Hydrological Processes

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Hydrological Effects of the Westward Expansion of Mediterranean Climate and Revegetation in Atlantic–Mediterranean Transitional Headwaters

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ABSTRACT

In this study, a complete hydro-climatic characterisation of six mid-mountain headwater catchments in a transitional Atlantic–Mediterranean ecotone in the Western Iberian Range (Spain) is performed. Three catchments exhibit bioclimatic characteristics that are Atlantic type (Oja, Najerilla and Albercos rivers) and the other three are Mediterranean (Cidacos, Linares and Añamaza). The analyses include, for each catchment: (i) trends in river discharges, precipitation and temperature (1965–2015); (ii) assessment of discharge response to precipitation variability at different accumulated time scales; (iii) changes in land use between 1978 and 2010; and (iv) trends in vegetation activity between 1982 and 2015. The results show: (1) a generalised decrease in annual river discharges, especially during spring and summer; (2) a decrease in precipitation, especially in catchments of the Atlantic domain; (3) a significant and widespread increase in annual, spring and summer temperatures; (4) a fast response of river discharges to precipitation dynamics in Atlantic catchments, and a more sustained (over time scales) response in Mediterranean ones; (5) a much closer climate–discharge relationship during winter, which disappears during summer months in all catchments; and (6) an increase in vegetation activity and forest cover in all catchments. These results point to a westward extension of Mediterranean climatic features into the Atlantic region, reflected in reduced spring precipitation (leading to lower discharges) and increased autumn precipitation in Atlantic catchments. In eastern catchments, Mediterranean conditions strengthen, with higher autumn precipitation and rising spring and summer temperatures, further reducing discharges. Although an increase in vegetation likely increases water consumption and evapotranspiration, the relatively short study period does not yet confirm a clear relationship with river discharge trends.

1 | Introduction

Land-use change is a central driver of global change, significantly altering the Earth's land surface and impacting natural resources, particularly the hydrological cycle, which directly affects freshwater availability and quality (Foley et al. 2005; Nadal-Romero and Cammeraat 2019). The Mediterranean basin, a key global change hotspot, is severely affected by climate change, with projected increases in temperature, decreases in precipitation, and more frequent droughts (Giorgi 2006; Dubrovský et al. 2014). In addition, the Mediterranean region has experienced continuous human-driven landscape transformations for over 10000 years, which intensified during the last decades, leading to substantial land-cover changes (Grove and Rackham 2003). Present-day Mediterranean

[Correction added on 11 June 2025, after first online publication: The citation for Arnáez et al. 2025 has been removed at the request of the corresponding author. The reference list has been updated accordingly.]

landscapes are a dynamic mosaic shaped by topography, soils, vegetation and historical land-use legacies, resulting in varying water resource vulnerability across the region (Milly et al. 2005; Milano et al. 2013; Arnáez et al. 2025).

Vegetation plays a crucial role in regulating water fluxes through interception and evapotranspiration, with forests generally exhibiting higher water consumption than grasslands (Bosch and Hewlett 1982; Zhang et al. 2001; Llorens and Domingo 2007). The hydrological impact of vegetation changes, however, varies depending on climate, land-cover disturbance extent, soil characteristics and vegetation type, particularly in arid and semiarid areas (Sahin and Hall 1996; Stednick 1996; Andréassian 2004; Wilcox et al. 2006; Gökbulak et al. 2016; Doblas-Miranda et al. 2017). Studies in Mediterranean catchments have shown that revegetation, especially forest recovery on abandoned farmland, can reduce water yields and alter river discharge dynamics (Beguería et al. 2003; Gallart and Llorens 2003; Morán-Tejeda et al. 2010; Gallart et al. 2011; López-Moreno et al. 2011; Lana-Renault et al. 2018), underscoring the complexity of soil-vegetation-water interactions in drylands (Wilcox et al. 2008). Although numerous studies have examined the impact of land-use changes on river discharges, the specific hydrological effects of revegetation, especially under varying climatic conditions, remain less understood.

In this context, monitoring and assessing hydroclimatic changes in transitional ecotones such as the Atlantic–Mediterranean are of great interest, as it is in these areas where the effects of climate change are expected to be more intense and their impacts on water resources greater (Diffenbaugh et al. 2007; García-Ruiz et al. 2011; IPCC 2022). In the case of the catchments of the Western Iberian Range, the interest is even greater, given that the abandonment of cultivated lands since the mid-20th century has led to an extensive natural revegetation process, accompanied by afforestation policies, with significant consequences for the available water resources (Peña-Angulo et al. 2021). Changes in land use, coupled with recent changing climate dynamics in this particular area increase in temperature and decrease in precipitation; (Diffenbaugh et al. 2007; García-Ruiz et al. 2011; IPCC 2022) threaten the future maintenance of both ecological flows and those necessary to ensure downstream supply, where the water resource is predominantly consumed by society.

Despite the growing importance of land use-driven hydroclimatic changes in transition ecotones (such the Atlantic–Mediterranean one), studies on this topic are relatively scarce. Within the Iberian Peninsula, research has been carried out on a wide-national scale or focused on headwater catchments of the Pyrenees (Beguería et al. 2003; López-Moreno et al. 2006, 2011) or the Duero basin (Morán-Tejeda et al. 2012). However, detailed studies focusing on this topic in regions with a sharp ecotonal transition, such as the Western Iberian Range, remain scarce. In order to fill this gap, the following objectives were established for the study: (i) to analyse the annual and seasonal trends in river discharges, precipitation and temperature that have occurred in the study catchments between 1965 and 2015; (ii) to characterise the hydrological response to variability and accumulated precipitation deficits using standardised indices at different accumulated time scales; (iii) to monitor the changes in land use and vegetation activity in the catchments over recent decades; (iv) to relate land use and vegetation changes with river discharge dynamics.

To address this, naturalised headwater catchments in the region of La Rioja (Spain) were selected, which are not regulated by dams or reservoirs and have well-documented river discharge data since 1965. Detailed analysis of hydroclimatic trends and land-use changes were conducted, utilising six catchments that are all part of the Ebro basin and share a similar overall northeast-facing aspect (Figure 1). Furthermore, these catchments exhibit a distinct transitional gradient from Atlantic to Mediterranean bioclimatic characteristics and are located within a 100 km radius (Table 1).

2 | Study Area

The Western Iberian Range, located in the Autonomous Community of La Rioja (Spain), is composed of a series of massifs that exhibit marked lithological and climatic diversity. In the western sector, the Sierra de la Demanda, Picos de Urbión and Sierra de Cebollera feature summits exceeding 2000 m a.s.l. Along these main summit lines, a complex network of rivers and ravines extends through steep, nearly straight slopes (Arnáez Vadillo and García-Ruiz 2007). The predominant lithological materials include Palaeozoic quartzites and shales, as well as Cretaceous limestones and sandstones. This area is influenced by humid Atlantic winds, with annual precipitation surpassing 700 mm and reaching up to 1100 mm at the highest elevations. The 0°C isotherm during winter lies above 1600 m a.s.l., and snowfall occurs above this threshold. Mean annual temperatures remain below 9°C across most of the region. Under these conditions, rivers carry substantial discharge and display a modest nival influence (oceanic pluvio-nival regime). Their response to exceptional rainfall events is moderate, leading predominantly to winter or early spring floods (García-Ruiz and Martín-Ranz 1992). Vegetation cover in this environment is dominated by forest and scrubland. Forested areas, covering approximately 57% of the territory, are largely composed of beech (*Fagus sylvatica*) and oak (*Quercus pyrenaica*).

In contrast, the eastern sector of the Western Iberian Range (Camero Viejo) consists of lower-altitude massifs, with summit lines that do not exceed 1750 m a.s.l., although the slopes remain steep. The lithology is varied, corresponding to Purbeck–Weald facies (quartz arenites, sandstones and limestones). The lower elevation and greater distance from Atlantic influences promote a more Mediterranean influenced climate, marked by higher temperatures, reduced precipitation and diminished snowfall. Mean annual temperatures range between 10°C and 11°C, whereas total annual precipitation ranges from 500 to 600 mm, reaching up to 800 mm at a few higher summits. Consequently, the rivers in this region lack a substantial nival component, exhibit reduced flow and display more pronounced torrential behaviour (García-Ruiz and Martín-Ranz 1992). Historically, these slopes were intensively cultivated using terraces or steep fields, resulting in widespread deforestation. After land abandonment, scrub recolonisation became reactivated. On siliceous substrates, this process tends towards dense scrub dominated almost exclusively by *Cistus laurifolius*, and on calcareous substrate, it is mainly dominated by *Genista scorpius*.

The study focused on six headwater catchments (not regulated by reservoirs) (Figure 1). Table 1 summarises their most significant

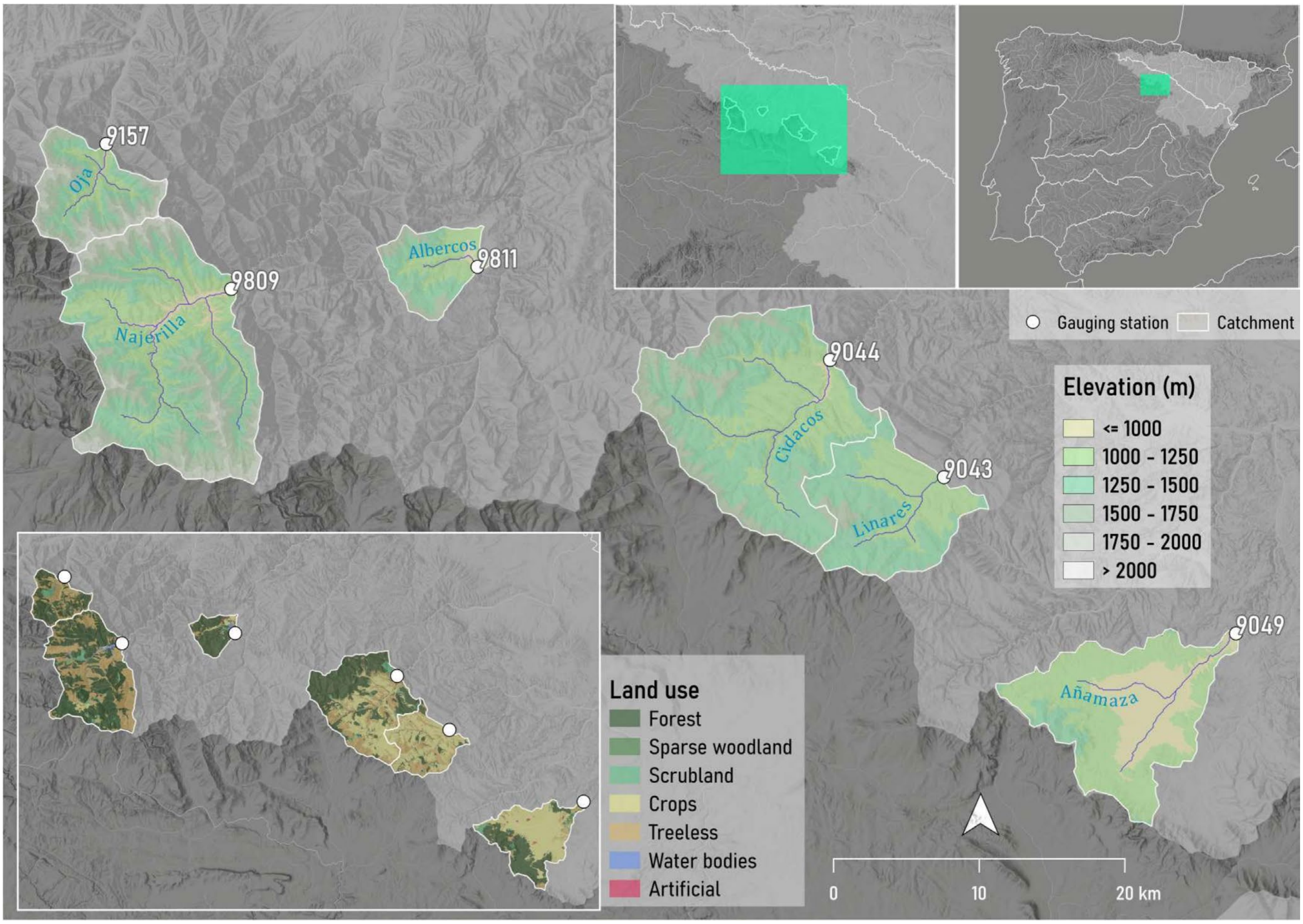

FIGURE 1 | Characteristics of the catchments included in the study: Location, elevation and land cover/use (CORINE Land Cover 2018). Numbers refer to gauging station ID.

characteristics, highlighting several gradients from northwest to southeast. The mean elevation across these catchments varies from 1502 m a.s.l. for Oja to 1064 m a.s.l. for Añamaza, also suggesting a range of climatic conditions influenced by altitude. Mean annual temperatures range from 7.3°C in Oja to 10.9°C in Añamaza, reflecting the varying climatic zones from more temperate conditions in higher altitudes to warmer conditions in lower areas. Precipitation patterns correspond with these temperature gradients, with higher rainfall in the more elevated and steeper catchments like Najerilla (634.5 mm) and Oja (614.1 mm), compared to the significantly lower precipitation of 415.2 mm in Añamaza.

The variation between catchments is also evident in the mean slope gradient, with Oja showing significantly steeper terrain (45.8%) compared to the gentler slopes of Añamaza (9.3%). Annual discharge values further highlight the contrasts between catchments, with the Atlantic ones such as Oja, Najerilla and Albercos exhibiting high specific discharge rates of 1.01, 0.72 and 1.10 hm^3/km^2, respectively, which are substantially higher than the 0.18, 0.16 and 0.01 hm^3/km^2 recorded for the Mediterranean ones (Cidacos, Linares and Añamaza), respectively. These differences underscore the varying hydrological responses and water availability across the catchments, likely driven by differences in physiography, climate and land use, and emphasise the Atlantic–Mediterranean transition that is the focus of this study.

3 | Data and Methods

3.1 | River Discharge Database

The monthly river discharge series (contributions in hm^3) used in the study were obtained from the website of the *Anuario de Aforos* (CEDEX; https://ceh.cedex.es/anuarioaforos/default.asp). The selection was based on their completeness (< 10% missing data) during the analysed period (1965–2015), and a linear regression model based on flow series from the same river course was used to fill the gaps in the series. The location of the gauging stations was used to delineate the drainage catchments for which regional series of precipitation, temperature and vegetation activity were calculated (Figure 1), using a 25 m resolution digital elevation model (https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1).

3.2 | Climatic Database

The climate data (monthly precipitation and temperature) used were from the Spain02 v5.0 gridded database (Herrera et al. 2012; Herrera et al. 2016; https://github.com/SantanderMetGroup). Utilising the values from the pixels ($0.1° \times 0.1° \approx 9 \times 9$ km) contained within the study catchments, regional series

TABLE 1 | Characteristics of the catchments included in the study. Averaged hydroclimatic variables correspond to the period 1965–2015.

Station ID	Domain	Catchment	Catchment area (km^2)	Mean elevation (m a.s.l.)	Mean slope (%)	Mean annual discharge (hm^3)	Specific discharge (hm^3/km^2)	Mean annual temperature (C°)	Mean annual precipitation (mm)
9157	Atlantic	Oja	65.1	1502	45.8	66.4	1.01	7.3	614.1
9809		Najerilla	238.3	1388	37.1	173.8	0.72	7.9	634.5
9811		Albercos	43.1	1297	23.4	47.3	1.10	9.4	517.9
9044	Mediterranean	Cidacos	225.2	1334	22.1	42.6	0.18	9.3	496.7
9043		Linares	105.1	1305	15.9	17.1	0.16	9.7	490.8
9049		Añamaza	149.5	1064	9.3	2.45	0.01	10.8	415.2

of monthly precipitation and temperature (1965–2015) were calculated, weighting the average of the values by the percentage of coverage of each grid pixel over the total extension of the catchment.

3.3 | Land Use and Vegetation Activity Databases

The analysis of land use changes was conducted using the national Crop and Land Use Map (*Mapa de Cultivos y Aprovechamientos*) published in 1978 and 2010 https://www.mapa.gob.es/es/cartografia-y-sig/ide/descargas/default.aspx. In both instances, the 1 ×1 km tiles express land use predominance. The analysis of land use changes is limited to the 1978–2010 period due to the availability of consistent and comparable land use data. The 1978 baseline is based on the national Crop and Land Use Map which provides the earliest detailed cartographic dataset covering the entire Spanish territory at an appropriate scale (1:50 000). Earlier systematic land use data are either unavailable or lack the spatial and thematic consistency necessary for reliable comparison with more recent datasets. The vegetation activity data (summarised in the normalised difference vegetation index, NDVI) correspond to two different datasets: (i) the GIMMS3g.v1 (Global Inventory Modeling and Mapping Studies) database (Pinzon and Tucker 2014), derived from AVHRR (Advanced Very High Resolution Radiometer) observations with a temporal coverage from 1982 to 2015, and a pixel size of (0.88° ×0.88°) approximately 8 × 8 km, and (ii) the MODIS (Moderate Resolution Imaging Spectroradiometer) NDVI data retrieved by Aqua and Terra satellites spanning from 2000 to 2015, with a spatial resolution of 250 ×250 m (Huete et al. 2002). The monthly NDVI values of both databases were processed in the same way as in Section 3.2 to calculate the regional NDVI series for each catchment.

3.4 | Hydro-Climatic Variables Standardisation

A measure of the hydrological response to climatic variability can be obtained by correlating standardised river discharges (comparable in time and space and free from bias in the frequency distributions; López-Moreno et al. 2013; Lorenzo-Lacruz et al. 2013) with standardised precipitation anomalies (accumulated over temporal scales from 1 to 24 months). For this purpose, the standardised precipitation index (SPI; McKee et al. 1993; McKee 1995) and the standardised streamflow index (SSI; Vicente-Serrano et al. 2012) were calculated on a monthly basis, using the data described in Sections 3.1 and 3.2.

3.5 | Trend Analysis and Pre-Whitening of the Series

For the detection of monotonic trends (1965–2015) in the seasonal and annual series of river discharges, precipitation, temperature and vegetation indices, the Mann–Kendall test was applied, with pre-whitening of the series to remove temporal autocorrelation (Yue et al. 2003) (using the zyp package in R).

TABLE 2 | Summary of river discharges trend analysis (1965–2015). Significant trends (p value < 0.1) are shown in bold font. Reduction of the average annual flow over the last 50 years is indicated in italics.

Gauging station ID	Domain	Catchment	Annual (hm^3)	Annual reduction from 1965 to 2015 (%)	Winter (hm^3)	Spring (hm^3)	Summer (hm^3)	Autumn (hm^3)
9157	Atlantic	Oja	−22.6	*−37*	2.5	−1.5	−2.8	−10.4
9809		Najerilla	−25.3	*−25*	2.1	−13.3	−4.5	2
9811		Albercos	−11.7	*−27*	−1.3	−4.4	**−2.7**	−1.5
Mean			−19.9	*−29.6*	1.1	−6.5	−3.3	−3.3
9044	Mediterranean	Cidacos	**−24.5**	*−45*	−7.7	**−11.8**	**−3.9**	−0.9
9043		Linares	−8.1	*−40*	−1.8	−0.04	**−0.4**	−0.2
9049.		Añamaza	−0.5	*−20*	−0.1	−0.1	0.1	−0.1
Mean			−11	*−35*	−3.2	−4	−1.4	−0.4

4 | Results

4.1 | Hydro-Climatic Trends Analysis

4.1.1 | River Discharges

The results of the river discharges trend analysis indicate a generalised decrease across all catchments (Table 2), with seasonal variations. On an annual scale, although all trends are negative, only in the case of Cidacos is it statistically significant. The same occurs in spring. It is in summer, the critical season for the maintenance of ecological flows and when evaporative demand is highest, that more significant negative trends have been recorded (Albercos, Cidacos and Linares). For the Oja catchment, there is a notable annual decrease in river discharge of –22.6 hm^3 (37% reduction), with the most notable seasonal decline observed in autumn (–10.4 hm^3), marking a 96% reduction over the study period. Interestingly, winter shows a slight increase of 2.5 hm^3 (12%). The Najerilla catchment exhibits a less severe annual reduction (–25%), with spring showing a particularly pronounced decrease (–13.3 hm^3, 22% reduction), and a slight increase in winter of 2.1 hm^3 (3%). Unlike Oja, Najerilla also sees a slight increase (8%) in discharges during autumn (2 hm^3). In the Albercos catchment, which exhibits a similar annual decrease (–27%) to that of Najerilla, the reductions are more evenly distributed across seasons, with the smallest decline in winter (–1.3 hm^3, 8% reduction). This contrasts with the slight increases observed in Oja and Najerilla during the same season. The Cidacos catchment shows a dramatic reduction of its annual river discharges over the period (45% reduction), with the largest seasonal drop in spring (–11.8 hm^3, 62% reduction). During winter, the Cidacos experiences a 52% decrease (–7.7 hm^3), the largest among the studied catchments in winter. The Linares catchment also shows a dramatic reduction of 40% of its average annual flow, with winter being the season that registers a higher reduction (–1.8 hm^3, 30%). Añamaza show relatively a minor annual decline (20% reduction), with minimal seasonal differences.

These results suggest a heterogeneous hydrological response across neighbouring catchments within the Atlantic–Mediterranean gradient. The annual mean values for the three Atlantic catchments indicate a 29.6% reduction, compared with 35% for the Mediterranean ones. Seasonally, these same averages show that flow losses are greatest in spring for both the Atlantic (–6.58 hm^3) and Mediterranean (–4 hm^3) catchments. In summer and autumn, losses remain higher in the Atlantic ones. However, this pattern does not hold in winter. During this season, the Atlantic catchments display a positive balance of 1.12 hm^3.

Figure 2 shows that the annual discharge rates are subject to considerable inter-annual variability, with pronounced fluctuations that reflect the inherent complexity of hydrological systems.

It is noteworthy that the depicted trends are not strictly monotonic; there are years with flow rates that surpass the mean, suggesting episodic recovery or the influence of anomalously wet years. The interannual variability of the river discharge rates is wider in the case of the Mediterranean catchments. In all cases, it is possible to identify particularly wet or high-flow years (1966, 1979 or 2013) or particularly dry years (1976, 1990 or 2002), which corroborate the predominant climatic control that exists over flow generation in these catchments.

4.1.2 | Precipitation

Trend analysis reveals a widespread decline in annual precipitation across all catchments (Table 3). The Albercos station exhibits the most pronounced annual decrease with a statistically significant value of −123.3 mm (24% reduction). Similarly, the Añamaza catchment shows a substantial reduction of a 23%, with an annual trend of −120.8 mm, underscoring a regional pattern of diminishing precipitation. Overall, the Atlantic catchments show losses of −95.5 mm, whereas the Mediterranean ones register −88.2 mm. Seasonal analysis further elucidates the complex dynamics at play. All stations register a decrease in winter, spring and summer precipitation, with the spring season experiencing notably significant drops, particularly in the Oja (−80.5 mm), Najerilla (−78.8 mm) and Albercos (−76.3 mm) catchments (Atlantic-type). These springtime reductions may have critical implications for water resource management, affecting everything from agricultural scheduling to ecosystem sustainability. Interestingly, autumn precipitation shows an increase across all the stations, particularly in the Cidacos (21.3 mm), Linares (17.6 mm) and Añamaza (16 mm) catchments (Mediterranean-type).

Figure 3 shows that all catchments encompass considerable inter-annual precipitation variability, evident through the fluctuating nature of the precipitation time series. The precipitation trends of the Atlantic-type catchments (Oja, Najerilla and Albercos) exhibit comparable patterns, as do those of the Mediterranean catchments (Cidacos, Linares and Añamaza). Despite all six catchments exhibiting overall declining precipitation trends, a temporal disparity is noted: Atlantic catchments experienced their wetter years (> 800 mm) predominantly in the first half of the study period, whereas the Mediterranean catchments observed their higher precipitation years (> 600 mm) more frequently in the latter half.

4.1.3 | Temperature

Temperature trends are much more homogeneous across the study area and the temporal scales analysed (Table 4). Significant positive trends are observed on an annual scale

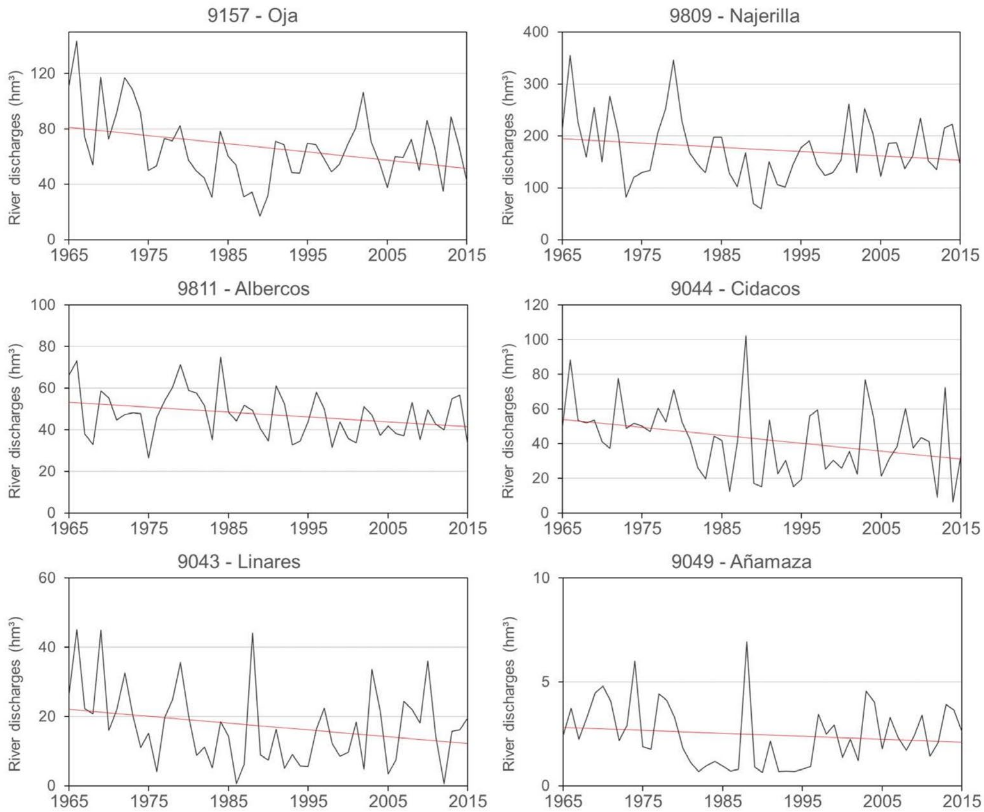

FIGURE 2 | Annual river discharges of the studied catchments between 1965 and 2015. Red line depicts the linear trend slope.

TABLE 3 | Summary of precipitation trend analysis (1965–2015). Significant trends (p value < 0.1) are shown in bold font.

Gauging station ID	Domain	River	Annual (mm)	Winter (mm)	Spring (mm)	Summer (mm)	Autumn (mm)
9157	Atlantic	Oja	−97.9	−41	**−80.5**	**−63.3**	1.9
9809		Najerilla	−65.3	−45.2	**−78.8**	**−60.8**	5.9
9811		Albercos	**−123.3**	−31	**−76.3**	**−53.3**	1.0
Mean			−95.5	−39.5	−78.5	−59.1	2.9
9044	Mediterranean	Cidacos	−70.9	−8.2	−42.5	−28.6	21.3
9043		Linares	−72.9	−12.9	−41.3	−35.3	17.6
9049		Añamaza	**−120.8**	−36.3	−21.5	**−49.9**	16
Mean			−88.2	−19.1	−35.1	−37.9	18.3

in all catchments, although these are particularly noteworthy in Albercos and the three Mediterranean catchments, where warming has exceeded 1°C since 1965. In comparison, the Oja and Najerilla catchments show more modest annual warming trends of 0.88°C and 0.72°C, respectively. At the seasonal scale, significant positive trends are observed in spring in all catchments, with larger increases in the Atlantic-type ones. Summer also shows significant increases in all catchments (except in Najerilla), with extraordinary warming that has surpassed 1.5°C in Cidacos and 2°C in Linares and Añamaza (Mediterranean-type). Autumn and winter temperatures do not show any significant trend in any catchment.

Figure 4 corroborates the overall increasing trend in temperatures across all catchments. The graphs for Albercos and the three Mediterranean-type catchments in particular exhibit more pronounced upward trajectories, suggesting these catchments are experiencing accelerated warming. The Oja and Najerilla catchments show a more gradual increase in temperature, with fewer instances of annual temperatures exceeding the long-term average. The catchment of Añamaza displays the highest temperature rises, with peaks that suggest episodes of significant warming, especially notable in the last decade of the record. Overall, it is clear that the last three decades of recordings were significantly hotter than the three previous ones in all catchments.

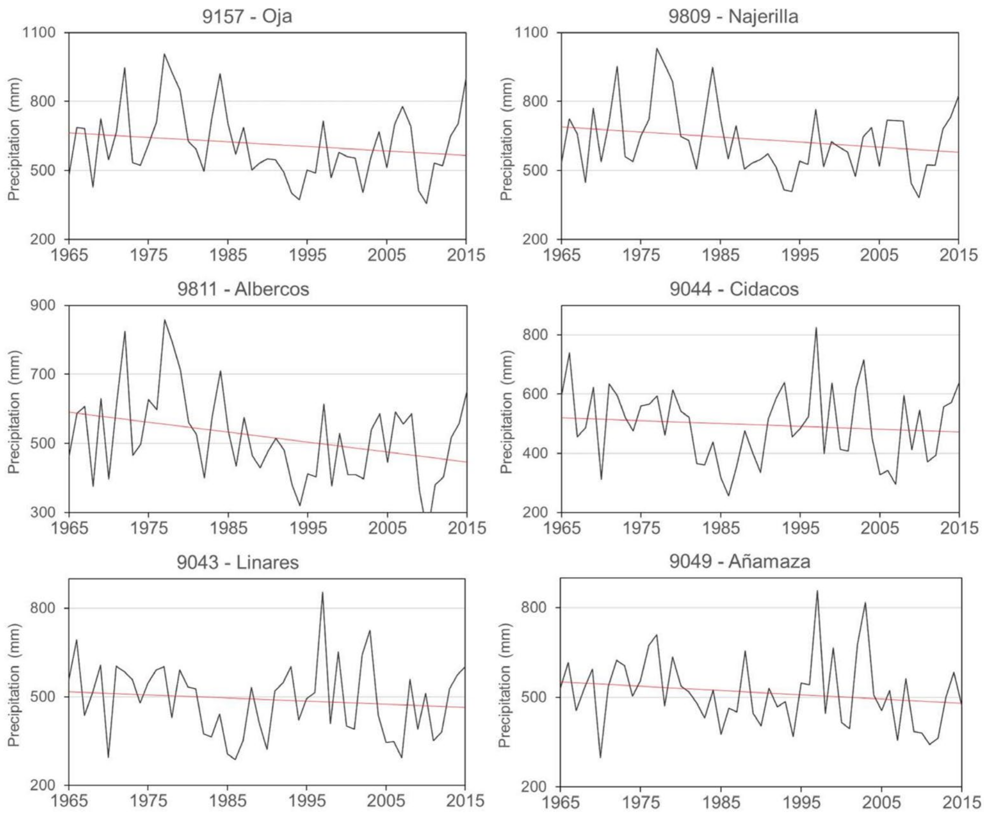

FIGURE 3 | Annual precipitation of the studied catchments between 1965 and 2015. Red line depicts the linear trend slope.

TABLE 4 | Summary of temperature trend analysis (1965–2015). Significant trends (*p* value < 0.1) are shown in bold font.

Gauging station ID	Domain	Catchment	Annual (C°)	Winter (C°)	Spring (C°)	Summer (C°)	Autumn (C°)
9157	Atlantic	Oja	**0.88**	−0.17	**1.43**	**0.71**	−0.13
9809		Najerilla	**0.72**	0.03	**1.42**	0.25	−0.20
9811		Albercos	**1.01**	0.28	**1.58**	**0.90**	0.38
Mean			0.87	0.05	1.48	0.62	0.02
9044	Mediterranean	Cidacos	**1.11**	−0.11	**1.08**	**1.69**	0.68
9043		Linares	**1.26**	−0.30	**1.04**	**2.08**	0.77
9049		Añamaza	**1.11**	−0.42	**1.09**	**2.01**	0.71
Mean			1.16	−0.28	1.07	1.93	0.72

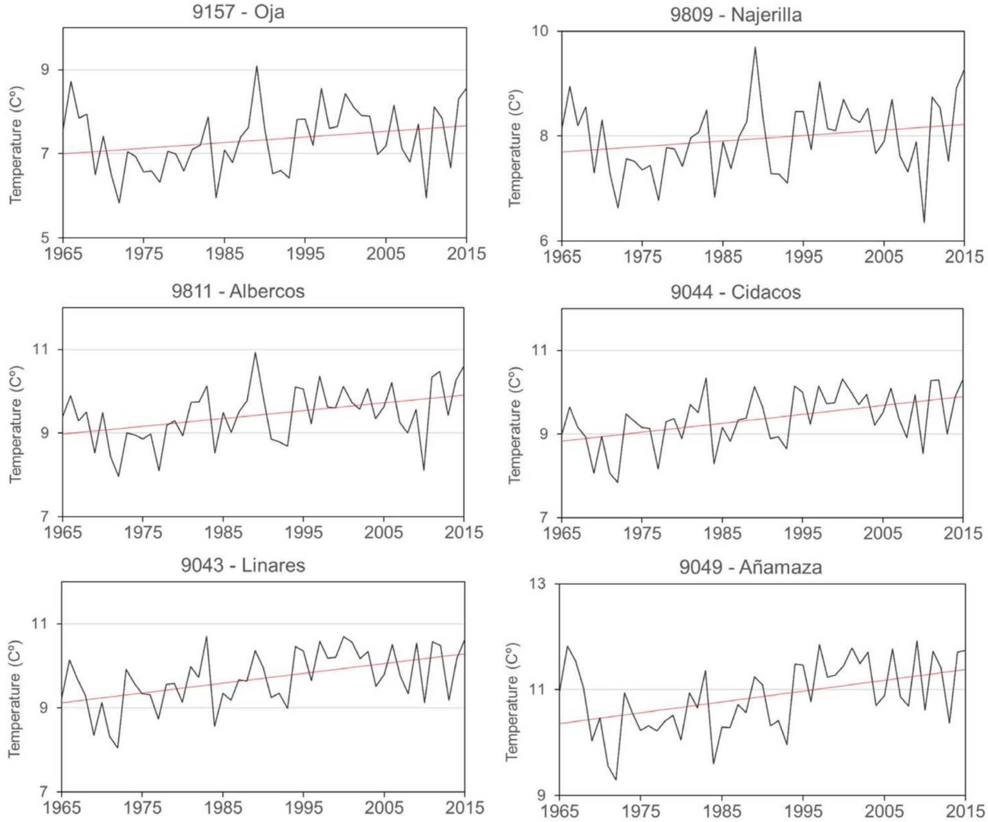

FIGURE 4 | Annual temperatures of the studied catchments between 1965 and 2015. Red line depicts the linear trend slope.

4.2 | Hydro-Climatic Interactions

The hydrological response (river discharges) to precipitation variability (accumulated precipitation over scales from 1 to 24 months) reveals a clear distinction between Atlantic and Mediterranean catchments. The former exhibited a relatively fast response to precipitation variability, with the highest correlation ($r \sim 0.4$) occurring at scales of 2 and 3 months (Figure 5, upper panels). This indicates that river discharges in Atlantic catchments depend primarily on the precipitation recorded during the current month and the two preceding months. On the other hand, Mediterranean catchments show a more intense ($r > 0.5$ in Linares and Cidacos) and sustained response (especially Añamaza) over time. The latter indicates a slower hydrological response to precipitation, which could be due to factors such as higher soil moisture deficit and gentler slopes.

Substantial differences arise at analysing monthly SSI-SPI correlations, which show a measure of the precipitation-discharge relationship, with lower panels in Figure 5 revealing the temporal evolution and seasonal patterns in the hydrological response to precipitation variability. In all the catchments, there is a notable seasonal shift, with lowest correlations ($r < 0.1$) concentrated in the summer and autumn months, particularly at shorter time scales, indicating that river discharges are hardly sensitive to recent precipitation volumes during these months and may depend on other factors (e.g., rainfall intensity, precedent soil moisture conditions). Under dry conditions, the high soil water deficit is exacerbated by higher water consumption by vegetation due to the high evaporative demand, practically nullifying the precipitation-discharge relationship.

Interestingly, in Cidacos and Añamaza, summer discharges show a relatively good correlation ($r \approx 0.5$) to accumulated precipitation at time scales of 5–13 months, suggesting that in these catchments, summer hydrological response is influenced by the rainfall recorded in spring (Añamaza) or even over the whole hydrological year (Cidacos). Conversely, in all catchments, the correlations are higher ($r > 0.7$) in winter and spring, especially at short (Oja 1–3 months, and Najerilla 1–5 months) or intermediate (Cidacos, Linares, Añamaza, 3–9 months) time scales, indicating that under wet conditions, river discharge is strongly influenced by the precipitation recorded during the current and the preceding months. These lower panels underscore the seasonal variability in the precipitation-discharge relationship and highlight differences in the hydrological memory across the studied catchments, likely driven by regional climatic, geological, physiographic, and land use factors.

4.3 | Changes in Land Uses and Vegetation Activity

Figure 6 illustrates the spatial distribution of land use changes in the study catchments between the 1970s and 2010. Each pixel (1×1 km) represents the predominant land use in the corresponding area. A summary of these land use changes during

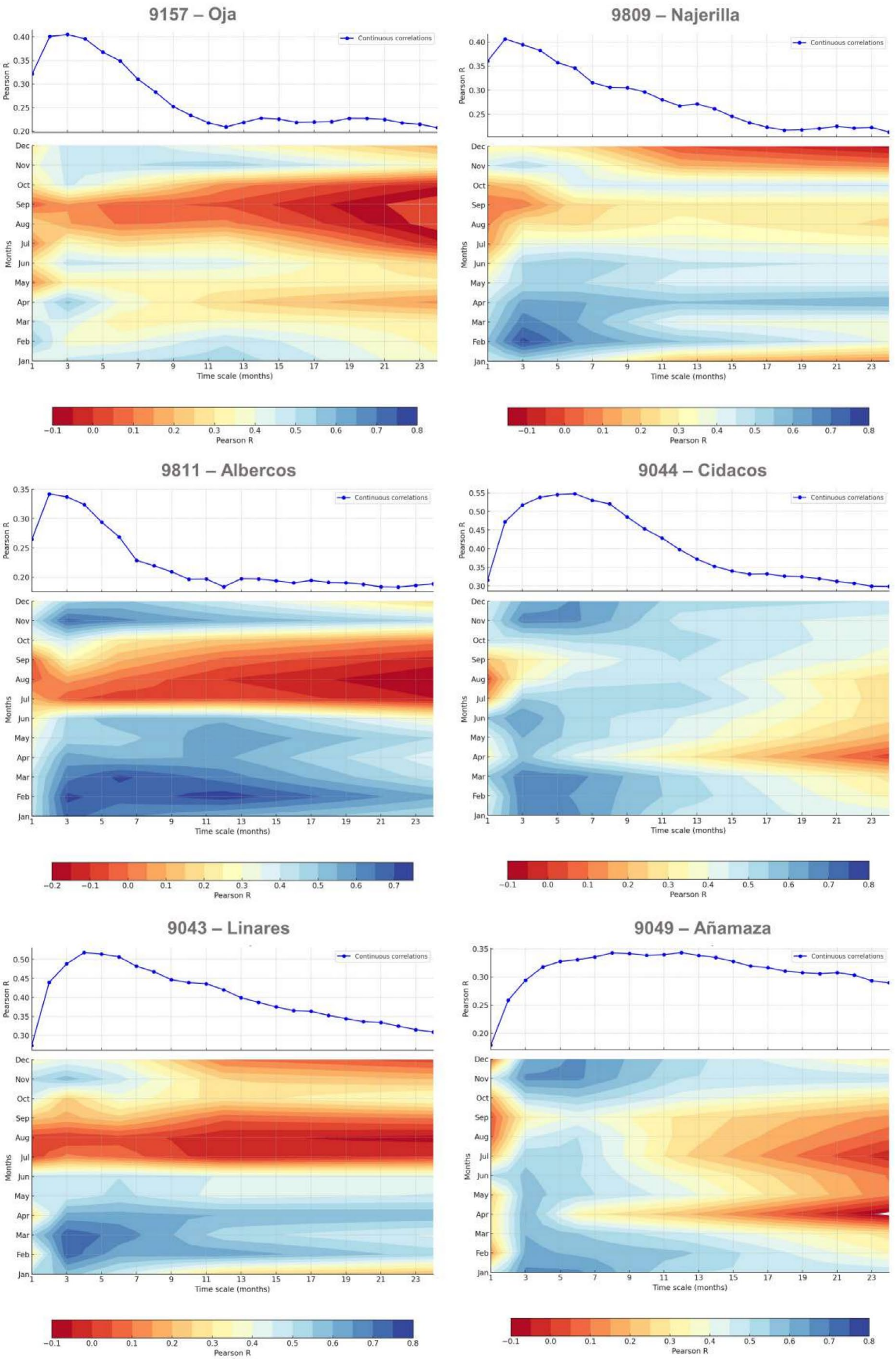

FIGURE 5 | Legend on next page.

FIGURE 5 | Upper panels: Continuous correlations between the SSI and the SPI at time scales accumulated from 1 to 24 months. Lower panels: Monthly correlations between the SSI and the SPI at time scales accumulated from 1 to 24 months.

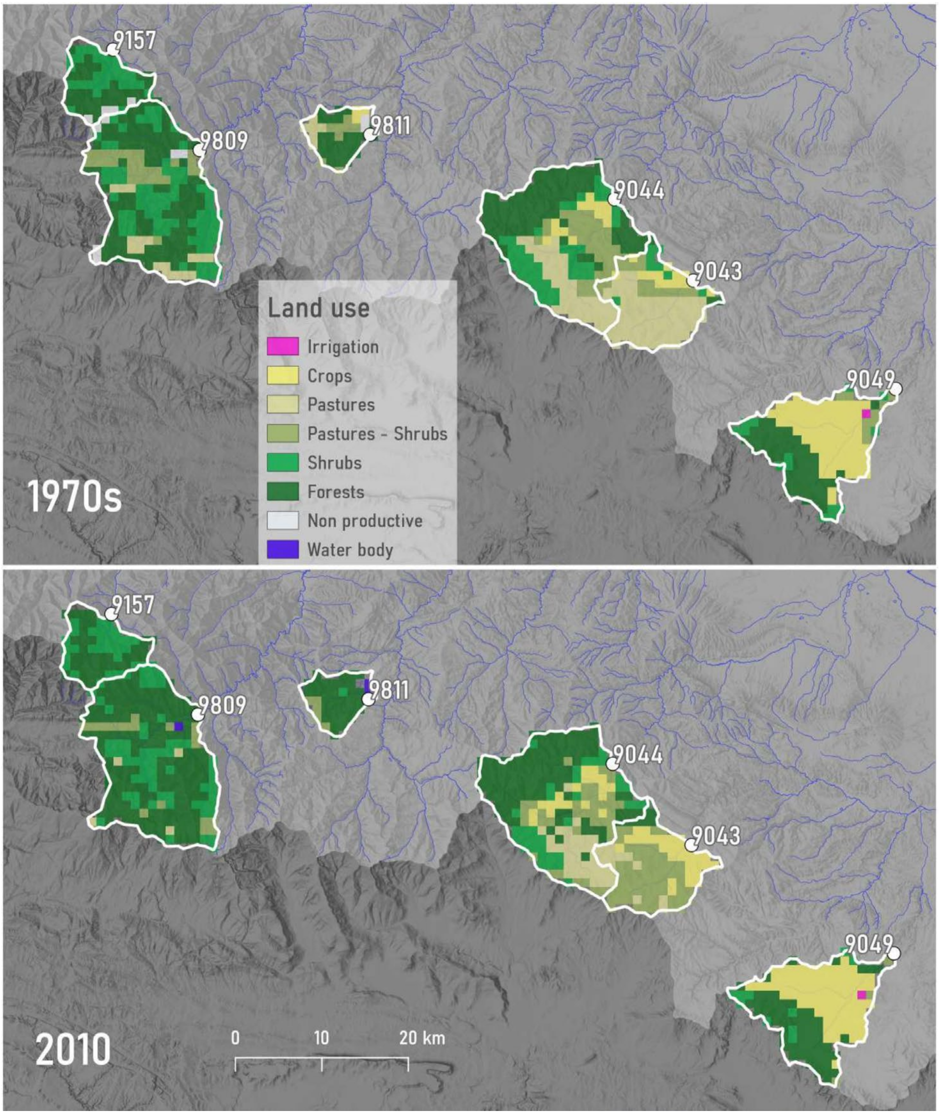

FIGURE 6 | Spatial distribution of land uses in the study area in 1970 and 2010. Pixels (1 × 1 km) depict land use predominance. *Source:* Mapa de cultivos y aprovechamientos. (https://www.mapa.gob.es/es/cartografia-y-sig/ide/descargas/default.aspx).

this period is shown in Figure 7. In the 1970s, the landscape was predominantly composed of pastures and crops in the Mediterranean catchments, and a significant presence of shrubland and forest in the Atlantic ones. In the Mediterranean catchments, forest was only present at higher elevations (Cidacos and Añamaza). The 2010 map (Figure 6, lower panel) and Figure 7 show a clear increase in forest cover, especially in the Atlantic catchments (Najerilla and Albercos). Meanwhile, pastures and shrubs decreased in most of the catchments, and so did crops, except for the three Mediterranean catchments where crop surface increased. The Linares catchment is a unique case, as it has the smallest forested area, shows an increase in cropland, yet exhibits the greatest growth in grassland–shrub cover.

The increase of forested areas reflects the process of general farmland abandonment in the headwaters and subsequent revegetation, due to both natural vegetation succession on former agricultural and pasture lands, and policies promoting afforestation in certain areas. This change is more pronounced in the Atlantic catchments, where farmland abandonment started earlier, compared to the Mediterranean ones, where pastures and crops still dominate or even increase, and where climatic conditions also favour rewilding processes. The transformation in land use is expected to have significant implications for hydrological processes, including changes in water consumption and runoff generation, particularly in forested areas where evapotranspiration may increase.

As depicted in Figure 7, the most notable land-use change during the study period was the increase in forested areas across all catchments. Table 5 summarises the changes in forest area coverage, with the greatest increases observed in the Atlantic-type catchments, despite these catchments having the largest forested

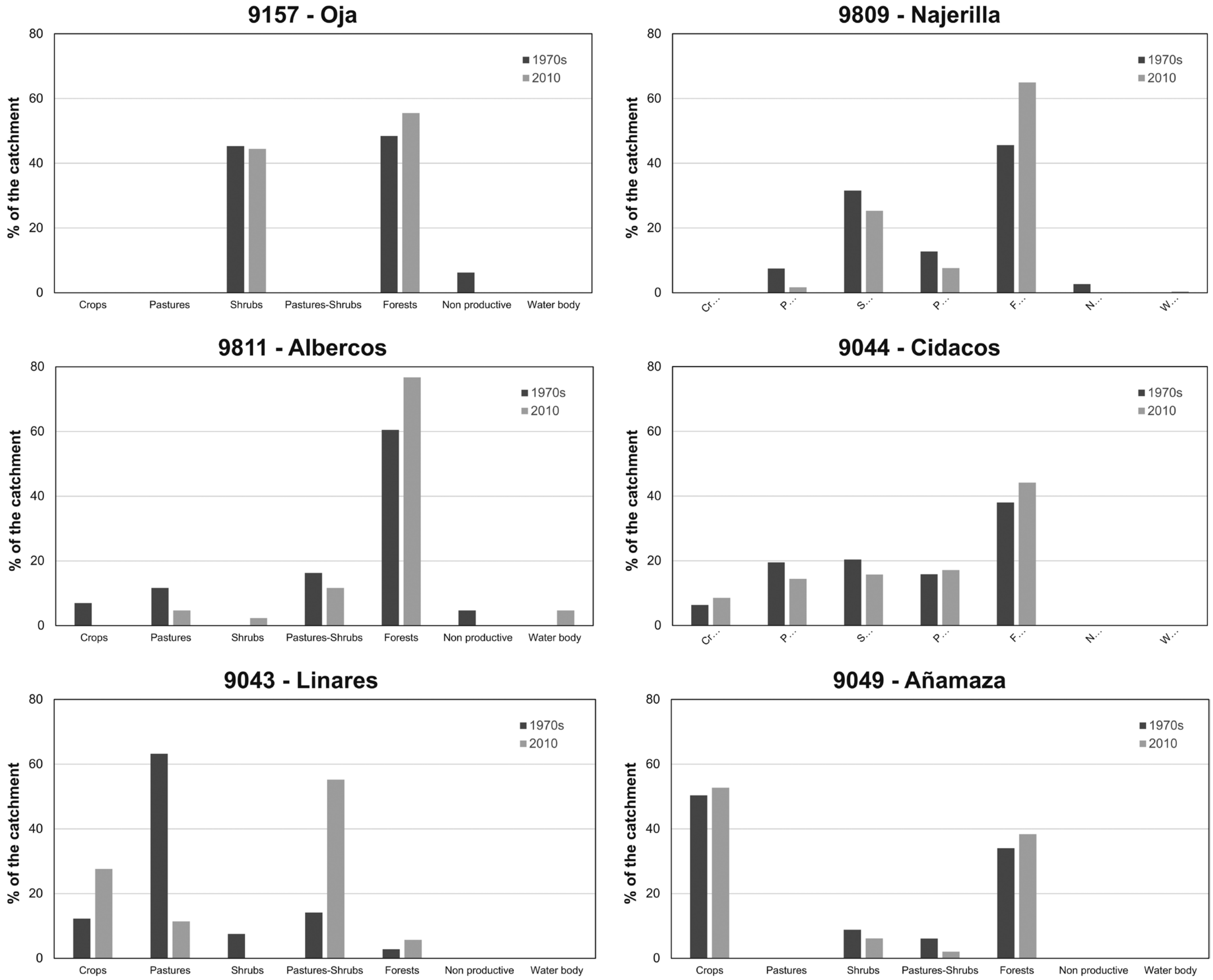

FIGURE 7 | Summary of land use changes that occurred between the decade of 1970 and 2010. *Source:* Mapa de cultivos y aprovechamientos (https://www.mapa.gob.es/es/cartografia-y-sig/ide/descargas/default.aspx).

TABLE 5 | Summary of forest cover dynamics.

Gauging station ID	Domain	Catchment	Forest area in 1978 (% of the catchment)	Forest area in 2010 (% of the catchment)	Forest area increase (from 1978 to 2010)
9157	Atlantic	Oja	48	55	+7
9809		Najerilla	45	64	+9
9811		Albercos	60	77	+17
9044	Mediterranean	Cidacos	38	44	+6
9043		Linares	3	6	+3
9049		Añamaza	34	38	+4

areas at the start of the study. The Mediterranean catchments show more modest increases, primarily due to a lower natural succession from scrubland to forest under drier conditions.

The revegetation process is also reflected in Table 6, which summarises the analysis of annual NDVI trends between 1982 and 2015 for the six studied catchments, presenting data from two NDVI sources: GIMMS (1982–2015) and MODIS (2001–2015). The table reports both the annual NDVI average and the trends for each dataset, with significant trends ($p < 0.1$) highlighted in bold. The GIMMS NDVI annual averages range from 0.408 (Añamaza) to 0.587 (Albercos) and illustrate the higher vegetation activity in the Atlantic catchments than the Mediterranean ones (see also Figures 6 and 7). All catchments exhibit positive trends between 1982 and 2015, with higher values in the Atlantic catchments, suggesting increased vegetation activity over the

TABLE 6 | Summary of annual NDVI trend analysis (1982–2015) from two datasets (GIMMS and MODIS). Significant trends (p value < 0.1) are shown in bold font.

Gauging station ID	Domain	Catchment	GIMMS NDVI annual average (1982–2015)	GIMMS NDVI trend (1982–2015)	MODIS NDVI annual average (2001–2015)	MODIS NDVI trend (2001–2015)
9157	Atlantic	Oja	0.558	**0.098**	0.591	**0.038**
9809		Najerilla	0.551	**0.081**	0.631	**0.046**
9811		Albercos	0.587	**0.077**	0.651	**0.024**
9044	Mediterranean	Cidacos	0.485	**0.048**	0.59	**0.042**
9043		Linares	0.496	**0.054**	0.595	0.011
9049		Añamaza	0.408	**0.058**	0.565	0.026

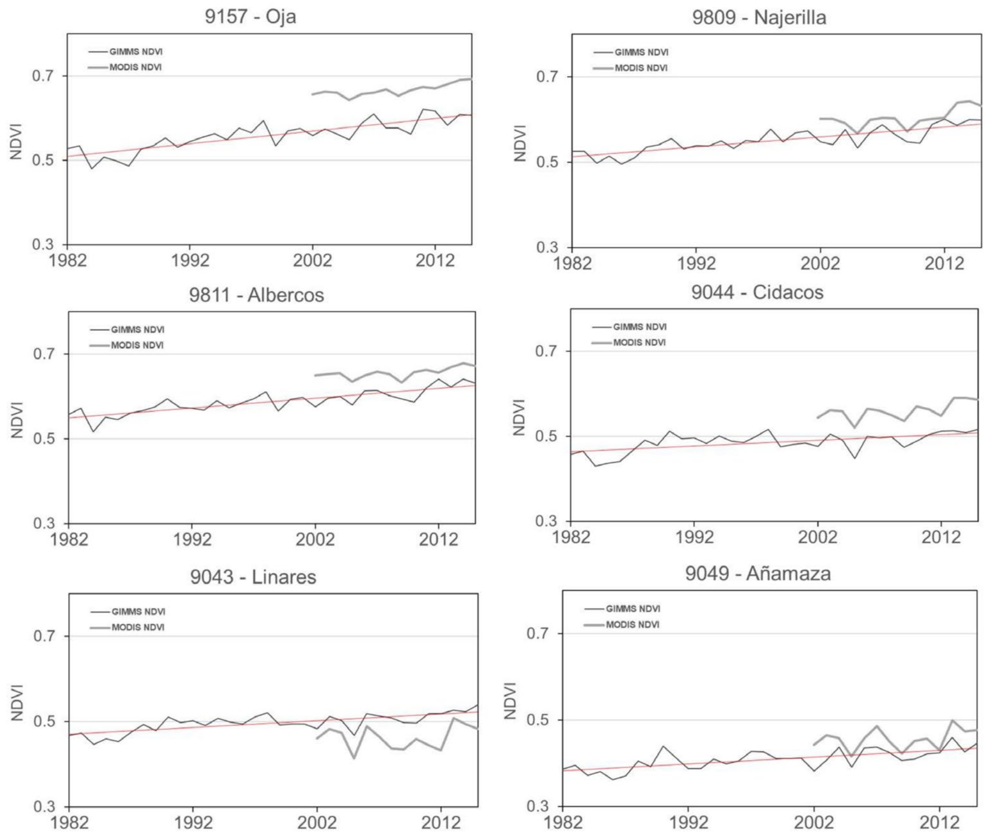

FIGURE 8 | Annual NDVI of the studied catchments between 1982 and 2015 (GIMMS) and between 2001 and 2015 (MODIS). Red line depicts the linear trend slope of the GIMMS annual series.

study period. The highest GIMMS NDVI trend is observed in the Oja catchment with a value of 0.098, indicating a larger greening trend, whereas the lowest trend is in the Cidacos catchment with 0.048. The MODIS NDVI data, covering a shorter and more recent period (2001–2015), show a similar pattern of positive trends, with annual averages ranging from 0.565 (Añamaza) to 0.651 (Albercos) and trends ranging from 0.046 (Najerilla) to 0.011 (Linares). The MODIS trends are lower overall compared to the GIMMS dataset and may indicate that the greening process was more intense at the beginning of the study period.

Figure 8 presents the annual NDVI values for the six studied catchments between 1982 and 2015 using the GIMMS dataset (black lines) and between 2001 and 2015 using the MODIS dataset (grey lines). In most catchments, there is a clear positive trend in NDVI over time, indicating an increase in vegetation activity. The Atlantic-type (Oja, Najerilla and Albercos) catchments exhibit a consistent increase in both GIMMS and MODIS NDVI values, reflecting a long-term greening trend, which aligns with the observed expansion of shrubs and forests in these catchments. In contrast, the Mediterranean (Cidacos, Linares and Añamaza) catchments show more stable or slightly fluctuating NDVI values over the period. Although there is a slight upward trend in the GIMMS data, it is less pronounced than in the Atlantic catchments. This is because, in these catchments, the vegetation expansion has been more

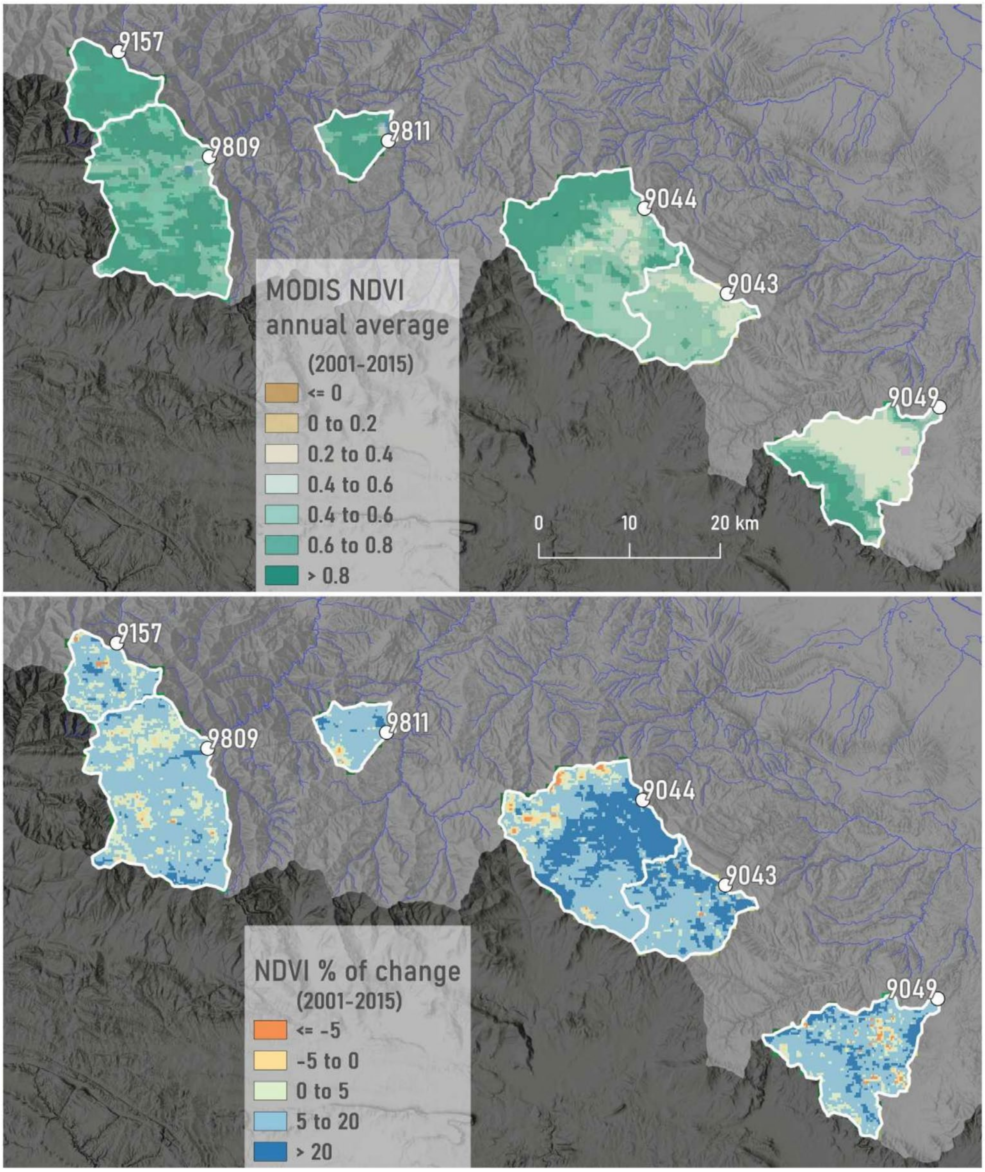

FIGURE 9 | Upper panel: Spatial distribution of averaged MODIS NDVI values for the period 2001–2015. Lower panel: NDVI change (%) for the period 2001–2015.

limited and has been accompanied by an increase of crops and pastures.

Figure 9 displays the spatialised distribution of changes in MODIS NDVI values for the study period between 2001 and 2015. The upper panel shows the average NDVI values across the six catchments during this period. Catchments exhibit a range of NDVI values, with the Atlantic catchments (Oja and Najerilla) showing relatively high NDVI values (0.6–0.8), indicating dense vegetation cover, likely corresponding to forested areas (oaks and pines). In contrast, the Mediterranean catchments (Cidacos, Linares and Añamaza) exhibit lower NDVI values, ranging between 0.4 and 0.6, consistent with less dense vegetation, such as shrubs and pastures. Figure 9, lower panel, illustrates the percentage change in NDVI between 2001 and 2015, highlighting areas with significant changes in vegetation cover. Most of the areas across all catchments show an increase in NDVI values, particularly in the Atlantic ones (Oja and Najerilla), where large areas display a 5%–20% increase in NDVI, suggesting enhanced vegetation growth, likely due to afforestation and natural vegetation recovery and densification. Some areas within the Mediterranean catchments (e.g., Cidacos and Linares) also show notable increases in NDVI, albeit less widespread than in the Atlantic catchments. In contrast, small areas, especially in the Najerilla and Cidacos catchments, exhibit slight decreases in NDVI (up to −5%), potentially reflecting localised land use changes or environmental stressors, such as wildfires.

5 | Discussion

5.1 | Hydro-Climatic Trends

River discharge trends observed in this study underscore the importance of considering both spatial and seasonal variability in hydrological studies. Our results highlight the complex interplay between climate change and regional hydrology, emphasising the need for targeted water resource management strategies that account for these intricacies. The significant trends, particularly the pronounced seasonal decreases in river discharges in some catchments, point to potential challenges in water availability and ecosystem sustainability under changing climatic conditions. Although the trend test only identified the annual trend in Cidacos as significant, Figure 2 shows that the declines in annual discharges have been important across all catchments. In the case of the Atlantic catchments, they have lost approximately 37% (Oja), 25% (Najerilla) and 27% of the mean annual discharge over the last 50 years. In the Mediterranean catchments, the decrease in annual contributions is even greater: a 45% reduction in Cidacos, 40% in Linares and 20% in Añamaza. Despite the interannual variability, results of the trend analysis suggest an overarching decline in flow rates across several catchments, consistent with the expected impacts of increased temperatures and decreased precipitation in the context of regional climate change. This decline is corroborated by the significant percentage decrease observed in prior studies and is symptomatic of the heightened vulnerability of Mediterranean catchments to hydrological alterations. These results are in line with those obtained in previous studies, which highlighted a generalised decline in river discharges in the Iberian Peninsula, both in rivers regulated by reservoirs and in naturalised headwater catchments (Lorenzo-Lacruz et al. 2012).

The results of the precipitation trend analysis show a significant contrast between the Atlantic and Mediterranean catchments (Table 3). On an annual scale, significant trends have only been observed in Albercos and Añamaza. However, there is a particular pattern in spring and summer seasons in which all the Atlantic catchments (Oja, Najerilla and Albercos) experience significant negative trends. These trends are critical, as they coincide with periods of higher temperatures and, therefore, greater water losses due to the high evaporative demand of the atmosphere, which could cause flash drought episodes (Vicente-Serrano et al. 2020; Noguera et al. 2021). Conversely, the trends during autumn are positive (although not significant) in all cases, which could be caused by the increase in temperature of the Mediterranean Sea and the rise in phenomena of isolated high-level depressions (cut-off lows) associated with the circulation of the jet stream (Romero et al. 1999). The results of the precipitation trends are consistent with those obtained in previous studies conducted in broader spatial contexts (González-Hidalgo et al. 2011).

Hydroclimatic trends revealed in this study are consistent with existing literature, suggesting a broader regional recent trend (taking the decade of 1960 as baseline) of decreasing precipitation, although being subject to high temporal variability if longer periods are considered (Vicente-Serrano et al. 2025b). These results have potential implications for water resource planning and climate change adaptation strategies. However, the attribution of the negative discharge trends to pluviometric decrease is not clear or unequivocal. The significant negative precipitation trends in spring and summer in the Atlantic catchments have not had a direct translation into river discharge trends (which are non-significant except in Albercos), and the decrease in discharges in Cidacos and Linares cannot be attributed to a decline in precipitation, since the latter trends are non-significant. This could suggest that other factors, such as temperature or consumption by increasing vegetation, also contribute to explaining the dynamics of river discharges (Beguería et al. 2003; Morán-Tejeda et al. 2012). The generalised upward precipitation trends found during autumn could potentially offset some of the seasonal deficits, albeit not significantly, and may be indicative of changing climatic patterns, such as the late-year intensification of rainfall events possibly linked to broader atmospheric changes (Romero et al. 1999).

Considering temperatures, if the 1990s or the first decade of the 2000s were identified as particularly warm periods across multiple catchments, this could reflect broader regional warming patterns that have been noted in climate data worldwide. These periods coincided with known climatic events, such as El Niño phases, which are typically associated with higher temperatures and drought episodes in many parts of the world (Vicente-Serrano et al. 2011). Specific years, such as 1995, 2003 or 2015, showed spikes in temperature, these representing anomalous years where factors such as heatwaves or particular atmospheric circulation patterns contributed to higher temperatures. For example, the European heatwave of 2003 is a well-documented event that led to significantly higher temperatures and is clearly reflected in climate datasets across the continent (Fink et al. 2004). Moreover, several studies highlighted increasing trends in spring and summer temperatures across the Mediterranean basin (inland and sea) (Hertig et al. 2010; Pastor et al. 2020) and more specifically, in Spain (Brunet et al. 2007).

The hydrological consequences of increasing temperature trends are highly relevant, as they are substantially enhancing water loss due to evaporation from water bodies (Lorenzo-Lacruz et al. 2025), as well as the evapotranspiration from vegetation, whereas also markedly reducing soil moisture. During spring, warming has been more pronounced in the Atlantic catchments, which receive greater snowfall contributions. This could be altering the timing of snowmelt peaks in this area, advancing them to early spring or late winter, favouring the observed increase in river discharges during winter (Morán-Tejeda et al. 2014, 2019). The uniformity of the warming trend, especially the pronounced summer increases (Table 4), suggests a strong regional response to broader climate change influences.

These findings provide clear evidence of the westward expansion of Mediterranean climatic characteristics into the Atlantic domain, as demonstrated by the pronounced decrease in spring precipitation (leading to lower river discharges) and the concurrent increase in autumn precipitation in the Atlantic catchments (Acero et al. 2012; Serrano-Notivoli et al. 2017a, 2017b; Senent-Aparicio et al. 2023). Simultaneously, the eastern catchments exhibit a strengthening of Mediterranean conditions, reflected by higher autumn rainfall—likely associated with isolated upper-level depressions (Paredes et al. 2006; Gonzalez-Hidalgo et al. 2023)—and increased spring and summer temperatures (Gonzalez-Hidalgo et al. 2015), which together contribute to reduced river discharges during these seasons.

These findings are critical as they point to potential impacts on catchment hydrology, including alterations in evapotranspiration rates, shifts in seasonal water availability and potential stress on aquatic ecosystems. Moreover, the data can inform climate adaptation strategies for water resource management, agricultural planning and conservation efforts in the region.

5.2 | Hydro-Climatic Interactions

Analysis of the hydrological response to precipitation variability (accumulated over 1–48-month timescales) reveals a pronounced differentiation between Atlantic and Mediterranean catchments. In Atlantic catchments, the steep terrain favours relatively fast runoff processes (López-Moreno et al. 2013; Lorenzo-Lacruz et al. 2013). Moreover, wetter conditions favour that catchment water reserves are reached easier and subsequent runoff generation may occur relatively quickly (Latron and Gallart 2008; Penna et al. 2013). The moderate correlation obtained would indicate the existence of a disruptive factor between climatic and hydrological variability, most likely related to the consumptive role of vegetation (predominantly well developed and consolidated forests in these Atlantic catchments). In the case of the Mediterranean catchments, the hydrological response occurs in a more sustained way and over longer temporal scales ($r \sim 0.55$ at 6 months), which would indicate, on the one hand, a more tended catchments physiography, with gentler slopes that would slow down runoff processes and ease infiltration and aquifer recharge (Lorenzo-Lacruz et al. 2017); on the other hand, it would highlight the role played in these environments by dried soils, which while recharging with moisture and infiltrating water, prevent the short-term activation of the precipitation-discharge relationship ($r < 0.3$ between the SSI and SPI at the 1-month scale) (Orth and Destouni 2018). In a similar way would act a lithology with higher water-holding capacity (Nickolas et al. 2017); and finally, Mediterranean catchments show a closer relationship between precipitation and discharge (higher maximum SSI-SPI correlations compared to the Atlantic catchments), due to the lower vegetation cover and density in these catchments (López-Moreno et al. 2013; Lorenzo-Lacruz et al. 2013). Furthermore, analysis of monthly SSI-SPI correlations revealed that hydrological response to climate variability is strong during wet conditions (winter) (max. Pearson $r \sim 0.7$) and it is almost null during dry conditions (summer) (Figure 5). In the context of warming, these findings underscore how enhanced atmospheric evaporative demand—driving vegetation evapotranspiration (Vicente-Serrano et al. 2019), open water evaporation from water bodies (Lorenzo-Lacruz et al. 2025) and dry soils wetting-saturation processes—can increasingly alter hydro-climatic interactions during the dry season.

5.3 | Changes in Land Use and Vegetation Activity

Land use and land cover changes occurred in the studied catchments have been observed in other mountain catchments in the Mediterranean region (García-Ruiz and Lana-Renault 2011; Lana-Renault et al. 2020), where the abandonment of pastures and farmland has led to a revegetation process. Overall, our study demonstrates a general trend of vegetation growth across the region, with some areas undergoing significant greening, particularly in the more forested Atlantic catchments, where land abandonments started earlier. Revegetation in the Mediterranean catchments has been more limited, since the lower altitude and the existence of wide valley bottoms have allowed for the maintenance of agricultural activity. Therefore, forests still account for less than 50% of the catchment surface.

The increase in vegetation cover in headwater catchments has profound implications for the relationship between precipitation and river discharge as vegetation, particularly forests, enhances evapotranspiration rates, reducing the amount of water that reaches streams and rivers (Gallart and Llorens 2004; Lana-Renault et al. 2018; Khorchani et al. 2021; Vicente-Serrano et al. 2025a). In the studied catchments, an overall decline in annual river discharges has been observed, which can be partly attributed to increased vegetation activity. However, no significant statistical relationship was found between the decline in discharge and trends in precipitation, temperature, or vegetation. Several factors may explain this result: (i) the decline in discharge is not statistically significant, (ii) the number of study cases is low and (iii) changes in vegetation cover have not been large enough to generate a meaningful impact on river discharges. Indeed, in all the studied catchments, the increase in forest cover during the study period remained below 10% of the catchment area—except at Albercos, where it reached +17%—which is relatively low compared to other areas in the Iberian Peninsula (Vicente-Serrano et al. 2019; Peña-Angulo et al. 2021). Sparse negative NDVI trends observed (Figure 9) may be partially attributed to wildfires. For example, between 15 and 18 August 1986, a forest fire occurred in the upper Najerilla river valley, affecting more than 1000 ha. Small holm oak groves, oak stands and scrubland were completely burned (García-Ruiz et al. 2013).

One factor behind the smaller-than-expected change in vegetation cover is the challenge of measuring plant activity in non-forest communities, which represent more than 50% of the surface of the studied catchment (except in Albercos). For example, annual NDVI values from MODIS are generally higher than those from GIMMS, except in Linares, largely due to the MODIS sensor's higher spectral resolution compared to GIMMS's AVHRR (Liu et al. 2022). This discrepancy also reflects the Maximum Value Compositing (MVC) technique (Holben 1986), which removes noise and reconstructs missing pixels (Julien and Sobrino 2019; Li et al. 2021). Although both NDVI databases employ MVC (Huete et al. 2002; Pinzon and Tucker 2014), GIMMS exhibits more noise because it integrates images from multiple satellites dating back to 1982. Another consideration is the higher NDVI of trees compared to shrubs and herbaceous plants (Senay and Elliott 2000; Pettorelli 2013). Some studies indicate that satellites may underestimate NDVI in mountainous or pasture areas, leading to underestimation of alpine vegetation and its phenological trends (Liu et al. 2018, 2022; Wang et al. 2021).

Nevertheless, some interesting findings can be withdrawn from this analysis that shows that the hydrological consequences of increased vegetation vary markedly between Atlantic and Mediterranean catchments due to differences in climate, soil and topography. In Atlantic catchments, which receive more consistent precipitation, a greater increase in vegetation (NDVI annual trend > +0.077 and forest cover increase > 9%) reduces river discharge (< 37%); yet the trend is not statistically significant. These catchments typically feature higher soil moisture retention and more resilient hydrological regimes—resistant to environmental perturbations—potentially buffering them from the impacts of increased evapotranspiration. In contrast, in the Mediterranean catchments, with a lower increase in vegetation cover and activity (NDVI trend < 0.058 and forest cover increase $< 6\%$), discharges have decreased in some cases dramatically (up to 45% decrease). This can be associated with a higher increase in temperatures in these catchments and to the fact that Mediterranean catchments are much more sensitive to changes in land cover (Peña-Angulo et al. 2021). The combination of higher atmospheric evaporative demand and low precipitation leads to a steeper reduction in water availability, particularly during the dry summer months (Vicente-Serrano et al. 2020). This is evident in the Cidacos and Linares catchments, where the reduction in river discharge is not only more pronounced but also extends across multiple seasons, highlighting the vulnerability of Mediterranean catchments to both climate and land-use changes. These trends suggest that as vegetation expands, the precipitation-discharge relationship becomes weaker, particularly in drier seasons, when much of the precipitation is used to fulfil soil moisture or lost through evapotranspiration before contributing to river discharge. In Atlantic catchments, whereas discharge reductions are also observed, the effect is less pronounced, likely due to higher overall precipitation and a less intense evaporative demand, which mitigates the impact of increased vegetation on river discharge. Extensive evidence shows that vegetation expansion enhances evaporative losses and systematically reduces streamflow. A synthesis of 94 paired-catchment experiments reported average reductions of 25–40 mm year^{-1} in runoff for every 10% increase in forest cover (Bosch and Hewlett 1982). Globally, Farley et al. (2005) found that afforesting grass- and shrublands decreases annual water yield by 31%–44%, with proportionally larger declines in seasonally dry regions. At the continental scale, modelling by Teuling et al. (2019) attributes an additional 35–60 $\text{km}^3\,\text{year}^{-1}$ of evapotranspiration (and widespread low-flow declines across southern Europe) to recent reforestation and forest ageing. Analyses of Spanish headwater basins show that vegetation greening intensifies hydrological droughts beyond what can be explained by climate alone (Peña-Angulo et al. 2021). Long-term monitoring in Spanish headwaters corroborates this pattern: spontaneous forest regrowth in the Vallcebre catchments raised actual evapotranspiration by ≈100 mm year^{-1} and drove marked streamflow reductions (Gallart et al. 2002). Reduction in river discharge due to revegetation has also been associated with an increase in interception rates. Research carried out at the small experimental catchment scale in the Iberian Peninsula has demonstrated the role of forest interception in the catchment hydrological dynamics. Observations by García-Ruiz et al. (2008) in small catchments with different vegetation covers in the Spanish Pyrenees have related the lower river discharge values under forest to the higher interception rates of trees (up to 27% of the rainfall in the case of *Fagus sylvatica*). Similarly, in a small catchment in the Sistema Central Range, Martínez-Fernández et al. (Martínez Fernández et al. 2013) associated the catchment's low capacity for runoff generation with interception by *Q. pyrenaica* (12% in winter and 18% in summer, Morán-Tejeda et al. 2013). More recently, in the Vallcebre catchments, Eastern Pyrenees, Molina et al. (2019) found a strong linear relationship between soil moisture content and throughfall amount for both *Pinus sylvestris* and *Q. pubescens*, illustrating the clear role of forests in decreasing the rainfall amount reaching the ground.

A clear trend of Mediterranean climatic characteristics extending westward into the Atlantic region was observed. This is evidenced by a marked decrease in spring precipitation—which leads to lower river discharges—and an increase in autumn precipitation in Atlantic catchments (Acero et al. 2012; Serrano-Notivoli et al. 2017a, 2017b; Senent-Aparicio et al. 2023). Moreover, a strengthening of Mediterranean climatic conditions is apparent in the eastern catchments: autumn precipitation increases (Paredes et al. 2006; Gonzalez-Hidalgo et al. 2023) while spring and summer temperatures also rise (Gonzalez-Hidalgo et al. 2015). As a result, river discharges decrease during these two seasons. Although acknowledging that vegetation expansion modifies water availability in catchments by increasing consumption and evapotranspiration, the data analysed (perhaps because the study period is still relatively short) do not conclusively demonstrate a clear relationship between these factors.

6 | Conclusion

This study revealed significant hydrological and climatic variability within a transitional gradient of just 100 km, underscoring the necessity of conducting detailed catchment-scale investigations. Increases in vegetation cover, rising temperature trends and a decline in precipitation are identified as key drivers behind the observed reductions in river discharge. However, this negative trend has yet to reach statistical significance in most of the analysed catchments.

This study highlights the imperative to reconsider water resource management from an integrated perspective—taking into account land-use changes in headwater areas—in order to achieve a sustainable balance between the future (and decreasing) availability of water resources and the growing demand.

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Data Availability Statement

The data supporting the findings of this study can be accessed at: Data on 'Hydrological Effects of the Westward Expansion of Mediterranean Climate and Revegetation in Atlantic–Mediterranean Transitional Headwaters' by Lorenzo-Lacruz et al. at https://zenodo.org/records/14761212, reference number 10.5281/zenodo.14761212.

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