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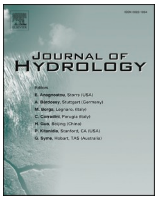

Research papers

Forest expansion and irrigated agriculture reinforce low river flows in southern Europe during dry years

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ABSTRACT

This study analyses the evolution of annual streamflow across Europe between 1962 and 2017, focusing on the connection of streamflow trends with climate dynamics and physiographic and land cover characteristics and changes. The spatial pattern of trends in streamflow shows strong agreement with the spatial patterns of climate trends, suggesting a climate control of these trends. However, analysing temporal evolution at the basin scale shows that the strong decrease in streamflow in southern Europe cannot be directly associated with climate dynamic. In fact, a negative trend related to non-climate factors clearly emerges. Rather, we show that forest growth and irrigated agriculture are the leading drivers of negative streamflow trends in southern Europe, particularly during dry years due to the greater proportion of green water consumption compared to blue water generation. These findings have significant implications, particularly in the context of widely embraced nature-based solutions for mitigating climate change, including carbon sequestration through forests and the planned expansion of irrigated agricultural lands in central and northern European countries as a response to rising crop water demands. These developments could potentially diminish water resources availability, leading to an increased occurrence and severity of low flow periods.

1. Introduction

Numerous studies have assessed annual streamflow changes in Europe during recent decades based on observations available at gauging stations. These studies show that changes are characterised by a distinct spatial pattern, with decreases in streamflow dominant in the basins of southwestern Europe and increases in northern Europe (Gudmundsson et al., 2019, 2017; Masseroni et al., 2021; Stahl et al., 2010). These spatial differences are also observed in the analysis of annual maximum floods, which tend to show decreases in frequency and severity in southern Europe and increase in the North (Blöschl et al., 2019). Factors that determine these changes have been suggested to be diverse. Some studies suggest the dominant role of recent climate trends (Masseroni et al., 2021), in which anthropogenic forcing could play an important role (Gudmundsson et al., 2017). Other studies suggest that human activities, including increased water demands, water regulation, and land use changes could play a more important role than climate driven trends in explaining the spatial differences of streamflow changes in Europe (Teuling et al., 2019a; Vicente-Serrano et al., 2019). The increase in number of dams, irrigation areas and urban and industrial water supply have evident consequences for streamflow (He et al., 2017; Ketchum et al., 2023; Tijdeman et al., 2018; S M Vicente-Serrano et al., 2017a; Wriedt et al., 2009), while land cover changes in natural areas (e.g., natural revegetation and forest increase) may also contribute to reduced runoff generation (Beguería et al., 2003a; García-Ruiz et al., 2011; Hoek van Dijke et al., 2022; Martínez-Fernández et al., 2013).

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Given the economic, social and environmental relevance water resource availability in Europe, it is important to determine the drivers of observed streamflow changes so that management strategies can be correctly informed. To this end, it is necessary to apply robust methodological approaches at the basin scale to analyse the temporal dynamics of streamflow, climate and other human and environmental drivers.

The main water availability problems in Europe occur in dry years since low flows can be especially severe (Laaha et al., 2017; Soulsby et al., 2021; Van Lanen et al., 2016). Some studies have suggested noticeable trends in the frequency and severity of periods with low river flows during recent decades in Europe (Peña-Angulo et al., 2022). Although the severity of the low flows is affected by several factors including warming processes (Martin et al., 2020; McCabe et al., 2017), evaporation (Massari et al., 2022; Teuling et al., 2013; Zhao et al., 2022), and water demands from different sources (Lorenzo-Lacruz et al., 2013; Peña-Angulo et al., 2021), the main origin of low river flows are commonly precipitation deficits (Berghuijs et al., 2017; Yang et al., 2018). For this reason, a particular focus on dry years is essential to determine if streamflow trends respond differently in comparison to wet years. The rationale for considering dry years in an independent manner is based on the important effect of vegetation on runoff generation that can be observed particularly during dry years (McQuillan et al., 2022). For example, Orth and Destouni (Orth and Destouni, 2018) showed that runoff generation (blue water) shows higher sensitivity than evapotranspiration (green water) to the occurrence of precipitation deficits in Europe, a pattern confirmed in the Alps by (Mastrotheodoros et al., 2020). This behaviour is due to the priority use of available water by plants for physiological processes associated with photosynthesis, explaining the fact that plant evapotranspiration represents a high percentage (about two-thirds) of total precipitation (Jasechko et al., 2013; Zhang et al., 2016). In dry years, plants seek to maintain transpiration at a similar magnitude to wet years to avoid reductions in carbon uptake (Babst et al., 2014; Gimeno et al., 2016; Green et al., 2019). The immediate consequence is that the proportion of surface water generated by runoff during dry years reduces noticeably in comparison to wet years (Boulet et al., 2021). If vegetation coverage is affected by large temporal changes, the partitioning of available water between runoff generation and vegetation consumption could be strongly altered. For example, increases in vegetation activity and coverage (e.g., through forest regeneration or creation of irrigated areas in drylands) reduces streamflow generation (Filoso et al., 2017; Hoek van Dijke et al., 2022; Scanlon et al., 2007). The implications of such changes for water resources availability are much more relevant during dry years, whereby runoff generation could be further reduced. With substantial implications for river low flow management.

There is limited observational evidence for the widespread hydrological implications of land cover changes during periods of low flows, but existing research suggests a reinforcement of low flow periods as shown in the headwaters of several natural basins of Spain (Peña-Angulo et al., 2021). In particular, (Vicente-Serrano et al., 2021) analysed the influence of vegetation changes on streamflow in a catchment of the central Spanish Pyrenees characterised by strong revegetation during the last decade, finding that associated decreases in streamflow were stronger in dry rather than wet years. These findings suggest that vegetation changes are of increased relevance for water yield in dry years, although this behaviour remains to be confirmed on broader scales.

This study analyses streamflow changes at the European scale using a dense database of gauging stations. While prior research has acknowledged the role of land transformations and water usage in explaining streamflow decline in southwestern Europe (Beguería et al., 2003b; Gallart et al., 2011; López-Moreno et al., 2011a; Morán-Tejeda et al., 2010), our study brings forth a significant novelty since we identify that the primary effect of these factors occurs during dry precipitation years, with substantial implications for the low flows downstream from the headwaters and the irrigation zones. This is the first time such a pattern has been demonstrated on a large scale, carrying profound hydrological implications for land management.

2. Data and methods

The data used in this study comprise a monthly streamflow dataset for 3224 gauging stations across Europe, developed and described in depth by (Peña-Angulo et al., 2022). The database contains complete records for the period 1962–2017. The total annual (October-September) streamflow was quantified at each gauging station in Hm^3. The drainage area of each gauging station was obtained using a digital elevation model (EU Copernicus data and information program, https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoringservice-eu-dem) at a spatial resolution of 100 m and ArcHydro tools in ArcGIS10.2©.

Climate information was obtained from two different sources. Gridded precipitation data were obtained from the E-obs database (Cornes et al., 2018) at the spatial resolution of 0.1 degrees and the necessary data to calculate the atmospheric evaporative demand (AED) by means of the FAO56 Penman-Monteith equation (Pereira et al., 2015) (air temperature, solar radiation, wind speed and humidity) was obtained from the ERA-5 Reanalysis (Hersbach et al., 2020) also at 0.1 degree resolution. Supplementary Information section A shows a justification of the data selection. We obtained the annual average (October-September) time series of precipitation and AED corresponding to each of the 3224 drainage basins. AED is not included in our analysis as a metric of total evapotranspiration but rather as one of the drivers (in addition to land cover changes) that may affect trends in streamflow since an increase of AED may reinforce evapotranspiration if water is available. For comparison with streamflow records, climate variables were also transformed to Hm^3.

We assessed long-term changes in forest cover by means of the Hilda database (Winkler et al., 2020) in 1960 and 2019 in each one of the basins and we quantified the percentage change over the period. Due to the unavailability of sufficient data sources for assessing the long-term evolution of irrigated lands at the basin scale, our analysis focused on the current surface area covered by irrigated lands. This information was extracted from the 2018 CORINE land cover gridded dataset (accessible at https://land.copernicus.eu/pan-european/corine-land-cover) and was subsequently aggregated for each river basin. While we acknowledge the limitation of not quantifying the evolution of irrigated surfaces over the study period, we assert that the existing distribution of irrigated lands serves as a robust proxy for gauging basin-level changes. This is supported by the consideration of the evolution quantified at the country scale, as illustrated in Fig. 1.

The methodology used in this study is based on the approach followed by (Vicente-Serrano et al., 2021) to determine the effect of changes in vegetation coverage on streamflow, with a special focus on the effect of partitioning of available water resources between green water (consumed by vegetation in the form of plant transpiration) and blue water (generated by surface runoff) during periods of low and high precipitation. We first analysed the magnitude of trend in annual streamflow for the period 1962–2017 for complete years and wet and dry years. Herein, wet years were defined as those exceeding the 50th percentile of precipitation over the period of record, while dry years were defined as those falling below the 50th percentile. The selection of other more extreme percentiles (e.g., 20th/80th and 30th/70th) to identify wet and dry years did not produce relevant differences in the obtained results (See Supplementary material, section B), while use of the median allows maximisation of the sample to analyse the long-term streamflow trends for wet and dry years. The hypothesis of this analysis is that the effect of forest increase and human activities (e.g. irrigation) on streamflow trends would be more evident during dry years in which water use by plants and human activities represents a higher percentage of total available water (Mastrotheodoros et al., 2020; Orth and

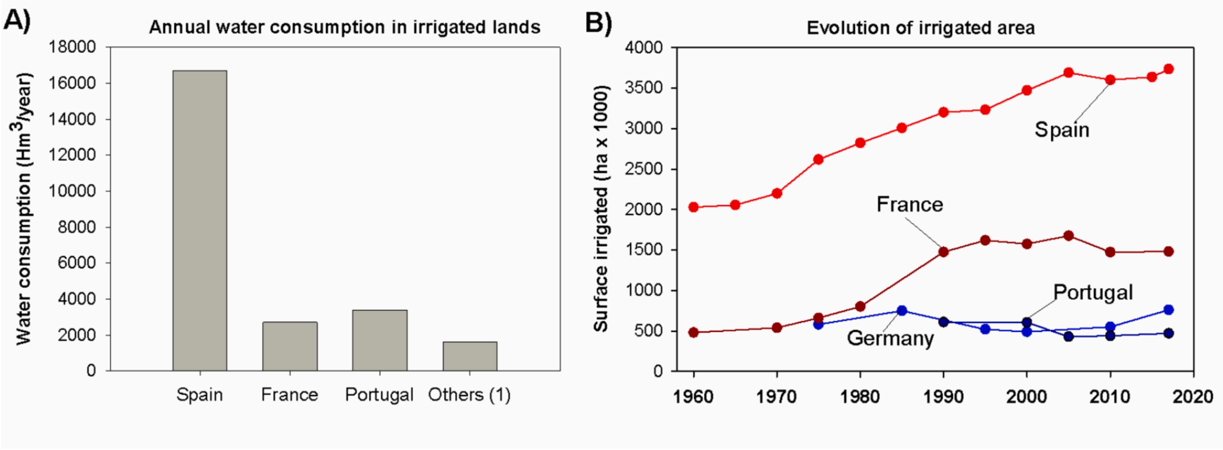

Fig. 1. A) Annual mean water consumption by irrigated lands in European countries (Rossi, 2019). (1) Does not include Italy and Greece which show values of 11,700 and 3900 Hm3/year, respectively but that are not included in the study. B) Evolution of the irrigated surface in the countries of Europe characterised by more irrigated area (except Italy and Greece). The of the data are Tamames (), , , Battude () and FENAREG (.
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Destouni, 2018). The trend in annual streamflow was analysed using a modified Mann-Kendall trend test, which returns the corrected p-values after accounting for temporal autocorrelation (Hamed and Ramachandra Rao, 1998). To assess the magnitude of change, we used a non-parametric Theil-Sen regression analysis between the series of years (independent variable) and the streamflow series (dependent variable). This method is more statistically robust than linear regression as it is not constrained by the normality of the series and the presence of outliers (Sen, 1968). The use of absolute units (Hm^3) to compare between streamflow and climate trends would produce important problems for spatial comparability (See Supplementary information, section C). To remove the strong differences in streamflow magnitude between basins analysed, and to allow comparison with climate variables, trends were quantified as the percentage change between the start (1962) and end years (2017), determined by means of the values of the regression line corresponding to these two years, with 1962 representing 100 percent. The same approach was applied to analyse long-term trends in precipitation and AED, also considering wet and dry years as for streamflow.

We analysed the spatial relationship between the sign and significance of the change in streamflow considering two significance levels (99 % and 95 %) with the distribution of different variables that include mean precipitation and AED, the magnitude of change in precipitation and AED, elevation, the irrigated area, forest cover and changes in forest cover. In addition, we also related the observed magnitude of change at each gauging station with the independent values of these variables to infer the possible drivers of change.

To quantify the magnitude of the annual streamflow trends associated with climate and other variables (e.g., vegetation changes) we used a linear multiple regression model, developed for each basin, with streamflow as the dependent variable and annual precipitation, annual AED, previous year precipitation, previous summer AED and time as the independent variables (Beguería et al., 2003a; López-Moreno et al., 2011b). The preference for employing a linear model over non-linear models was driven by concerns related to overfitting in the latter. For additional information, refer to the Supplementary Information section D for more comprehensive details. Time was included in the models as a proxy for the progressive evolution of natural vegetation, other land cover changes (e.g. the increase of the irrigation surface) or other factors (e.g., the increase of urban or industrial demands). It can be argued that the linear approach associated with time tends to produce a smooth signal, potentially underestimating the impact of abrupt changes related to irrigation (e.g., the creation of new reservoirs or irrigated lands) or land cover changes (e.g., reforestation). However, even in basins where significant irrigation transformations have been documented, a linear model remains the most comprehensive method for modelling streamflow changes (Vicente-Serrano et al., 2017b).

The forward stepwise selection of predictors was used in the construction of regression models using a threshold of 0.05 (Hair et al., 1995). Forward stepwise regression starts with no predictors and adds one variable at a time to the model. The variable added at each step is the one that improves the model the most, usually based on a criterion like the lowest p-value or the highest increase in the adjusted R2. By adding variables sequentially, the model avoids including variables that don't add significant predictive power. If two variables are highly collinear (strongly correlated), stepwise selection is less likely to include both, because once one of them is included, the other will not add much to the model and hence is not selected.

We quantified the independent role of each variable (precipitation, AED and time) using the regression Beta coefficient, which varies between −1 and 1. This provides information on the weight that each independent variable has in determining the changes observed in the dependent variable, in this case annual streamflow. The analysis was applied to the series of all years but also to the series of wet and dry years.

To examine the relationship between the spatial patterns of beta coefficients associated with time and changes in forest cover and the percentage of irrigated area within each basin, we categorized the basins into four groups based on the percentage of forest change (<-20 %, −20–0 %, 0–20 %, and > 20 %) and two groups based on the extent of irrigated surface (below and above 5 % of the total surface). We then compared the beta coefficient values associated with time for all years, humid years, and dry years within these basin categories using boxplots. To determine if there were statistically significant differences in the beta coefficients among these basin categories, we employed a One-way Analysis of Variance (ANOVA) and conducted the post-hoc Tamhane test, which considers variations in variances among the categories.

3. Results

Streamflow trends show pronounced spatial differences across Europe from 1962 to 2017 for all years, wet and dry years, with a predominant decreasing trend in large areas of the Iberian Peninsula, southern France and some basins of central Germany (Fig. 2). In some basins of the Iberian Peninsula and southern France the decrease in streamflow has been more than 50 % between 1962 and 2017. In contrast, a predominantly increasing trend is evident for basins in Ireland, northern and western parts of the UK, Scandinavia and the Baltic region. Overall, the number of gauging stations that show a

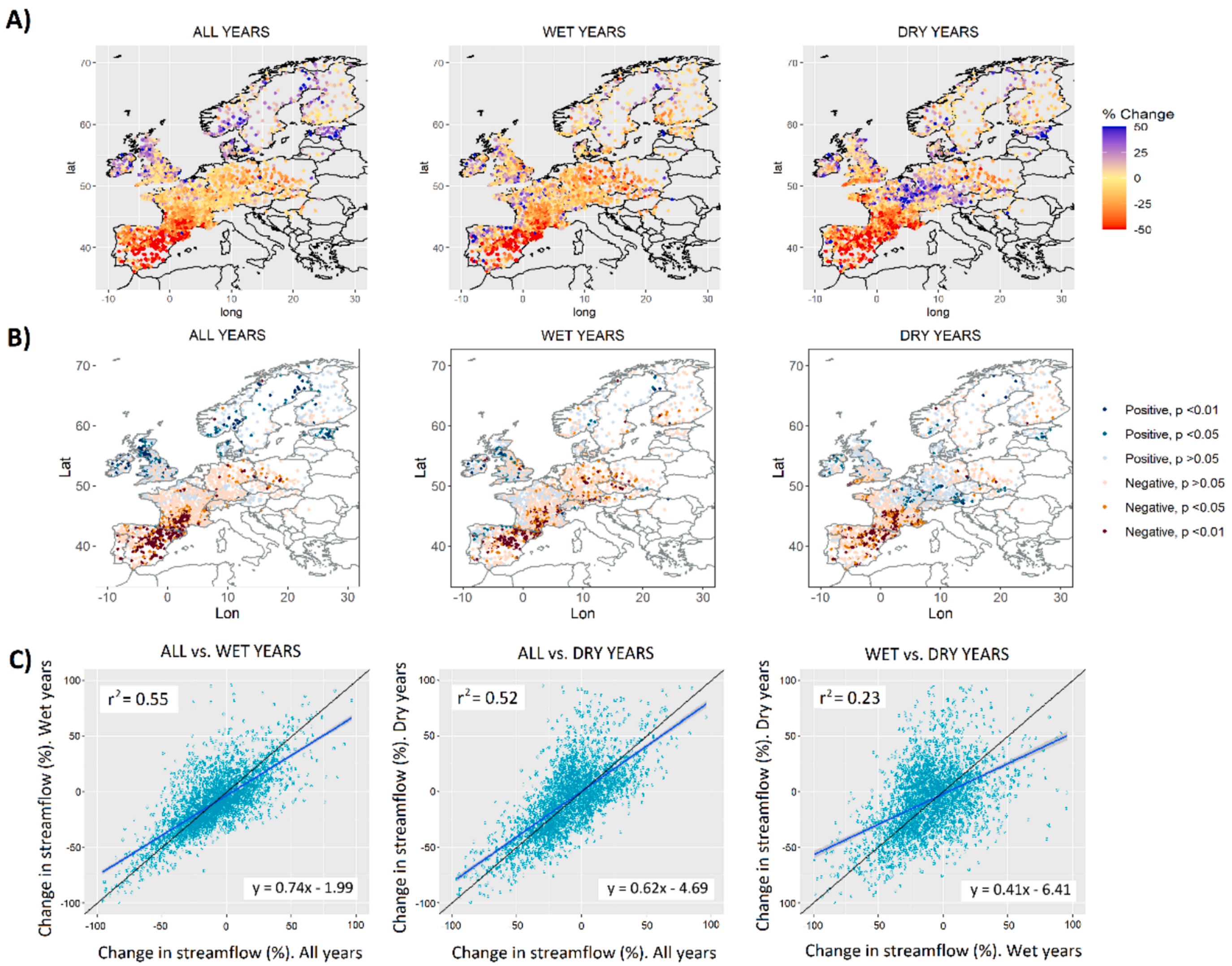

Fig. 2. A) Magnitude of change in streamflow in percent (1962 representing 100 percent) between 1962 and 2017 considering all, wet and dry years. B) Statistical significance of streamflow changes considering all, wet and dry precipitation years. C) Spatial relationship between the magnitude of change in annual streamflow for all, wet and dry years.

streamflow decrease is greater than the number showing an increase. A large number of stations located in southern Europe show statistically significant negative trends. A similar spatial pattern is found for streamflow trends assessed for wet and dry years, although the number of stations with statistically significant trends decreases as a consequence of the smaller sample size. The most important difference is that for dry years, although some regions of central Europe show an increase of streamflow, the decrease in streamflow expands over the entire Iberian Peninsula in comparison to all years and wet years. The spatial pattern shows high agreement between the magnitude of change in streamflow for all, wet and dry years, but less so comparing between dry and wet years (Fig. 2C).

The spatial pattern of streamflow trends suggests some climatic control since there are noticeable differences in the change of precipitation and AED between basins that show a significant increase or decrease in streamflow (Fig. 3). Basins showing significant negative streamflow trends are characterised as the most arid, with low precipitation and high AED, and by opposite precipitation and AED trends, i.e., a negative precipitation and a positive AED trend. These results contrast with those in basins showing increasing streamflow trends, which tend to show increases in precipitation and a more limited increase in AED.

However, climate control based on consistency in spatial patterns of change in streamflow and climate must be carefully interpreted since the magnitude of temporal changes between the analysed variables could differ considerably. Moreover, additional non-climatic variables may also explain the spatial pattern of streamflow change. For example, the strong negative trend in annual streamflow over large areas of southern Europe contrasts with much more modest precipitation decrease during the study period (Fig. 4). In addition, there are no significant precipitation trends for the sub-sample of wet years. In fact, there are very few basins in which a significant decrease of precipitation has been recorded between 1962 and 2017 in northeastern Spain and southern France. As both variables are quantified in the same units (Hm^3), and changes analysed in percentages, they are perfectly comparable. The differences in percent change (between precipitation and streamflow) are more than 50 % in the majority of basins in the Iberian Peninsula and southern France, but also in some basins of eastern Germany and Poland (Fig. 5A). A similar spatial pattern of differences between streamflow and precipitation trends is found for wet and dry years. Thus, observing the spatial relationship between the magnitude of change in precipitation and streamflow, the range of change in precipitation between basins shows a lower range than observed for streamflow. Several basins characterised by strong streamflow decreases show small decrease or even an increase in precipitation. In fact, the relationship between

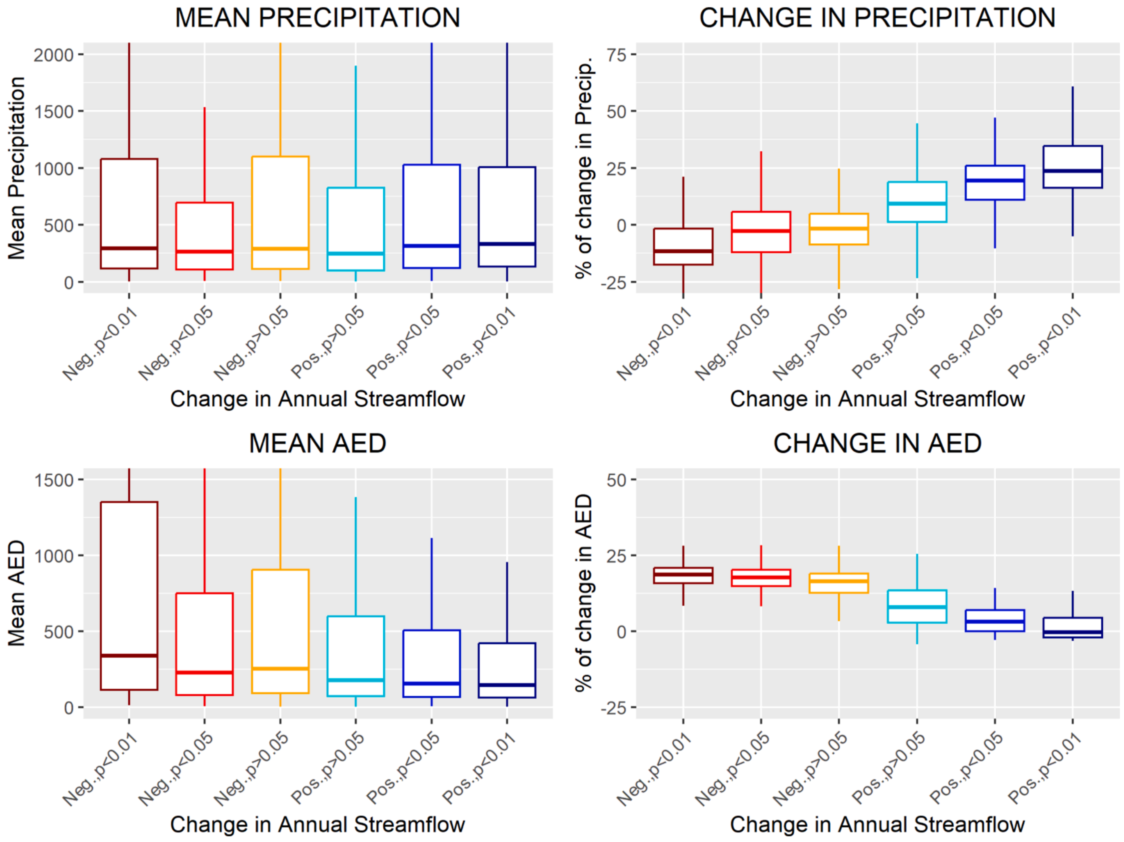

Fig. 3. A) Box-plots showing the distribution of mean precipitation and AED and the magnitude of change in precipitation and AED as a function of the statistical significance of changes in annual streamflow.

changes in these variables is weak ($r^2 = 0.226$) and even weaker for changes recorded during wet and dry years. What is observed at the European scale is a very important increase in AED (Fig. 5C), which is, in general, very homogenous spatially (except in the British-Irish Isles and Scandinavia), and statistically significant in the vast majority of basins. Therefore, differences in streamflow and AED trends are very strong, but the spatial relationship between streamflow and AED changes are also weak for all, wet and dry years (Fig. 5D).

Therefore, the limited spatial relationship between changes in streamflow and precipitation, and the very different magnitude of changes found for both variables suggests that climate is unlikely to be the main driver of observed changes in streamflow. In fact, if we analyse other non-climatic variables, noticeable differences can be also found. For example, basins that show a larger decrease in streamflow tend to be characterised by higher elevation, a higher percentage of forest area and positive trends in the percentage of forest area (Fig. 6). This is in contrast to the characteristics observed in basins with positive trends in streamflow, which show smaller changes in the percentage of forest area. Thus, analysing these patterns we could hypothese that basin characteristics, including forest area, and vegetation change could explain the spatial differences of streamflow trends across Europe. This finding reinforces the limitations of establishing possible control of streamflow changes based on the spatial consistency of hypothesised drivers (both climatic and human management, including land cover changes).

A more robust approach to determine the changes in streamflow is to focus on the temporal relationships of plausible drivers at the basin scale. Fig. 7, shows the spatial distribution of the percentage of variance of the stepwise regression models using precipitation, AED and time (in years) as independent variables to explain streamflow. The percentage of variance in streamflow explained by the three variables shows some spatial differences, although the values are higher than 50 % in the majority of Europe. The percentage of variance reduces in some basins for wet, but particularly for dry years.

In the vast majority of basins, precipitation enters in the stepwise regression models as a statistically significant predictor (Fig. 8). Precipitation from the previous year also influences some basins, particularly in northern Europe and the Mediterranean basins of the Iberian Peninsula, where it can impact reservoir storage, affecting water releases in the following year. Only for dry years is precipitation excluded for some basins. By contrast AED is not included in the majority of models. Moreover, the few basins in which AED enters the regression models (14 % of the total) do not show a coherent geographical pattern suggesting a strong influence of AED for particular regions. In addition, the percentage of basins in which AED is included in the models reduces considerably for dry years (7 %), although AED from the previous summer plays a role in basins in central and northern Europe, suggesting that the effects of summer evapotranspiration are noticeable in the following hydrological year (this variable is included in the models for 17.1 % of the basins, and 10.1 % during dry years). Finally, in a large percentage of basins, time is also a significant addition to models, particularly for all years (34 %), but also wet (23 %) and dry years (21 %). This clearly suggests that in many European basins, there is a temporal component of annual streamflow, indicative of a trend that is not explained by climate variables (i.e., precipitation and AED).

The role of the five variables explaining the evolution of streamflow is quantified by means of the beta regression coefficients, which allow spatial comparisons, independently of the magnitude of the variables. Precipitation consistently plays the most significant role in explaining streamflow evolution across all three cases (Fig. 9). However, precipitation from the previous year also plays an important role in the Mediterranean basins of the Iberian Peninsula and in central and northern Europe, especially during dry years, when long-term water storage becomes crucial for understanding streamflow. The influence of AED is

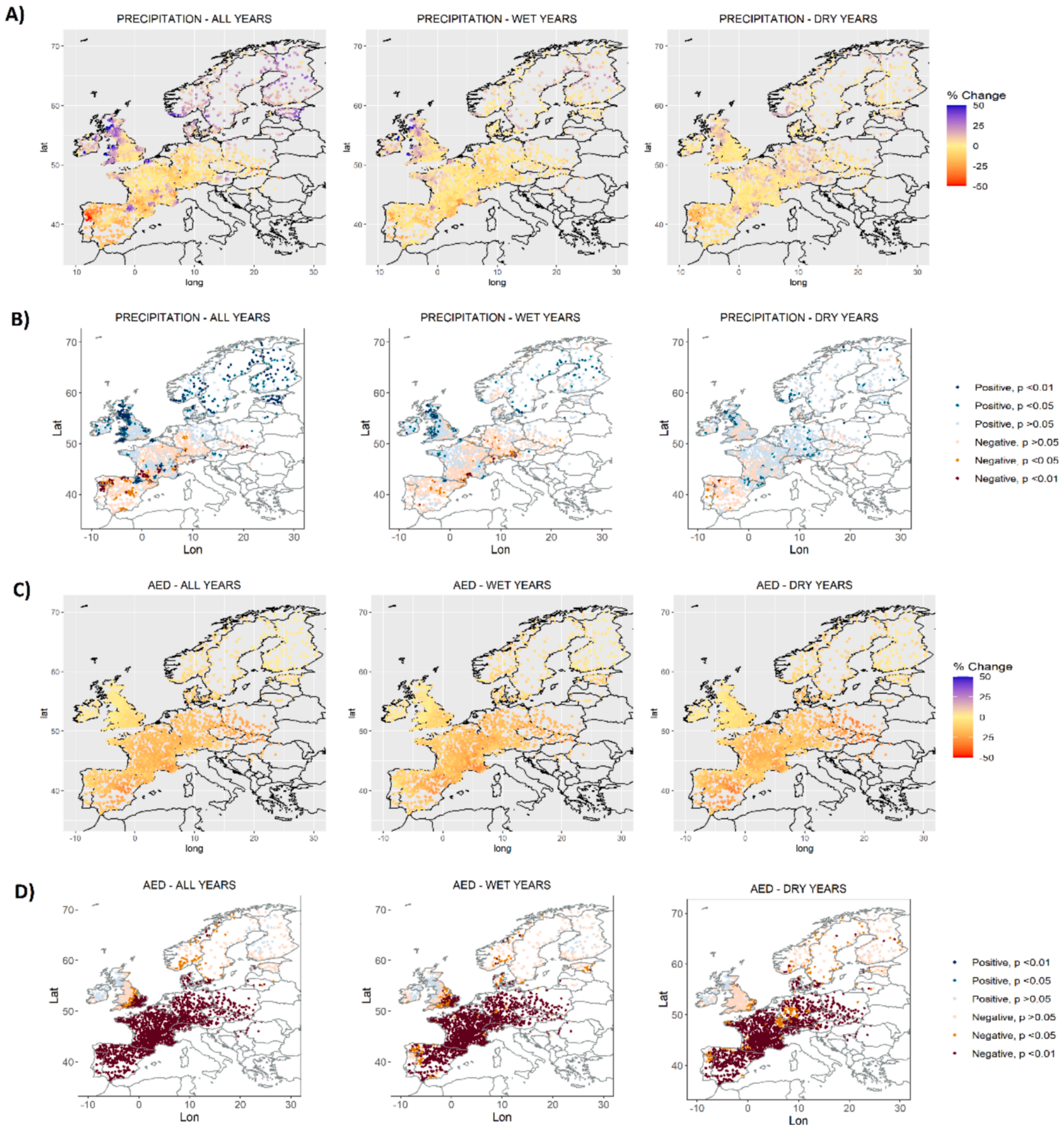

Fig. 4. A) Magnitude of change in precipitation in percent (1962 representing 100 percent) between 1962 and 2017 considering all, wet and dry years. B) Statistical significance of precipitation changes considering all, wet and dry years. C) Same as A) but for AED. D) Same as B) but for AED.

negligible in most basins, but the AED from the previous summer shows a greater impact in basins located in central and northern Europe.The role of time is highly relevant in several basins, particularly in southern France and the Iberian Peninsula, which means that the negative streamflow trend recorded in these regions cannot be related to the evolution of precipitation and AED. Moreover, the role of time is more pronounced in southern Europe when analysing dry years exclusively, in which the beta coefficients associated with time show more negative values in comparison to the beta coefficients associated to time for all and wet years (Fig. 10). This shows that the negative trend in streamflow associated with non-climatic factors is more evident during the dry years.

The identification of drivers of non-climatic trends in annual streamflow in southern Europe is complex given the different factors that may play a role from local to regional scales, including the different forest types, forest sucession stages and crop irrigation practices. Nevertheless, the spatial patterns of forest change show an increase in forest cover in the southern european regions in which the beta coefficients associated with time show negative values (Fig. 11). Moreover, the highest percentages of irrigated area relative to basin area are also

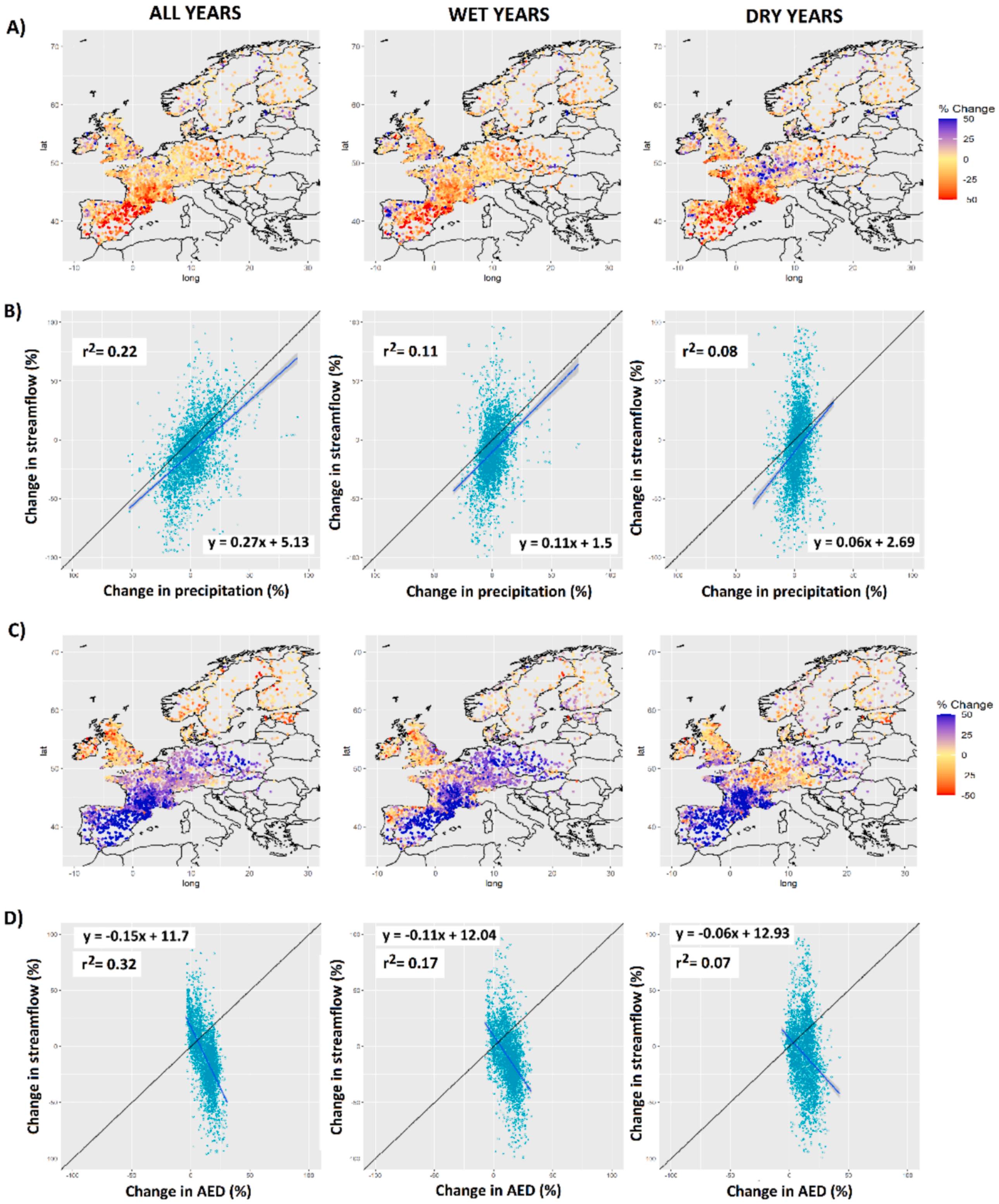

Fig. 5. A) Difference in the magnitude of change in precipitation and streamflow (both in percent) between 1962 and 2017 considering all, wet and dry years. B) Spatial relationship between changes in precipitation and streamflow obtained for all, wet and dry years. C) Difference in the magnitude of change in AED and streamflow (both in percent) between 1962 and 2017 for all, wet and dry years. D) Spatial relationship between changes in AED and streamflow obtained for all, wet and dry years.

recorded in basins of southern Europe, which show a large water consumption annually and a large increase in irrigated area during the study period (Fig. 1).

To identify potential factors driving changes in annual streamflow unrelated to climate, we conducted a comparative analysis involving beta coefficients linked to time, the percentage of forest cover change between 1960 and 2019 in each basin, and the irrigated surface within these basins (Fig. 12). Although there is some dispersion in the data, the

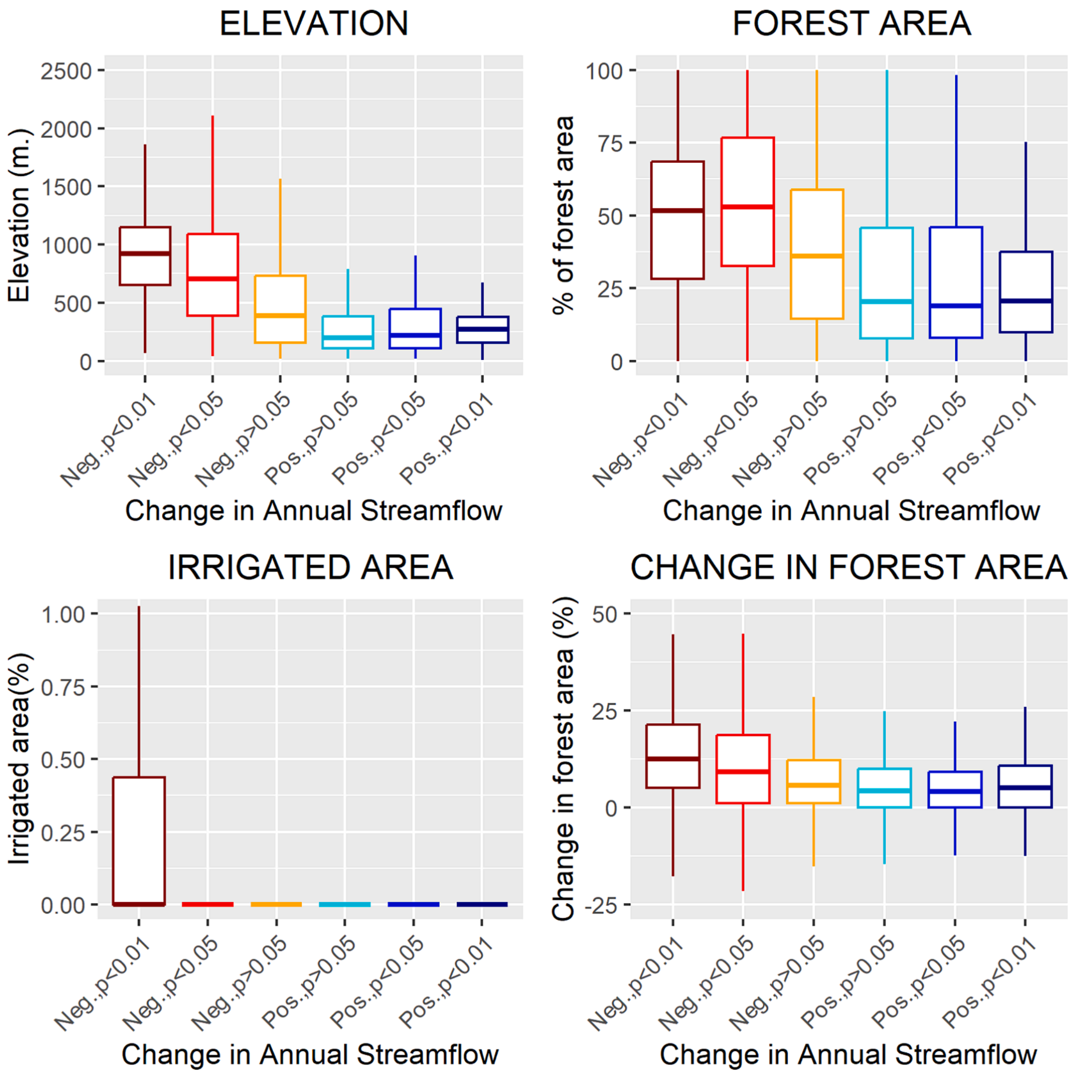

Fig. 6. Box-plots showing the distribution of values for different basin physiographic and land cover characteristics as a function of the statistical significance of changes in annual streamflow.

beta coefficients reveal distinct patterns among basins experiencing either an increase or decrease in forest cover, and these differences are statistically significant between the different groups for all years, dry years (confirmed via One-Way ANOVA and Tamhane post-hoc test, $p < 0.05$) and also between humid years with the exception of the groups −20–0 % and 0–20 %). A similar trend is observed when considering the percentage of irrigated area in each basin. There are significant variations in the beta coefficients between basins with above and below 5 % irrigated surface, again across all years, humid years, and dry years. Nonetheless, the most significant discovery lies in the pronounced variations in the beta coefficients associated with time, particularly evident during dry years. This points to a decline in streamflow, unrelated to climate influences, within basins marked by an overall expansion of forest cover and the adoption of crop irrigation practices. These observations indicate that the changes in land cover are substantially intensifying the occurrence and severity of low streamflows, particularly during dry precipitation years.

4. Discussion

This study analysed the evolution of streamflow in Europe during the period 1962–2017 using more than 3000 gauging stations, with a specific focus on trends observed during wet and dry precipitation years. We found an important decrease in streamflow recorded in areas of southern Europe, which is in agreement with previous studies (Gudmundsson et al., 2019, 2017; Masseroni et al., 2021; Teuling et al., 2019a; Vicente-Serrano et al., 2019). The increase in streamflow recorded in parts of northern Europe is consistent with precipitation increases. Some studies have suggested that the spatial patterns of streamflow changes in Europe and particularly the strong decrease observed in southern Europe can be related to anthropogenic climate change (Gudmundsson et al., 2017). We show that even when focusing on a period in which precipitation shows some decline in southern Europe, although embedded in long-term stationary precipitation behaviour (Peña-Angulo et al., 2020), the large streamflow decrease cannot be explained by precipitation alone. The decrease in streamflow in the majority of basins in southern Europe show statistically significant trends and reductions in streamflow of more than 50 % between 1962 and 2017. By contrast, the reduction in precipitation is small in these areas (approximately 5 %) and in most basins non-statistically significant. Therefore, the large decrease of streamflow in southern Europe cannot be related to the precipitation change alone.

It could be argued that increases in evapotranspiration have been more important than precipitation in explaining the decline in streamflow in southern Europe. If AED increases and water is available, then evapotranspiration could increase in vegetated areas to maintain the

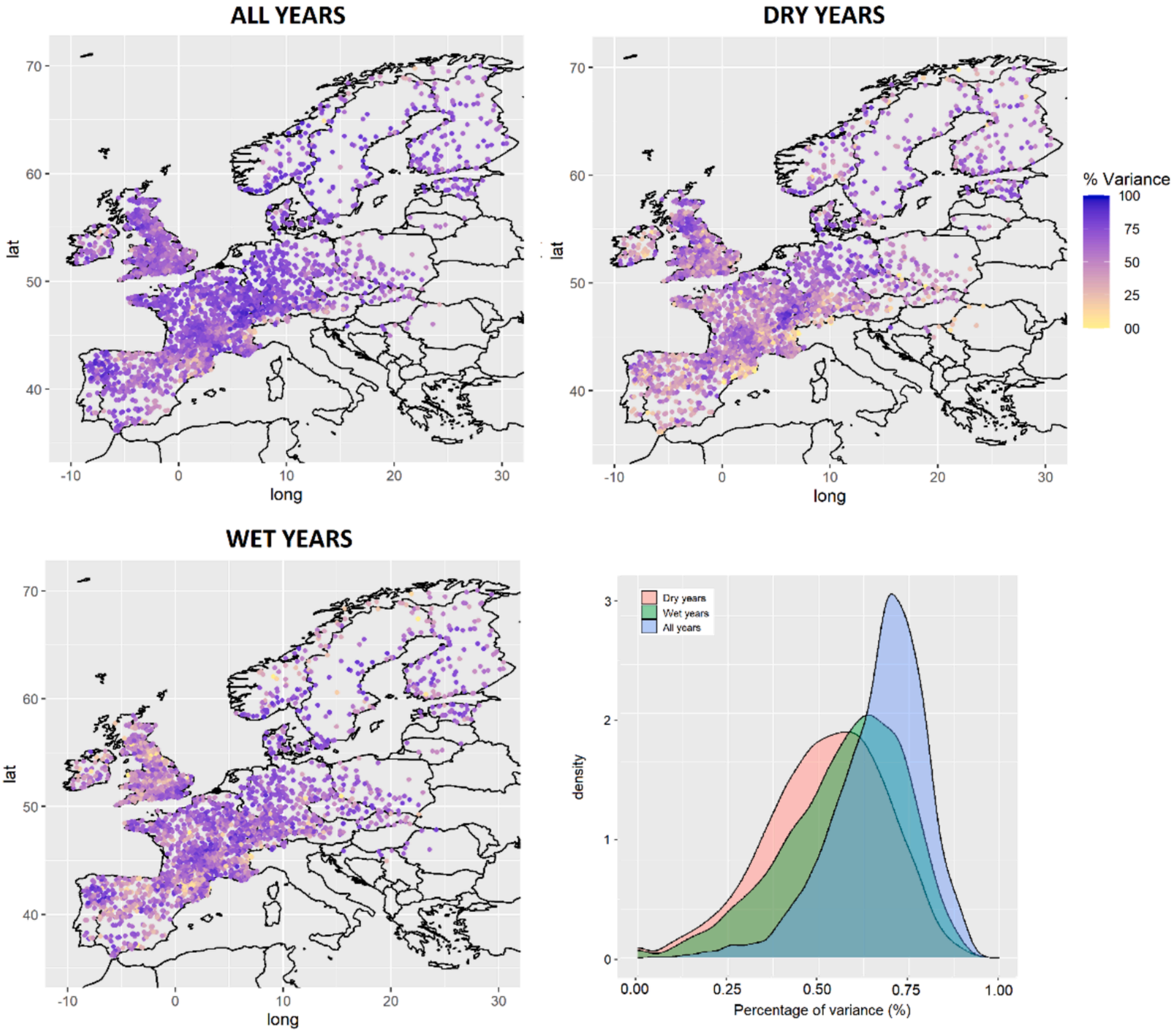

Fig. 7. Maps: percentage of the variance (R^2 coefficients) in annual streamflow explained by each stepwise regression model considering annual precipitation, annual AED, previous year precipitation, previous summer AED and time as independent variables for all, wet and dry years. The density plots show the distribution of the percentage of variance explained by the models.

evapotranspiration deficit (the difference between plant evapotranspiration and atmospheric demand) to zero in order to limit plant water stress. In fact, some negative effect of enhanced AED on streamflow variability has been identified in southern Europe (Vicente-Serrano et al., 2014).

Some modelling studies have suggested an increase of evapotranspiration in Europe (Frank et al., 2015; Zhang et al., 2016; Zhang et al., 2012), increasing the severity of low flows in the region (Massari et al., 2022). In fact, evapotranspiration increases, together with increased water demand in urban areas; has probably been the main driver of streamflow reduction in southern Europe. However, this increase cannot be related to the enhanced AED but mostly to recent trends in land management. This is supported by the small role of AED in comparison to precipitation in explaining the temporal variability of streamflow in southern Europe (Vicente-Serrano et al., 2014), a pattern that is also widely identified at the global scale (Berghuijs et al., 2017; Yang et al., 2018). Our study supports this finding, since AED was not included as a significant variable in the vast majority of basin scale regression models to explain the evolution of streamflow over the last decades. Moreover, it is difficult to discern a distinctive evolution in AED across Europe that may suggest a differential influence between central and southern Europe since in the vast majority of basins, the evolution of AED has been positive and statistically significant. Thus, the magnitude of increase in AED has been very homogeneous across continental Europe, in agreement with previous studies (Vicente-Serrano et al., 2020).

We conclude that in southern Europe in comparison to changes in tree cover and irrigation, the changes in precipitation and AED have played a relatively minor role in explaining the spatial distribution of streamflow trends across Europe. This conclusion is reinforced by the presence of a predominant temporal component that is not explained by the trends in precipitation and AED, which is a significant feature in a substantial percentage of the regression models applied to the southern European basins. It's important to note that the increase in forest cover has consistently been associated with reduced streamflow in the majority of global basins (Hoek van Dijke et al., 2022), and the alterations in land cover and water management practices, particularly in southern Europe, have had notable hydrological consequences (García-Ruiz et al., 2011; Teuling et al., 2019b). In particular, vegetation has strongly increased in the headwaters of Mediterranean mountain areas as consequence of rural exodus and land abandonment (García-Ruiz and Lana-Renault, 2011; Lasanta et al., 2017), a process that has increased water consumption by natural vegetation in the form of plant transpiration and leaf interception (green water), decreasing available water resources downstream (blue water) (Beguería et al., 2003a; López-Moreno et al., 2011b; Vicente-Serrano et al., 2021). In addition, land intensification in other areas by means of irrigation have a larger effect.

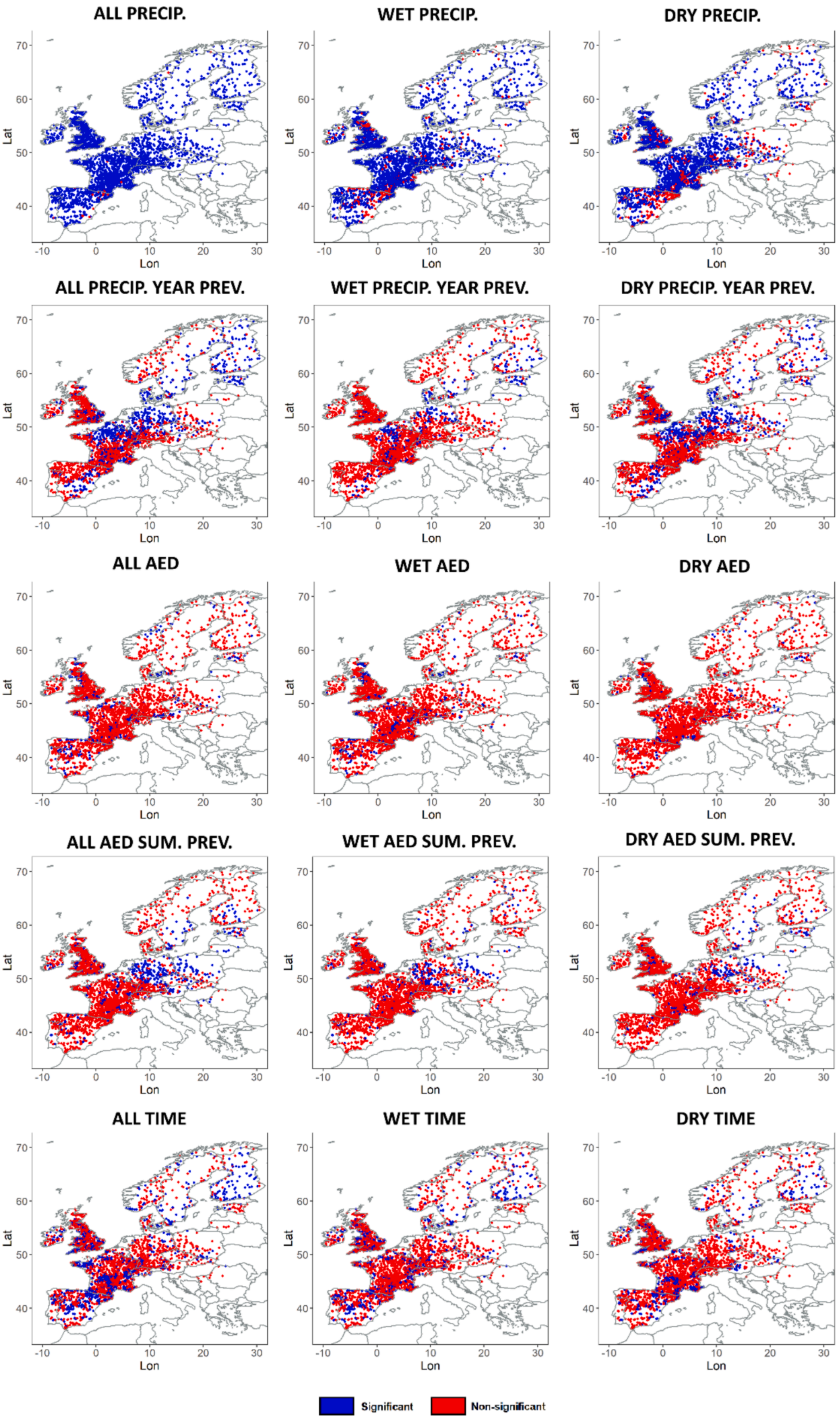

Fig. 8. Basins in which the five independent variables: annual precipitation, annual AED, previous year precipitation, previous summer AED and time are included (significant (0.05 level)) or not (non-significant) in the stepwise regression models with streamflow as the independent variable for all, dry and wet precipitation.

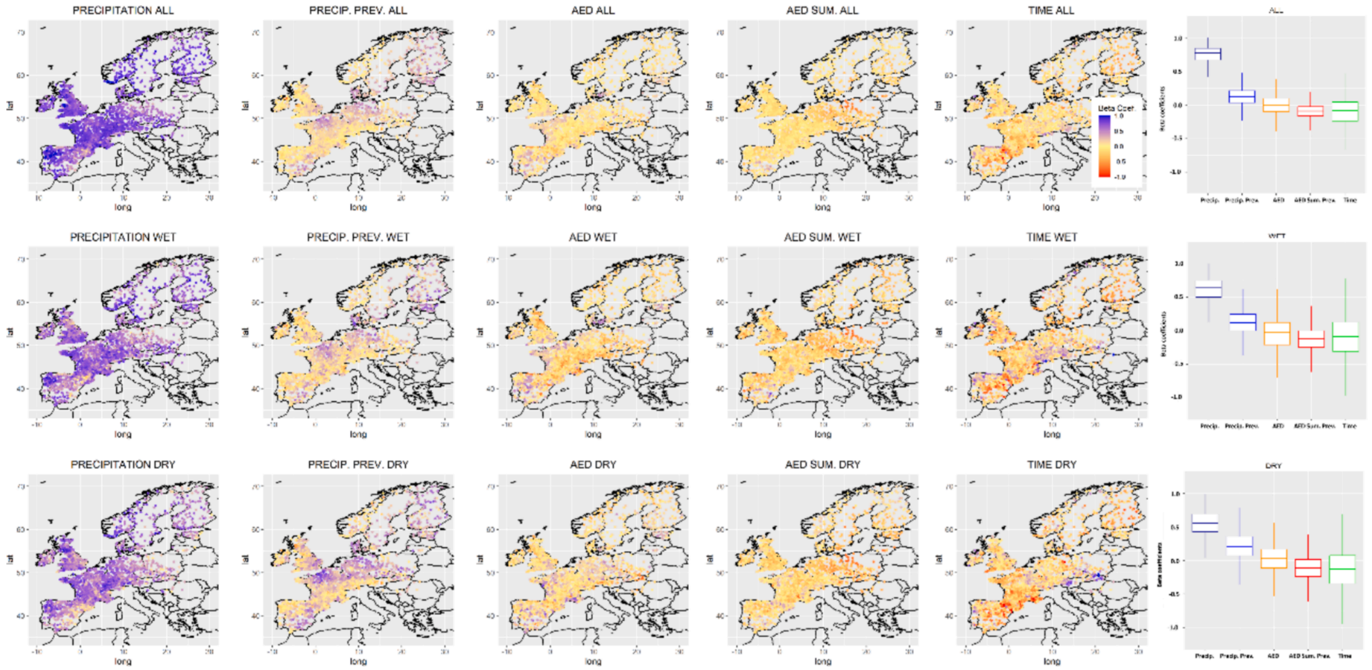

Fig. 9. Spatial distribution of the beta coefficients obtained from the independent regression models for the five independent variables: precipitation, previous year precipitation, AED, previous summer AED and time corresponding to all, dry and wet years. Box-plots show the distribution of the beta coefficients for each variable and group of years.

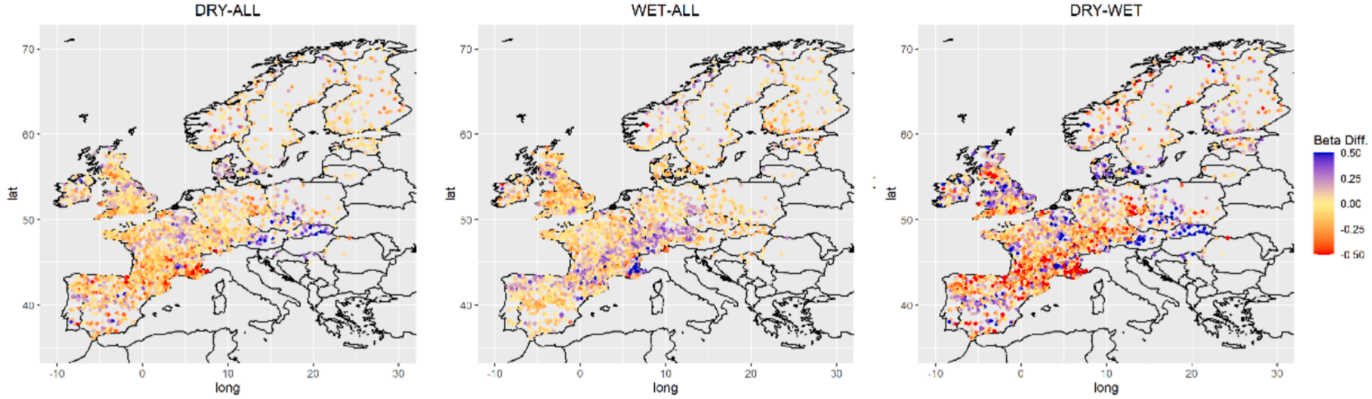

Fig. 10. Difference between the beta coefficients obtained by means of the stepwise regression models between all and dry years (left), between all and wet years (central) and between dry and wet years (right).

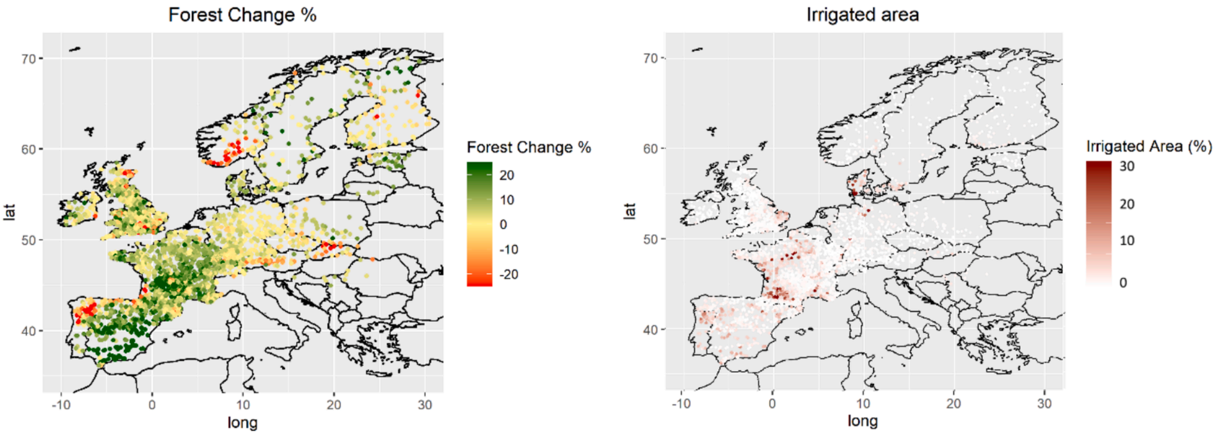

Fig. 11. Spatial distribution of the % of forest change and the percentage area of irrigated lands in each of the analysed basins across Europe.

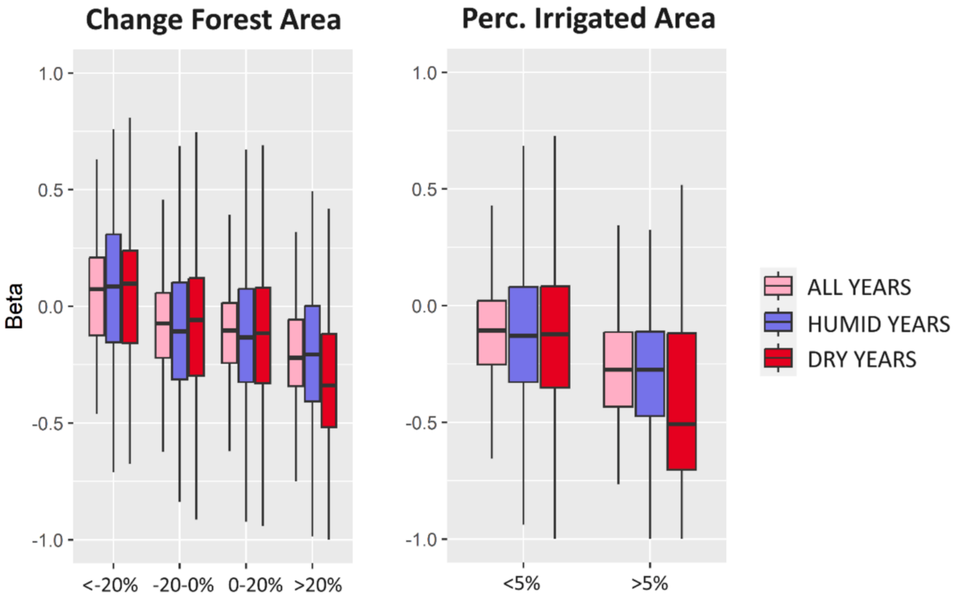

Fig. 12. Boxplots showing the standardized beta coefficients associated to time as a function of the changes in forest area and the percentage of irrigated area during all, wet and dry years.

The number and capacity of reservoirs has strongly increased in southern Europe to meet growing water demands from large irrigated polygons developed in former drylands in recent decades (Pinilla, 2006). Not only has irrigated surface area increased but production on irrigated lands has intensified with more crop cycles per year and the cultivation of market-oriented crops that demand more water to increase the benefits associated with agricultural practices (Beguería et al., 2022; Lana-Renault and Morán-Tejeda, 2020). Even in areas where irrigated lands have been modernised by means of pressurisation, the total plant transpiration has not been reduced given more cultivation cycles (Lecina et al., 2010). High AED in areas of southern Europe could have contributed to increased water losses by plant transpiration in the new forest lands and in irrigated areas but the large decrease of streamflow found in these areas can be only explained by the described land cover changes. The negative and statistically significant beta coefficients corresponding to time support this assessment and stress that spatial differences in annual streamflow trends in Europe cannot be associated to anthropogenic climate change as suggested by previous studies (Gudmundsson et al., 2017).

A significant source of uncertainty in our analysis stems from the lack of long-term data on the evolution of irrigated lands at the basin scale. While irrigation expansion is widely recognized as a critical driver of streamflow reduction, especially in southern Europe, the absence of high-resolution historical data hinders a precise quantification of its impact. Most available datasets, such as CORINE, only provide information from the 1990s onward, with considerable uncertainty regarding earlier trends. As highlighted by some studies (Estrela et al., 2012; Mezger et al., 2022), land-use changes, including irrigation, have played a key role in modifying hydrological regimes in southern Europe. However, without reliable data on the spatial and temporal distribution of irrigated lands, particularly before the 1960s, attributing streamflow changes directly to irrigation expansion remains challenging. This uncertainty necessitates caution when interpreting the results, as we rely on indirect assessments and proxies to approximate the role of irrigation.

Nevertheless, despite these data limitations, the robustness of our conclusions is supported by multiple lines of evidence. First, the spatial patterns of streamflow reduction align well with known irrigation development hotspots, consistent with broader regional trends identified in previous studies (Vicente-Serrano et al., 2017). Second, the historical evolution of agricultural practices, with irrigation expansion accelerating in the second half of the 20th century, provides further context for our findings. The significant rise in water consumption, particularly in southern Europe, strongly suggests that irrigation is a primary driver of streamflow decline. Although we acknowledge the inherent uncertainties, the convergence of evidence from hydrological and climatic studies reinforces the validity of our conclusions regarding the impact of land-use changes on streamflow patterns.

The importance of land cover changes in explaining streamflow trends in Europe is further supported by the differential streamflow trends found between wet and dry years. These trends are not related to precipitation changes that could support more frequent dry years in recent decades. Rather, the precipitation trends identified for dry and wet years are small and not statistically significant in the vast majority of basins. Recent studies have suggested that different hydroclimate drivers cause low flows of different magnitudes in Europe (Brunner et al., 2022). However, the contrasting streamflow trends observed during dry and wet years strongly indicate that external factors, independent of climate, play an essential role. This is evident from the significantly lower runoff coefficients observed in forested areas during dry years (Boulet et al., 2021). We have found that the temporal component included in the regression models shows stronger negative coefficients in dry than in wet years in southern Europe. This suggests that the negative streamflow trends explained by non-climatic factors are more pronounced in dry years. By contrast, in central and northern Europe there are no appreciable differences between wet and dry years. These results are consistent with the expected response to increased evapotranspiration as a consequence of land transformations given the differential partitioning of precipitation between green and blue water during dry periods (Mastrotheodoros et al., 2020; Orth and Destouni, 2018). To find this behaviour in a large number of catchments of southern Europe is significant since it suggests large scale effects on the severity of river low flows due to increases in vegetation coverage. The relationship of these trends in beta coefficients with changes in vegetation coverage and activity shows strong dispersion, but we find that the control of forest change and irrigated surface is much stronger for dry versus wet and all years, reinforcing the hypothesis that vegetation changes on streamflow trends are more relevant during dry years.

These results have large implications to understand the dynamic of the blue and green water partition across Europe over the last decades, particularly during drought periods, in which the partitioning between blue and green water becomes even more skewed, with green water, representing a higher percentage of the total water balance. This is particularly significant in southern Europe, where forest regrowth and irrigation expansion have altered the natural hydrological regime. In times of drought, vegetation continues to use available soil moisture (green water) to sustain transpiration, while the lack of precipitation reduces the replenishment of blue water (streams, rivers, and reservoirs) since enhanced forest cover would increase evapotranspiration rates, even during dry periods, when blue water availability is critically low. As a result, during droughts, the proportion of water allocated to green water increases substantially, reducing the streamflow and aggravating low-flow conditions downstream (Lana-Renault and Morán-Tejeda, 2020; Mastrotheodoros et al., 2020). This shift in water partitioning is particularly acute in irrigated areas (Vicente-Serrano et al., 2017). During droughts, when blue water resources are scarce, the demand for irrigation increases to sustain crop yields since dry conditions are usually accompanied by enhanced atmospheric demand given stability and land–atmosphere feedbacks (Miralles et al., 2019). This intensified use of water for irrigation further depletes blue water resources (Funes et al., 2021), especially in southern Europe where irrigation already accounts for a significant share of water consumption (Estrela et al., 2012), highlighting that irrigation not only increases water demand but also accelerates the depletion of blue water during drought periods, when natural replenishment is minimal. The increase in evapotranspiration in irrigated lands, combined with forest-driven green water uptake, means that in drought periods, a larger proportion of the available water is consumed by plants, leaving less blue water available for human needs.

These findings have large implications for land cover and low flow management in regions where precipitation is projected to decrease during this century (Douville et al., 2021). Landscape management in the headwaters could reduce the severity of low flows in the medium and lower reaches of rivers and improve the availability of water for high demand activities such as irrigation during dry periods. For these reasons, current policies and recommendations for landscape rewilding as part of nature based approaches (Keesstra et al., 2018; Nesshöver et al., 2017) to mitigate climate change with a focus on carbon sequestration in Europe, and creating new irrigated lands in central and northern Europe to address the increasing water demands of crops due to rising temperatures, could have substantial and detrimental hydrological effects during critical periods. Given the far-reaching hydrological consequences, it is imperative that these results be fully integrated into the long-term management of land use in Europe in order to diminish the severity of hydrological low flows.

5. Conclusions

The main conclusions of this study are summarised here:

- Southern Europe’s streamflow reduction, more than 50 % in many basins, can not be fully explained by a small (5 %) decrease in precipitation.
- Evapotranspiration increases, driven by changes in vegetation and land use, are likely the main factor behind streamflow reductions in southern Europe.
- Anthropogenic climate change was suggested as a contributor to these trends, but changes in land management, such as increased forest cover and irrigation, had a stronger impact on streamflow reduction, particularly in dry years.
- In southern Europe, streamflow trends during dry years were more strongly influenced by land cover changes than during wet years, highlighting the importance of vegetation in regulating low flows.
- The expansion of irrigation and forested areas, particularly in former drylands, exacerbated the streamflow decline due to increased water consumption by plants.
- Policy recommendations for landscape rewilding and irrigation expansion could worsen hydrological conditions during critical low-flow periods, especially in regions with projected precipitation declines.
- Land use management must incorporate these findings to mitigate the severity of low flows and ensure water availability for essential activities like irrigation during dry periods.

CRediT authorship contribution statement

Sergio M. Vicente-Serrano: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ahmed El Kenawy:** Writing – review & editing, Formal analysis, Data curation. **Dhais Peña-Angulo:** Writing – review & editing, Software, Formal analysis, Data curation. **Jorge Lorenzo-Lacruz:** Writing – review & editing, Software, Methodology, Data curation. **Conor Murphy:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Jamie Hannaford:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Simon Dadson:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Kerstin Stahl:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Iván Noguera:** Writing – review & editing, Software, Resources. **Magí Fraquesa:** Writing – review & editing, Visualization, Software. **Beatriz Fernández-Duque:** Visualization. **Fernando Domínguez-Castro:** Writing – review & editing, Methodology, Conceptualization.

Declaration of competing interest

The authors 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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Author contribution

SM.V.S conceived research, developed the analysis and wrote the first draft, A.K., D.P and J.L. generated the database, wrote R code and contributed to the analysis, C.M. and J.M. contributed with data and the discussion of the results, S.D. and K.S. discussed the results. I.N., M.F., B.F.D. and F.D.C. contributed to the analysis, the discussion of the results and the development of the plots and maps. All the authors contributed to the manuscript writing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2025.132818.

Data availability

Data is available in public repositories

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