CROSSDRO

Deliverable

4.4 European cross-sectorial impact model validation

This deliverable shows the connection between vegetation processes and hydrological drought severity considering two perspectives: the use of standardized drought indices and the assessment of the trends in water resources availability associated to changes in vegetation. These two perspectives provide similar results and they stress the relevant cross-sectorial (ecological-hydrological) connections to explain the severity of hydrological droughts in Europe. The deliverable illustrates in Spain and at the European scale how the changes in vegetation may clearly increase the severity of hydrological droughts downstream. The obtained results suggest that current recommendations related to nature-based solutions to increase the availability of water resources in the region should be reconsidered.

Unravelling the role of vegetation on the different trends between climatic and hydrologic drought in headwater catchments of Spain

1. Introduction

The availability of water resources is among the most pressing issues in the Mediterranean region and elsewhere around the world. With problems of water stress and scarcity projected to increase in the next decades, most Mediterranean countries are expected to suffer from deficits in freshwater supply, mainly due to population growth (Arnell 2004), high irrigation water demands (Rodríguez Díaz et al. 2007, Wriedt et al. 2009) and climate change processes (Pascual et al. 2015), amongst other stressors. In the Mediterranean, outputs from climate models suggest a general decrease of precipitation and an increase of the atmospheric evaporative demand (AED) (Giorgi & Lionello 2008, Hertig & Tramblay 2017, Lionello & Scarascia 2018, Raymond et al. 2019, Vicente-Serrano et al. 2020c). These projected changes will likely reinforce the frequency and intensity of droughts, posing further challenges to the limited available water resources in the region (Forzieri et al. 2014, Roudier et al. 2016).

In the Mediterranean region, water resources mostly originate in mountain headwaters (Viviroli & Weingartner 2004). Intense transformation of land cover during the last decades has impacted these areas, mainly by abandonment of traditional agriculture and livestock practices (Garcia-Ruiz & Lasanta-Martinez 1990, Vicente Serrano et al. 2000, Lasanta & Vicente-Serrano 2007, Vicente-Serrano et al. 2012b, García-Ruiz et al. 2015). Specifically, pasture and crop areas have rapidly transformed to shrub and forest lands: a process often accelerated by extensive tree plantations after 1960 (Vicente Serrano et al. 2000, Poyatos et al. 2003, Lasanta-Martínez et al. 2005, Lasanta & Vicente-Serrano 2007, Serra et al. 2008, Stellmes et al. 2013).

The increase in vegetation greening could have important geomorphological and hydrological impacts (García-Ruiz & Lana-Renault 2011). It is well-recognized that forests, due to plant physiology, consume more water than crops and pastures (Scanlon et al. 2007, Zhou et al. 2010, Beck et al. 2013, Teuling et al. 2019). Accordingly, the partition between blue and green water has noticeably favored the second one (Orth & Destouni 2018). This situation leads to a general decrease of streamflow, compared to that suggested by climate trends (Vicente-Serrano et al. 2019). This pattern is particularly evident in Spain, where different studies have suggested that natural revegetation has contributed significantly to the reduction in water resources in the mountain headwaters (e.g. Beguería et al. 2003, López-Moreno et al. 2011).

In Spain, river streamflow has decreased significantly over the last decades (López-Moreno et al. 2011, Lorenzo-Lacruz et al. 2012, Martínez-Fernández et al. 2013, Vicente-Serrano et al. 2014c, Coch & Mediero 2016). For example, studies have demonstrated that the annual streamflow in the basins of the Mediterranean exhibited a decline by more than 50% (e.g. Sánchez-Chóliz & Sarasa 2015, Vicente-Serrano et al. 2019). Also, other works have indicated an increase in the frequency of hydrological droughts—i.e., reductions in streamflow (e.g. Lorenzo-Lacruz et al. 2013, Coch & Mediero 2016). The intensification of hydrological droughts downstream the main irrigation polygons in Spain could affect the water management and demand, particularly for irrigation (Vicente-Serrano et al. 2017a). Studies have also found that an increase in the frequency and severity of hydrological droughts was important in the medium and low courses in the area of the basins, even with stronger impacts than those of climatic droughts -i.e., reductions in precipitation (Vicente-Serrano et al. 2014c). According to Domínguez-Castro et al. (2019), no clear trends in climatic droughts were observed in Spain over the period 1961-2014.

Yet, detailed assessments of changes in hydrological droughts over the headwaters of the river basins in Spain are lacking. Detailed assessments are important from the hydroclimatic perspective, given that these headwaters are mostly unregulated and accordingly less impacted by human infrastructures. In addition, a reliable assessment of these changes could contribute to better understanding of runoff production at the whole basin scale (Viviroli & Weingartner 2004, López-Moreno et al. 2011). Furthermore, a comprehensive assessment of hydrological droughts could improve understanding of the role of vegetation changes and mechanisms in the development and intensification of hydrological drought in these regions. Thus, analyzing the evolution of the climatic and hydrological droughts on non-regulated basins could also help isolating the possible impacts of land cover changes on the propagation of the climatic droughts to hydrological droughts.

Using non-regulated basins of Spain as test cases, this study therefore addresses the following questions. First, How trends in hydrological droughts different to climatic droughts in non-regulated basins of Spain?, Second, What is the role of vegetation changes on the possible trend differences between climatic and hydrological drought?, Third, What spatial patterns emerge in the trend differences between climatic and hydrological drought that can be related to vegetation changes?

2. Material

This study employed the monthly streamflow data gauged at the headwaters of the Spanish basins. We collected data from national and local water management agencies, including the Ministry of transport, mobility and urban agenda and Centro de Estudios y Experimentación de Obras Públicas (CEDEX) (http://ceh-45 flumen64.cedex.es/anuarioaforos/default.asp; last access) besides the Catalan (http://aca.gencat.cat/ca/inici; last access), Basque (http://www.uragentzia.euskadi.eus/u81-470002/es/; last access), and Andalusian (https://www.agenciamedioambienteyagua.es/; last access) water management agencies. Herein, we only considered the series with less than 25% of missing data for the entire study period (1961-2013). The series were reconstructed and quality controlled using the best correlated data from neighboring series. Further details on the data processing and validation can be found in Vicente-Serrano et al. (2019). The dataset in this study initially included a total of 472 monthly streamflow series spanning the continental Spain and covering the period 1961-2013. Nevertheless, we decided to exclude the series located in the middle and lower course and those impacted by large perturbations related to water regulation (e.g. damming) and urban and irrigation extractions. Following this decision, all basins with relevant regulation upstream were excluded. To this end, the final dataset included 226 headwaters (Figure 1). The selected basins are generally small, with an average area of 523 km^2. The drainage basin of each gauging station was identified by means of ArcHydrotool (ArcGIS10.2©) using a Digital Terrain Model at a spatial resolution of 100 m (http://info.igme.es/cartografiadigital/otra/mdt5.aspx ; last access).

For each selected basin, we extracted the corresponding meteorological data from a newly developed high-resolution (1x1 km) gridded dataset for Spain. The methodology for developing this dataset and its main spatial and temporal characteristics is described in Vicente-Serrano et al. (2017a). In this study, we employed the meteorological data at a monthly scale for precipitation, air temperature, relative humidity, sunshine duration and wind speed spanning the period from 1961 to 2013. We computed the atmospheric evaporative demand based on the FAO-56 Penman-Monteith reference evapotranspiration (ETo) equation (Allen et al. 1998). Tomas-Burguera et al. (2019) contains details of this dataset.

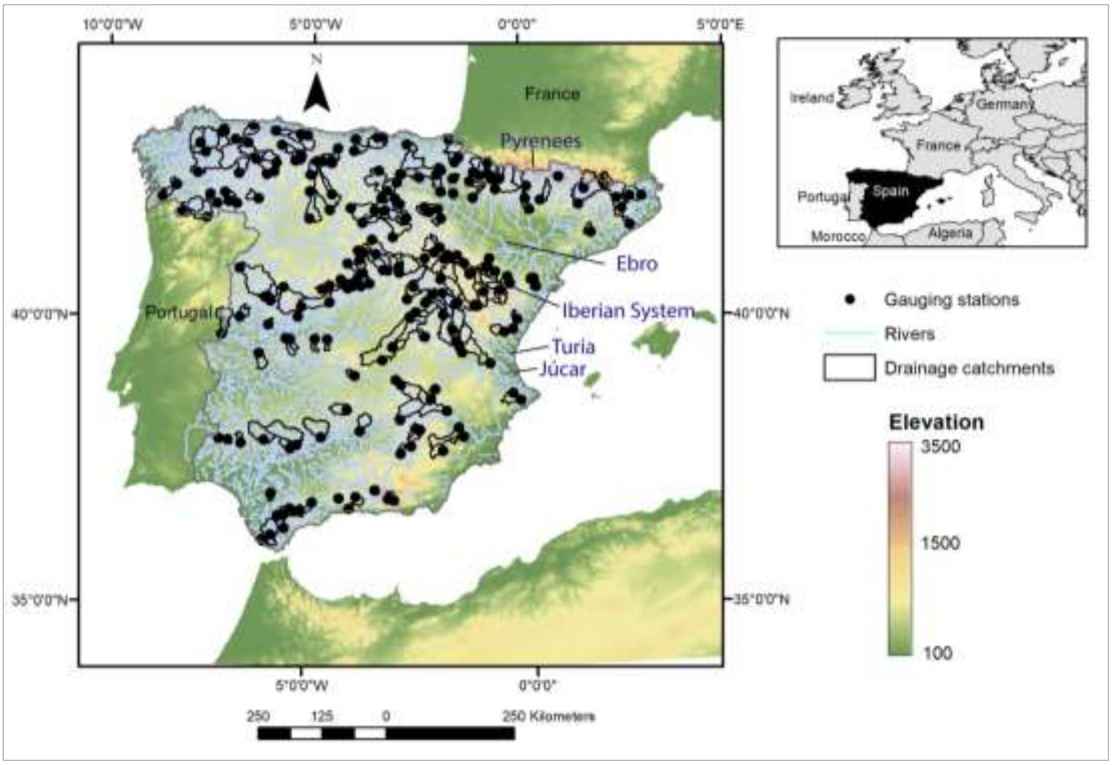


Figure 1: Spatial distribution of the gauging stations and drainage basins selected for this study. The base map shows the elevation (m) and rivers of the Iberian Peninsula.

We also used land cover information using two official land cover maps provided by the Ministry of Agriculture of Spain (https://www.mapama.gob.es/es/cartografia-y-sig/publicaciones/agricultura/; last access). The first map was published in 1978 based on the aerial photographs of 1956-1957, providing a good baseline of the vegetation conditions for the beginning of the study period. The second map was published in 2010, representing land cover conditions in recent decades. Both maps are available in a digital (vector) format at a spatial scale of 1:50,000, capturing the main land cover classes in Spain. Alongside the analysis of changes in the different land cover types, we also calculated the difference in the surface area represented by the various forest classes (e.g. coniferous, broadleaf and mixed forests) between 1958 and 2010.

Also, we used an auxiliary dataset to characterize vegetation changes in Spain. This dataset includes the Normalized Difference Vegetation Index (NDVI), which was developed using the daily NOAA-AVHRR images available from 1981 onwards. A description of this dataset is available in Vicente-Serrano et al. (2020). Herein, the annual average of NDVI values was aggregated for each drainage basin using the sum of the bi-weekly NDVI data for the entire period from 1981 to 2013.

3. Methods

For quantifying climatic and hydrologic droughts, this study employed two different indices to characterize drought at the basin scale. We calculated the Standardized Precipitation Evapotranspiration Index (SPEI) to assess climatic drought at time scales ranging from 1- to 48-month (Vicente-Serrano et al. 2010). The use of this range of timescales allows for characterizing the distinct hydrological response to the varying temporal scales of climate droughts (López-Moreno et al. 2013, Peña-Gallardo et al. 2019). Compared with other drought indices, SPEI showed better performance in capturing the temporal variability of hydrological variables in Spain, including soil moisture (e.g. Scaini et al. 2015) and streamflow (e.g. Vicente-Serrano et al. 2014c). To compute SPEI, we employed the monthly data of precipitation and ETo for each basin. On the other hand, the Standardized Streamflow Index (SSI) (Vicente-Serrano et al. 2012a) was used to characterize hydrological droughts. This index allows for a direct spatial and temporal comparison of the streamflow series, especially amongst regions with different hydroclimatic conditions (Vicente-Serrano et al. 2012a). While our assessment was made primarily at the basin level, we also calculated a regional series of SPEI and SSI for the whole study area using a simple arithmetic average of streamflow and climate series for all basins.

Following the run theory (Yevjevich 1967), several criteria serve to identify independent drought events based on thresholds (Fleig et al. 2006). In this study, we adopted a threshold of -0.84 to define drought events using SPEI/SSI (Lorenzo-Lacruz et al. 2013, Vicente-Serrano & Beguería 2016). This threshold corresponds to a 20% of probability in the standard normal probability distribution and correspondingly a return period of 1 in 5 years, which refers to a moderate drought. Once the drought events were identified, we computed the corresponding series of drought frequency, duration and magnitude. The drought duration was defined as the number of consecutive months with SPEI/SSI values lower than -0.84, while the drought magnitude was computed following the classical approach of Dracup et al. (1980). Specifically, the SPEI/SSI values were integrated over the full length of each dry period, where the total magnitude of negative values during a drought event was transformed - for operative purposes- to positive values.

Once climatic and hydrologic droughts were quantified, we used statistical methods to assess possible temporal changes. For this purpose, we employed the nonparametric Mann-Kendall statistic to assess the statistical significance of changes in the frequency, duration and magnitude of climatic and hydrological droughts over the study period (1961-2013). The statistical significance was assessed at the 95% level ($p<0.05$). A modified version of the Mann-Kendall statistic was used to limit the impact of autocorrelation, which might be introduced in the series, on trend detection. This statistic returns the corrected p-values after accounting for temporal pseudo-replication (Hamed & Ramachandra Rao 1998). To assess the amount of change in the series of drought duration and magnitude, we applied an ordinary linear regression model, in which the series of time is the independent variable, while the drought duration or magnitude is the dependent variable. The slope of the regression indicates the amount of change, with higher slope values suggesting greater changes and vice versa.

Finally, to assess the role of vegetation changes on the differences in trends between climatic and hydrologic droughts, we compared changes in the climatic and hydrological droughts and linked them with changes in forest total surface and NDVI using Pearson's r correlations. We used a linear regression model to obtain the Beta coefficients, allowing assessment of the independent role of changes in each land cover type (Hair et al. 1995). Also, this procedure limits the possible cross-influence of changes in other land cover types, which is important given the relevant succession processes and replacements between the different vegetation types.

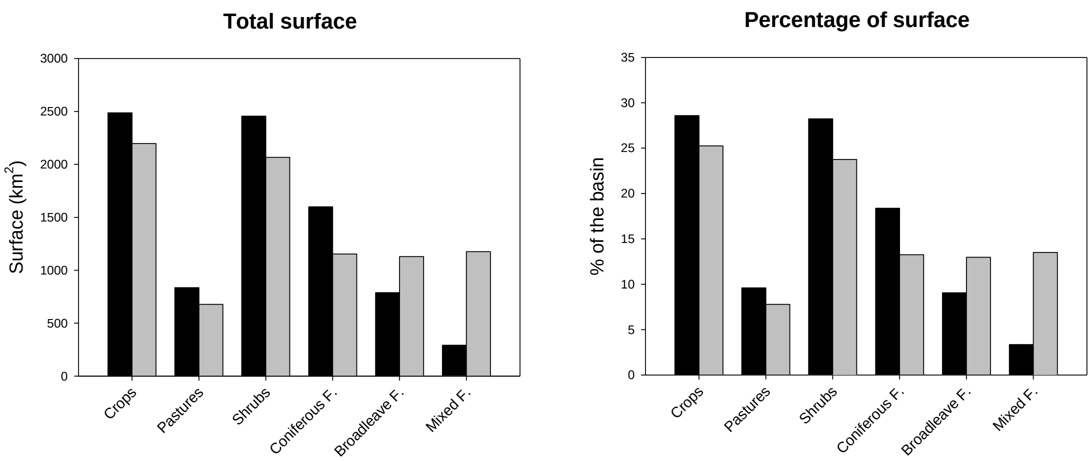
4. Results

4.1 Land cover changes

Changes in land cover types in the study area show an increase in forest area compared to other plant covers over the past five decades (Figure 2a). Overall, results suggest an increase in the forest total surface from 2678.9 km^2 (30.7% of the whole domain) to

3458.3 km^2 (almost 40%). As depicted in Figure 2b, the increase in the total area of forests has been evident for the majority of basins. Some basins experienced stronger changes in their forest area, as compared to the total area of the basin, representing more than 30% of the basin surface. Notably, the most pronounced increase amongst the different forest types was found for mixed forest (883.9 km^2). Exceptionally, a decrease in the forest surface was noted in few basins, mainly spanning southern and southeastern Spain (Figure 2c). In the same context., a dominant increase of the Normalized Difference Vegetation Index (NDVI) was evident for all basins, even in those with a decrease in heir forest surface. Nonetheless, some considerable spatial differences in the amount of NDVI changes can be observed, with stronger changes over eastern and northeastern Spain.

a)



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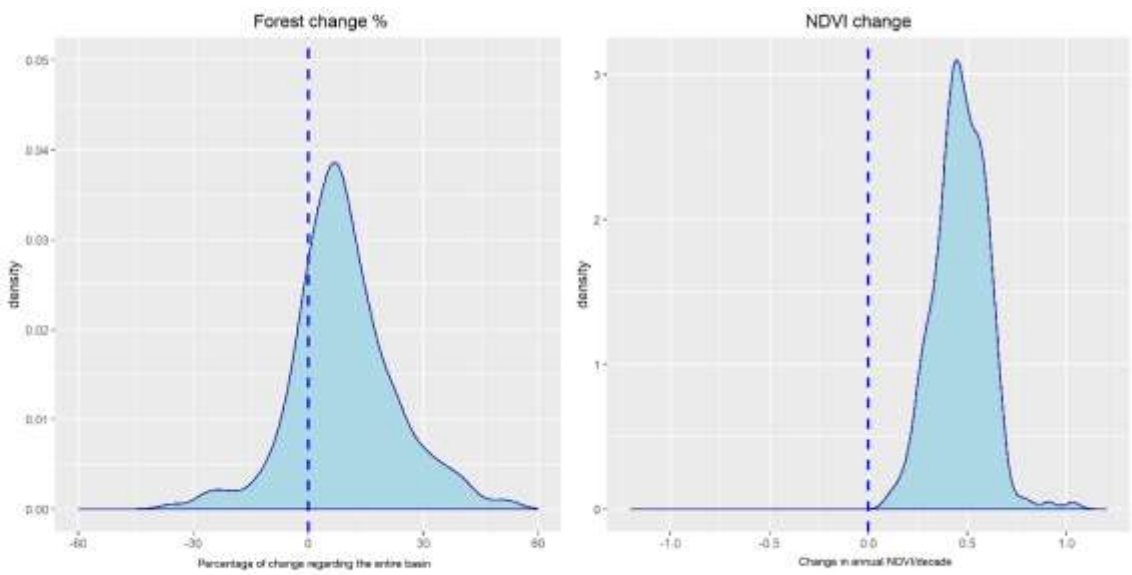

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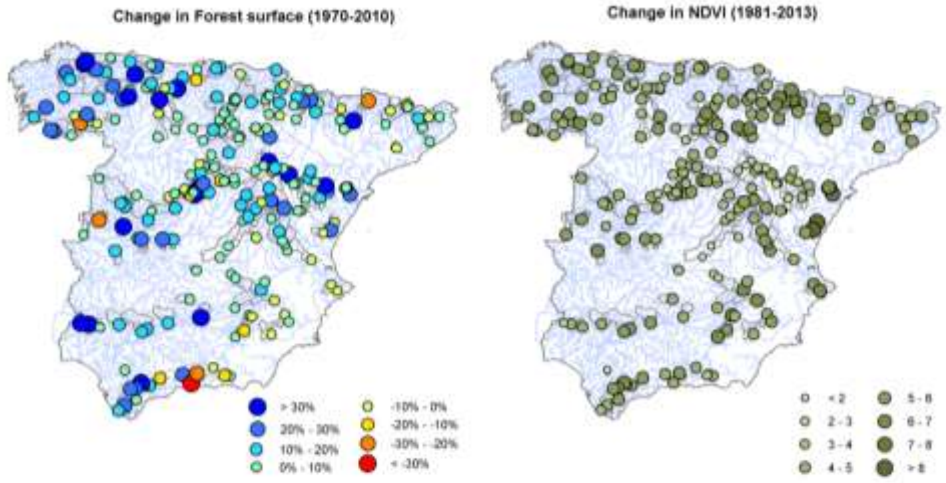

Figure 2a) Total surface and percentage of the study area with the different land cover types in the 1970s (black) and 2010 (grey). b) Density plots showing changes in the proporotional area of forests (%) with respect to the total surface of the basin (left panel), and changes in the annual NDVI between 1981 and 2012 (right panel). c) Spatial distribution of the magnitude of change in the percentage of forest surface in relation to the total surface of the basin (left), and magnitude of change of the annual NDVI from 1981 to 2013 (right).

4.2. Evolution of climatic and hydrologic droughts

The Standardized Streamflow Index (SSI) and Standardized Precipitation Evapotranspiration Index (SPEI) indices show a greater agreement, from the correlation coefficient computed, at 3-month timescale (Pearson's r = 0.74), considering the regional series over the whole study area (Figure 3). This means that, regionally, temporal variability of the SSI is mostly determined by the climate conditions recorded under the current and the previous two months. Overall, Figure 3 suggests that SSI shows less dependency on climatic conditions at longer timescales, given that the correlation coefficient between SSI and SPEI decreases as the timescale increases. This motivated analyzing the evolution of the climatic droughts using SPEI at 3-month timescale.

A notable temporal agreement is observed in the occurrence of drought events of SSI and SPEI at 3-month timescale for the period 1961-2013 by means of a regional series for the whole study area (eg 1964, 1988, 1995, 2001, 2005 and 2011) (Figure 4). Nevertheless, changes in hydrological drought were much stronger than climatic drought since severe drought events, as revealed by SSI, were identified mainly during the 2000s and 2010s. In particular, SSI showed a decrease on the order of -0,21 z-unit/decade, while SPEI declined by -0.07 z-unit/decade.

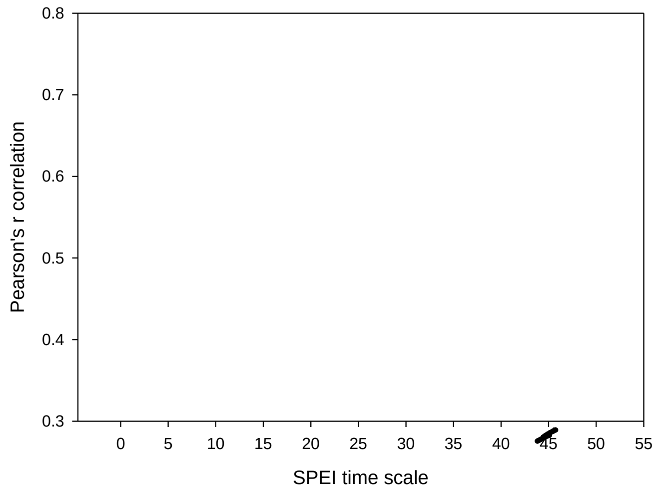

Figure 3: Pearson's r correlation calculated between the SSI and SPEI at different time scales. The correlation was computed for the regional series of all basins.

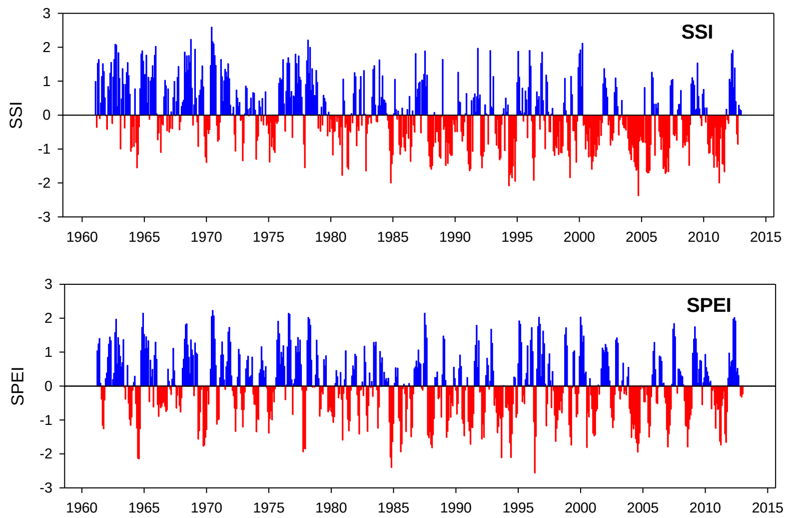

Figure 4: Temporal evolution of the regional series of SSI and 3-month SPEI from 1961 to 2013.

The temporal evolution of the regional series of severity, duration and frequency drought on annual scale show a major increase of these characteristic in hydrological drought than those of climatic drought (Figure 5). Specifically, changes in hydrological droughts were statistically significant ($p<0.05$), whereas changes in climatic droughts were small and statistically non-significant ($p>0.05$). Furthermore, in severity and duration a change point in the early 1990's is detected. Before the 1990's, SPEI shows higher values for drought severity and duration, while after the 1990's, SSI shows higher values. This result suggests that hydrological droughts were more reinforced in their severity over the analyzed natural catchments, compared with the severity of climatic drought.

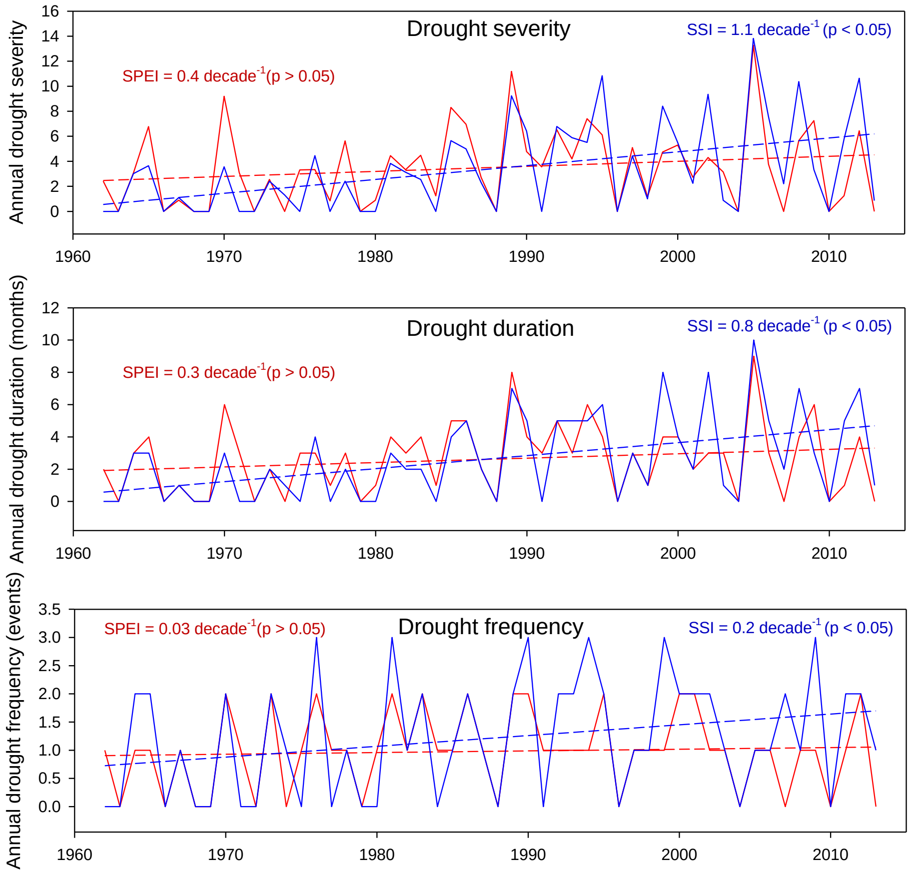

Figure 5: Evolution of the regional series of annual drought severity, duration and frequency obtained from the monthly series of SSI (blue lines) and SPEI (red lines).

Considerable spatial differences exist, where more negative trends were identified considering SSI than SPEI (Figure 6). Specifically, the strongest decrease in SSI was noted in the Mediterranean basins, such as the Ebro, Turia and Júcar basins. The headwaters of these basins originated mainly in the Iberian range and the Pyrenees. In contrast, the basins located in the western portions of the Iberian Peninsula exhibited smaller changes, and even positive changes. This spatial pattern was evident for both SPEI and SSI. Importantly, although negative changes of SSI and SPEI dominated over the majority of the basins (Figure 7), a strong spatial difference exists in the magnitude of changes. Notably, even nearby basins showed different amounts of change. This high spatial variability is confirmed in Figure 8, but for changes in the series of drought severity, duration and frequency. As illustrated, a relationship is evident between the spatial distribution of changes in SPEI and those of SSI, where the basins showing more increase in the severity of climatic drought tended to exhibit stronger hydrological droughts. Again, this result indicates that changes in hydrological droughts were more accelerated than climatic droughts, especially in the eastern Spain (Figure 9 and Table 1).

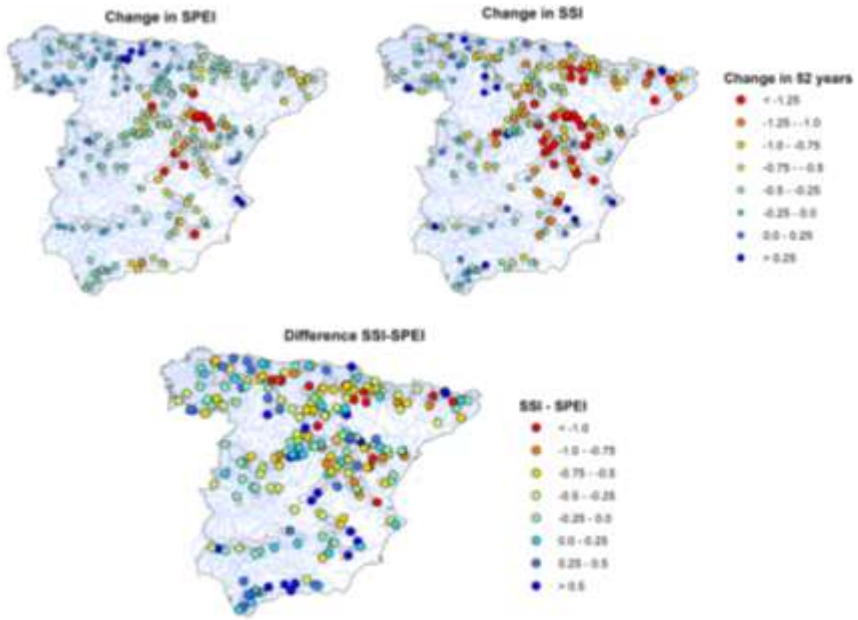

Figure 6: Spatial distribution of the SPEI and SSI changes and their differences between 1961 and 2013. Values above/below (+/-) 0.35 are statistically significant at the 95% level (p<0.05).

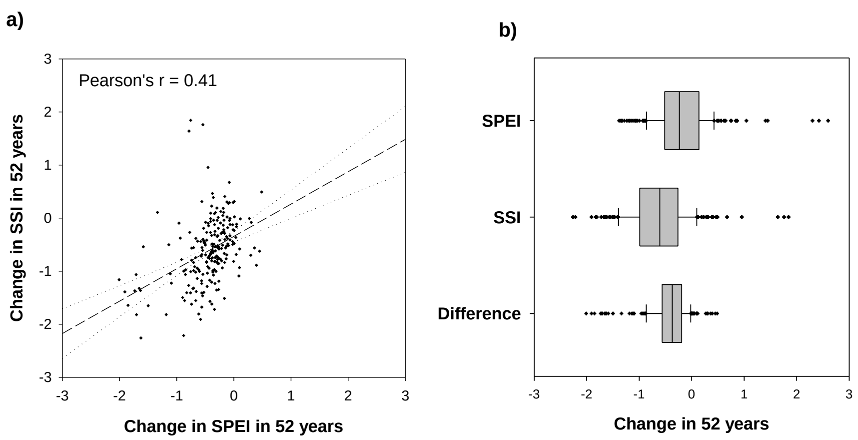

Figure 7: a) Relationship between the magnitude of change in SPEI and SSI for the analysed basins, b) Box-plot showing the the amount of change in SPEI, SSI and their differences. The amount of change is provided in z-unit/decade. The central solid line indicates the median. The whiskers represent the 10th and the 90th, while the 25th and the 75th are plotted as the vertical lines of the bounding boxes. The dots refer to the extreme values.

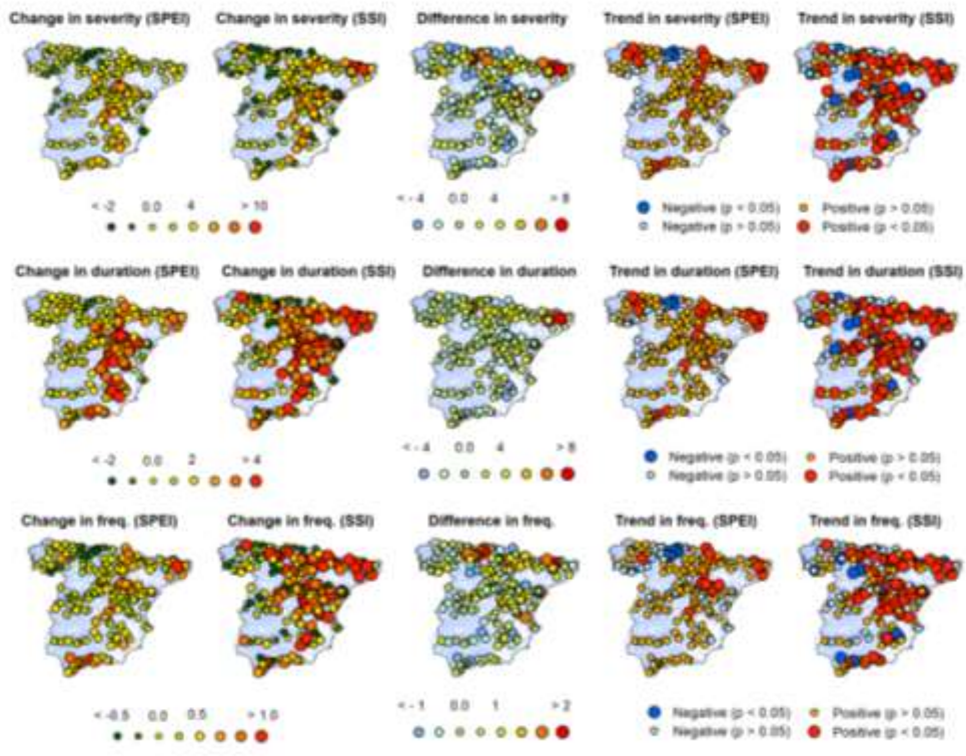

Figure 8: Spatial distribution of the changes in drought severity, duration and frequency between 1961 and 2013 and their statistical significance using SPEI and SSI indices.

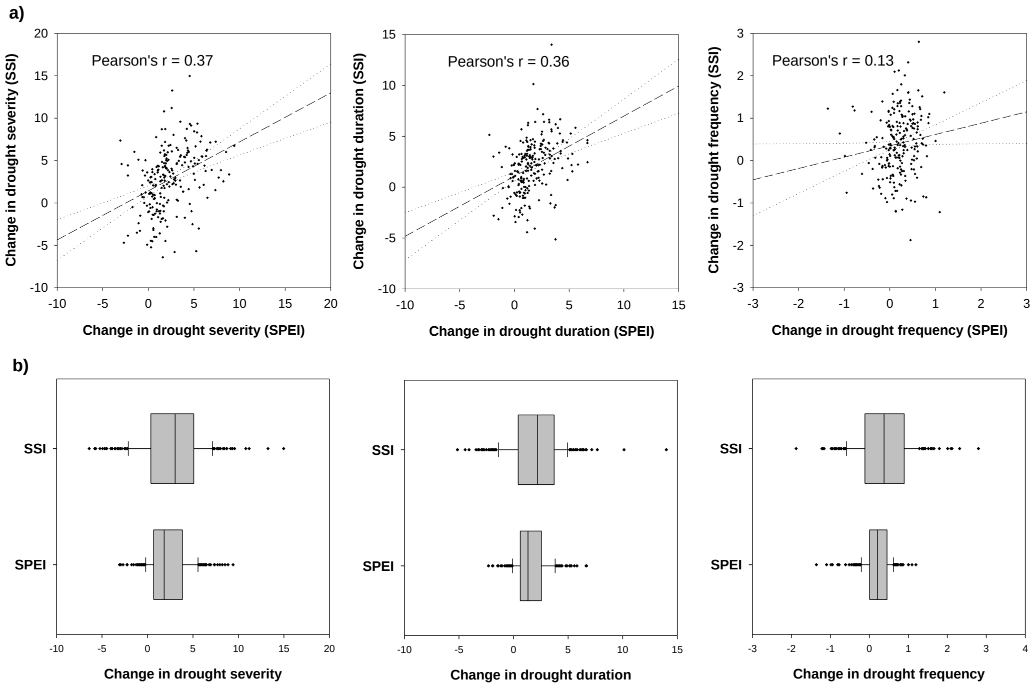

Figure 9: a) Relationship between changes in drought severity, duration, and frequency based on SPEI and those of SSI for the analysed basins, b) Box-plot showing changes in drought severity, duration, and frequency obtained from SPEI and SSI series. The amount of change is provided in z-unit/decade. The central solid line indicates the median. The whiskers represent the 10th and the 90th, while the 25th and the 75th are plotted as the vertical lines of the bounding boxes. The dots refer to the extreme values.

Table 1: Number of basins showing positive and negative trends in the severity, duration and frequency of the drought events between 1961 and 2013.

	Severity (SPEI)	Severity (SSI)	Duration (SPEI)	Duration (SSI)	Frequency (SPEI)	Frequency (SSI)
Significant negative ($p < 0.05$)	3	12	4	11	6	10
Non-significant negative ($p > 0.05$)	24	41	22	36	48	55
Non-significant positive ($p > 0.05$)	171	82	171	86	154	86
Significant positive ($p < 0.05$)	28	91	29	93	18	75

4.3. Influence of vegetation changes

In basins characterized by lack of water regulation and management,previous studies have established a general increase in forest surface as the most plausible explanation of the intensification of hydrological droughts in relation to the evolution of climatic droughts (e.g., Evaristo & McDonnell 2019). This increase was evident in our study area, especially in the last decades. Results indicate that the increase in vegetation coverage corresponded to a more pronounced increase in severity and duration of hydrological droughts, as compared to earlier decades characterized by lower vegetation coverage (Figure 10). In contrast, differences in climatic drought severity between periods with different forest coverage were almost non-significant.

Findings inform an overall increase of the severity of hydrological droughts across the whole study area. However, this trend cannot be explained by the evolution of climatic droughts. Rather, it is more linked to the observed increase of the forest coverage. However, it is noteworthy indicating that the impacts of changes in vegetation coverage on the evolution of hydrological drought evolution are apparently complex. This complexity is evident in this study, given that the response of hydrological droughts to the evolution of the vegetation coverage is unidirectional over space (Figure 10).

In spite of the increase of the vegetation coverage at the basin level, no significant relationship is detectable between the spatial changes of forest surface and those of the severity and duration of hydrological droughts, as compared to the evolution of climatic droughts. A similar pattern was also noted when comparing NDVI changes between 1981 and 2013 and changes in the frequency, duration, and severity of hydrological drought and, in comparison to climatic drought trends. These findings, combined with the observed disagreement between climatic and hydrologic droughts, indicate that the dependency between forest coverage, vegetation greening, and climatic and hydrological drought is spatially complex (Figure 11). We should stress, however, that in more mature forests (e.g. coniferous, broadleaf, and mixed forests), the forest succession processes seem to have a significant impact on differences in the evolution of hydrological and climatic droughts (Table 2). As listed, for the coniferous and broadleaf forests, results suggest statistically significant correlations between the difference in the evolution of the drought variables and the average surface of these forests. Notably, coniferous and mixed forests represent the dominant forests in the study area. Results also suggest, however, that differences occur in the sign of correlation with these two major forests. Specifically, changes in the total area covered by coniferous forests showed a statistically significant negative significant correlation with the spatial changes in the difference between hydrological and climatic droughts. In contrast, the mixed forests exhibited a statistically significant positive correlation. The differences in the sign of the correlation may highlight the role of the forest succession, as many basins witnessed a dominant replacement of coniferous forest by mixed forests. Interestingly, these basins showed a stronger increase in the severity of hydrological droughts than in climatic droughts.

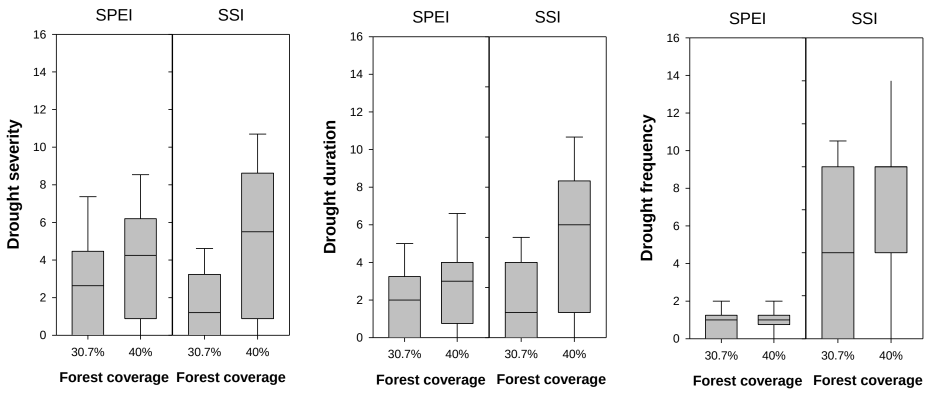

Figure 10: Box-plots showing the differences between the severity, duration, and frequency of drought events during two periods (1962-1986 and 1987-2013), which correspond to different forest coverage (30.7% vs. 40%, respectively)

To account for the possible role of the dominant forest types, we employed a linear regression model, in which differences in the severity and duration between hydrologic and climatic droughts served as dependent variable. Changes in the different land cover types and NDVI were independent variables. Based on the values of beta coefficient, which removes the influence of the shared variance among variables, results revealed that the observed changes in the total surface covered by mixed forests was the most significant variable contributing to the the spatial variability of of the magnitude of changes between hydrological and climatic droughts. Results also suggested contributions of the increase in the area of broadleaf forests, while the negative values of Beta coefficient indicated less contribution of shrubs and coniferous forests (Table 3).

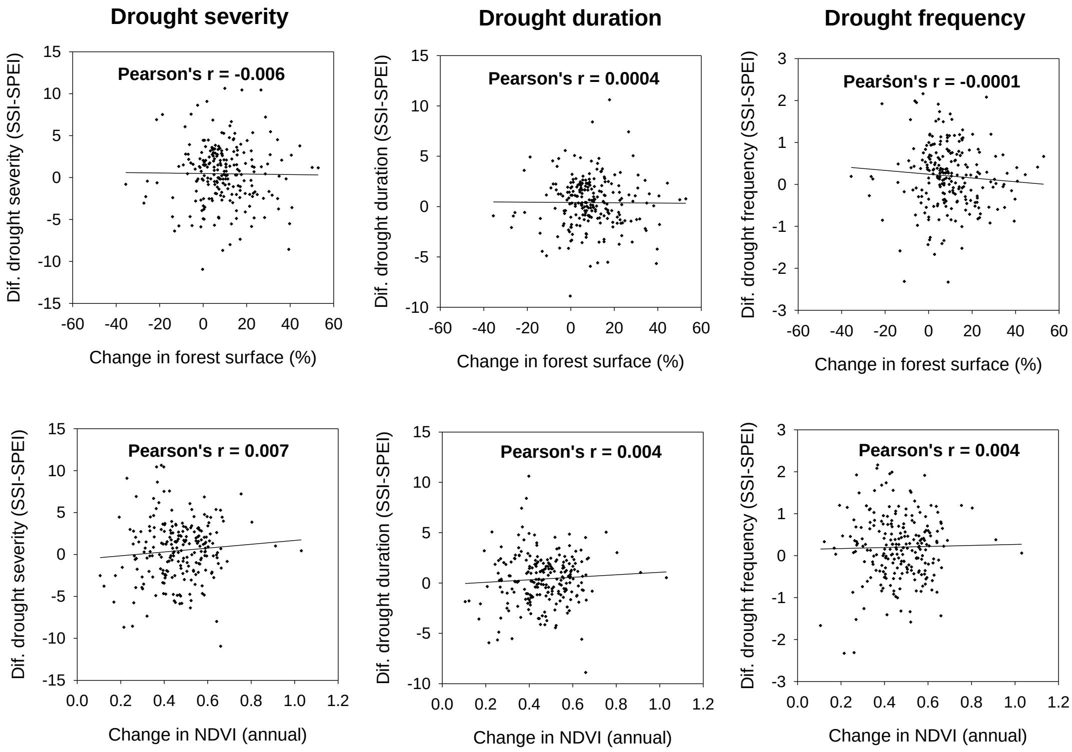

Figure 11: Scatterplots showing the relationship between the difference in the changes in the severity, duration and frequency of hydrological droughts with climatic droughts, as compared to changes in the percentage of forest surface corresponding to each basin (top), and changes in the annual NDVI (bottom)

5. Discussion

5.1. Changes in the vegetation coverage

The headwaters of the Spanish Mediterranean mountains have subjected to dominant natural revegetation processes in recent decades (Gallart et al. 2011, García-Ruiz & Lana-Renault 2011). These processes are clearly observed in the natural basins analyzed in this study, where the total areas of forests have markedly increased during the last four decades. Based on space-based products, different studies have also identified a dominant increase of the vegetation coverage in Spain over the last decades (e.g. Julien et al. 2011, Stellmes et al. 2013, Vicente-Serrano et al. 2020b). This study confirmed previous findings, given that all the analyzed basins exhibited a dominant increasing trend in vegetation activity between 1981 and 2013. The mentioned land abandonment would be the main factor that explains the dominant increase in vegetation activity (Lasanta et al. 2020). Nevertheless, this study also indicates that the increase of forest surface corresponded to succession processes that mainly impacted more mature forests over the last decades. The main socioeconomic changes that affected Spain accelerated forest recovery during the first half of the 20th century (Garcia-Ruiz & Lasanta-Martinez 1990, García-Ruiz & Lana-Renault 2011, Lasanta et al. 2020). Later, in the 1970s, most of the abandoned fields were recollonised by shrubs and forests (Lasanta-Martínez et al. 2005, Lasanta et al. 2017). In more recent decades, the increase in forest surface continued, mainly with a replacement of shrubs and coniferous forests with more mature broadleaf and mixed forests. These complex land cover, combined with frequent succession processes, may pose further challenges when assessing the possible spatial differences in the role of vegetation processes on hydrological drought changes.

Table 2: Pearson's r correlation coefficients between the spatial patterns of the difference of change between hydrologic and climatic droughts, the surface (%) of different land cover types in 2010s, the average NDVI, changes (%) in the surface of each land cover type between the 1970s and 2010s, and the magnitude of change in the annual NDVI between 1981 and 2013.

	Severity	Duration	Frequency
Crop surface	-0.09	-0.07	-0.04
Pasture surface	0.09	0.07	-0.03
Shrub surface	0.07	0.06	0.02
Coniferous For. Surface	0.16*	0.17*	0.10
Broadleaf For. Surface	0.05	0.04	-0.02
Mixed For. Surface	0.18*	0.19*	0.09
Average NDVI	0.11	0.10	-0.01
Difference crop surface	-0.06	-0.05	0.00
Difference pasture surface	-0.02	-0.04	-0.01
Difference shrub surface	-0.03	-0.03	0.07
Difference conif. For. Surface	-0.14*	-0.14*	-0.12
Difference broad. For surface	-0.04	-0.06	-0.12
Difference mixed For. Surface	0.16*	0.16*	0.08
NDVI change	0.08	0.07	0.02

5.2 Evolution of climatic and hydrological droughts

The results of this study show a dominant negative trend in SSI and SPEI indices, suggesting more hydrological drying conditions over the past decades. This drying corresponds to an acceleration of the of the frequency, duration and severity of drought events, albeit with stronger changes in hydrological droughts than in climatic droughts. Taken these findings together, the enhanced hydrological drought conditions and the increase in the severity and duration of these droughts is a seemingly dominant pattern in the headwaters of the Spanish basins, albeit with the lack of water regulation and/or changes in human water demands in these basins. This finding is consistent with the decrease in streamflow found by Coch & Mediero (2016) for 60 gauging stations located in near-natural basins in Spain between 1949 and 2009.

Table 3: Beta standardized coefficients obtained from two linear regression models, considering the difference of change between hydrological and climatic drought severity and duration for each basin, changes in the different land cover types, and annual NDVI changes as input variables.

	Drought Severity	Drought Duration
Change NDVI	0.29	0.11
Change crop area	0.08	0.01
Change pasture area	0.47	0.35
Change shrub area	-0.17	-0.33
Change conif. Forest area	-0.43	-0.36
Change broadleaf forest area	0.51	0.27
Change mixed forest area	1.09	1.12

Numerous studies have indicated non-significant changes in precipitation totals over Spain during the last decades (Vicente-Serrano et al. 2020a, Peña-Angulo et al. 2020). In contrast, other contributing drivers of drought evolution (e.g. atmospheric evaporative demand) exhibited a statistically significant increase in the past decades (Vicente-Serrano et al. 2014b), mainly driven by temperature rise and relative humidity decrease (Vicente-Serrano et al. 2014a b, Tomas-Burguera et al. 2020). As such, the inclusion of the atmospheric evaporative demand in the calculation of drought indices (e.g. SPEI) suggests a drying trend during the past decades, which is lacking in studies based on precipitation-based drought indices alone (e.g. González-Hidalgo et al. 2018). Nevertheless, that this study suggests statistically non-significant changes is noteworthy, in the severity and duration of climatic drought over the headwaters of the Spanish basins. Interestingly, the study findings indicate significant trends in the hydrological drought and their frequency, duration, and intensity over the selected basins.

5.3 Dependency between hydrological droughts and vegetation cover changes

Given the high water consumption of forest (Evaristo & McDonnell 2019), the increased forest surface, and forest densification over the headwaters of the Spanish basins, it is reasonable to assume that the dominant observed increase in the duration, severity and frequency of hydrological droughts across these catchments can be linked to the observed evolution of the vegetation, as this study suggests for the whole study area. Previous studies have indicated that changes in vegetation are the main driver of the streamflow decrease in some headwater catchments in Spain (e.g. Beguería et al. 2003, Gallart et al. 2011, López-Moreno et al. 2011, Morán-Tejeda et al. 2012, Salmoral et al. 2015). As such, we consider that intensification of the severity of hydrological droughts in the headwaters of the Spanish basins could be attributed to the evolution of the vegetation cover, recalling that changes in climate droughts were not substantial in these basing during the same period.

In the absence of other influences, it is reasonable to attribute the observed mismatch between the trends in climatic and hydrological droughts to the observed general increase of the vegetation coverage in the study domain. Simply, forests consume more water in comparison to shrubs and pastures (Gyenge et al. 2002, Scanlon et al. 2007, Aranda et al. 2012, Filoso et al. 2017, Quinteiro et al. 2018, Evaristo & McDonnell 2019). Different studies attributed streamflow decreases to the increase of water consumption by vegetation, especially in reforested areas (e.g. Scanlon et al. 2007, Filoso et al. 2017, Evaristo & McDonnell 2019). We should also stress that the impacts of vegetation coverage increase on hydrological droughts cannot be discussed independently from other important drivers (e.g. atmospheric evaporative demand). In particular, the atmospheric evaporative demand could increase the severity of hydrological drought (Salmoral et al. 2015), especially in the lower reaches of the humid catchments, where soil water availability is unlimited. Nevertheless, although the enhanced atmospheric evaporative demand could contribute partly to the intensification of hydrological droughts in the analyzed basins, its role in streamflow variability and trends is less pronounced compared to the role of precipitation (Yang et al. 2018, Vicente-Serrano et al. 2019), or land cover changes (see also Vicente-Serrano et al.

2019). Results based on the SPEI reveal weak and statistically non-significant changes in climatic droughts. In contrast, results considering SSI indicate stronger and significant changes in hydrological droughts over the study domain.

We must note that, although the influence of the vegetation coverage on the reduction of streamflow average is very relevant in Spain, this role is particularly critical during the climate droughts. This is simply because of the shortage of water resources (Orth & Destouni 2018), which affects irrigation and water supply and thus vegetation growth. While this specific feedback has not been addressed comprehensively in this study, we consider that the partition between blue and green water is more likely favorable to the latter during the episodes of climate droughts, as vegetation tends to depend on soil moisture to maintain its photosynthetic activity and growth.

We must also stress that, although attributing the intensified hydrological droughts to changes in vegetation coverage is feasible with high confidence over the whole study domain, we did not find a robust spatial coherence between the magnitude of change in the severity of hydrological droughts and the magnitude of changes in the forest coverage or vegetation activity (as identified by remote sensing data) since the differences between climatic and hydrological drought trends were not spatially consistent with changes of vegetation coverage. Morán-Tejeda et al. (2012) identified a clear signal on the effect of forest coverage on streamflow reduction in the headwaters of the Duero river (NW Spain). Their study also indicated, however, no direct linkage between the magnitude of change in forest coverage and the observed runoff decrease. They explained this finding by the notion that other important variables related to forest type, age, and structure, in addition to the physiographic, geologic and edaphic characteristics of each basin, make it difficult to establish linear relationships between the magnitude of the afforestation process and the observed trend in river flows.

In this study, we include a complete set of basins, with higher hydroclimatic variability than those analyzed by Morán-Tejeda et al. (2012). The selected study basins also showed different rates of revegetation processes and accordingly varying vegetation densities. As such, it is expected that the different photosynthetic activities amongst these basins could make their response to hydrological drought different. Moreover, the differences in the length of vegetation activity periods and vegetation species could have an influence on the response of these basins to hydrological droughts, as they strongly determine the annual rates of actual evapotranspiration by plants (Frank et al. 2015). Also, the hydrological influence of vegetation changes is expected to be higher when forests densify to more mature stages, in comparison to the initial stages of succession. During these early stages, pastures and shrubs are typically replaced by young forests with less mature root systems and accordingly different water demands than the preexistent shrub coverage. This issue could explain the significant correlation found between the spatial patterns of temporal mismatch between climatic and hydrological droughts and changes in the total areas covered by breoadleaf and mixed forests. The latter forests tend to be more mature than earler succession phases domianted mainly by coniferous forests (Vicente-Serrano et al. 2006). The role of the vegetation coverage will also interact with other physiographic and climatic conditions. For example, the influence of vegetation changes can be extremely relevant in high elevations, as trees reduce strongly the snowpack and cause an earlier snowmelt (Sanmiguel-Vallelado et al. 2019). This would increase the severity of hydrological droughts downstream during the melting period.

6. Conclusions

This study presents a detailed assessment of changes in hydrological drought over the over non-perturbed headwater catchments of Spain, including changes in both climatic drought and vegetation cover. The main results provide response to the main questions raised in the introduction:

i) The climatic drought determines the hydrological drought, however there are other factors that make this relationship more complex. The hydrological droughts exhibited larger increases in their frequency, duration, and severity than climatic droughts.

ii) Changes in vegetation have a strong impact on the relationship between climatic and hydrological drought over time. The total areas of forests and the NDVI values showed a remarkable increase during the last four decades and the overall increase in the duration, severity, and frequency of hydrological droughts over the headwaters of the Spanish basins can be linked to an increase in forest total area and forest densification.

iii) Although there is no consistent spatial relationhip between changes in the severity of hydrological drought and changes in forest surface, the advance of many forests to more mature succession stages, with a broader coverage of broadleaf and mixed forests, can partially explain the observed spatial variability of hydrological drought trends.

Results of this work have important implications for the management of water resources in Spain, given that vegetation coverage is expected to continue growing and densifying in the future. This fact may pose further challenges to the limited water resources in the lowlands, creating competences amongst the different water uses (e.g. irrigation and urban supply). This situation will likely become more complicated during the frequent drought periods that affect the region. For this reason, more effective forest management practices (Martín-Benito et al. 2010, Vose et al. 2016, Evaristo & McDonnell 2019), clearing shrublands, combined with more intense livestock pressure (Lasanta 2019, Lasanta et al. 2019, Khorchani et al. 2020) could control the revegetation processes and thus increase runoff production in the headwaters. Improved forest management is also important from hydrological and socioeconomic perspectives, given that the headwaters are the most critical areas for the generation of water resources in the Mediterranean region, and likely elsewhere around the world.

References

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Food and Agriculture Organization of the United Nations.

Aranda, I., Forner, A., Cuesta, B., Valladares, F., 2012. Species-specific water use by forest tree species: From the tree to the stand. Agric Water Manag 114, 67–77.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. Glob Environ Chang 14, 31–52.

Beck, H.E., Bruijnzeel, L.A.M., Van Dijk, A.I.J., McVicar, T.R., Scatena, F.N., Schellekens, J. 2013. The impact of forest regeneration on streamflow in 12 mesoscale humid tropical catchments. Hydrol Earth Syst Sci 17, 2613–2635.

Beguería. S., López-Moreno, J.I., Lorente, A., Seeger, M., García-Ruiz, J.M., 2003.

Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. Ambio 32, 283–286.

Coch, A., Mediero, L. 2016. Trends in low flows in Spain in the period 1949–2009. Hydrol Sci J 61, 568–584.

Domínguez-Castro, F., Vicente-Serrano, S.M., Tomás-Burguera, M., Peña-Gallardo, M., Beguería, S., El Kenawy, A., Luna, Y., Morata, A., 2019. High spatial resolution climatology of drought events for Spain: 1961–2014. Int J Climatol. 39, 5046-5062.

Dracup, J.A., Lee, K.S., Paulson, Jr. E.G., 1980. On the statistical characteristics of drought events. Water Resour Res 16, 289–296.

Evaristo, J., McDonnell, J.J. 2019. Global analysis of streamflow response to forest management. Nature 570, 455–461.

Filoso, S., Bezerra, M.O., Weiss, K.C.B., Palmer, M.A., 2017. Impacts of forest restoration on water yield: A systematic review. PLoS One 12, e0183210.

Fleig, A.K., Tallaksen, L.M., Hisdal, H., Demuth, S., 2006. A global evaluation of streamflow drought characteristics. Hydrol Earth Syst Sci 10, 535–552.

Forzieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F., Bianchi, A., 2014. Ensemble projections of future streamflow droughts in Europe. Hydrol Earth Syst Sci 18, 85–108.

Frank, D.C., Poulter, B., Saurer, M., Esper, J., Huntingford, C., Helle, G., Treydte, K., Zimmermann, N.E., Schleser, G.H., Ahlström, A., Ciais, P., Friedlingstein, P., Levis, S., Lomas, M., Sitch, S., Viovy, N., Andreu-Hayles, L., Bednarz, Z., Berninger, F., Boettger, T., D'alessandro, C.M., Daux, V., Filot, M., Grabner, M., Gutierrez, E., Haupt, M., Hilasvuori, E., Jungner, H., Kalela-Brundin, M., Krapiec, M., Leuenberger, M., Loader, N.J., Marah, H., Masson-Delmotte, V., Pazdur, A., Pawelczyk, S., Pierre, M., Planells, O., Pukiene, R., Reynolds-Henne, C.E., Rinne, K.T., Saracino, A., Sonninen, E., Stievenard, M., Switsur, V.R., Szczepanek, M., Szychowska-Krapiec, E., Todaro, L., Waterhouse, J.S., Weigl, M., 2015. Water-use efficiency and transpiration across European forests during the Anthropocene. Nat Clim Chang 5, 579–583.

Gallart, F., Delgado, J., Beatson, S.J.V., Posner, H., Llorens, P., Marcé, R., 2011. Analysing the effect of global change on the historical trends of water resources in the headwaters of the Llobregat and Ter river basins (Catalonia, Spain). Phys Chem Earth 36, 655–661.

García-Ruiz, J.M., Lana-Renault, N., 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region - A review. Agric Ecosyst Environ 140, 317–338.

Garcia-Ruiz, J.M., Lasanta-Martinez, T. 1990. Land-use changes in the Spanish Pyrenees. Mt Res & Dev 10, 267–279.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Glob Planet Change 63, 90–104.

González-Hidalgo, J.C., Vicente-Serrano, S.M., Peña-Angulo, D., Salinas, C., Tomas-Burguera, M., Beguería, S. 2018. High-resolution spatio-temporal analyses of drought episodes in the western Mediterranean basin (Spanish mainland, Iberian Peninsula). Acta Geophys 66, 381–392.

Gyenge, J.E., Fernández, M.E., Salda, G.D., Schlichter, T.M., 2002. Silvopastoral systems in Northwestern Patagonia II: Water balance and water potential in a stand of Pinus ponderosa and native grassland. Agrofor Syst 55, 47–55.

Hair, J.F., Anderson, R.E., Tatham, R.L., Black, W.C. 1995. Multivar Data Anal.

Hamed, K.H., Ramachandra, R.A., 1998. A modified Mann-Kendall trend test for autocorrelated data. J Hydrol 204, 182–196.

Hertig, E., Tramblay, Y. 2017 Regional downscaling of Mediterranean droughts under past and future climatic conditions. Glob Planet Change 151, 36–48.

Julien, Y., Sobrino, J.A., Mattar, C., Ruescas, A.B., Jiménez-Muñoz, J.C., Sòria, G., Hidalgo, V., Atitar, M., Franch, B., Cuenca, J., 2011. Temporal analysis of normalized difference vegetation index (NDVI) and land surface temperature (LST) parameters to detect changes in the Iberian land cover between 1981 and 2001. Int J Remote Sens 32, 2057–2068.

Khorchani, M., Nadal-Romero, E., Tague, C., Lasanta, T., Zabalza, J., Lana-Renault, N., Domínguez-Castro, F., Choate, J., 2020. Effects of active and passive land use management after cropland abandonment on water and vegetation dynamics in the Central Spanish Pyrenees. Sci Total Environ 717.

Lasanta-Martínez, T., Vicente-Serrano, S.M., Cuadrat-Prats, J.M., 2005. Mountain Mediterranean landscape evolution caused by the abandonment of traditional primary activities: A study of the Spanish Central Pyrenees. Appl Geogr 25.

Lasanta, T. 2019a Active management against shrubland expansion: Seeking a balance between conservation and exploitation in the mountains. Geogr Res Lett 45, 423–440.

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M.P., Lana-Renault, N. 2017. Space–time process and drivers of land abandonment in Europe. Cbatena 149, 810–823.

Lasanta, T., Nadal-Romero, E., García-Ruiz, J.M., 2019. Clearing shrubland as a strategy to encourage extensive livestock farming in the Mediterranean Mountains. Geogr Res Lett 45, 487–513.

Lasanta, T., Nadal-Romero, E., Khorchani, M., Romero-Diaz, A., 2020. A review of abandoned lands in Spain: from local landscapes to global management strategies. Cuad Investig Geografica 0.

Lasanta, T., Vicente-Serrano, S.M., 2007. Cambios en la cubierta vegetal en el pirineo aragonés en los últimos 50 años. Pirineos.

Lasanta, T., Vicente-Serrano, S.M., 2012. Complex land cover change processes in semiarid Mediterranean regions: An approach using Landsat images in northeast Spain. Remote Sens Environ 124.

Lionello, P., Scarascia, L., 2018. The relation between climate change in the Mediterranean region and global warming. Reg Environ Chang 18, 1481–1493.

López-Moreno, J.I., Vicente-Serrano, S.M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., García-Ruiz, J.M., 2011. Impact of climate evolution and land use changes on water yield in the ebro basin. Hydrol Earth Syst Sci 15.

López-Moreno, J.I., Vicente-Serrano, S.M., Zabalza, J., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., Morán-Tejeda, E., 2013. Hydrological response to climate variability at different time scales: A study in the Ebro basin. J Hydrol 477, 175–188.

Lorenzo-Lacruz, J., Mońan-Tejeda, E., Vicente-Serrano, S.M., Ĺopez-Moreno, J.I., 2013. Streamflow droughts in the Iberian Peninsula between 1945 and 2005: Spatial and temporal patterns. Hydrol Earth Syst Sci 17.

Lorenzo-Lacruz, J., Vicente-Serrano, S.M., López-Moreno, J.I., Morán-Tejeda, E., Zabalza, J. 2012. Recent trends in Iberian streamflows (1945-2005). J Hydrol 414–415.

Martín-Benito, D., Del Río, M., Heinrich, I., Helle, G., Cañellas, I., 2010. Response of climate-growth relationships and water use efficiency to thinning in a Pinus nigra afforestation. For Ecol Manage 25, 967–975.

Martínez-Fernández, J., Sánchez, N., Herrero-Jiménez, C.M., 2013. Recent trends in rivers with near-natural flow regime: The case of the river headwaters in Spain.

Prog Phys Geogr 37, 685–700.

Morán-Tejeda, E., Ceballos-Barbancho, A., Llorente-Pinto, J.M., López-Moreno, J.I., 2012. Land-cover changes and recent hydrological evolution in the Duero Basin (Spain). Reg Environ Chang 12, 17–33.

Orth, R., Destouni, G., 2018. Drought reduces blue-water fluxes more strongly than green-water fluxes in Europe. Nat Commun 9.

Pascual D, Pla E, Lopez-Bustins JA, Retana J, Terradas J (2015) Impacts of climate change on water resources in the Mediterranean Basin: a case study in Catalonia, Spain. Hydrol Sci J 60:2132–2147.

Peña-Angulo, D., Vicente-Serrano, S.M., Domínguez-Castro, F., Murphy, C., Reig, F., Tramblay, Y., Trigo, R.M., Luna, M.Y., Turco, M., Noguera, I., Aznárez-Balta, M., García-Herrera, R., Tomas-Burguera, M., El Kenawy, A., 2020. Long-term precipitation in Southwestern Europe reveals no clear trend attributable to anthropogenic forcing. Environ Res Lett 15, 094070.

Peña-Gallardo, M., Vicente-Serrano, S.M., Hannaford, J., Lorenzo-Lacruz, J., Svoboda, M., Domínguez-Castro, F., Maneta, M., Tomas-Burguera, M., Kenawy, A.E., 2019. Complex influences of meteorological drought time-scales on hydrological droughts in natural basins of the contiguous Unites States. J Hydrol 568, 611–625.

Poyatos, R., Latron, J., Llorens, P., 2003. Land use and land cover change after agricultural abandonment: The case of a Mediterranean Mountain area (Catalan Pre-Pyrenees). Mt Res Dev 23, 362–368.

Quinteiro, P., Rafael, S., Villanueva-Rey, P., Ridoutt, B., Lopes, M., Arroja, L., Dias, A.C., 2018. A characterisation model to address the environmental impact of green water flows for water scarcity footprints. Sci Total Environ 626, 1210–1218.

Raymond, F., Ullmann, A., Tramblay, Y., Drobinski, P., Camberlin, P., 2019. Evolution of Mediterranean extreme dry spells during the wet season under climate change. Reg Environ Chang.

Rodríguez Díaz, J.A., Weatherhead, E.K., Knox, J.W., Camacho, E., 2007. Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain. Reg Environ Chang 7, 149–159.

Roudier, P., Andersson, J.C.M., Donnelly, C., Feyen, L., Greuell, W., Ludwig, F., 2016. Projections of future floods and hydrological droughts in Europe under a +2°C global warming. Clim Change 135, 341–355.

Salmoral, G., Willaarts, B.A., Troch, P.A., Garrido, A., 2015. Drivers influencing streamflow changes in the Upper Turia basin, Spain. Sci Total Environ 503–504, 258–268.

Sánchez-Chóliz, J., Sarasa, C., 2015. River flows in the Ebro basin: A century of evolution, 1913-2013. Water (Switzerland) 7, 3072–3082.

Sanmiguel-Vallelado, A., Camarero, J.J., Gazol, A., Morán-Tejeda, E., Sangüesa-Barreda, G., Alonso-González, E., Gutiérrez, E., Alla, A.Q., Galván, J.D., López-Moreno, J.I., 2019. Detecting snow-related signals in radial growth of Pinus uncinata mountain forests. Dendrochronologia 57.

Scaini, A., Sánchez, N., Vicente-Serrano, S.M., Martínez-Fernández, J., 2015. SMOS-derived soil moisture anomalies and drought indices: A comparative analysis using in situ measurements. Hydrol Process 29.

Scanlon, B.R., Jolly, I., Sophocleous, M., Zhang, L., 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. Water Resour Res 43.

Serra, P., Pons, X., Saurí, D., 2008. Land-cover and land-use change in a Mediterranean landscape: A spatial analysis of driving forces integrating biophysical and human factors. Appl Geogr 28, 189–209.

Stellmes, M., Röder, A., Udelhoven, T., Hill, J., 2013. Mapping syndromes of land change in Spain with remote sensing time series, demographic and climatic data. Land use policy 30, 685–702.

Teuling, A.J., de Badts, E., Jansen, F.A., Fuchs, R., Buitink, J., van Dijke, A.J., Sterling, S., 2019. Climate change, re-/afforestation, and urbanisation impacts on evapotranspiration and streamflow in Europe. Hydrol Earth Syst Sci Discuss 2019, 1–30.

Tomas-Burguera, M., Beguería, S., Vicente-Serrano, S.M., 2020. Climatology and trends of reference evapotranspiration in Spain. Int J Climatol. https://doi.org/10.1002/joc.6817

Tomas-Burguera, M., Vicente-Serrano, S., Beguería, S., Reig, F., Latorre, B., 2019. Reference crop evapotranspiration database in Spain (1961-2014). Earth Syst Sci Data 11:1917–1930.

Vicente-Serrano, S., Domínguez-Castro, F., Murphy, C., Hannaford, J., Reig, F., Peña-Angulo, D., Tramblay, Y., Trigo, R., MacDonald, N., Luna, M., McCarthy, M., Van der Schrier, G., Turco, M., Camuffo, D., Noguera, I., El Kenawy, A., García-Herrera, R., Becherini, F., della Valle, A., 2020a. Long term variability and trends of droughts in Western Europe (1851-2018). Int J Climatol. https://doi.org/10.1002/joc.6719

Vicente-Serrano, S.M., Azorin-Molina, C., Sanchez-Lorenzo, A., Morán-Tejeda, E., Lorenzo-Lacruz, J., Revuelto, J., López-Moreno, J.I., Espejo, F., 2014.) Temporal evolution of surface humidity in Spain: Recent trends and possible physical mechanisms. Clim Dyn 42.

Vicente-Serrano, S.M., Azorin-Molina, C., Sanchez-Lorenzo, A., Revuelto, J., López-Moreno, J.I., González-Hidalgo, J.C., Moran-Tejeda, E., Espejo F (2014b) Reference evapotranspiration variability and trends in Spain, 1961-2011. Glob Planet Change 121:26–40.

Vicente-Serrano, S.M., Beguería, S., 2016. Comment on 'Candidate distributions for climatological drought indices (SPI and SPEI)' by James H. Stagge et al. Int J Climatol 36.

Vicente-Serrano, S.M., Beguería, S., Lasanta, T., 2006. Spatial diversity of vegetal activity in abandoned fields of the central Spanish Pyrenees: Analysis of the processes of succession by means of Landsat imagery (1984-2001). Pirineos.

Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. J Clim 23.

Vicente-Serrano, S.M., Lopez-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J.M., Azorin-Molina, C., Morán-Tejeda, E., Revuelto, J., Trigo, R., Coelho, F., Espejo, F., 2014c. Evidence of increasing drought severity caused by temperature rise in southern Europe. Environ Res Lett 9, 044001.

Vicente-Serrano, S.M., López-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., Morán-Tejeda, E., 2012a. Accurate Computation of a Streamflow Drought Index. J Hydrol Eng 17.

Vicente-Serrano, S.M., Martín-Hernández, N., Reig, F., Azorin-Molina, C., Zabalza, J., Beguería, S., Domínguez-Castro, F., El Kenawy, A., Peña-Gallardo, M., Noguera, I., García, M., 2020b. Vegetation greening in Spain detected from long term data (1981–2015). Int J Remote Sens 41, 1709–1740.

Vicente-Serrano, S.M., McVicar, T., Miralles, D., Yang, Y., Tomas-Burguera, M., 2020c. Unravelling the influence of atmospheric evaporative demand on drought under climate dynamics. Wiley Interdiscip Rev Clim Chang . https://doi.org/10.1002/wcc.632

Vicente-Serrano, S.M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., López-Moreno, J., Beguería, S., Noguera, I., Harrigan, S., Vidal, J.P., 2019. Climate, irrigation, and land-cover change explain streamflow trends in countries bordering the Northeast Atlantic. Geophys Res Lett 46:10821–10833.

Vicente-Serrano, S.M., Tomas-Burguera, M., Beguería, S., Reig, F., Latorre, B., Peña-Gallardo, M., Luna, M.Y., Morata, A., González-Hidalgo, J.C., 2017a. A High Resolution Dataset of Drought Indices for Spain. Data 2.

Vicente-Serrano, S.M., Zabalza-Martínez, J., Borràs, G., López-Moreno, J.I., Pla, E., Pascual, D., Savé, R., Biel, C., Funes, I., Azorin-Molina, C., Sanchez-Lorenzo, A., Martín-Hernández, N., Peña-Gallardo, M., Alonso-González, E., Tomas-Burguera, M., El Kenawy, A., 2017b. Extreme hydrological events and the influence of reservoirs in a highly regulated river basin of northeastern Spain. J Hydrol Reg Stud 12, 13–32.

Vicente-Serrano, S.M., Zabalza-Martínez, J., Borràs, G., López-Moreno, J.I., Pla, E., Pascual, D., Savé, R., Biel, C., Funes, I., Martín-Hernández, N., Peña-Gallardo, M., Beguería, S., Tomas-Burguera, M., 2017c. Effect of reservoirs on streamflow and river regimes in a heavily regulated river basin of Northeast Spain. Catena 149.

Vicente-Serrano, S.M., Zouber, A., Lasanta, T., Pueyo, Y., 2012b. Dryness is accelerating degradation of vulnerable shrublands in semiarid mediterranean environments. Ecol Monogr 82.

Vicente Serrano, S.M., Lasanta, T., Cuadrat, J.M., 2000. Transformation of the Pyrenean landscape as a result of the abandonment of traditional economic activity. Pirineos.

Viviroli, D., Weingartner, R., 2004. The hydrological signifance of mountains: From regional to global scale. Hydrol Earth Syst Sci 8, 1016–1029.

Vose, J.M., Miniat, C.F., Luce, C.H., Asbjornsen, H., Caldwell, P.V., Campbell, J.L., Grant, G.E., Isaak, D.J., Loheide, S.P., Sun, G., 2016. Ecohydrological implications of drought for forests in the United States. For Ecol Manage 380, 335–345.

Wriedt, G., der Velde, M., Aloe, A., Bouraoui, F., 2009. Estimating irrigation water requirements in Europe. J Hydrol 373, 527–544.

Yang, Y., Zhang, S., McVicar, T.R., Beck, H.E., Zhang, Y., Liu, B., 2018. Disconnection Between Trends of Atmospheric Drying and Continental Runoff.

Water Resour Res 54, 4700–4713.

Yevjevich, V., 1967. An objective approach to definitions and investigations of continental hydrologic droughts., (Hydrology. Fort Collins, Colorado State University, Colorado State University.

Zhou, G., Wei, X., Luo, Y., Zhang, M., Li, Y., Qiao, Y., Liu, H., Wang, C., 2010. Forest recovery and river discharge at the regional scale of Guangdong Province, China. Water Resour Res 46.

Factors controlling streamflow trends in Europe during dry and wet precipitation years

1.Introduction

Recent studies have showed streamflow changes in Europe during the last decades based on the observations available in gauging stations. These studies agree to show that the evolution is characterised by noticeable spatial differences, with a dominant decrease of streamflow in basins of Southwestern Europe and the increase in northern Europe (Gudmundsson et al., 2017, 2019; Masseroni et al., 2021; Stahl et al., 2010). These spatial differences are also observed in the analysis of the annual maximum floods, which tend to decrease in frequency and severity in South Europe and increase in the North (Blöschl et al., 2019). The factors that determine these changes have been suggested to be diverse. Some studies suggest dominant role of recent climate trends (Masseroni et al., 2021), in which anthropogenic forcing could play a relevant importance (Gudmundsson et al., 2017). Other studies suggest that human activities, including water demands, water regulation, and land use changes could play a more important role than climate trends to explain the spatial differences of recent streamflow changes in Europe (Teuling et al., 2019; S.M. Vicente-Serrano et al., 2019). The increase of damming, irrigation areas and urban and industrial supply has evident consequences on streamflow (He et al., 2017; Tijdeman et al., 2018; S M Vicente-Serrano et al., 2017; Wriedt et al., 2009), and land cover changes in natural areas (e.g., natural revegetation and forest increase) also may contribute to reduce runoff generation (S. Beguería et al., 2003; García-Ruiz et al., 2011; Hoek van Dijke et al., 2022; Martínez-Fernández et al., 2013). Given economic, social and environmental relevance of water resources availability in Europe, it is necessary to determine with robustness what are the drivers of streamflow changes because depending of the dominant factors, there are important management implications. In fact, it is necessary to apply robust methodological approaches at the scale of hydrological basin to analyse the temporal dynamic of streamflow, climate and other human and environmental drivers.

Main problems of water availability in Europe are recorded in dry years since hydrological droughts can be particularly severe (Laaha et al., 2017; Van Lanen et al., 2016; Soulsby et al., 2021). Some studies have suggested noticeable trends in the frequency and severity of hydrological droughts during the last decades in Europe

(Peña-Angulo et al., 2022). Although the severity of hydrological droughts is affected by several factors that may include 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 hydrological droughts are commonly precipitation deficits (Berghuijs et al., 2017; Yang et al., 2018). For this reason, a particular focus on the years characterised by a low precipitation magnitude is essential to determine if streamflow trends respond differently to these conditions in comparison to years characterised by high precipitation. The rationale of considering dry years of an independent manner is based on the important effect of vegetation on the generation of water resources that can be observed particularly during dry years (McQuillan et al., 2022). For example, Orth and Destouni (2018) showed that runoff generation (blue water) shows higher response 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 consequence of the prioritary use of the available water by plants for physiological processes associated to photosynthesis, explaining that plant evapotranspiration represents a high percentage (about two thirds) of the total precipitation (Jasechko et al., 2013; Zhang et al., 2016). In dry years, plants try to maintain transpiration in similar magnitude to that recorded in 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 the surface water generated by runoff reduces noticeably in comparison to that generated during humid years. If the vegetation coverage is affected by important temporal changes, this partition between blue and green water could be strongly altered. For example, the increase of the vegetation activity and coverage (e.g., by means of forest regeneration of the creation of irrigated areas in drylands) reduces streamflow generation (Filoso et al., 2017; Hoek van Dijke et al., 2022). The practical implications for water resources availability of these vegetation changes are much more relevant during dry years, in which runoff generation could be further reduced as consequence of the changes. This issue has strong implications for hydrological drought management.

There are few scientific evidences of the particular hydrological implications of the vegetation changes during drought events, but the existing results suggest a reinforcement of hydrological drought severity as showed 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 processes during the last decade and showed that the associated decrease of streamflow is stronger in dry than in humid years. These evidences suggest that vegetation changes are of particular relevance for water generation in dry years although this behaviour must be confirmed on broader scales.

This study analyses streamflow changes at the European scale using a dense database of gauging stations with particular focus on the assessment of the drivers of streamflow changes and the possible differential changes of streamflows between dry and wet years that could be associated to vegetation changes.

2. Data and methods

The main information used in this study has been a monthly streamflow dataset that contains information of 3324 gauging stations, which was developed and described in depth by Peña-Angulo et al. (2022). The database contains complete records for the period 1962-2017. Total annual (October-September) streamflow was quantified in each gauging station in Hm^3. The spatial distribution of the available gauging stations is showed in the Figure 1. 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 25m and ArcHydro tools in ArcGIS10.2©.

Climate information was obtained from two different sources. Gridded precipitation data was 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): air temperature, solar radiation, wind speed and air humidity was obtained from the ERA-5 Reanalysis (Hersbach et al., 2020) also at 0.1 degrees of spatial resolution. We obtained the average time series of precipitation and AED corresponding to each one of the 3324 drainage basins. The series of mm of the climate variables were transformed to Hm^3 considering the surface area of the basin in order to be comparable with the magnitude of streamflow records. The climate information was also summarised annually for the same period that streamflow data (October-September). In addition to the hydrological and climatic information, we used data of relevant land cover characteristics, which include the surface area covered by irrigated lands. This information was obtained from European statistics and summarised for each one of the river basins under study. Finally, we assessed possible changes in the land cover characteristics. For this purpose we used two different databases. On the one hand we quantified the surface area covered by forests in the Hilda database (Winkler et al., 2020) in 1960 and 2019 in each one of the basins and we quantified the changes in percentage over the period. Finally, we also included the change of the Normalized Difference Vegetation Index (NDVI) obtained from satellite imagery from 1981 to 2015, using the GIMMS dataset (Pinzon & Tucker, 2014). The NDVI is highly related to the leaf area and the fraction of vegetation coverage (Carlson & Ripley, 1997), being a proxy of the whole vegetation changes at the basin scale.

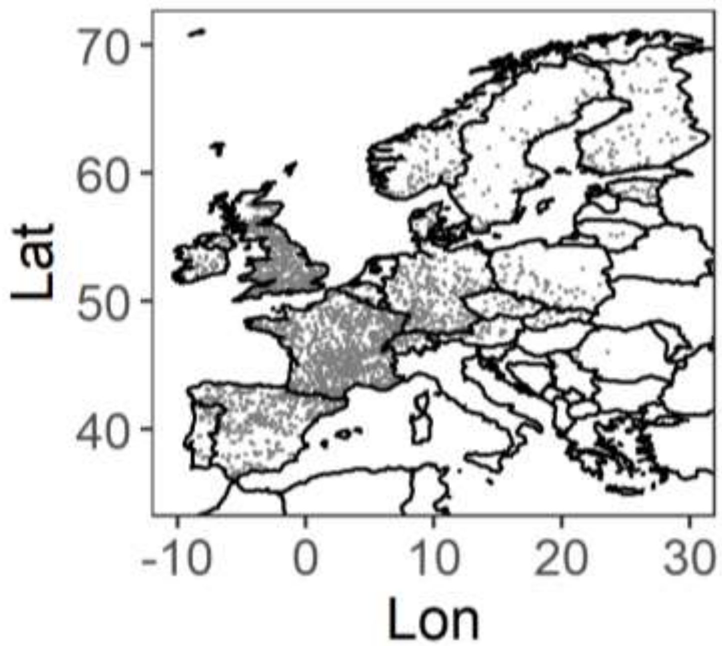

Figure 1. Spatial distribution of the gauging stations used for the European continent between 1962 and 2017

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 the vegetation coverage on the streamflow, with special focus of the effect on the partition of the available water resources between green, which is consumed by vegetation in the form of plant transpiration, and blue water, generated by surface runoff and during periods of low and high precipitation. We first analyzed the magnitude of the trend in annual streamflow during the period 1962-2017 considering the complete years and also the series of streamflow in each station for the wet and dry years according to the magnitude of the annual precipitation. Herein, wet years were defined as those exceeding the 50th percentile of precipitation over the period of record. On the other hand, dry years were determined as those with rainfall falling below the 50th percentile. The hypothesis of applying this analysis is that the effect of land cover changes and some 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 related to the total available water (Mastrotheodoros et al., 2020; Orth & Destouni, 2018). Trend in annual streamflow was analyzed by means of a modified Mann-Kendall trend test, which returns the corrected p values after accounting for temporal pseudoreplication (Hamed & Ramachandra Rao, 1998). To assess the magnitude of change, we used a linear regression analysis between the series of years (independent variable) and the streamflow series (dependent variable). The same analysis was applied to the series of precipitation and AED, also considering wet and dry years as for streamflow.

We analysed the spatial relationship between the sign and significance of change in streamflow considering two significance levels (99% and 95%) with the distribution values of different variables that include the mean precipitation and AED, the magnitude of change in precipitation and AED, the area of the drainage basin, elevation, the irrigation area, forest surface, mean NDVI and the changes in the forest surface and the NDVI. In addition, we also related the observed magnitude of change in the particular gauging stations with the independent values of these variables.

To quantify the magnitude of the annual streamflow trends that may be associated with climate trends and other variables (e.g., vegetation changes), we used a multiple regression with streamflow as the dependent variable and precipitation, AED, and time as the independent variables (S. Beguería et al., 2003; López-Moreno et al., 2011) that was applied in each one of the gauging stations analysed. Time was included in the models as a proxy for the progressive evolution of natural vegetation, other land cover changes (e.g. increase of the irrigation surface) or other factors (e.g., the increase of urban or industrial demands). The forward stepwise selection of predictors was used in the construction of regression models using a threshold of 0.05 (Hair et al., 1995). We quantified the independent role of each one of the variables (precipitation, AED and time) by means of the regression Beta coefficient, which oscillate between -1 and 1.

3. Results

Figure 2 shows the changes in streamflow from 1962 to 2017 considering the complete series and the series corresponding to the dry and humid precipitation years. Streamflow trends show pronounced spatial differences in Europe, with a dominant decline in large areas of the Iberian Peninsula, southern France and in some basins of central Germany. In some of these basins of the Iberian Peninsula and southern France the decrease of streamflow has been higher than 50% between 1962 and 2017. In contrast, there is an increase in basins of Ireland, North and West United Kindom, Scandinavia and the Baltic region. Nevertheless, the number of gauging stations that show a streamflow decrease is higher than the number of stations showing an increase. Thus, a large number of stations located in southern Europe show statistically significant negative trends. The spatial pattern mostly resembles considering the trends in streamflow for the low and high precipitation years, although the number of stations with statistically significant trends decreases as consequence of the smaller sample. The most relevant difference is that for dry precipitation years, the decrease in streamflow expands over the whole Iberian Peninsula. Spatial pattern shows high agreement between the magnitude of change in streamflow for all years and the magnitude of change found for humid and dry years, although it is necessary to remark that this relationship decreases comparing the magnitude of change in humid and dry years.

The spatial pattern of streamflow trends could suggest some climatic attribution since there are noticeable differences in the average precipitation and AED between basins that show a significant increase or decrease in streamflow (Figure 3). Thus, the basins showing significant negative trends in streamflow are characterised for being the most arid, with low precipitation and high AED, and also characterised by a different evolution in precipitation and AED. Thus, they show a dominant negative trend in precipitation and a positive trend in AED. These trends contrast with those recorded in the basins that show a dominant increase of annual streamflow as they show a dominant increase of precipitation and a more limited increase in AED.

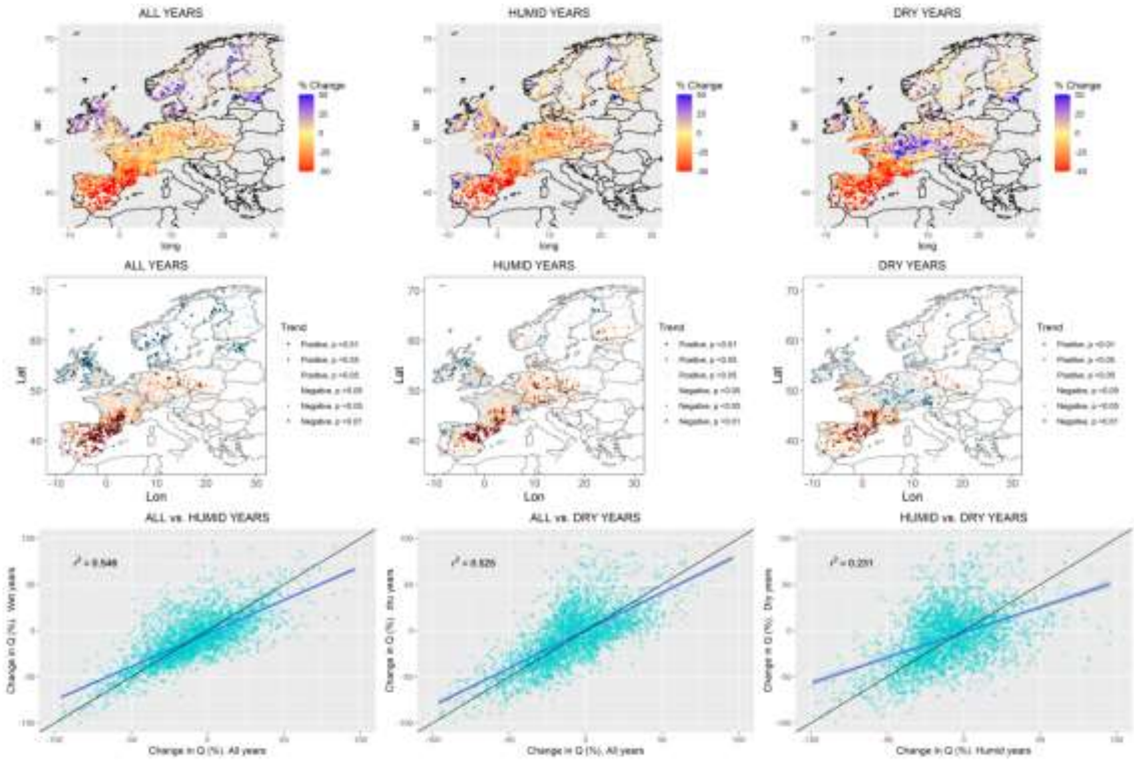

Figure 2. Top: Magnitude of change of streamflow in percentage (1962 = 100) between 1962 and 2017 considering all, humid and dry years. Middle: Statistical significance of streamflow changes considering all, humid and dry years. Bottom: Spatial relationship between the magnitude of the annual streamflow changes for all, humid and dry years.

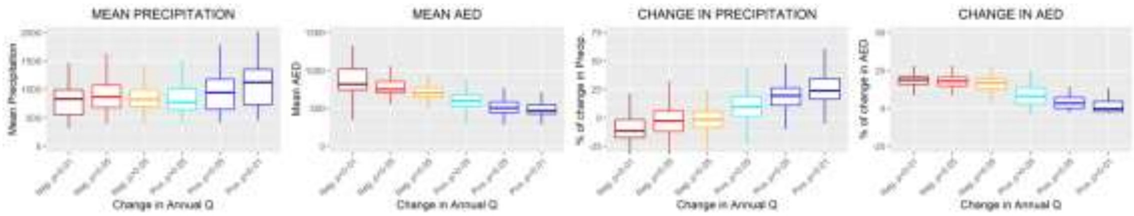

Figure 3: Box-plots showing the distribution of mean precipitation and AED and the magnitude of change in precipitation and AED as a function of the statistical significance of changes in annual streamflow.

Nevertheless, this kind of attribution associated to similar spatial patterns of streamflow and climatic trends must be carefully interpreted since the magnitude of the temporal patterns of the analysed variables could differ considerably. Moreover, other variables, different to the climate, could also explain the spatial pattern of streamflow change. For example, the strong negative trend of annual streamflow over large areas of south Europe contrasts with the trend observed in precipitation, which is characterised by much lower decrease (Figure 4). In addition, there are not precipitation trends considering the subsamples of humid years. In fact, there are very few basins in which a significant decrease of precipitation has been recorded between 1962 and 2017 (in Northeast Spain and Southern France). Both variables are quantified in the same units (Hm^3), and the changes analysed in percentages, so they are perfectly comparable. The differences in the percentage of change are higher than 50% in the majority of basins recorded in the Iberian Peninsula and South France, but also in some basins of eastern Germany and Poland (Figure 5). Similar spatial pattern of differences between streamflow and precipitation is found considering the changes observed for humid and dry precipitation 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 oscillation than the range of change in streamflow. Several basins characterised by strong streamflow decrease show small decrease or even increase in precipitation. In fact, the relationship between the changes in these variables is small ($r^2 = 0.226$) and even lower considering the changes recorded during the humid and dry precipitation years.

What is observed at the European scale is a very important increase of the AED, which is in general very homogenous spatially, except in the British Islands and Scandinavia, and statistically significant in the vast majority of basins. Thus, the differences in the trend of streamflow with the trends in AED are very high, and the spatial relationship between changes in streamflow and AED are also low considering the sample of all years, but also the humid and dry years (Figure 5).

Therefore, the limited spatial relationship existing between the changes in streamflow and the changes in precipitation, and the very different magnitude in the changes found in both variables suggest that climate attribution in the spatial pattern of streamflow trends is not very evident. In fact, if we analyse other variables different to the climate, noticeable differences can be also found. For example, basins that show a higher decrease in streamflow tend to be characterised by more elevation, a higher percentage of forest area and positive trends in the percentage of forest area and in NDVI. This is in opposition to the characteristics observed in the basins with positive trends in streamflow as they show smaller changes in the NDVI and in the percentage of forest area. Thus, analysing these patterns we could hypothesise that the characteristics of the basins, including forest area, and the changes in vegetation could explain the spatial differences of streamflow trends across Europe. Nevertheless, the spatial relationship between the magnitude of change of annual streamflow is small (Figure 7). This finding reinforces the limitations of stablishing possible attribution of the changes in streamflow based on the spatial patterns of different factors (both climatic and human management, including land cover changes).

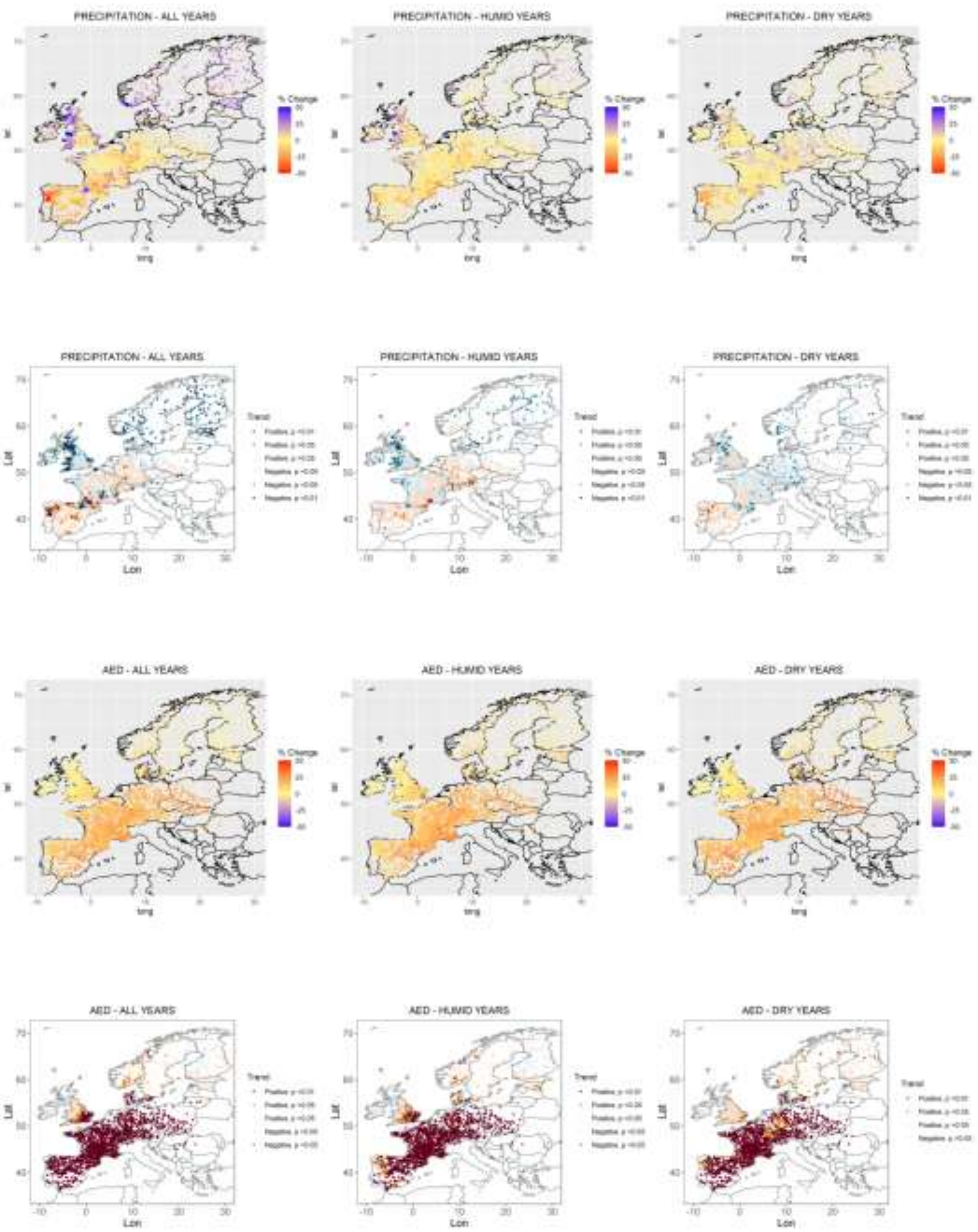

Figure 4: First row: Magnitude of change of precipitation in percentage (1962 = 100) between 1962 and 2017 considering all, humid and dry years. Second row: Statistical significance of precipitation changes considering all, humid and dry years. Third row: same that first row but for AED. Fourth row: same as third row but for AED.

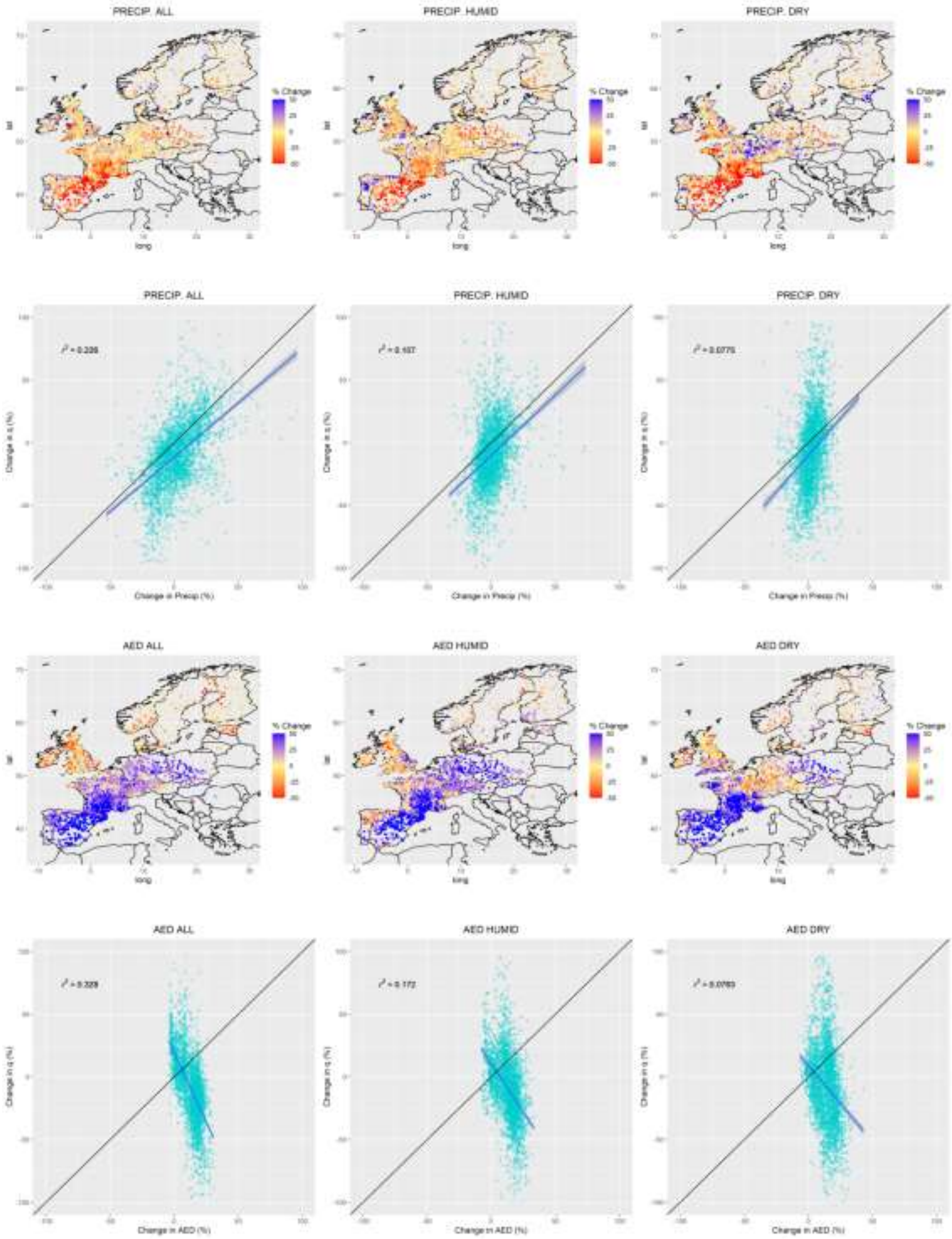

Figure 5: First row: Difference in the magnitude of change in precipitation and streamflow (both in percentage) between 1962 and 2017 considering all, humid and dry years. Second row: Spatial relationship between the changes in precipitation and streamflow obtained considering all, humid and dry precipitation years. Third Difference in the magnitude of change in AED and streamflow (both in percentage) between 1962 and 2017 considering all, humid and dry years. Fourth row: Spatial relationship between the changes in AED and streamflow obtained considering all, humid and dry precipitation years.

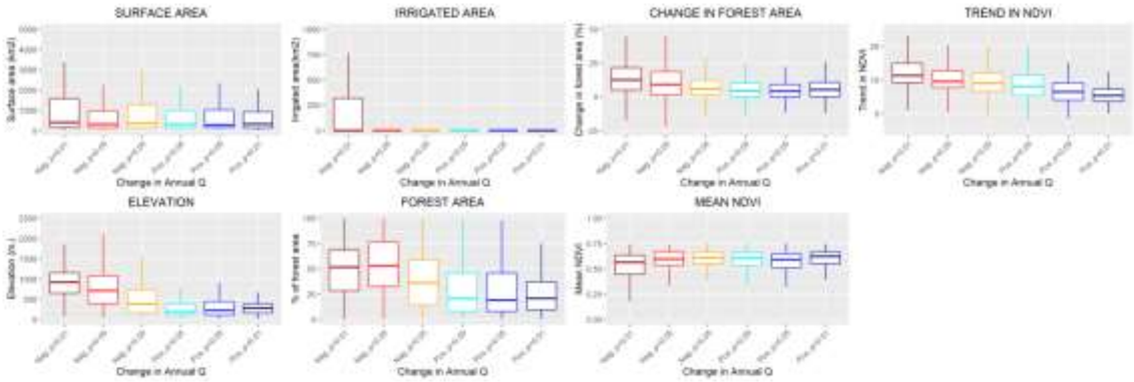

Figure 6. Box-plots showing the distribution of the values of different basin physiographic and land cover characteristics as a function of the statistical significance of the changes in annual streamflow.

A more robust approach to assess a possible attribution of changes in streamflow should be to focus on the temporal relationships at the basin scale. The initial results of this analysis are illustrated in the Figure 8, which shows the spatial distribution of the R^2 coefficients of the stepwise regression models that use precipitation, AED and time (in years) as independent variables to explain the streamflow dynamic. The percentage of variance of 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 the variance reduces in some basins considering the humid but mostly the dry years.

In the vast majority of basins, precipitation enters in the stepwise regression models as it is statistically significant (Figure 9). Only considering the dry years, precipitation does not enter in the regression models in some particular basins, particularly in southern Europe. In opposition to precipitation, the AED does not enter in the majority of models. Moreover, the few basins in which this variable enters in the regression models (14% of total) do not show a geographical pattern that suggests a high role of the AED in a particular region. In addition, the percentage of basins in which AED is includeed in the models reduces considerably considering the dry years (8%). Finally, in a large percentage of basins, time also enters significantly in the models, particularly considering all years (35%), but also humid (24%) and dry years (24%). This result clearly suggests that in several basins of Europe there is a temporal component in the annual streamflow, indicative of a trend that is not explained by the dynamic of climate variables (Precipitation and AED).

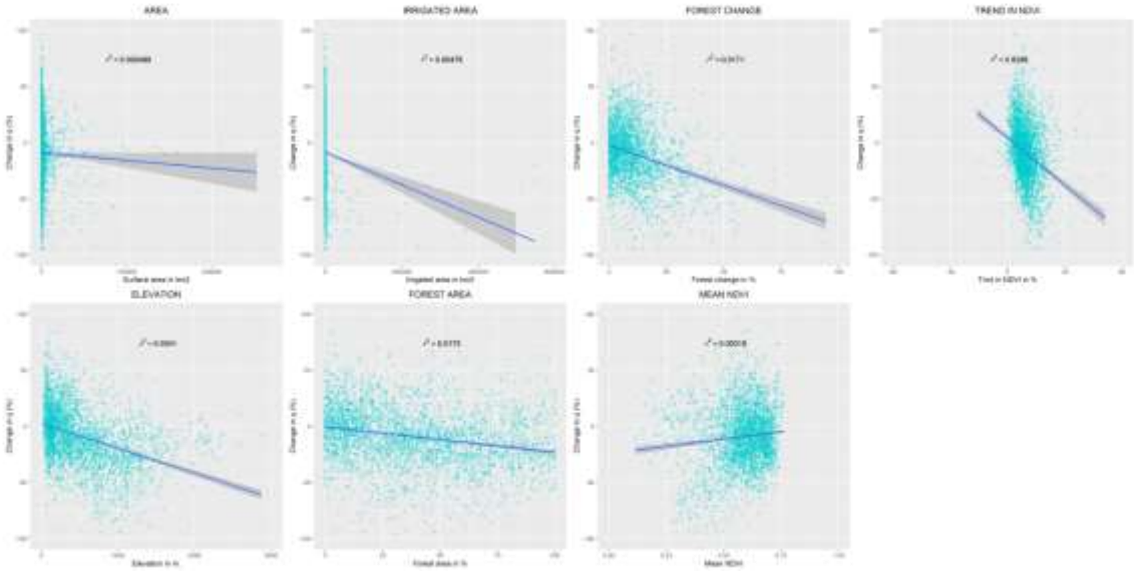

Figure 7. Spatial relationship between different physiographic and land cover characteristics of each basin and the changes in annual streamflow between 1962 and 2017.

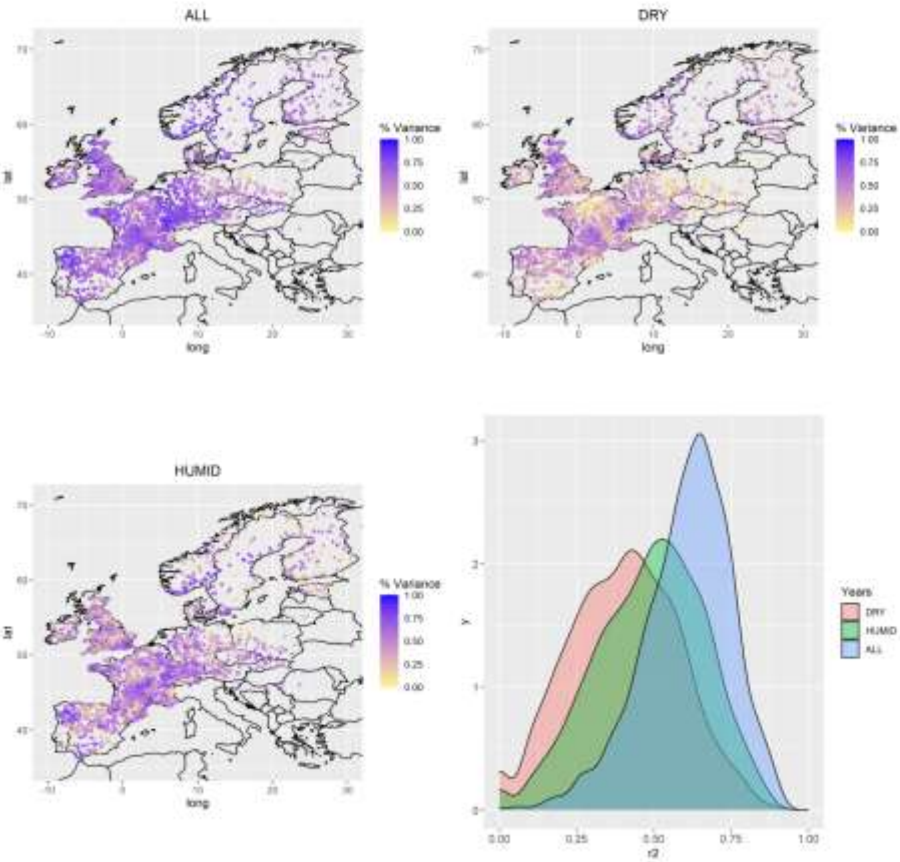

Figure 8. Maps: percentage of the variance in annual streamflow explained by each stepwise regression model considering precipitation, AED and time as independent variables during all, humid and dry precipitation years. The density plots show distribution in the percentage of variance explained by the models.

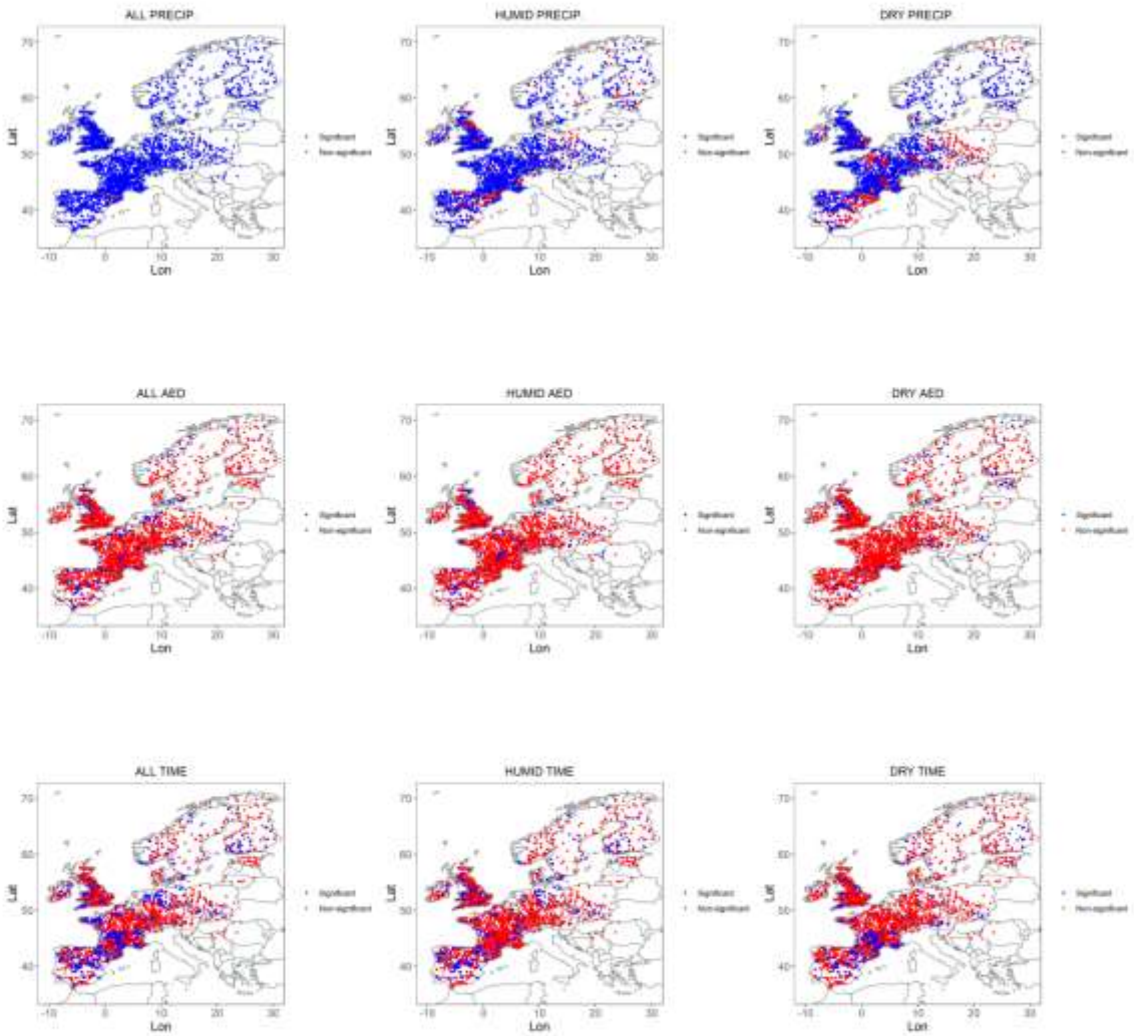

Figure 9. Basins in which the three independent variables: precipitation, AED and time are included or not in the stepwise regression models with streamflow as independent variables for all, dry and humid precipitation years.

The role of the three variables explaining the evolution of streamflow is quantified by means of the beta regression coeffcients, which allow spatial comparisons, independently of the magnitude of the variables. The role of precipitation is always the highest in the explanation of the dynamic of streamflow considering all, humid and dry years (Figure 10). The role of AED is close to zero in the vast majority of basins. Nevertheless, the role of time is highly relevant in several basins, particularly in southern France and the Iberian Peninsula, which means that the negative trend of stremflow recorded in these regions cannot be attributed to the climate behaviour. Moreover, the role of the time is better recognised analysing exclusively the dry years, in which the beta coefficients associated to time show more negative values (Figure 11). This sugests that the negative evolution of streamflow associated to non-climatic factors is more evident during the dry years.

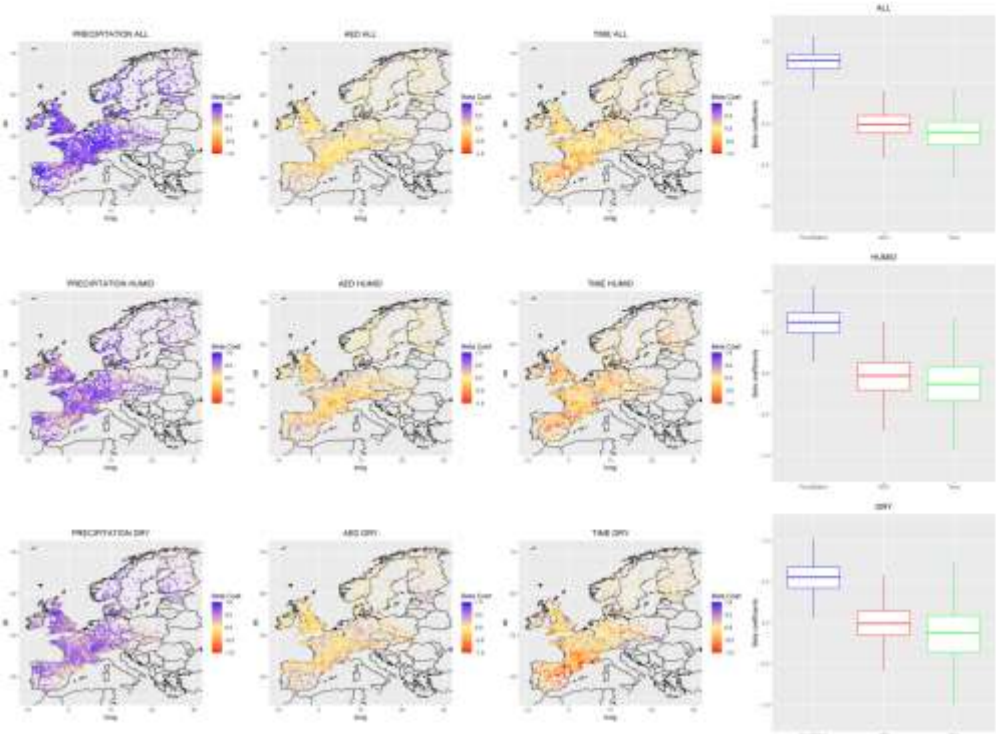

Figure 10. Spatial distribution of the beta coefficients obtained from the independent regression models for the three independent variables: precipitation, AED and time corresponding to all, dry and humid preecipitation years. Box-plots show the distribution of the values of the beta coefficients for each variable and group of years.

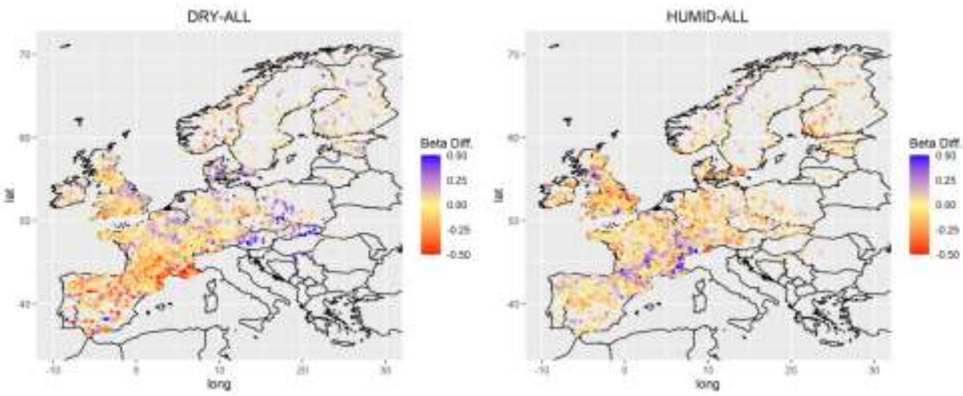

Figure 11. Difference between the beta coefficients obtained by means of the stepwise regression models between all and dry years (left) and betweeen all and humid years (right).

To find the drivers that control the dominant non-climatic trends in annual streamflow in south Europe is complex given the different factors that may play a role from local to regional scales. To asses possible drivers of change, we have related the beta coefficients corresponding to the time with some physiographic and land variables of each basin and fitted a general additive model to each pair of variables in order to extract possible patterns in the general complexity of relationships (Figure 12). The different plots for all, humid and dry years suggest small control of basin phisiography of the spatial patterns of the beta coefficients associated to time. Elevation and basin area do not show a relationship with the spatial distribution of these beta coefficients considering all years but also dry and humid years. The relationship of the beta coefficients with the percentage of forest area of each basin, the mean NDVI and the area covered by irrigated lands is also low, in the last case probably as consequence of the small number of basins characterised by large irrigated lands. Nevertheless, the assessment of vegetation changes allows to infer an interesting pattern since although the dispersion is high, there is a dominant tendency to record more negative coefficients in the basins characterised by a higher increase of forest surface or NDVI. A relevant issues is that this pattern is mostly recorded considering the beta coefficients obtained in thee independeent analysis of dry percipitation years. Although the dispersion of the relationship is high, this finding suggests that in dry years a decline of streamflow, non-related to the climate dynamic, could be more evident in basins of southern Europe characterised by a general increase of forest surface and vegetation activity.

4. Discussion and conclusions

This study has analysed the evolution of streamflow in Europe during the period 1962-2017 based on more than 3000 gauging stations, with the special focus on the trends observed during wet and dry precipitation years. In general, we have showed an important decrease of streamflow recorded in areas of South Europe, which is in agreement with previous studies (Gudmundsson et al., 2017, 2019; Masseroni et al., 2021; Teuling et al., 2019; S.M. Vicente-Serrano et al., 2019). The increase of streamflow recorded in some areas of North Europe shows agreement with the precipitation increase recorded in this region. Nevertheless, the strong increase of streamflow in southern Europe is not explained by the evolution of precipitation during the studied period, which shows small decrease that is dominantly non significant statistically. Thus, the difference between the magnitude of change in streamflow, and the magnitude of change in precipitation is very important in South Europe. Some studies had suggested that the spatial patterns of streamflow changes in Europe and particularly the strong decrease observed in Southern Europe could be attributed to the anthropogenic climate change (Gudmundsson et al., 2017). Here we have observed that even focusing in a period in which precipitation shows some decline in southern Europe, although embedded in a long-term stationary precipitation behaviour (Peña-Angulo et al., 2020), the strong streamflow decrease cannot be explained by the evolution of precipitation. The decrease of streamflow has been very important in the majority of the basins of southern Europe, with statistically significant trends and reductions of streamflow higher than 50% between 1962 and 2017. On the contrary, the reduction of precipitation is small in these areas (approximately 5%) and in most of the basins non-statistically significant. Therefore, the strong decrease of streamflow in southern Europe cannot be clearly attributed to the recent dynamic of precipitation.

It could be argued that the increase of evapotranspiration has been more important than precipitation to explain the strong decline of streamflow in the region. Thus, this could support main effect of the climate dynamic on streamflow trends associated to the enhanced AED observed in the last decades (S. M. S. Vicente-Serrano et al., 2020). If AED increases and water is available in the soil, then evapotranspiration could increase in vegetated areas to maintain the 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 (Sergio M Vicente-Serrano et al., 2014) that could support this hypothesis.

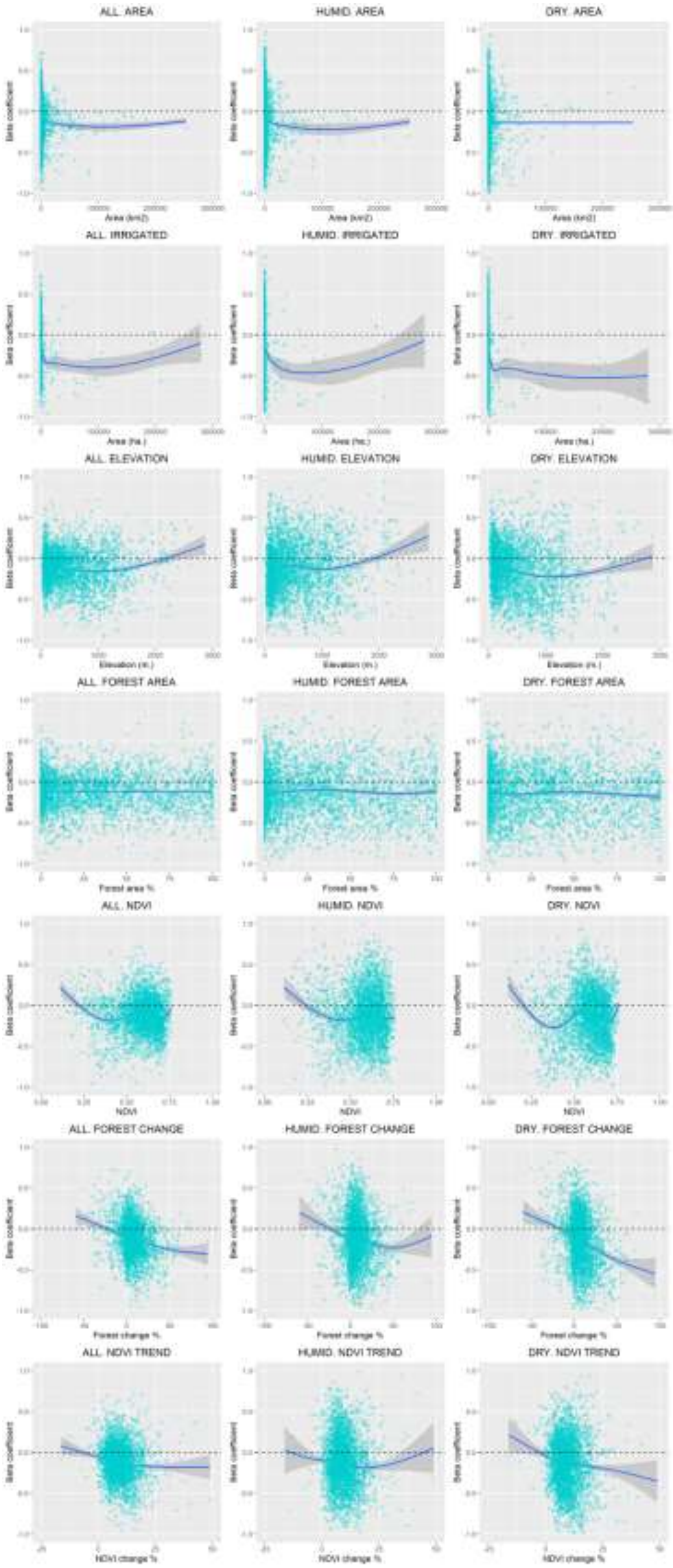

Figure 12: Scatterplots and fitted GAM curves relating the spatial distribution of different physiographic and land variables in each basin with the beta coefficients of the time variable obtained from the stepwise regression models for all, dry and humid years.

Some modelling studies have suggested an increase of evapotranspiration in Europe (Frank et al., 2015; Zhang et al., 2012, 2016), which would have a role to increase the severity of hydrological droughts in the region (Massari et al., 2022). In fact, evapotranspiration increase, together increases in water supply to urban areas, has probably been the main driver of streamflow reduction in South Europe. Nevertheless, this increase cannot be attributed 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 to explain temporal variability of streamflow in southern Europe (Sergio M Vicente-Serrano et al., 2014), a pattern that is also widely identified at the global scale (Berghuijs et al., 2017; Yang et al., 2018). The results of our study also support this assessment, since AED has not been included in the vast majority of the statistical models obtained at the basin scale to explain the evolution of streamflow over the last decades since this variable did not contribute to explain the dynamic of streamflow in comparison to precipitation and time. Moreover, there is not a distinctive evolution in the AED across Europe that could suggest a differential influence between central and south Europe since in the vast majority of basins, the evolution of the AED has been positive and statistically significant. Thus, the magnitude of increase in the AED has very homogeneous across Europe, in agreement with previous studies (S. M. S. Vicente-Serrano et al., 2020).

We consider that the climate trends have played a small role to explain the spatial patterns of streamflow trends across Europe in comparison to the effect of non-climate factors. This is supported by the existence of a dominant non-climate temporal component, which is included in a high percentage of the regression models obtained for the basins of southern Europe and that is essential to explain streamflow trends in these basins. Land cover and water management changes have been very important in the region, with noticeable hydrological consequences (García-Ruiz et al., 2011; Teuling et al., 2019). In particular, vegetation has strongly increased in the headwaters of the main Mediterranean mountain areas as consequence of rural exodus and land abandonment (García-Ruiz & Lana-Renault, 2011; Lasanta et al., 2017), a factor that has increased water consumption by natural vegetation in the form of plant transpiration and leaf interception (green water), decreasing the water resources downstream (blue water) (S. Beguería et al., 2003; López-Moreno et al., 2011; S M Vicente-Serrano et al., 2021). In addition, land intensification in other areas had a similar effect. The increase in the number of reservoirs and the capacity of reservoir storage has strongly increased in southern Europe with the main purpose of supplying water demands of the large irrigated polygons developed over former drylands in the last decades (Pinilla, 2006). Moreover, not only the surface irrigated has increased, but also irrigated lands have been intensified with more crop cycles per year and the cultivations of crops that demand more water in order to increase the benefits associated to the agricultural practices (Santiago Beguería et al., 2022) This has caused that even in areas in which irrigated lands have been modernised by means of pressurisation, the total plant transpiration has not been reduced (Lecina et al., 2010). High AED of the areas of Southern Europe could have contributed to increase 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 the series of time support this assessment and stress that spatial differences in annual streamflow trends in Europe cannot be attributed to antrophogenic climate change as suggested by previous studies (Gudmundsson et al., 2017).

The large importance of land cover changes and vegetation activity trends to explain the differential streamflow trends in Europe is supported by the differential streamflow trends found between humid and dry precipitation years. This differential trend is not related to precipitation changes that could support more frequent dry years in the last decades. Thus, the precipitation trends identified corresponding to the dry and wet years are small and not statistically significant in the vast majority of basins. Recent studies have suggested the existence of different hydroclimate drivers to cause hydrological droughts of different magnitude in Europe (Brunner et al., 2022). Nevertheless, the differential streamflow trends found in dry and humid preecipitation years suggest that some external factors different to the climate may play an essential role. We have found that the temporal component included in the regression models shows much more negative coefficients in dry than in humid years in southern Europe. This means that the negative stremflow trends that are not explained by climate trends are more pronounced in dry years. On the contrary, in central and North Europe there are not appreciable differences. These results are consistent with the expected response to increased evapotranspiration as consequence of land transformations given the differential partition of the precipitation between green and blue water during dry periods

(Mastrotheodoros et al., 2020; Orth & Destouni, 2018). This behaviour had been previously observed in a catchment of the central Spanish Pyrenees affected by a large natural revegetation during the last decades (S M Vicente-Serrano et al., 2021). To find this behaviour in a large number of catchments of southern Europe is highly relevant since it suggests large scale effects caused by increased vegetation coverage on the severity of hydrological droughts. The relationship of these trends in Beta coefficients with the trends of vegetation coverage and activity shows important dispersion, but we have found that the relationship is much stronger considering dry versus humid and all years, reinforcing the hypothesis that vegetation changes on streamflow trends are more relevant during dry years. This finding has strong implications for land cover and hydrological drought management in areas in which it is projected a precipitation decrease during this century (Douville et al., 2021) since actuations at the landscape level in the headwater could reduce the severity of hydrological droughts in the medium and low course of the rivers and guarantee the availability of water for high demanding activities as irrigation during dry periods. Thus, the current policied and recommendations for landscape rewilding and nature-based solutions to mitigate climate change with focus related to carbon sequestration in Europe (Keesstra et al., 2018; Nesshöver et al., 2017) could have important hydrological effects, reducing the availability of water resources and particularly increasing the frequency and severity of hydrological droughts.

References

Babst, F., Bouriaud, O., Papale, D., Gielen, B., Janssens, I. A., Nikinmaa, E., et al. (2014). Above-ground woody carbon sequestration measured from tree rings is coherent with net ecosystem productivity at five eddy-covariance sites. *New Phytologist*, *201*(4), 1289–1303. https://doi.org/10.1111/nph.12589

Beguería, S., López-Moreno, J. I., Lorente, A., Seeger, M., & García-Ruiz, J. M. (2003). Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. *Ambio*, *32*(4), 283–286. https://doi.org/10.1579/0044-7447-32.4.283

Beguería, Santiago, Haro-Monteagudo, D., Palazón, L., & García-Ruiz, J. M. (2022). Interacciones montaña-llanura frente al cambio global: desafíos y oportunidades en la gestión del territorio y de los recursos hídricos en Riegos del Alto Aragón.

Pirineos, *177*(SE-Artículos), e072. https://doi.org/10.3989/pirineos.2022.177005

Berghuijs, W. R., Larsen, J. R., van Emmerik, T. H. M., & Woods, R. A. (2017). A Global Assessment of Runoff Sensitivity to Changes in Precipitation, Potential Evaporation, and Other Factors. *Water Resources Research*, *53*(10), 8475–8486. https://doi.org/https://doi.org/10.1002/2017WR021593

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., et al. (2019). Changing climate both increases and decreases European river floods. *Nature*, *573*(7772), 108–111. https://doi.org/10.1038/s41586-019-1495-6

Brunner, M. I., Van Loon, A. F., & Stahl, K. (2022). Moderate and Severe Hydrological Droughts in Europe Differ in Their Hydrometeorological Drivers. *Water Resources Research*, *58*(10), e2022WR032871. https://doi.org/https://doi.org/10.1029/2022WR032871

Carlson, T. N., & Ripley, D. A. (1997). On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment*, *62*(3), 241–252. https://doi.org/10.1016/S0034-4257(97)00104-1

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., & Jones, P. D. (2018). An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets. *Journal of Geophysical Research: Atmospheres*, *123*(17), 9391–9409. https://doi.org/10.1029/2017JD028200

Douville, H., Raghavan, K., & Renwick, J. (2021). Water cycle changes. In *Climate Change 2021: The Physical Climate, Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Filoso, S., Bezerra, M. O., Weiss, K. C. B., & Palmer, M. A. (2017). Impacts of forest restoration on water yield: A systematic review. *PLoS ONE*, *12*, e0183210.

Frank, D. C., Poulter, B., Saurer, M., Esper, J., Huntingford, C., Helle, G., et al. (2015). Water-use efficiency and transpiration across European forests during the Anthropocene. *Nature Climate Change*, *5*(6), 579–583. https://doi.org/10.1038/nclimate2614

García-Ruiz, J. M., & Lana-Renault, N. (2011). Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region - A review. *Agriculture, Ecosystems and Environment*, *140*(3–4), 317–338. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-79952359525&doi=10.1016%2Fj.agee.2011.01.003&partnerID=40&md5=4b0b71e5a5c79c588b88e9281ced9d01

García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta-Martínez, T., & Beguería, S. (2011). Mediterranean water resources in a global change scenario. *Earth-Science Reviews*, *105*(3–4). https://doi.org/10.1016/j.earscirev.2011.01.006

Gimeno, T. E., Crous, K. Y., Cooke, J., O'Grady, A. P., Ósvaldsson, A., Medlyn, B. E., & Ellsworth, D. S. (2016). Conserved stomatal behaviour under elevated CO2 and varying water availability in a mature woodland. *Functional Ecology*, *30*(5), 700–709. https://doi.org/https://doi.org/10.1111/1365-2435.12532

Green, J. K., Seneviratne, S. I., Berg, A. M., Findell, K. L., Hagemann, S., Lawrence, D. M., & Gentine, P. (2019). Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature*, *565*(7740), 476–479. https://doi.org/10.1038/s41586-018-0848-x

Gudmundsson, L., Seneviratne, S. I., & Zhang, X. (2017). Anthropogenic climate change detected in European renewable freshwater resources. *Nature Climate Change*, *7*(11), 813–816. https://doi.org/10.1038/nclimate3416

Gudmundsson, L., Leonard, M., Do, H. X., Westra, S., & Seneviratne, S. I. (2019). Observed Trends in Global Indicators of Mean and Extreme Streamflow. *Geophysical Research Letters*, *46*(2), 756–766. https://doi.org/10.1029/2018GL079725

Hair, J. F., Anderson, R. E., Tatham, R. L., & Black, W. C. (1995). No Title. *Multivariate Data Analysis*.

Hamed, K. H. K. H., & Ramachandra Rao, A. (1998). A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology*, *204*(1–4), 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X

He, X., Wada, Y., Wanders, N., & Sheffield, J. (2017). Intensification of hydrological drought in California by human water management. *Geophysical Research Letters*, *44*(4), 1777–1785. https://doi.org/10.1002/2016GL071665

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hoek van Dijke, A. J., Herold, M., Mallick, K., Benedict, I., Machwitz, M., Schlerf, M., et al. (2022). Shifts in regional water availability due to global tree restoration. *Nature Geoscience*, *15*(5), 363–368. https://doi.org/10.1038/s41561-022-00935-0

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y., & Fawcett, P. J. (2013). Terrestrial water fluxes dominated by transpiration. *Nature*, *496*(7445), 347–350.

https://doi.org/10.1038/nature11983

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., & Cerdà, A. (2018). The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2017.08.077

Laaha, G., Gauster, T., Tallaksen, L. M., Vidal, J. P. J.-P., Stahl, K., Prudhomme, C., et al. (2017). The European~2015 drought from a hydrological perspective. *Hydrology and Earth System Sciences*, *21*(6), 3001–3024. https://doi.org/10.5194/hess-21-3001-2017

Van Lanen, H. A. J., Laaha, G., Kingston, D. G., Gauster, T., Ionita, M., Vidal, J.-P., et al. (2016). Hydrology needed to manage droughts: the 2015 European case. *Hydrological Processes*, *30*(17), 3097–3104. https://doi.org/10.1002/hyp.10838

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M. P., & Lana-Renault, N. (2017). Space–time process and drivers of land abandonment in Europe. *Catena*, *149*, 810–823. https://doi.org/10.1016/j.catena.2016.02.024

Lecina, S., Isidoro, D., Playán, E., & Aragüés, R. (2010). Irrigation modernization and water conservation in Spain: The case of Riegos del Alto Aragón. *Agricultural Water Management*, *97*(10), 1663–1675. https://doi.org/10.1016/j.agwat.2010.05.023

López-Moreno, J. I., Vicente-Serrano, S. M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., & García-Ruiz, J. M. (2011). Impact of climate evolution and land use changes on water yield in the ebro basin. *Hydrology and Earth System Sciences*, *15*(1). https://doi.org/10.5194/hess-15-311-2011

Lorenzo-Lacruz, J., Mońan-Tejeda, E., Vicente-Serrano, S. M., & Ĺopez-Moreno, J. I. (2013). Streamflow droughts in the Iberian Peninsula between 1945 and 2005: Spatial and temporal patterns. *Hydrology and Earth System Sciences*, *17*(1). https://doi.org/10.5194/hess-17-119-2013

Martin, J. T., Pederson, G. T., Woodhouse, C. A., Cook, E. R., McCabe, G. J., Anchukaitis, K. J., et al. (2020). Increased drought severity tracks warming in the United States{\textquoteright} largest river basin. *Proceedings of the National Academy of Sciences*, *117*(21), 11328–11336. https://doi.org/10.1073/pnas.1916208117

Martínez-Fernández, J., Sánchez, N., & Herrero-Jiménez, C. M. (2013). Recent trends in rivers with near-natural flow regime: The case of the river headwaters in Spain.

Progress in Physical Geography, *37*(5), 685–700. https://doi.org/10.1177/0309133313496834

Massari, C., Avanzi, F., Bruno, G., Gabellani, S., Penna, D., & Camici, S. (2022). Evaporation enhancement drives the European water-budget deficit during multi-year droughts. *Hydrology and Earth System Sciences*. https://doi.org/10.5194/hess-26-1527-2022

Masseroni, D., Camici, S., Cislaghi, A., Vacchiano, G., Massari, C., & Brocca, L. (2021). The 63-year changes in annual streamflow volumes across Europe with a focus on the Mediterranean basin. *Hydrology and Earth System Sciences*, *25*(10), 5589–5601. https://doi.org/10.5194/hess-25-5589-2021

Mastrotheodoros, T., Pappas, C., Molnar, P., Burlando, P., Manoli, G., Parajka, J., et al. (2020). More green and less blue water in the Alps during warmer summers. *Nature Climate Change*, *10*(2), 155–161. https://doi.org/10.1038/s41558-019-0676-5

McCabe, G. J., Wolock, D. M., Pederson, G. T., Woodhouse, C. A., & McAfee, S. (2017). Evidence that recent warming is reducing upper Colorado river flows. *Earth Interactions*, *21*(10). https://doi.org/10.1175/EI-D-17-0007.1

McQuillan, K. A., Tulbure, M. G., & Martin, K. L. (2022). Forest water use is increasingly decoupled from water availability even during severe drought. *Landscape Ecology*. https://doi.org/10.1007/s10980-022-01425-9

Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., et al. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2016.11.106

Orth, R., & Destouni, G. (2018). Drought reduces blue-water fluxes more strongly than green-water fluxes in Europe. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-06013-7

Peña-Angulo, D., Vicente-Serrano, S. M. M., Domínguez-Castro, F., Murphy, C., Reig, F., Tramblay, Y., et al. (2020). Long-term precipitation in Southwestern Europe reveals no clear trend attributable to anthropogenic forcing. *Environmental Research Letters*, *15*(9), 094070. https://doi.org/10.1088/1748-9326/ab9c4f

Peña-Angulo, D., Vicente-Serrano, S. M., Domínguez-Castro, F., Noguera, I., Tomas-Burguera, M., López-Moreno, J. I., et al. (2021). Unravelling the role of vegetation on the different trends between climatic and hydrologic drought in headwater catchments of Spain. *Anthropocene*, *36*, 100309. https://doi.org/https://doi.org/10.1016/j.ancene.2021.100309

Peña-Angulo, D., Vicente-Serrano, S. M., Domínguez-Castro, F., Lorenzo-Lacruz, J., Murphy, C., Hannaford, J., et al. (2022). The Complex and Spatially Diverse Patterns of Hydrological Droughts Across Europe. *Water Resources Research*, *58*(4). https://doi.org/10.1029/2022WR031976

Pinilla, V. (2006). The development of irrigated agriculture in twentieth-century Spain: A case study of the Ebro basin. *Agricultural History Review*, *54*(1), 122–141.

Pinzon, J. E., & Tucker, C. J. (2014). A non-stationary 1981-2012 AVHRR NDVI<inf>3g</inf>time series. *Remote Sensing*, *6*(8), 6929–6960. https://doi.org/10.3390/rs6086929

Soulsby, C., Scheliga, B., Neill, A., Comte, J.-C., & Tetzlaff, D. (2021). A longer-term perspective on soil moisture, groundwater and stream flow response to the 2018 drought in an experimental catchment in the Scottish Highlands. *Hydrological Processes*, *35*(6). https://doi.org/10.1002/hyp.14206

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., Van Lanen, H. A. J., Sauquet, E., et al. (2010). Streamflow trends in Europe: Evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences*, *14*(12), 2367–2382. https://doi.org/10.5194/hess-14-2367-2010

Teuling, A. J., Van Loon, A. F., Seneviratne, S. I., Lehner, I., Aubinet, M., Heinesch, B., et al. (2013). Evapotranspiration amplifies European summer drought. *Geophysical Research Letters*, *40*(10), 2071–2075. https://doi.org/10.1002/grl.50495

Teuling, A. J., de Badts, E., Jansen, F. A., Fuchs, R., Buitink, J., van Dijke, A. J., & Sterling, S. (2019). Climate change, re-/afforestation, and urbanisation impacts on evapotranspiration and streamflow in Europe. *Hydrology and Earth System Sciences Discussions*, *2019*, 1–30. https://doi.org/10.5194/hess-2018-634

Tijdeman, E., Hannaford, J., & Stahl, K. (2018). Human influences on streamflow drought characteristics in England and Wales. *Hydrology and Earth System Sciences*, *22*(2), 1051–1064. https://doi.org/10.5194/hess-22-1051-2018

Vicente-Serrano, S. M. S., McVicar, T. R. T. R., Miralles, D. G. D. G., Yang, Y., & Tomas-Burguera, M. (2020). Unraveling the influence of atmospheric evaporative demand on drought and its response to climate change. *WIREs Climate Change*, *11*(2), e632. https://doi.org/10.1002/wcc.632

Vicente-Serrano, S.M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., et al. (2019). Climate, irrigation, and land-cover change explain streamflow trends in countries bordering the Northeast Atlantic. *Geophysical Research Letters*, *46*(19), 10821–10833. https://doi.org/10.1029/2019GL084084

Vicente-Serrano, S M, Zabalza-Martínez, J., Borràs, G., López-Moreno, J. I., Pla, E., Pascual, D., et al. (2017). Extreme hydrological events and the influence of reservoirs in a highly regulated river basin of northeastern Spain. *Journal of Hydrology: Regional Studies*, *12*, 13–32. https://doi.org/10.1016/j.ejrh.2017.01.004

Vicente-Serrano, S M, Domínguez-Castro, F., Murphy, C., Peña-Angulo, D., Tomas-Burguera, M., Noguera, I., et al. (2021). Increased Vegetation in Mountainous Headwaters Amplifies Water Stress During Dry Periods. *Geophysical Research Letters*, *48*(18), e2021GL094672. https://doi.org/https://doi.org/10.1029/2021GL094672

Vicente-Serrano, Sergio M, Lopez-Moreno, J.-I., Beguería, S., Lorenzo-Lacruz, J., Sanchez-Lorenzo, A., García-Ruiz, J. M., et al. (2014). Evidence of increasing drought severity caused by temperature rise in southern Europe. *Environmental Research Letters*, *9*(4), 044001. https://doi.org/10.1088/1748-9326/9/4/044001

Winkler, K., Fuchs, R., Rounsevell, M. D. A., & Herold, M. (2020, August 20). HILDA+ Global Land Use Change between 1960 and 2019. PANGAEA. https://doi.org/10.1594/PANGAEA.921846

Wriedt, G., der Velde, M., Aloe, A., & Bouraoui, F. (2009). Estimating irrigation water requirements in Europe. *Journal of Hydrology*, *373*(3–4), 527–544. https://doi.org/10.1016/j.jhydrol.2009.05.018

Yang, Y., Zhang, S., McVicar, T. R., Beck, H. E., Zhang, Y., & Liu, B. (2018). Disconnection Between Trends of Atmospheric Drying and Continental Runoff. *Water Resources Research*, *54*(7), 4700–4713. https://doi.org/10.1029/2018WR022593

Zhang, Y., Leuning, R., Chiew, F. H. S., Wang, E., Zhang, L., Liu, C., et al. (2012). Decadal Trends in Evaporation from Global Energy and Water Balances. *Journal of Hydrometeorology*, *13*(1), 379–391. https://doi.org/10.1175/JHM-D-11-012.1

Zhang, Y., Peña-Arancibia, J. L. J. L., McVicar, T. R. T. R., Chiew, F. H. S. F. H. S., Vaze, J., Liu, C., et al. (2016). Multi-decadal trends in global terrestrial evapotranspiration and its components. *Scientific Reports*, *6*(1), 19124.

https://doi.org/10.1038/srep19124

Zhao, M., A, G., Liu, Y., & Konings, A. G. (2022). Evapotranspiration frequently increases during droughts. *Nature Climate Change*, *12*(11), 1024–1030. https://doi.org/10.1038/s41558-022-01505-3