetation greenness on discharge. However, the three indices only predict a fraction of the variability of the runoff trends, with a relatively low adjusted $R^2$ ($R^2 = 0.07$). While the model explains a limited portion of the variance in runoff trends, significant associations were found between runoff trends and precipitation and NDVI trends (Table S3), suggesting that recent vegetation greenness trends have detectable catchment-scale hydrological impacts.

The increase in vegetation greenness as observed in the 294 selected stations (Fig. 4) can be the result of an overall increase in vegetation greenness, for instance related to the slight increase in precipitation over this period or as a response to forest maturation after afforestation. However, it can also be a response to land use change, such

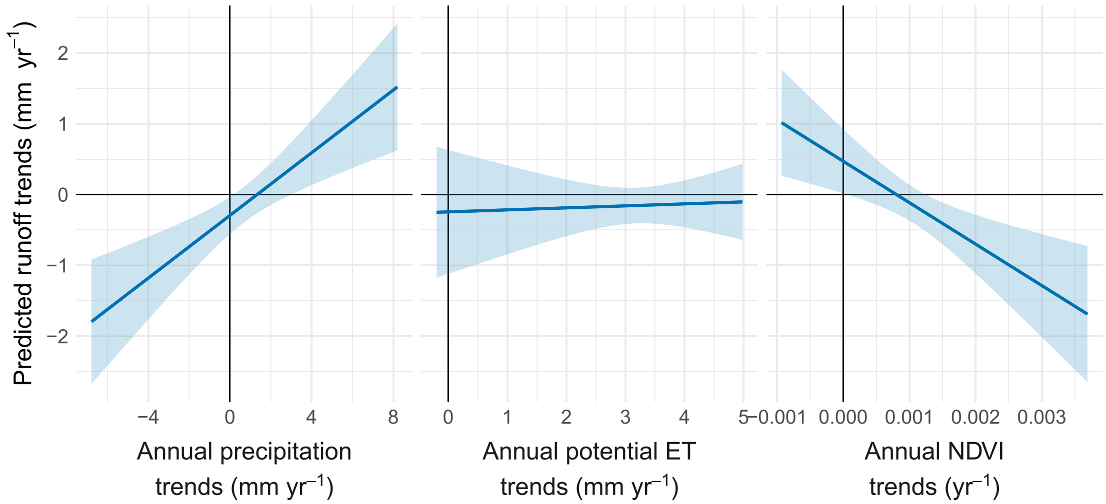


**Fig. 5.** Partial effects for trends in precipitation (mm yr-1), potential evapotranspiration (mm yr-1) and NDVI (yr-1) as predictors for trends in runoff (mm yr-1), obtained from the multiple linear regression model. The partial effects indicate the contribution of each of the indicators to annual runoff trends while keeping the other indicators constant. We used the absolute trends in annual runoff, precipitation and potential evapotranspiration to make the trends comparable between the selected stations.

as afforestation, agricultural abandonment and expansion of irrigated agriculture. Here we consider the period 1992–2022, which coincides with the period for which satellite-based land use maps (ESA CCI Land Cover; Harper et al., 2023) and NDVI images were available for the Mediterranean Basin. Vegetation greenness increased in many parts of the Mediterranean Basin between 1992 and 2022 (Fig. 6(a)), especially in the Iberian Peninsula, the Balkans and Türkiye, while a decrease is observed in some areas in the Maghreb and the Levant subregions, which confirms previous studies (Gouveia et al., 2016; Banti et al., 2019; Vicente-Serrano et al., 2020; Li et al., 2021; Rhif et al., 2022). The transformation from cropland to tree cover is the most common land use change in the Mediterranean Basin between 1992 and 2022 (Fig. 6(b)), especially in the Iberian Peninsula, the Balkans and Türkiye, causing most increase in vegetation greenness among the considered land use transitions (Fig. 6(c)). Surprisingly, the transition from tree cover to cropland also led to an increase in vegetation greenness. This might indicate that forests are replaced by irrigated crops and may also explain the general increase in vegetation greenness for stable cropland. The second most common land use transition is from sparse vegetation to cropland, which almost exclusively occurred in the Maghreb subregion, without any notable change to vegetation greenness. At the same time, several stable land use classes, including cropland, grassland, tree cover and shrubland, showed an increase in vegetation greenness, with most increase shown for stable tree cover. While indeed the highest increase in vegetation greenness occurred in the locations characterized by the transition from cropland to tree cover, there is a general tendency of an increase in vegetation greenness in the Mediterranean Basin.

The partial effects of the trends in precipitation and NDVI on annual runoff trends confirm their counteracting roles, with a positive relationship for precipitation trends and an equally strong negative relationship for NDVI trends. This suggests that an increase in vegetation greenness may cause a decrease in runoff, as suggested in previous studies on afforestation (Bosch and Hewlett, 1982; Farley et al., 2005; Boix-Fayos et al., 2007; van Dijk and Keenan, 2007; Filoso et al., 2017) and revegetation after agricultural abandonment (García-Ruiz and Lana-Renault, 2011; Khorchani et al., 2022). Because of the general increase in vegetation greenness across the Mediterranean Basin, it is difficult to judge how important land use change has been in driving changes in discharge trends. Land use change indeed leads to some substantial differences in vegetation greenness trends, generally with higher increases for transitions towards tree cover and lower changes with transitions towards urban areas and shrubland. However, land use change impacts on discharge trends at the catchment scale were likely limited, because of the general increase in vegetation greenness in most stable land use classes. Therefore, it still remains an open question what has been the role of land use change as compared to the general increase in vegetation greenness on discharge trends in the Mediterranean Basin.

Our analysis focused on a recent period for which satellite images were available. While it is likely that more drastic land use changes occurred before this period, especially in the northern part of the Mediterranean Basin (Boix-Fayos et al., 2007; García-Ruiz and Lana-Renault, 2011; Vallejo et al., 2012; Lasanta et al., 2015; van Leeuwen et al., 2019; Eekhout et al., 2020; Skulska et al., 2020; Quintas-Soriano et al., 2022). Hence, the observed increase in vegetation greenness in natural land use classes may also have been a response to these earlier land use changes, indicating the progression towards mature vegetation conditions. The available land use maps at the scale of the Mediterranean Basin from before the satellite era (i.e. before 1980) are based on global land use models, such as HILDA+ (Winkler et al., 2021) and HYDE (Klein Goldewijk et al., 2017). These model-based land use maps are found to be substantially different compared to the satellite-based land use maps (Li et al., 2018; Winkler et al., 2021). This does not provide much confidence in using model-based land use maps to analyze land use change and assess their impacts on discharge trends at the scale of the Mediterranean Basin. Future research exploring the impacts of land-use change on observed discharge trends in the Mediterranean Basin are likely limited to catchment-scale assessments for which reliable land use maps are available.

### 3.3. *Impact of reservoir construction*

The long-term discharge analysis showed that stations with upstream reservoirs exhibit slightly different discharge trends compared to stations without upstream reservoirs (Fig. 2). We performed an additional analysis considering the 35 stations with upstream reservoirs for which at least 20 years of data were available in the periods before and after reservoir construction. In these 35 stations, the mean and maximum discharge decreased by about 30% after reservoir construction (Fig. 7;

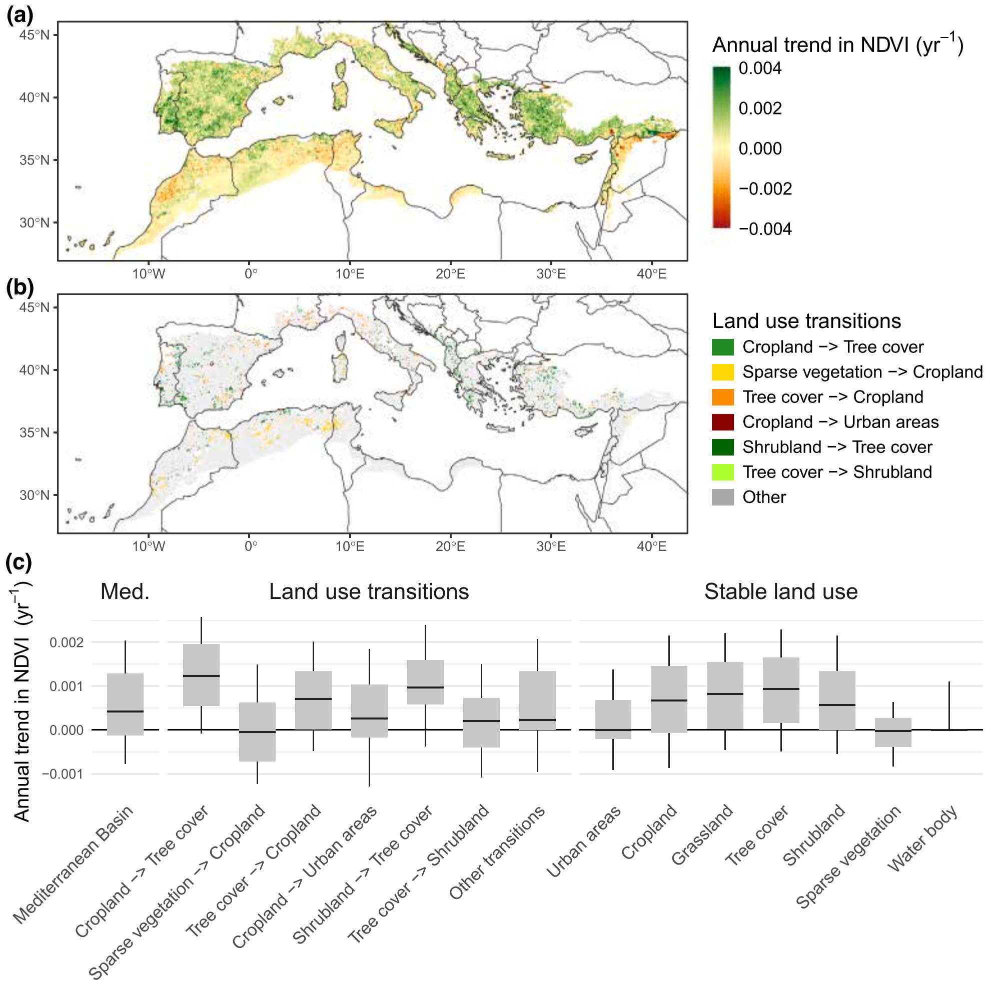


**Fig. 6.** NDVI trends and land use transitions for the period 1992–2022. (a) Annual trends in NDVI (yr$^{-1}$). (b) Main land use transitions, based on the ESA CCI land cover maps (Harper et al., 2023). (c) Annual trends in NDVI (yr$^{-1}$) as obtained from panel (a) for the entire Mediterranean Basin, the main land use transitions from panel (b) and the stable land use classes. The boxes indicate the interquartile range (25th and 75th percentiles), the black horizontal line represents the median (50th percentile) and the whiskers extend to the 10th and 90th percentiles.

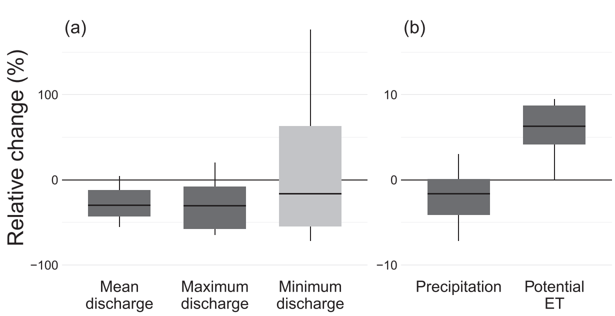


**Fig. 7.** Relative change (Theil-Sen slopes; %) in (a) mean, maximum and minimum discharge and (b) precipitation and potential evapotranspiration for the 35 selected stations with upstream reservoirs (1914–2022), for which sufficient data were available before and after reservoir construction. The relative change was obtained by the difference between the averages for the before and after periods, divided by the average of the before period. The dark grey boxplots indicate relative changes that are significantly different from 0, obtained from the Wilcoxon signed-rank test ($p < 0.05$) and the standardized effect size ($r > 0.2$). The boxes indicate the interquartile range (25th and 75th percentiles), the black horizontal line represents the median (50th percentile) and the whiskers extend to the 10th and 90th percentiles.

median value). The median change in minimum discharge is also negative (−16%), however, the relative change is not as consistent as for mean and maximum discharge, with a large share of stations showing an increase in minimum discharge. At the same time, precipitation decreased (−2%) and potential evapotranspiration increased (6%), which may explain the observed decrease in mean and maximum discharge, although the changes in precipitation were modest, compared to the change in mean and maximum discharge.

We applied linear regression to show the relationship between annual runoff and precipitation for each of the 35 stations, with the aim of assessing how the runoff regime (i.e. the precipitation–runoff relationship) changed due to reservoir construction (Fig. 8). Most stations show a considerable difference in the precipitation–runoff relationship before and after reservoir construction. This relationship is mostly characterized by a steeper slope for the period before reservoir construction, representing the “natural” response of the runoff–precipitation relationship. However, in most cases the relationship flattens out after reservoir construction. This suggests that reservoir construction and, more specifically, reservoir operations indeed affect the discharge regime. Significant differences between the linear models for the two periods were obtained for six stations (indicated with a star in Fig. 8), i.e., the Esla, Guadalmena, Guatizalema, Tajuña and Tamuja stations in

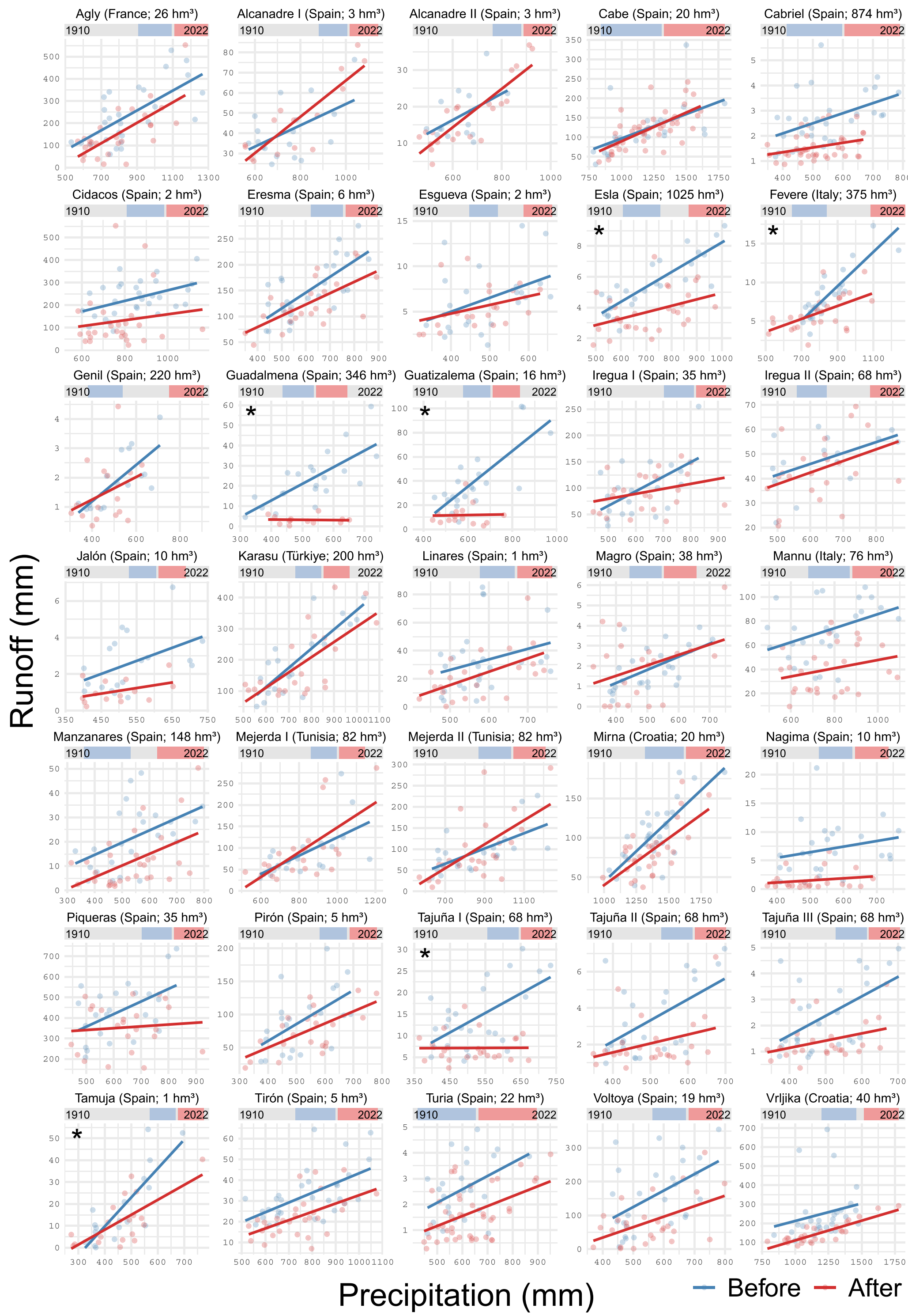


**Fig. 8.** Annual runoff (mm) vs. precipitation (mm) for the 35 selected stations with upstream reservoirs, differentiating between the before (blue) and the after construction period (red). Linear regression is applied to the two point clouds, with runoff being the dependent variable and precipitation the independent variable. The star in the top left corner indicates whether the before and after regression lines are significantly different from each other ($p<0.05$; $t$-test). The timeline above each scatter plot shows the temporal coverage of the two considered periods on a scale from 1910 to 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Spain and the Fevere station in Italy. These significantly different trends were obtained for several stations with large reservoir capacities, i.e., the Esla (1025 hm$^3$), Fevere (375 hm$^3$) and Guadalmena (346 hm$^3$) stations. However, other stations with a large reservoir capacity (i.e., >100 hm$^3$), such as the Cabriel, Geril, Karasu and Manzanares stations, show limited differences in the precipitation–runoff relationship before and after reservoir construction. Significant changes in the discharge regime were also obtained in the Tamuja and Guatizalema stations, both with a fairly small reservoir capacity (1 and 16 hm$^3$, respectively). Previous studies showed that even small dams may trigger large effects on discharge trends (Wisser et al., 2010; Habets et al., 2018; Sadaoui et al., 2018), as well as, water that is being diverted from the main river for irrigation purposes (Ouassanouan et al., 2022). Hence, the size of the reservoir seems to be less of a predictor for the impact on discharge trends. Due to the scale of the study, we could only account for large reservoirs from publicly available databases, which limits the ability of generalization of the results. Moreover, it is likely that stations without upstream reservoirs (according to the two global dam databases) may in fact contain small reservoirs capable of modifying the discharge regime. Future studies would benefit from a more exhaustive database of small reservoirs and diversion works in the Mediterranean Basin, to account for these smaller structures on discharge trends.

Our results confirm other studies that showed a decrease in annual runoff after reservoir construction (Ibàñez et al., 1996; Yang et al., 2021). In particular the study by Batalla et al. (2004), who applied a similar approach in the Ebro River basin and obtained a similar decrease in annual runoff (−30%). Although, in our case the observed decrease in runoff may be partially explained by a decrease in precipitation, this impact is expected to be small because precipitation decreased by only 2% between the before and after periods for the selected stations. The increase in potential evapotranspiration and a likely increase in vegetation greenness may have contributed, as well (Fig. 6). However, it is difficult to assess the impact of changes in vegetation greenness, because of a lack of satellite data for the full extent of the considered period (1914–2022). Nevertheless, it is likely that an increase in irrigated agriculture and related water use from reservoirs partly explains the significant decrease in mean discharge. Irrigation is the main use in 26 of the 53 considered reservoirs (Table S4), followed by (domestic) water supply (19 out of 53 reservoirs). A previous study in the Ebro River basin showed that around 75% of the decrease in mean discharge was attributed to irrigation water use and the remainder to increased evaporation from the reservoir (Ibàñez et al., 1996). Irrigation is the main use of the reservoirs in 4 out of 6 stations for which we obtained a significant change in discharge regime before and after reservoir construction. This suggests that irrigation is likely one of the main drivers of change in discharge regime following reservoir construction (Batalla et al., 2004). It is also likely that reservoir construction provoked an increase in irrigated agriculture and subsequent increase in water extractions from different sources, including reservoirs and groundwater aquifers (Di Baldassarre et al., 2018). Moreover, irrigation demand is projected to increase in the Mediterranean Basin due to increasing temperatures and decreasing precipitation (Fader et al., 2016; Eekhout et al., 2025). It is therefore likely that rainfed agriculture will increasingly be replaced by irrigated agriculture to keep agriculture profitable (Garrote et al., 2015; Malek and Verburg, 2021), putting more pressure on the available water resources.

The change in discharge regime after reservoir construction is also reflected in the observed change in hydrological extremes. Maximum discharge decreased as a response to reservoir construction, which confirms previous studies (Batalla et al., 2004; Piqué et al., 2016; Vicente-Serrano et al., 2017). However, a more severe decrease in maximum discharge was observed in Mediterranean catchments in the south of France and north of Spain (−35% to −54%) (Batalla et al., 2004; Piqué et al., 2016). Hence, reservoirs clearly serve as a buffer to reduce the impact of flood events. Often reservoir operations are adjusted to allow more water storage during flood events, for instance, by decreasing the reservoir storage in the days prior to an extreme precipitation event (Mediero et al., 2007; Delaney et al., 2020). Mixed results were obtained for low flows, for which the median value decreases, but a considerable number of stations show an increase in low flows (Fig. 7). Similar results were obtained in other studies in the Mediterranean Basin, which showed either increasing (López-Moreno et al., 2009; Vicente-Serrano et al., 2017) or decreasing low flows (Batalla et al., 2004) after reservoir construction. Nevertheless, reservoirs are more often associated with an increase in low flows, for instance, as a response for maintaining a minimal ecological flow (Belmar et al., 2019) or because of an increase in the release of water during summer months for irrigation purposes (Batalla et al., 2004). However, it may be the case that ecological flows are not being maintained because the main purpose is providing water for irrigation purposes, ultimately leading to a decrease in low flows. This illustrates that the impact of reservoirs on low flows principally depends on reservoir operations.

### 3.4. Implications

Streamflow in the Mediterranean Basin has been fluctuating between periods of increase and decrease from 1921 to 2020. While these fluctuations were initially correlated with precipitation trends, more recently precipitation does not seem to be the main driver of streamflow (Fig. 2). We showed that an increase in vegetation greenness and reservoir operations may have had significant impacts on discharge trends and may have weakened the influence of climate variability on streamflow. The Mediterranean Basin is identified as one of the global hotspots for climate change (Giorgi, 2006), which is characterized by a projected decrease in precipitation (Carvalho et al., 2022) and runoff (Eekhout et al., 2025). Most climate change assessments only account for the impact of climate change, while neglecting other relevant environmental or human influences on streamflow, such as land use change, changes in vegetation greenness and reservoir construction. Most consistent results have been obtained in studies that consider reservoir construction and changes in reservoir operations under climate change, including a decrease in irrigation water supply and an increase in water demand (Mereu et al., 2016; Carvalho-Santos et al., 2017; Beça et al., 2023; Okkan et al., 2023). When both climate and land use change are considered, studies often find that land use change has a comparatively minor impact on streamflow (Baltas and Karaliolidou, 2008; Molina-Navarro et al., 2014; Serpa et al., 2015; Candela et al., 2016; Pham et al., 2019). Studies that consider the transition from cropland to tree cover (Stefanova et al., 2015; Pham et al., 2019), project an additional decrease in streamflow, which aligns with our results considering the impact of vegetation greening. Changes in vegetation greenness have been considered in a few studies (Eekhout et al., 2018; Sirigu and Montaldo, 2022), however, these studies did not specifically evaluate the impact of changes in vegetation greenness as compared to climate change alone. As a result, it remains unclear how projected changes in vegetation greenness, climate and their possible feedbacks (Millán et al., 2005; Millán, 2014) will affect streamflow in the Mediterranean Basin.

### 3.5. Limitations

In this study, we aimed at explaining discharge trends with climate trends, vegetation greening and reservoir construction. Given the large-scale extent of the study area and the requirement for a continuous century-long climate record, we selected the global CRU dataset (Harris et al., 2020). This dataset has a rather coarse 0.5° resolution, which limits the accuracy of the catchment-average precipitation and temperature estimates, especially in smaller catchments. The typical convective rainfall events in Mediterranean Basin (Dayan et al., 2015; Michaelides et al., 2018; Llasat et al., 2021), result in a high spatial variability of rainfall patterns, which is not captured by the coarse resolution, a limitation inherent to all large-scale gridded databases. Nevertheless, the CRU dataset seems temporally consistent with a recent long-term precipitation analysis for the Mediterranean Basin based on station data (Vicente-Serrano et al., 2025b), which gives confidence in the long-term precipitation trends of the dataset. In our analysis, we excluded 77 stations because of unrealistically high runoff coefficients. This might have been caused by the uncertainty and coarse resolution of the precipitation dataset, but also because of inaccuracies in the calculation of runoff, due to hydrometric uncertainties or faulty catchment delineation. The latter maybe in particular relevant for the Mediterranean context, where catchment boundaries obtained from topographic data (i.e. digital elevation models), as used in this study, often diverge from the phreatic catchment due to the widespread presence of karstic lithology in Mediterranean catchments (Nikolaidis et al., 2013; Hartmann et al., 2015).

The stations we considered in this study were not equally distributed within the Mediterranean Basin, with the majority of the stations located in Spain (>50%; Table S2). This spatial imbalance has some consequences for the validity of the conclusions for the entire Mediterranean Basin. We assessed how the spatial distribution affects the overall results by subdividing the dataset into four Mediterranean subregions (i.e. Iberian Peninsula, North-Central Mediterranean, Levant and Maghreb). We then determined the trends in mean discharge for each subregion separately and assessed the significance of the obtained discharge trends (Figure S1). These results suggest that for the periods 1941–1970 and 1981–2010 the results from the entire dataset are likely biased towards the trends obtained from the Iberian Peninsula. The results for the other subregions for these two periods mostly diverge from the overall trends, as shown in Fig. 2. On the contrary, the results for the periods 1951–1980, 1961–1990, 1971–2000 and 1991–2020 can be considered uniform among the four subregions and are consistent with the overall results.

Through multiple linear regression, we showed that trends in precipitation and vegetation greenness have a similar, but opposite, impact on runoff trends in the period 1982–2022. However, the regression model only explains a small fraction of the variance within the data ($R^2 = 0.07$). It is important to note that the objective of this regression analysis was not to maximize predictive power (i.e., explain the total variance in runoff trends), but to quantify the relative sensitivity of runoff trends with respect to climate trends and vegetation greening. The regression model does not account for variables that are often used to explain the hydrological response between catchments, such as topography, lithology and land use. The regression model is likely also affected by the uncertainties from the coarse resolution climate dataset, as mentioned before. Moreover, the regression model does not account for the relevant anthropogenic drivers that may substantially alter the catchment water balance and lead to vegetation greening locally, such as an increase in (groundwater) abstractions and irrigation water use, which are highly relevant in the Mediterranean Basin (Zdruli, 2014). The use of NDVI as a proxy for vegetation greenness may also be subject to uncertainties. NDVI is known to be sensitive to soil background effects in semi-arid environments (Huete, 1988), which are abundant in the Mediterranean Basin. Additionally, the annual regression model does not account for plant phenological shifts that are occurring in the Mediterranean Basin, including earlier greening in the spring and a general lengthening of the growing season (Gordo and Sanz, 2010), which likely affects the seasonal timing of plant water use and may thus induce changes to the water balance. Nevertheless, independently of the existing uncertainties, our multiple linear regression model demonstrates that precipitation and vegetation greening have significant partial effects on recent runoff trends, showing a positive association for precipitation and a negative one for vegetation greening. Future studies may consider expanding the regression model with more catchment characteristics, to include anthropogenic drivers and use different vegetation indices that are better suited for Mediterranean environments.

## 4. Conclusions

Here we assessed the evolution of annual streamflow (mean, maximum and minimum discharge) from 1914 to 2022 using data obtained from 654 discharge stations throughout the Mediterranean Basin. Our analysis identified distinct periods of increasing (1941–1970) and decreasing mean discharge (1961–2000). Maximum discharge shows similar, although more modest temporal trends, while minimum discharge only showed limited fluctuations throughout the study period. Most changes in mean discharge can be related to changes in precipitation, however, the relationship between discharge and precipitation attenuates from 1981 onward. This suggests that other environmental or human impacts are at play causing the impact of precipitation on streamflow variability to decrease.

Detailed evaluation of discharge trends for the period 1982–2022 shows an increase in precipitation, potential evapotranspiration and vegetation greenness, while all three discharge indicators remained stable. Through multiple linear regression we show that these more recent trends in precipitation and vegetation greenness may have counteracting, but equally strong impacts on annual runoff trends. Vegetation greenness increased in the majority of the Mediterranean Basin, in particular for locations characterized by increasing tree cover, but also in stable land use classes. This suggests that vegetation greenness is not only related to land use change, but is a general trend within the Mediterranean Basin, especially for the Iberian Peninsula, the Balkans and Türkiye. Explanations for this trend can vary from densification of vegetation in natural land use classes to expansion of irrigated agriculture, which may have had an important impact on streamflow between 1982 and 2022. The exact role of the latter requires further research.

Reservoir construction caused a 30% decrease in mean and maximum discharge, while mixed results were obtained for minimum discharge. Although climate change may explain part of these trends, our results clearly show that the discharge regime (i.e., runoff–precipitation relationship) is affected by reservoir construction. Runoff not only shows a general decrease, in several cases the strength of the relationship between precipitation and runoff variability decreases, as well. This suggests that reservoir operations can strongly impact the discharge regime, even in reservoirs with limited capacity. Altogether, over the last century, discharge trends in the Mediterranean Basin can only partly be explained by precipitation variability, with important additional contributions from human impacts characterized by reservoir construction and recent vegetation greening.

## CRediT authorship contribution statement

**Joris P.C. Eekhout:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hamouda Boutaghane:** Writing – review & editing, Resources. **Hamouda Dakhlaoui:** Writing – review & editing, Resources. **El Mahdi El Khalki:** Writing – review & editing, Resources. **Gökçen Uysal:** Writing – review & editing, Resources. **Sergio M. Vicente Serrano:** Writing – review & editing, Conceptualization. **Yves Tramblay:** Writing – review & editing, Resources, Conceptualization. **Joris de Vente:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Joris Eekhout reports financial support was provided by Ministry of Science, Innovation and Universities. Joris de Vente reports financial support was provided by Ministry of Science, Innovation and Universities. Joris de Vente also reports financial support was provided by Agencia Estatal de Investigación. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data for this article can be found online at doi:10.1016/j.jhydrol.2026.135387.

## Data availability

The streamflow data for Europe were obtained from the Estreams (v1.0) dataset (https://zenodo.org/records/13154470). The streamflow data for mainland France were obtained from Eaufrance (https://hydro.eaufrance.fr/). The streamflow data for Türkiye were obtained from the State Hydraulic Works (DSI) (https://www.dsi.gov.tr/Sayfa/Detay/744). The streamflow data for Morocco, Algeria and Tunisia were obtained from various local and national water resources agencies, but are not publicly available. Part of the dataset is made available in Tramblay et al. (2024). The climate data were obtained from CRU (v4.08) (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.08/). The NDVI data were obtained from AVHRR GIMMS-3G+ (https://doi.org/10.3334/ORNLDAAC/2187). The reservoir data were obtained from Global Dam Watch (https://www.globaldamwatch.org/database) and GeoDAR (https://doi.org/10.5281/zenodo.6163412).

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