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Increased Vegetation in Mountainous Headwaters Amplifies Water Stress During Dry Periods

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Key Points:

- Forest secondary succession is the main driver of streamflow trends in mountain Mediterranean areas
- The effects of vegetation changes on water availability strongly differ between dry and humid periods
- Trends in streamflow in response to vegetation changes are mostly recorded during the dry and warm season

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The dynamics of blue and green water partitioning under vegetation and climate change, as well as their different interactions during wet and dry periods, are poorly understood in the literature. We analyzed the impact of vegetation changes on blue water generation in a central Spanish Pyrenees basin undergoing intense afforestation. We found that vegetation change is a key driver of large decreases in blue water availability. The effect of vegetation increase is amplified during dry years, and mainly during the dry season, with streamflow reductions of more than 50%. This pattern can be attributed primarily to increased plant water consumption. Our findings highlight the importance of vegetation changes in reinforcing the decrease in water resource availability. With aridity expected to rise in southern Europe over the next few decades, interactions between climate and land management practices appear to be amplifying future hydrological drought risk in the region.

Plain Language Summary

Forest recovery, due to human land abandonment, has been observed in several regions worldwide. To improve integrated land and water management, it is crucial to explore how these changes affect resource availability in water-stressed areas. Forest regeneration has resulted in a large decrease in streamflow in a natural catchment in southwestern Europe, which cannot be explained by climate change. During the dry season, forest regeneration amplifies the impact of drought and water availability, with less impacts in the wet season. Therefore, the effects of vegetation recovery on water resources differ based on water availability, with the most serious implications for water resources occurring during dry periods.

1. Introduction

The partitioning of precipitation between blue water, defined as runoff generation, and green water, representing water consumption by vegetation, determines the availability of surface water resources for human activities and freshwater ecosystems (Rulli et al., 2013). Green water is the largest fraction globally (Wang & Dickinson, 2012), but is challenging to quantify (Mueller et al., 2013). Modeling studies suggest a general increase in green water in recent decades, as a consequence of higher plant leaf area (Forzieri et al., 2020; Zeng et al., 2018), longer vegetative periods (Lian et al., 2020), and greater atmospheric evaporative demand (AED) (Vicente-Serrano, McVicar et al., 2020).

The total vegetation coverage controls the relationship between total evaporation and total precipitation at the catchment scale (Zhang et al., 2001). This would explain how hydrological processes are impacted by changes in leaf area index and plant biomass (Forzieri et al., 2020; Zeng et al., 2018) and the replacement of plant species through secondary succession (Leuschner & Rode, 1999). Studies indicate that reduced tree coverage increases runoff generation after disturbances (Bosch & Hewlett, 1982) since after reduction of the dominant vegetation of a catchment, evaporation is usually reduced (Anderegg et al., 2016; Wine et al., 2017; Winkler et al., 2017). Overall, re-afforestation practices and natural secondary succession reduce runoff production (Filoso et al., 2017), although the magnitude of change is highly dependent on the vegetation types and the environmental conditions, such as average precipitation (Brown et al., 2005) and forest age (Teuling & Hoek van Dijke, 2020).

In southern Europe, different studies have shown a general reduction of streamflow in recent decades (Gudmundsson et al., 2017; Lorenzo-Lacruz et al., 2012; Stahl et al., 2010). Land abandonment and/or re-afforestation have resulted in a large increase in vegetation coverage in the region's headwaters (Lasanta-Martínez et al., 2005; Lasanta et al., 2017; Sanjuán et al., 2018) and different studies have stressed the fundamental role of higher plant transpiration in explaining streamflow trends in the region (García-Ruiz et al., 2011; Teuling et al., 2019; Vicente-Serrano et al., 2019). Thus, in the Mediterranean mountainous areas of Spain, the increase in the forest surface is the most plausible explanation for streamflow reductions in the headwaters (Beguería et al., 2003; Buendia et al., 2016; Martínez-Fernández et al., 2013; Morán-Tejeda et al., 2012).

Unraveling the interaction between vegetation and climate variability, as well as their impact on the partitioning of precipitation into blue and green water, is a high-priority research topic. While an increase in green water consumption has been linked to greening (Forzieri et al., 2020; Ukkola et al., 2016), it is unclear how water availability and seasonality affect the dependency between vegetation changes and precipitation partitioning. Although some studies have identified a dominance in the green water in response to drought events (Orth & Destouni, 2018), particularly during warm years (Mastrotheodoros et al., 2020), there is little understanding of the interaction between vegetation changes and the interannual and interannual variability of climate conditions to explain anomalies and long-term streamflow trends.

We hypothesize that dominant re-vegetation changes in mountain Mediterranean areas of southern Europe have been the primary cause of the large decline in streamflow observed in recent decades. Nevertheless, the role of these vegetation changes in the partition of precipitation between blue and green water is dependent on interannual climate variability, with the role being stronger during dry years when the system has less available water. Moreover, the role of the vegetation changes in the blue and green partition would be seasonally dependent, with the role of vegetation being stronger in summer dry season, when vegetation is more active.

Here, we analyze the influence of vegetation changes on blue water generation in a humid natural basin (the upper Aragón basin) over the last six decades (1962–2019). This basin, located in the Spanish Pyrenees (2181 km^2), is characterized by intense secondary succession toward more mature vegetation communities (See Details in Text S1), representing a “typical” example of recent observed vegetation changes in mountainous areas of southern Europe (García-Ruiz et al., 2011; Lasanta et al., 2017). Accordingly, results of this work can be applied to a broad spatial region in Southern Europe, where water scarcity is a serious socioeconomic and environmental issue.

2. Material and Methods

2.1. Data

Daily streamflow data for the basin was provided by the Ebro Basin Management Agency (*Confederación Hidrográfica del Ebro* (CHE), http://www.chebro.es/; last accessed February 1, 2021). We derived the streamflow (in cubic hectometers, Hm^3) generated over the entire basin draining to the Yesa reservoir, which has been calculated by the CHE since 1962 by means of a mass balance using the reservoir data at the daily scale. The accuracy of this mass balance calculation was verified using monthly streamflow data from five available gauging stations spanning the study domain (Figure S3). Data were summarized for the wet (November-June) and dry (July-October) seasons, as well as annually (Figure S4). Herein, hydrological year spans the period between October and September.

Climate data were obtained from a high-resolution (1.1 km) weekly gridded data set for the whole of Spain from 1962 to 2019. This data set was developed using the most complete register of meteorological data provided by the Spanish National Meteorological Service (Agencia Estatal de Meteorología (AEMET), http://www.aemet.es/es/portada; last accessed 1 February 2021). The raw data were quality controlled, homogenized, and interpolated to a common grid resolution of 1.1 km. Further details about this data set development are outlined in Vicente-Serrano, Tomas-Burguera et al. (2017). The gridded data of air temperature, relative humidity, sunshine duration (as a proxy for solar radiation), and wind speed were used to calculate atmospheric evaporative demand (AED) by means of the FAO-56 Penman-Monteith equation (Pereira et al., 2015). The complete drainage area, which was obtained from a digital elevation model at a spatial resolution of 100 m using ArcHydrotools in ArcGIS 10.2, was used to aggregate monthly precipitation and AED series over the entire basin. To be comparable with streamflow data, climate data were transformed to Hm^3 using the total basin area.

Land cover maps for the decades of 1960 and 2010 were provided by the Spanish Ministry of Agriculture (https://www.mapa.gob.es/es/cartografia-y-sig/publicaciones/agricultura/mac_2000_2009.aspx; last accessed February 1, 2021). Based on interpreting aerial photographs and conducting fieldwork, these maps were created at a spatial scale of 1:50000. To illustrate possible changes in greening conditions, the Normalized Difference Vegetation Index (NDVI) was calculated at a spatial resolution of 1.1 km using the NOAA-AVHRR images covering the period from 1981 to 2015 (Vicente-Serrano, Martín-Hernández et al., 2020) combined with MODIS NDVI (https://modis.gsfc.nasa.gov/data/dataprod/mod13.php) for the period 2000–2019. Both datasets were standardized using the reference period 2000–2015.

2.2. Methods

We have analyzed the magnitude of the trend in annual P, Q and AED to quantify the magnitude of the annual Q trend that may be associated to climate trends and vegetation changes. Significance of trends in hydrological and climatic variables 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 in the different variables, we used a linear regression analysis between the series of time (independent variable) and the climatic and hydrological series (dependent variable). To quantify the magnitude of the annual Q trend that may be associated with climate trends and vegetation changes, we analyzed the annual trend magnitude of P, Q and AED. To figure out how climate and vegetation changes affect annual streamflow, we used multiple regression with streamflow as the dependent variable and precipitation, AED, and time as the independent variables (Beguería et al., 2003). Time was included in the models as a proxy for the progressive evolution of vegetation in the basin as a consequence of secondary succession. Due to the fact that the series only began in 1981, including NDVI was not possible; however, NDVI shows a clear linear increase (Figure S2), indicating that time can be used as a surrogate.

The forward stepwise selection of predictors was used in the construction of regression models using a threshold of 0.05 (Hair et al., 1995). For the annual streamflow analysis, annual precipitation totals and annual AED were considered as independent variables. Seasonally, there are large differences in the time windows in which climate variables are accumulated and affect streamflow, since they depend on physiographic and climatic variables (Barker et al., 2016; López-Moreno et al., 2013). For this reason, we first determined the precipitation and AED cumulative periods with the strongest correlations to streamflow (Figure S5). For the wet and dry seasons, higher correlations were obtained with precipitation accumulated for 10 months before the end of the season. Therefore, the wet season precipitation totals from September to June were used as the independent variable in the regression model, while the dry season precipitation totals from January to October were used as the dependent variable. For the wet season, the maximum correlation between AED and streamflow was obtained for nine months, and for the dry season, the maximum correlation was obtained for 10 months.

The ordinary least square regression method was used to assess trends for wet and dry years and seasons. Herein, wet years (seasons) were defined as those exceeding the 70th percentile of precipitation over the period of record. On the other hand, dry years (seasons) were determined as those with rainfall falling below the 30th percentile.

3. Results and Discussion

Annual precipitation in the basin shows high variability, with a non-significant decrease of 8% in annual totals observed between 1962 and 2019 (Figure 1). Over the same time period, AED increased by 5.7%, which is statistically significant at the 95% level ($p < 0.05$). From 1962 to 2019, the annual streamflow in the catchment decreased by more than 40%, which is consistent with the pattern observed in other natural non-managed basins in Spain (Martínez-Fernández et al., 2013). The decrease in annual streamflow is close

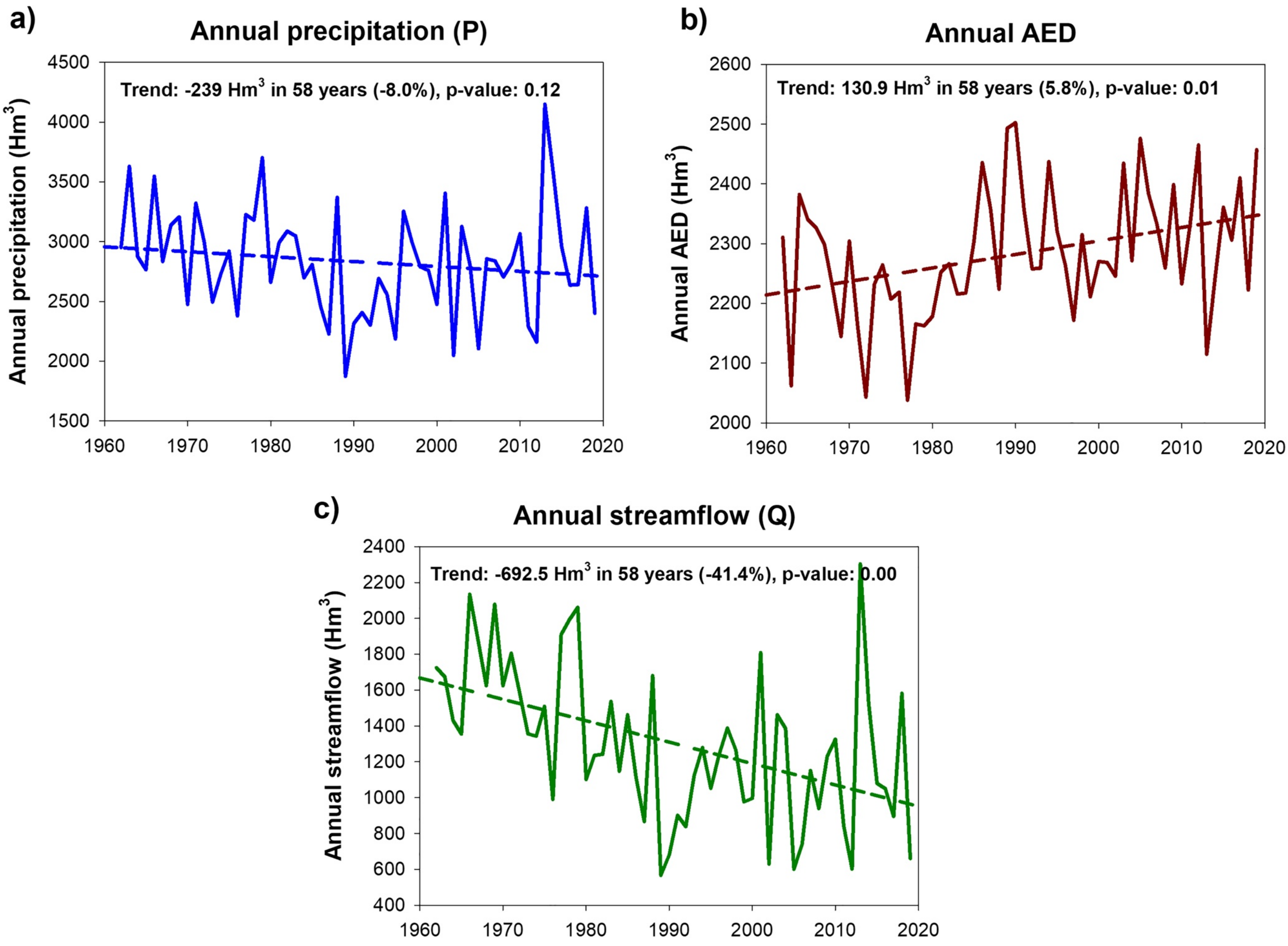

Figure 1. Temporal evolution of annual precipitation (a), atmospheric evaporative demand (AED) (b) and streamflow (c) in the upper Aragón basin for 1962–2019. Dashed lines represent the linear trend obtained by means of least-squares. The percentage changes between 1961 and 2019 are obtained from the regression lines. P-values are obtained by means of the modified Mann-Kendall test (See Section 2.2).

to the increase (34.1%) in the estimated evaporation by means of the annual water balance. The decrease in streamflow cannot be attributed to changes in precipitation. Our findings indicate that annual precipitation decreased by 239.6 Hm^3 over the 58-year study period, while annual streamflow declined by 692.5 Hm^3. This difference (452.85 Hm^3) can be attributed to the net increase in evaporation. An assumption can be made that the amount of increase in AED between 1962 and 2019 corresponds to Evapotranspiration (E), as consequence of direct radiative forcing associated to warming. Nonetheless, this increase is only 130.9 Hm^3 and there are still 321 Hm^3 of streamflow decline between 1962 and 2019 that would not be explained by the observed climate trend. Moreover, it is important to note that the increase in observed AED cannot be completely associated to the increase in E since during summer months soil moisture deficits are common and there is an evaporation deficit (E-AED), which is the main driver controlling forest growth in the region (Vicente-Serrano et al., 2015). Thus drought has significant consequences on vegetation activity and growth in the study area (Camarero et al., 2011; Pasho et al., 2011; Peguero-Pina et al., 2007; Vicente-Serrano et al., 2021). After removing the role of precipitation, the non-climate-related streamflow decline would range between 321 Hm^3 (if AED increase is fully representing an increase in E) and 452.8 Hm^3 (assuming E changes are not driven by AED). These numbers represent between 46% and 65% of total streamflow decline, which would be explained primarily by the basin's secondary succession process.

The secondary role of the observed increase in AED in the streamflow reduction is confirmed by the regression analysis. Over the period 1962–2019, regression analysis using precipitation, AED, and time (in years, as a proxy for the effect of secondary succession and general greenness) as predictors of annual streamflow

Table 1
Correlation Coefficients of the Linear Stepwise Regression Analysis in Which Annual and Seasonal Streamflow was the Dependent Variable and Precipitation, Atmospheric Evaporative Demand and Time (in Years) Were the Independent Predictors

		Partial correlations		
	R^2	Precipitation	AED	Time
Annual	0.82	0.88	−0.09 (n.s.)	−0.64
Wet season (November–June)	0.87	0.92	−0.06 (n.s.)	−0.63
Dry season (July–October)	0.48	0.31	−0.21	−0.49

Note. R^2 represents the percentage of total variance of the independent variable explained by the predictors. Partial correlations represent the role of each independent variable, removing the influence of the covariates. Predictors showing a non-significant (0.05 level) role in explaining streamflow variability were not included in the final models.

explains 82% of the variability in streamflow. However, AED was removed from our final model because it was not a significant predictor (Table 1). According to the partial correlation, precipitation has the largest (positive) influence on annual streamflow, while time exhibited a significant (negative) correlation. Annual precipitation showed a significant negative correlation with annual AED (Figure S6). The role of cloudiness in reducing solar radiation and air temperature can explain this negative relationship between precipitation and AED. Notably, the correlation between annual AED and streamflow was statistically non-significant after fixing (controlling) precipitation effect.

Seasonally, there is also a large decrease in streamflow, being much stronger (−63.7%) during the dry season (Figure S7). Again, this decrease can not be driven by precipitation, which showed a statistically non-significant decrease on the seasonal scale. During the dry season, AED showed a significant negative partial correlation with streamflow, but its influence on streamflow is minor compared to precipitation and time. In the dry season, the inclusion of AED in the linear model accounted only for 2.3% of the total variance in streamflow.

It can be concluded that while the interannual variability of streamflow is strongly correlated with annual precipitation totals, the decrease in streamflow cannot be explained by either precipitation decrease or enhanced AED. Rather, decreasing streamflow trends can be mostly associated with the progressive increase in vegetation cover and greenness over time. Previous studies suggested that the effect of increased greenness on precipitation partitioning between blue and green water is more pronounced in dry areas (Ukkola et al., 2016; Zeng et al., 2018). Based on empirical observations from the upper Aragón basin, where average precipitation is 1,300 mm year^{-1}, our findings suggest that in a humid region affected by secondary succession and increased greenness, vegetation changes can also play a key role in reducing blue water.

Furthermore, we found the effect of secondary succession on the partitioning of precipitation to be strongly differential between wet and dry years. Both precipitation and AED show similar non-significant trends during wet and dry years (Figure S8). However, a small (−15.4%) and non-significant decrease in annual streamflow was found in wet years, compared to a larger (−52.1%) and statistically significant decrease during dry years (Figure 2). The role of AED on streamflow evolution is non-statistically significant during either wet or dry years (Table S1). In wet years, green water increase is expected as a consequence of higher water consumption by more dense vegetation coverage but during these years, the abundance of precipitation makes that secondary succession and greenness have less impact on streamflow trend. In contrast, in dry years secondary succession tends to reduce blue water, in favor of increased green water use. Thus, blue water has been shown to decrease more during dry than wet years in Europe (Orth & Destouni, 2018), so it would be expected that the effect of secondary succession and increased greenness would be amplified during dry years. Vegetation tends to adapt maximum transpiration to available soil moisture (Grossiord et al., 2020), consuming water necessary for physiological processes as the first "ecosystems priority" by increasing water use efficiency (Peters et al., 2018) and, consequently, reducing blue water generation. The differential effect of greenness on streamflow reduction between dry and humid regions (Ukkola et al., 2016; Zeng et al., 2018) identified by previous studies, is shown in the upper Aragón basin between wet and dry

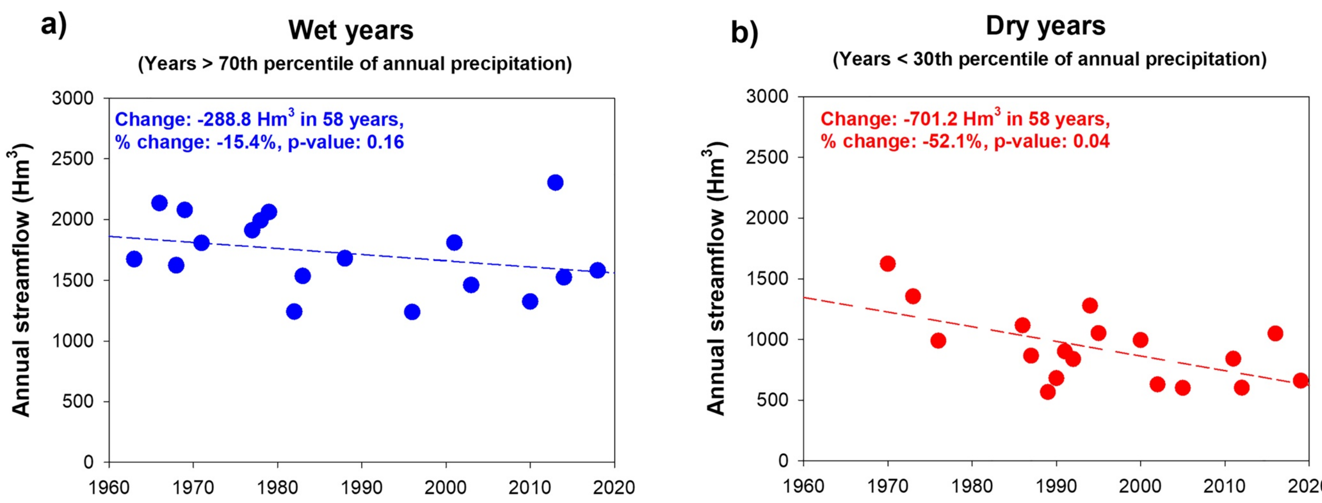

Figure 2. Evolution of annual streamflow during wet (a) and dry (b) precipitation years.

years; in wetter years the greater availability of water in the system, generates proportionally more blue water than during dry years.

The influence of secondary succession also differs between wet and dry seasons (Figure 3). Precipitation and AED reveal non-significant changes in the wet season (November-June) in both wet and dry seasons (Figure S9). Similarly, no significant decrease in streamflow is found since the decrease of blue water during dry seasons is not statistically significant. In the upper Aragón basin vegetation activity shows strong seasonality. As a consequence of cold air temperatures and dominant snow coverage in winter, vegetation activity is low during these months. Therefore, although secondary succession contributes to some decrease in blue water generation in the wet season, particularly during dry periods (Table S1), the main effect is recorded during the warmer dry season (July-October), which is characterized by high vegetation activity, and consequently water consumption over the different altitudinal belts that characterize vegetation in the basin (García-Ruiz et al., 2015). A significant decrease in streamflow during the dry season is evident in both dry and wet periods, with declines being more pronounced in rainy periods. Even in wet periods, the decrease in blue water during the dry season has been significant, probably as consequence of increased plant coverage and greenness. Consequently the decrease in dry season blue water generation has been dramatic during both dry and wet periods. Increased plant water needs as a consequence of enhanced AED and competition for available soil moisture not only cause strong decreases in blue water but also episodes of plant stress, low plant growth and forest dieback in response to drought (Vicente-Serrano et al., 2021), which have become reinforced due to vegetation changes, climate variability and change in recent decades (Camarero et al., 2011; Macias et al., 2006).

Future climate change scenarios over the Mediterranean region show decreases in precipitation and more frequent droughts (Lionello & Scarascia, 2018). Large increases in AED are also projected (Vicente-Serrano, McVicar et al., 2020). Under these scenarios, it is expected that blue water generation will decrease further in large areas of southern Europe affected by land abandonment (Lasanta et al., 2017), plant colonization and secondary succession (García-Ruiz et al., 2011). However, large uncertainties are associated with trends in future vegetation cover. While vegetation changes in the region have been considerable to date, potential remains for significant future changes, including the replacement of coniferous forests and shrublands by broadleaf forests below elevations of 1,600 m a.s.l., and the advance of shrublands and forests at elevations above 2,000 m a.s.l., as consequence of the pasture abandonment and increases in air temperature (Sanjuán et al., 2018). This evolution could affect future availability of water resources since once the current dominant young forests reach more mature levels they may demand more water, as old forests have a lower water yield response (Teuling & Hoek van Dijke, 2020). Although increased atmospheric CO_2 concentrations could have limited plant water needs (Swann, 2018), our results suggest that water availability for socio-economic activities have been primarily driven by water demands from vegetation changes. This finding concur with modeling studies at larger scales (Mankin et al., 2019).

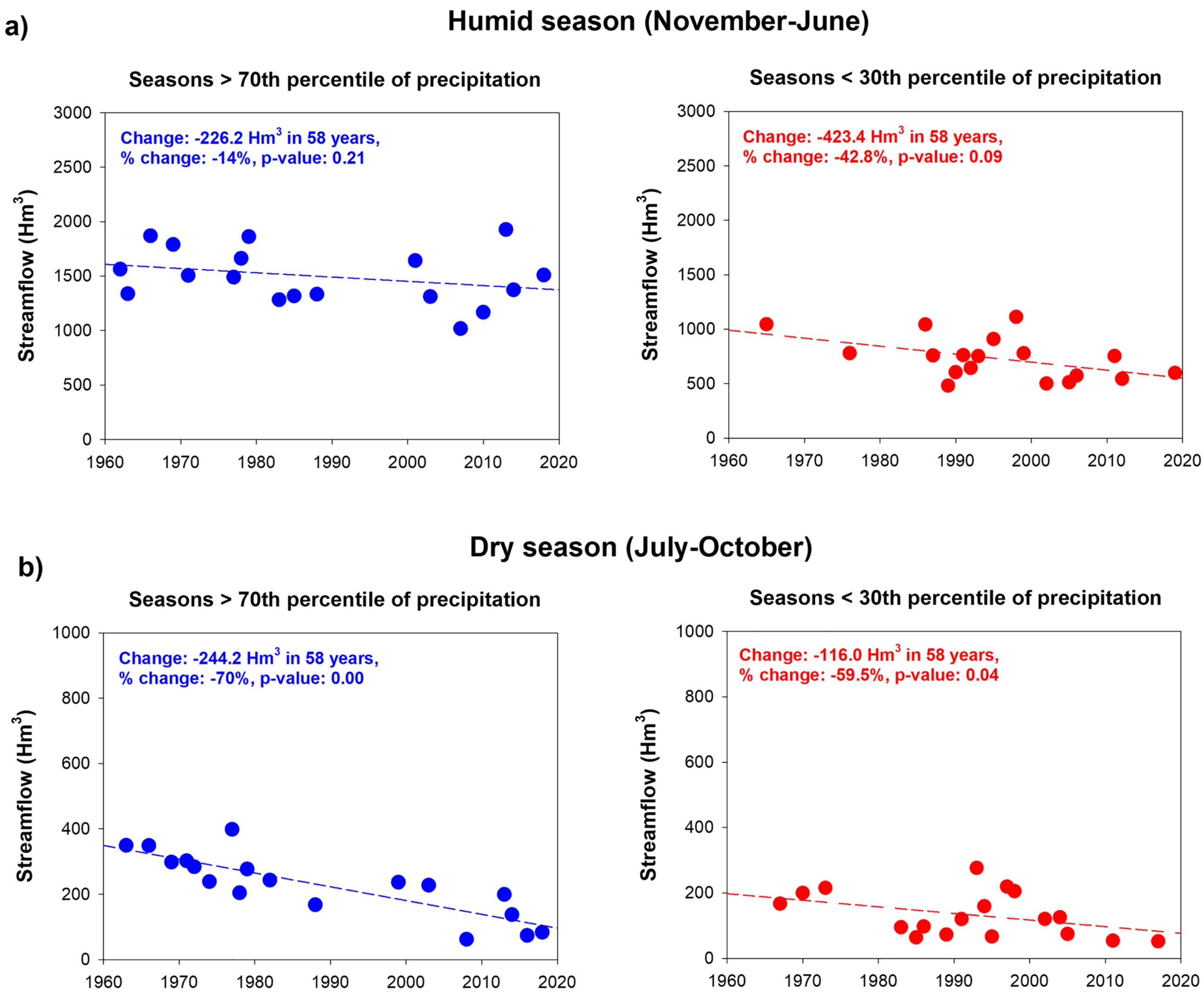

Figure 3. Evolution of annual streamflow during the wet (a) and dry (b) seasons during high and low precipitation periods.

Mountainous areas in southern Europe are the water towers (Viviroli & Weingartner, 2004) in which the usable water resources of the region are generated. Water supply to irrigated areas is already restricted during dry years in the study domain (Vicente-Serrano, Zabalza-Martínez et al., 2017, Vicente-Serrano et al., 2021). These findings, coupled with projected land use and climate change in southern Europe suggest that sustainable land management practices must be focused on limiting green water losses to enhance availability of blue water into the future. In this light, practices such as thinning (Manrique-Alba et al., 2020) and clearing shrublands for livestock (Lasanta et al., 2019) could be considered sustainable water management practices in southern Europe (García-Ruiz et al., 2020).

4. Conclusions

This study analyzed the partition of the available water resources between blue and green water in a Spanish mountainous Mediterranean basin from 1960 to 2019. The study basin is characterized by substantial plant secondary succession processes. Overall, the main conclusions of this study can be summarized: (a) blue water has declined by 40% in the study domain over the last six decades, (b) climate trends accounted for a small portion of blue water reduction, (c) the strong decrease in streamflow can be explained largely by the process of plant secondary succession and increased vegetation, (d) the partition of precipitation trends between blue and green water trends differs between dry and wet years, (e) there is stronger increase in the total basin evaporation during dry years, which drastically limits the production of blue water, posing major challenges to water availability during droughts episodes and (f) there are significant seasonal differences in the role of dry and humid years in precipitation partitioning between blue and green water. The most pronounced impacts can be noted during dry season, when vegetation is more active and consume more water, reducing dramatically water resources, even in wet summers.

Data Availability Statement

The data used in this study can be downloaded at: https://doi.org/10.5281/zenodo.5287430.

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