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The role of forest maturity in extreme hydrological events

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Abstract

This study aims to clarify the influence of forests, as well as other prevalent land cover types, on extreme hydrological events through a land cover gradient design. We selected 10 catchments within a gradient of forest land cover, in which there were 15 years of simultaneous daily hydrological and meteorological data, and an additional forest descriptor, forest maturity. The study was developed in a heterogeneous region in the Cantabrian Mountains (NW Spain). This area includes different vegetation types and has a long history of human disturbance and land use change that has produced a gradient in forest cover. This study focuses on regular hydrological extremes: regular floods and low flow events. Specific objectives were to observe the relationship between land cover and extreme hydrological events, once the variance explained by precipitation was removed, and compare the effectiveness of forest coverage and maturity to predict them. Partial correlations and ordinary least square regressions were developed using hydrological indices, obtained from flow records, and hydrological parameters calculated through modelling, using the Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data (IHACRES) software and hydrometeorological data. Land cover characteristics were better able to predict floods than low flows. Forests were associated with less extreme flow events (lower intensity and frequency of floods and greater base flows), whereas shrub formations did the opposite. These results were more evident using forest maturity than using forest coverage. This study indicates that hydrological modelling may benefit in the future from considering not only the coverage of different land cover types but also the conservation status of the different vegetation formations.

KEYWORDS

Cantabrian Mountains, catchment hydrology, IHACRES, land cover, maturity, native forests

1 | INTRODUCTION

Flood and low flow events represent a demonstration of extreme hydrologic variability, constituting a primary driver of stream biological communities and ecosystem functioning (Lake, 2000; Resh et al., 1988). Such events may cause greater impacts in river ecosystems than changes in flow means averaged over years (Woodward et al., 2016). The magnitude and frequency of high and low flows regulate numerous ecological processes (Poff et al., 1997), which may influence the goods and services that they provide to humans. High flows provide ecological benefits by maintaining ecosystem productivity and diversity. For example, high flows remove and transport fine sediments that would otherwise fill the interstitial spaces in productive gravel habitats (Beschta & Jackson, 1979). Flows of low magnitude also provide ecological benefits. Periods of low flow may present recruitment opportunities for riparian plant species in regions where floodplains are frequently inundated (Wharton et al., 1981). The frequency, intensity and duration of extremes is expected to increase due to climate change (Intergovernmental Panel on Climate Change, 2012). However, land use changes, which are mostly induced by human activities, also affect hydrological processes, such as water interception, resulting in alterations of surface and subsurface flows (Niraula, Meixner, & Norman, 2015; Wang, Kalin, Kuang, & Tian, 2014). Changes in the land cover mosaic may attenuate or exacerbate the hydrological effects of climate change on riverine communities and ecosystems, as climatic disturbances coupled with increasing anthropogenic disturbances can cause significant impacts on hydrological processes and aquatic functions (sensu Zhang, Wei, & Li, 2016). In this context, the stated surface and subsurface flows may be estimated using “quick” and “slow” flows, respectively, to study such hydrological processes based on water interception. “Slow” involves volumes with a high time of concentration (e.g., base flows), which is the time that water takes to flow from the most remote point in a catchment to its outlet. “Quick” is associated with a low time of concentration. Croke, Merritt, and Jakeman (2004) based their study on an analogous reasoning, though the authors stated that more work was required to improve the links among these components.

Recent studies show increasing trends in forest area in Europe over the past few decades (Spiecker, Mielikäinen, Köhl, & Skovsgaard, 2012). Socioeconomic adjustments, such as those linked to the EU Common Agricultural Policy, have led to an important rural exodus and the subsequent abandonment of agricultural land, a cessation of coppicing and a reduction in grazing in natural communities (e.g., Benayas, Martins, Nicolau, & Schluz, 2007). Today, forests cover nearly 40% of the European surface (European Commission, 2015). Trees have greater water requirements than other vegetation types, as they intercept more precipitation and present greater transpiration rates (e.g., Bosch & Hewlett, 1982). Thus, their expected effect on river flows is a general reduction when forests spread, grow and mature (Johnson, 1998).

The development of “paired-catchment” experimental designs has aimed to clarify forest influence on the water cycle (Hewlett, 1971; Hewlett, 1982; Cosandey, 1995). These studies are generally based on selecting two similar and geographically close catchments, subjected to the same climatic regime, and assuming that different hydrologic responses will be driven by differences in forest extent. The review of paired-catchment studies in temperate zones developed by Bosch and Hewlett (1982) indicated that the effect of forest expansion is a decrease in water yield. Since then, additional paired catchment studies have been reported in the literature (Brown, Zhang, McMahon, Western, & Vertessy, 2005; Hornbeck, Adams, Corbett, Verry, & Lynch, 1993; Li et al., 2017; Stednick, 1996; Vertessy, 1999; Vertessy, 2000). Such studies have evidenced the ability of disturbances on forests to alter low and, especially, high flows (increasing the magnitude and duration of peak flows; Zhang et al., 2016). However, further catchment scale research is necessary to advance our understanding of forest impact on hydrology, particularly studies focused on large basins (>10 km^2), with additional descriptors of forest characteristics (besides area) and more than two observed catchments (Andreassian, 2004). In their review, Zhang et al. (2017) indicated that forest coverage “merely serves as a basic indicator without differentiating forest species, stand age and structure, growth potential, and disturbance types”, indicating that “a suitable forest change indicator should not only express forest cover change (…) but also account for forest characteristics.” More complete studies that clarify the relationship between forests and hydrological processes may allow for the improvement of the design of strategies (i.e., implementation of green infrastructures) for the adaptation to the effects of climate change on catchment hydrology (e.g., Community Forests Northwest, 2010).

Forest maturity, defined as the degree of development of forest vegetation (in a conceptual gradient that goes from preforest to young forest, then forest and finally mature forest), may be an important factor to determine forest–river flow relationships, as the long process of native forest formation involves many steps that increase water retention (Fisher & Eastburn, 1974; Fisher & Stone, 1969). Tree roots grow into fissures and aid in the breakdown of bedrock, penetrating compacted soil layers and allowing soil aeration and water infiltration. A vegetative ground cover modifies the temperature and moisture conditions below, and the subsequent increase in organic matter on the top soil horizons has the potential to influence runoff patterns (Fisher & Eastburn, 1974; Fisher & Stone, 1969). Given the interaction of these processes with the hydrological cycle, the use of maturity as a descriptor of forest characteristics in empirical catchment-scale designs may improve our understanding of forests' influence on river ecosystems.

The aim of this study was to improve the understanding of how forests and other predominant land cover types influence the occurrence of recurrent floods and low flows using a land cover gradient design. To achieve this, we used 10 large catchments (between 30 and 650 km^2) in the Cantabrian Mountains (NW Spain) with a gradient of forest cover resulting from human management since the 15th century. Such a forest cover gradient is very difficult to find within similar climatic conditions, especially with 15 contemporary years of gauge records and meteorological data in such a relatively high number of catchments (compared with the two typically used in paired-catchment studies). Thus, this study aimed to provide empirical evidence without modelling the underlying biophysical processes. We defined forest cover not only through forest coverage but also using forest maturity. Our specific objectives were (a) to observe the relationship between land cover and extreme hydrological events once the variance explained by precipitation was removed and (b) to compare the effectiveness of forest coverage and maturity, as well as other predominant land cover types, to predict such extremes. We expected mature forests to smooth hydrological extremes caused by precipitation regimes through water interception (aided by ground vegetation and organic soils), in opposition to young forest formations or other land cover types. Thus, forest maturity was expected to be negatively associated with the intensity and frequency of floods (and with quick flows, used to represent the proportion of surface flows) and positively related to base flows (and slow flows, used to represent the proportion of subsurface flows) better than forest coverage.

2 | MATERIAL AND METHODS

2.1 | Study area

This study was developed in the Cantabrian Mountains, which extend for more than 300 km across northern Spain, nearly parallel to the Cantabrian Sea. This mountain range constitutes a distinct province of the larger Alpine System physiographic division. Glaciers and fluvial erosion are the two main processes that have shaped their relief, composed mainly of sedimentary materials such as limestone and conglomerates. These mountains present an Atlantic climate with annual precipitation and temperature around 1.160 mm and 9,5 °C, respectively. Areas located at lower latitudes show sub-Mediterranean characteristics, with higher temperatures and summer low flows (Ninyerola, Pons, & Roure, 2007). This environmental heterogeneity shelters a mix of tree species including beeches (*Fagus sylvatica*), birches (*Betula ssp*.) and different species of oaks (*Quercus petraea*, *Q. robur*, *Q. pyrenaica* and *Q. rotundifolia*), in a transition from the Atlantic to the sub-Mediterranean areas. Shrub vegetation spans a similar gradient, varying from semiarid communities mixed with annual grasslands and crops in the southeast to shrubs and young forests in the north and west, with alpine vegetation and bare rock at higher elevations and slopes.

A set of 10 catchments (Figure 1; Table 1a) was selected to represent a land cover (particularly, forest) gradient within a climatically similar region. A previous screening process ensured that the catchments presented similar soil properties and climatic regimes, as well as suitable flow data. Their land cover gradient characterizes the legacy of human management and land use practices for the last 400 years. After the foundation of the "Real Fábrica de Artillería de la Cavada" (in English, the Royal Artillery Factory in La Cavada) in 1616, the native forests in the eastern extreme were intensively exploited for more than 200 years in order to obtain wood for naval construction. Since then, this area has been kept deforested for stockbreeding through the combined use of fire and cattle grazing. Consequently, the eastern part of the study area is dominated by a mixture of shrubs with a predominance of dry heathland communities and extensive pastureland. Only some isolated patches of forest remain on steep hillslopes. In contrast, the western catchments have not experienced relevant deforestation processes and present mature forest patches. The presence of brown bear (*Ursus arctos*) and Cantabrian capercaillie (*Tetrao urogallus cantabricus*) in these catchments, unlike the eastern extreme (Blanco-Fontao, Obeso, Banuelos, & Quevedo, 2012; Gonzalez et al., 2016), is evidence of a better state of conservation. This history of contrasting landscape use in nearby catchments with a similar climate and the existence of contemporary flow gauges and meteorological stations across them make our study area a unique setting for our land cover gradient design.

2.2 | Land cover characteristics

Land cover information was obtained through remote sensing imagery. A suitable Landsat TM image of the study area taken in 2010, with a minimum cloud cover and a relatively high sun elevation angle, was downloaded from the United States Geological Survey. This year was selected due to the availability of suitable hydrometeorological records (see details in Section 2.4). Landsat images present a scale of 1:20.000, suitable to monitor regional land cover in sensitive areas for local management (European Environment Agency, 1995). This allowed the mapping of our study area at a resolution of 30 m. The image was radiometrically and atmospherically corrected using the algorithms available in the Geographic Resources Analysis Support System or GRASS (GRASS Development Team, 2015). A complementary digital elevation model was obtained from Laser Imaging Detection and Ranging (LIDAR) data (Centro Nacional de Información Geográfica, 2014) and resampled to 30 m to match the spatial resolution of the image.

Two classifications of the study area were developed to obtain land cover types and forest maturity in each catchment. First, a per-pixel classification was made using a maximum likelihood (ML) algorithm over a combination of spectral information and topographic layers derived from the 30-m digital elevation model. ML (Conese & Maselli, 1992; Schowengerdt, 1983; Strahler, 1980) is the most widely used algorithm for classifying medium-resolution satellite images because of its easy implementation in many software packages and the satisfactory results provided (Alvarez-Martinez, Stoorvogel, Suarez-Seoane, & Calabuig, 2010; de Carvalho, Clevers, Skidmore, & de Jong, 2004). The ML algorithm assigned pixels to the land cover class with maximum membership probability, although they may have an almost equal probability of membership to another class (Lewis, Brown, & Tatnall, 2000), generating a "hard" classification. Testing points were used to construct confusion matrices (Congalton, 1991), using standard accuracy assessment methods (Stehman & Czaplewski, 1998), to detect misclassification errors. Land cover types with a coverage, averaged among catchments, lower than 10% were discarded for subsequent analyses due to their low occurrence at the catchment scale (forest plantation, agricultural, denuded rock and urban). The relative coverage occupied by the other (prevalent) land cover types in each catchment (forest, shrubs and pasture land) was obtained through the proportion of pixels belonging to each class according to the ML algorithm. Each coverage (forest, shrubs and pasture land) was defined as the area occupied by the corresponding patch according to this first (hard) classification. Second, a fuzzy k-means classification yielded

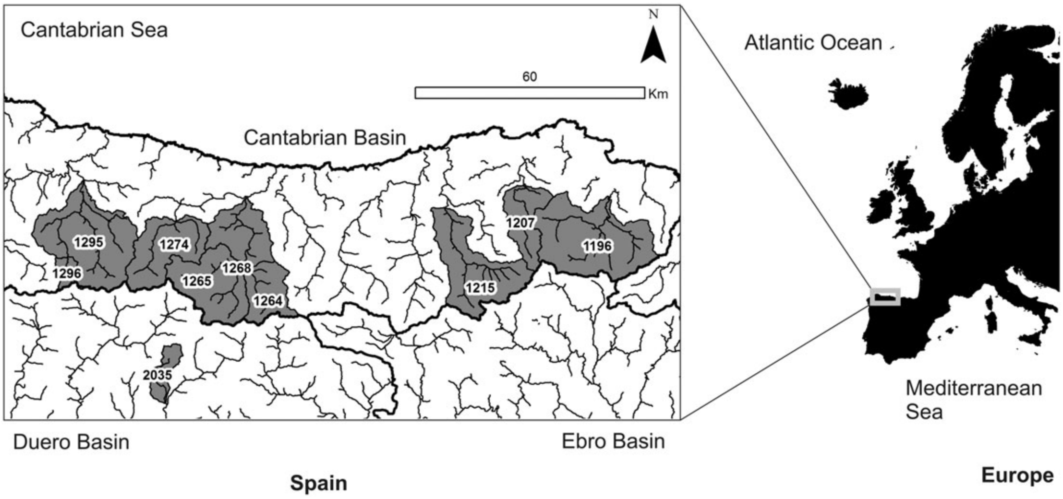

FIGURE 1 Catchments with hydrological records in the study area of the Cantabrian Mountains

TABLE 1 Topographic and hydrologic (a) and land cover (b) characteristics, together with the estimated change in land coverages (c) of the selected catchments in the Cantabrian Mountains ordered from west (top) to east (bottom). Gauge codes and main river names are provided in the first column

(a)	Topographic and hydrologic characteristics					
Code (name)	Area (km^2)	Altitude (m)	Slope (%)	Mean runoff (mm)	Mean flow (m^3/s)	Mean daily precipitation (mm)
1296 (Ponga)	34	1.277	29	16	2	4
1295 (Sella)	480	1.005	29	13	18	4
1274 (Cares)	266	1.454	31	9	8	5
2035 (Besandino)	70	1.498	19	5	1	3
1265 (Deva—O.)	296	1.185	26	5	4	4
1268 (Deva—P.)	648	1.029	27	6	15	4
1264 (Bullón)	156	972	25	4	2	3
1215 (Pas)	358	599	19	8	9	3
1207 (Miera)	161	563	21	9	5	4
1196 (Asón)	492	558	20	13	22	3

(b)	Land cover (1995–2010) characteristics (%)			
Code (name)	Forest coverage	Forest maturity	Shrub coverage	Pasture coverage
1296 (Ponga)	57	82	37	3
1295 (Sella)	36	75	45	7
1274 (Cares)	13	72	31	9
2035 (Besandino)	6	52	43	22
1265 (Deva—O.)	33	77	38	14
1268 (Deva—P.)	33	75	40	13
1264 (Bullón)	49	78	35	12
1215 (Pas)	29	55	60	8
1207 (Miera)	20	48	63	11
1196 (Asón)	29	62	49	14

(c)	1995–2010) variation (%)			Annual variation (%)		
Code (name)	Forest	Shrubs	Pasture	Forest	Shrubs	Pasture
1296 (Ponga)	10,43	−7,68	−0,42	0,70	−0,51	−0,03
1295 (Sella)	9,71	−6,10	−1,32	0,65	−0,41	−0,09
1274 (Cares)	3,81	1,01	−1,04	0,25	0,07	−0,07
2035 (Besandino)	1,74	3,93	−8,94	0,12	0,26	−0,60
1265 (Deva—O.)	11,00	−4,64	−5,00	0,73	−0,31	−0,33
1268 (Deva—P.)	10,38	−4,21	−4,18	0,69	−0,28	−0,28
1264 (Bullón)	14,21	−9,45	−4,00	0,95	−0,63	−0,27
1215 (Pas)	7,13	−6,18	−0,86	0,48	−0,41	−0,06
1207 (Miera)	3,88	1,10	−3,93	0,26	0,07	−0,26
1196 (Asón)	6,95	−4,09	−0,74	0,46	−0,27	−0,05

membership probabilities for each land cover type at the pixel level. Forest maturity, the degree of development of forest vegetation, was estimated using an indirect measure: the probability of forest class membership obtained through the fuzzy classification, calculated as the average per-pixel forest probability in each of the selected catchments. Pixels with a higher probability represent old, dense forest patches that can be interpreted as developed, mature forest (undisturbed). They are not degraded and do not present a mixture of other land cover types (i.e., degradation or fragmentation at the pixel level). The pixels with a high probability of being forest according to the fuzzy classification are assumed to capture the spectral signal of mature and highly structured forests, as they will match those selected as the training dataset of the forest class. For this purpose, the most mature and best-conserved forest pixels were carefully selected for the training dataset of the classification. On the contrary, pixels with a low probability of forest class membership are those belonging to a different land cover type or to forests with a certain degree of heterogeneity at the pixel level due to forest fragmentation (for more details, see Alvarez-Martinez et al., 2010; Alvarez-Martinez et al., 2017).

Given that the development of the classification procedure requires a “training dataset” specific to the Landsat image, the development of multiple classifications belonging to multiple years to ensure the absence of changes in land cover types with time was not an option. However, a Landsat image taken in 1984 from a previous study allowed for the analysis of the variation in land cover types between 1984 and 2010. To obtain the 1984 land cover map, we applied a procedure using the training dataset for the 2010 image. The training dataset was overlaid with aerial photographs from the National Flight of Spain, generated in 1980–1986 (Centro Nacional de Información Geográfica, 2014), and orthorectified with a root mean square error smaller than the pixel size. This dataset consisted of a set of ground control points (GCPs) that were checked against the photos. When they did not match the corresponding land cover class, they were moved to the nearest patch. New points for classifying the 1984 image were then obtained from training areas of 16 pixels created around these ground control points. Overall classification accuracy was estimated to be roughly over 80% using an independent dataset from a second photointerpretation of the aerial images, obtained by excluding buffers of 1 km around training locations. Once the 1984 land cover maps were obtained, a linear rate of change between 1995 and 2010 was estimated dividing the variation in each land cover type by the area of each catchment. This rate was used to calculate the mean coverage of each land cover type in the period in each catchment.

2.3 | Meteorological and hydrological data

Meteorological records were acquired from the Spain02 database (version 4), developed by the "Agencia Estatal de Meteorología" (the State Meteorological Agency) and the "Universidad de Cantabria" (University of Cantabria). The database includes gridded datasets interpolated with rainfall and temperature data from over 2.500 stations in Spain at different resolutions for the period 1971–2007 (Herrera et al., 2012; Herrera, Fernandez, & Gutierrez, 2016). Meteorological series (rainfall and temperature) were obtained by averaging those cells belonging to the grid within each catchment. The resulting rainfall and temperature series were represented using box plots to verify that the catchments in the study area presented reasonably similar climatic regimes. This assumption was statistically tested using Kruskal–Wallis, which allows tests with two or more samples.

Flows recorded by the "Red Oficial de Estaciones de Aforo" (the Official Network of Gauging Stations) were obtained from the "Anuario de Aforos" database available online at the "Centro de Estudios y Experimentación de Obras Públicas" (2016, the Centre for Studies and Experimentation on Public Works). Only the gauging stations located at the outlet of each catchment were considered. Flow records were tested to detect deficiencies (see details in Peñas, Barquin, Snelder, Booker, & Alvarez, 2014). Each flow series was divided by its mean to remove catchment-size effect and allow comparison among catchments (Poff, Olden, Pepin, & Bledsoe, 2006).

Once all data were collected and prepared, we developed the analyses (see text below and Figure 2).

2.4 | Analysis of the effect of precipitation and land use on hydrological regime

Two sets of hydrologic indicators (indices and parameters) were computed to characterize, respectively, regular floods and low flows (hydrological extremes) and water interception caused by ground vegetation and soils, estimated through quick and slow flows. In other words, we used two different and independent analyses to relate hydrological characteristics to land cover descriptors. One is based on the calculation of hydrological indices from data series (15 years) obtained at 10 flow gauges (empirical data). The other is based on the development of independent hydrological models for each of those 10 catchments (process-based data) to estimate quick and slow flows (model parameters) as a proxy for water interception, developed using flow, precipitation and temperature data (details below). In both cases, a total of 10 data points was obtained.

In the empirical approach, three hydrological indices were chosen to summarize extreme hydrological events through flow records: (a) the maximum 3-day mean annual flow (Qmax); (b) the mean number of high flow events per year using an upper threshold of 9 times the median flow over all years (Qh); and (c) the base flow index (BFI, the 7-day minimum flow divided by mean annual daily flow averaged across all years). The latter was used to characterize low-flow conditions, whereas the two others were used to characterize flood regimes (magnitude and frequency), as in

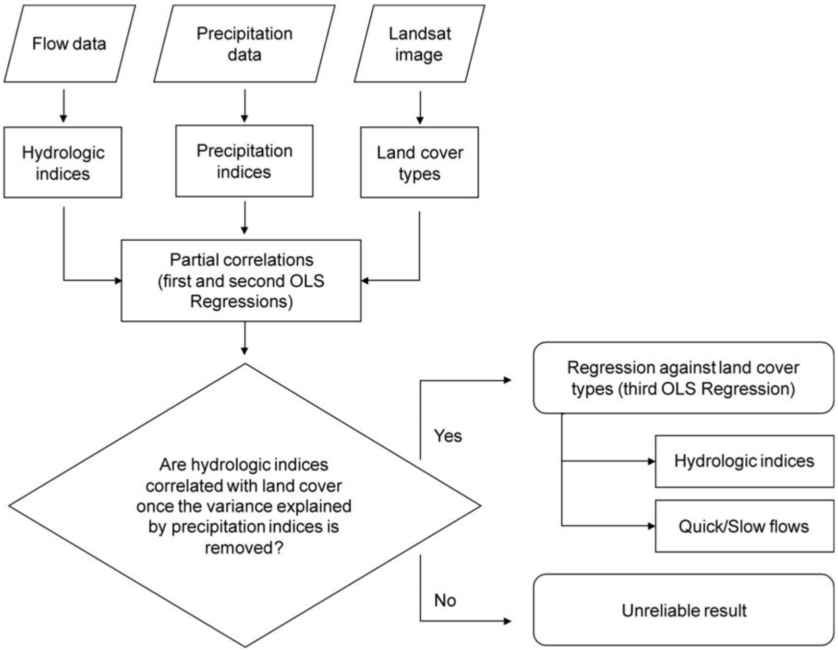

FIGURE 2 Flow chart with a summary of the methods employed in this study. OLS = ordinary least square

previous studies (e.g., Belmar, Velasco., & Martinez-Capel, 2011; Olden & Poff, 2003; Peñas et al., 2014; Richter, Baumgartner, Powell, & Braun, 1996; Snelder et al., 2009). The period selected for computation of hydrologic indices was 1995–2010, to ensure 15 years of records (Kennard, Mackay, Pusey, Olden, & Marsh, 2010) and match the timing of the LANDSAT image taken by the United States Geological Survey. This is not a study period, because the analyses are based on an image taken in 2010, but a set of data with sufficient records to guarantee the accuracy of the indices computed. Such indices were also calculated using contemporary precipitation series, which provided: (a) the maximum 3-day mean annual precipitation (Pmax); (b) the mean number of high precipitation events per year using an upper threshold of 9 times the median precipitation over all years (Ph); and (c) the 7-day minimum precipitation divided by mean annual daily precipitation averaged across all years (P-BFI).

In the process-based approach, we computed 10 independent hydrological models for each of the selected catchments based on a physical model (Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data; IHACRES; Jakeman & Hornberger, 1993) that uses precipitation, temperature (or evapotranspiration) and flow data. This model is composed of a non-linear loss module that converts precipitation to effective precipitation and a linear routing model that converts effective precipitation to streamflow. The non-linear module comprises a storage coefficient (c), a time constant for the rate of drying (tw) of the catchment at a fixed temperature (20 °C) and a factor (f) that modulates for changes in temperature. A configuration of two parallel storages in the linear routing module was implemented using the period with the best data, as they did not present gaps (2000–2007). Kim, Croke, Jakeman, and Chiew (2011) proposed that an 8-year calibration period is appropriate for obtaining a reasonable catchment response, yielding stable and reasonable high model performance and reducing variation in parameter values over time. They used this length in subsequent studies based on the IHACRES rainfall-runoff model (e.g., Kim & Lee, 2014). Using IHACRES, the proportional volumes of quick (υq) and slow (υs) flows were calculated in each catchment to estimate the proportion of surface and subsurface flows (e.g., Croke et al., 2004), which allows an estimation of water interception caused by ground vegetation and soils on the basis that those watersheds with greater water interception will present slower flows. This allows a better understanding of the response observed using hydrological indices.

Partial correlation based on ordinary least square (OLS) regression, previously used in studies on catchment land cover (e.g. King et al., 2005) and hydro-climatic studies (e.g., Burn, 2008; Hornbeck et al., 1993), was employed. Partial correlation was used to estimate the correlation that remains between land cover descriptors and the selected hydrological indices once the variance explained by precipitation indices has been removed. If partial correlation is unable to find relationships between land cover and hydrology, any relationship found between hydrological indices and land cover descriptors must be considered unreliable (as it would be explained by precipitation indices). The three hydrological indices (Qmax, Qh, and BFI) were predicted through OLS regression using the three precipitation indices (Pmax, Ph and P-BFI). Then, by means of a second OLS regression, we explored whether land cover characteristics predicted the hydrological variance not explained by precipitation indices (i.e., the residuals of the first model run).

2.5 | Relationship between hydrologic indicators and land cover descriptors

To contrast the effectiveness of different land cover descriptors to predict recurrent hydrological extremes and water interception, they were used to predict the hydrological indices and parameters through a third OLS regression. Dependent variables were transformed to reduce heteroscedasticity (King et al., 2005), using decimal logarithms for flow indices and the arcsine of the squared root for the hydrological parameters, as they were proportions (McDonald, 2014). All analyses were carried out using the R software (version 3.1.3; R Core Team, 2015) with the base package "stats."

3 | RESULTS

The 10 studied catchments displayed reasonably similar climatic regimes, with only a very subtle gradient from west to east of slightly increasing temperature and decreasing rainfall (Figure 3). The Kruskal–Wallis test showed that there were no statistically significant differences among the 10 catchments, either in terms of temperature or precipitation (*p* value ~ 0).

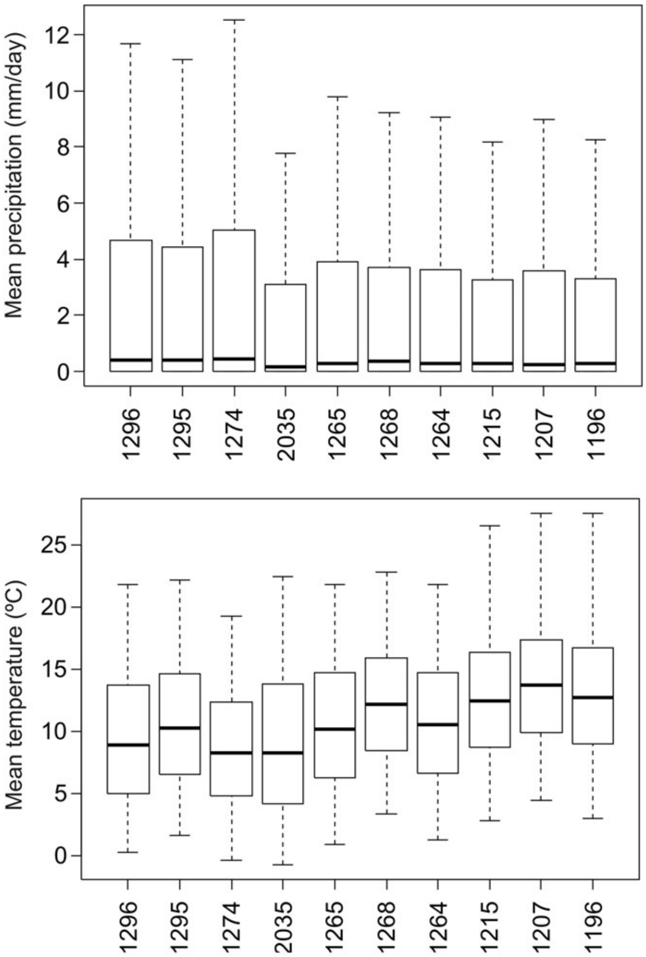

FIGURE 3 Daily precipitation and temperature variability for the period 1995–2010 in the 10 catchments of the Cantabrian Mountains, ordered from west (left) to east (right). Boxplots show quartiles. Whiskers show maxima and minima (outliers excluded)

The 2010 overall classification accuracy for all land cover types was 82,59%. Similar values were obtained for forest, shrub and pasture land cover types (84%, 82% and 81%, respectively), those (prevalent) types with at least a 10% coverage averaged among catchments. Forest maturity showed the lowest values in the catchments located in the east (between 48% and 62%), whereas the maximum value was observed in the west (with 82%, in Ponga). This value indicates the probability of forest land cover type within this catchment, independent of the area that forest class covers (which is why probability/maturity may be greater than coverage, as in Ponga). Once the land cover types were averaged for the period 1995–2010 with the linear rate obtained (1984–2010), forest coverage showed a pattern similar to maturity. With the exceptions of the catchments 1295 (Sella) and 1274 (Cares), the three catchments in the eastern part presented the lowest values (between 20% and 29%), whereas the western catchment presented the greatest value (57%). Shrub coverage showed almost the opposite pattern. The three catchments in the eastern zone presented the greatest values (between 49% and 63%), whereas the eastern catchment presented (almost) the lowest value. Pastureland did not show any similar pattern (Table 1b). Assuming linear land cover changes between 1984 and 2010, as stated, the percentage of catchment change was always lower than 15% across the period of records (1995 to 2010), that is, less than 1% annually (Table 1c). The maximum percentage (around annual 1%) was observed in forest in those catchments where it is more widespread, whereas the catchments with less forest land cover type presented lower rates.

Only the BFI showed a statistically significant correlation with precipitation regimes, with a value around 50% (Table 2). On the contrary, the hydrological indices associated with the magnitude and frequency of floods (Qmax and Qh) showed a very low correlation with their corresponding precipitation indices (less than 10%). Land cover characteristics, particularly shrub coverage and forest maturity, showed a significant relationship with Qmax after removing the variance explained by precipitation, around 70% and 50%, respectively (Table 2; Figure 4). The correlation obtained with Qh was similar in the case of shrub coverage but lower in the case of forest maturity (below 40%). In all partial correlations, forest maturity showed higher correlation scores with hydrological indices than forest coverage, which never showed values greater than 11% (or statistically significant).

Forest maturity and shrub coverage showed the strongest ability to predict extreme hydrological events. Forest maturity showed a negative relationship with the magnitude and frequency of floods and

TABLE 2 Squared *R*-values obtained from regression modelling of hydrological indices against the same indices computed using precipitation (left) and partial correlations of hydrological indices with land cover characteristics (right). Values are expressed in percentage

	Precipitation indices (regression model)			Land cover characteristics (partial correlation)			
Hydrological index	**Pmax**	**Ph**	**P-BFI**	**fc**	**fm**	**shc**	**pc**
Qmax	07	—	—	08	47**	68***	03
Qh	—	05	—	01	36*	72***	07
BFI	—	—	53**	11	24	08	17

Note. Qmax = maximum flow; Qh = high flow events; BFI = base flow index; fm = forest maturity; fc = forest coverage; shc = shrubs coverage, pc = pasture coverage.

*significant at ≤ 0,1. **significant at ≤ 0,05. ***significant at ≤ 0,01.

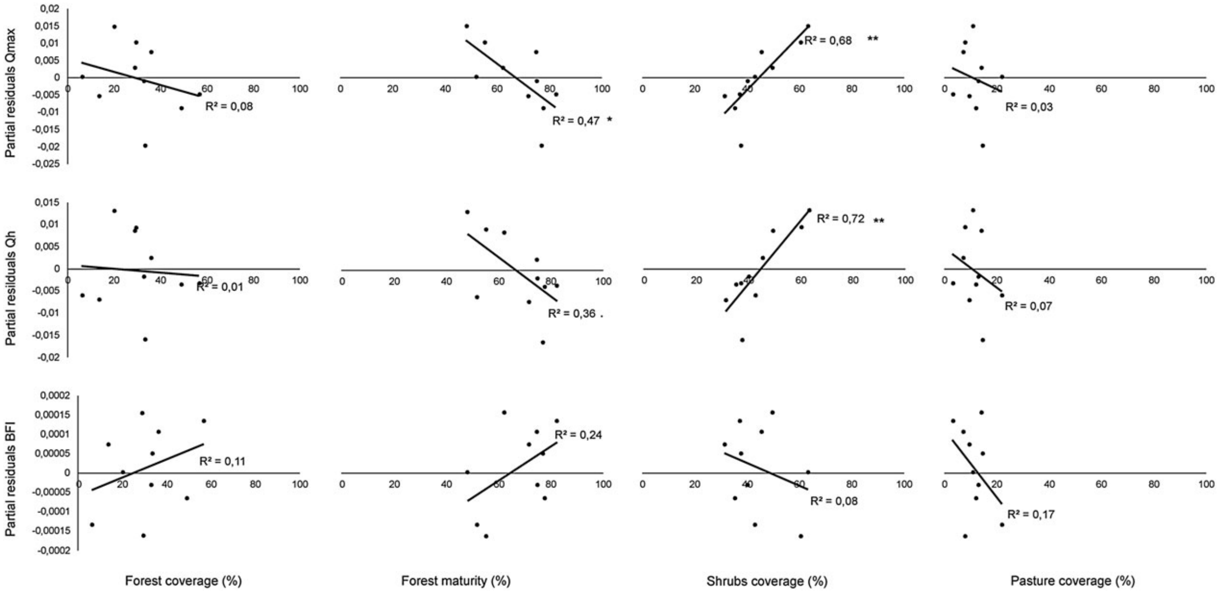

FIGURE 4 Partial correlations between land use characteristics and hydrological indices for the period 1995–2010 in the 10 catchments of the Cantabrian Mountains. Qmax = mean 3-day maximum annual flow; Qh = number of high flow events per year using an upper threshold of 9 times the median flow over all years; BFI = base flow index. Significance levels: "·" ≤ 0,1; "*" ≤ 0,05; "**" ≤ 0,01

positive with the base flow. This relationship was statistically significant, with a coefficient of determination between 40% and 55% (Figure 5). Shrub coverage showed opposite trends. Although BFI showed a lower significance, the other hydrological indices showed the lowest *p* values and highest coefficients of determination (around 80%) of all regressions with land cover descriptors. Forest coverage did not show statistically significant results, with coefficients of determination lower than 5%.

Forest maturity and shrub coverage also presented the strongest ability for quick/slow flow prediction, as the R^2 values and *p* values show (Figure 6). Slow flows were positively correlated with forest maturity and negatively with shrub coverage and the opposite for quick flows. Whereas shrub coverage showed a coefficient of determination around 40%, forest maturity showed a coefficient around 60%. This output was supported by the high model fit obtained using IHACRES with the 10 selected catchments, always greater than 50% (Table 3).

TABLE 3 Models developed using IHACRES for the 10 selected catchments indicating model parameters and model fit (R^2)

Site	c	tw	f	υs	υq	R^2
1296 (Ponga)	0,00	27,00	3,00	0,78	0,22	0,65
1295 (Sella)	0,01	7,00	0,50	0,61	0,39	0,76
1274 (Cares)	0,01	7,00	0,00	0,81	0,19	0,51
2035 (Besandino)	0,00	2,00	2,50	0,40	0,60	0,82
1265 (Deva—O.)	0,01	2,00	2,00	0,92	0,08	0,81
1268 (Deva—P.)	0,00	22,00	0,00	0,77	0,23	0,78
1264 (Bullón)	0,00	2,00	3,00	0,91	0,09	0,84
1215 (Pas)	0,01	17,00	0,50	0,74	0,26	0,83
1207 (Miera)	0,01	17,00	0,00	0,38	0,62	0,83
1196 (Asón)	0,01	27,00	0,00	0,43	0,57	0,86

Note. c = storage coefficient; tw = time constant for the rate of drying; f = factor that modulates changes in temperature; υs = slow flows; υq = quick flows.

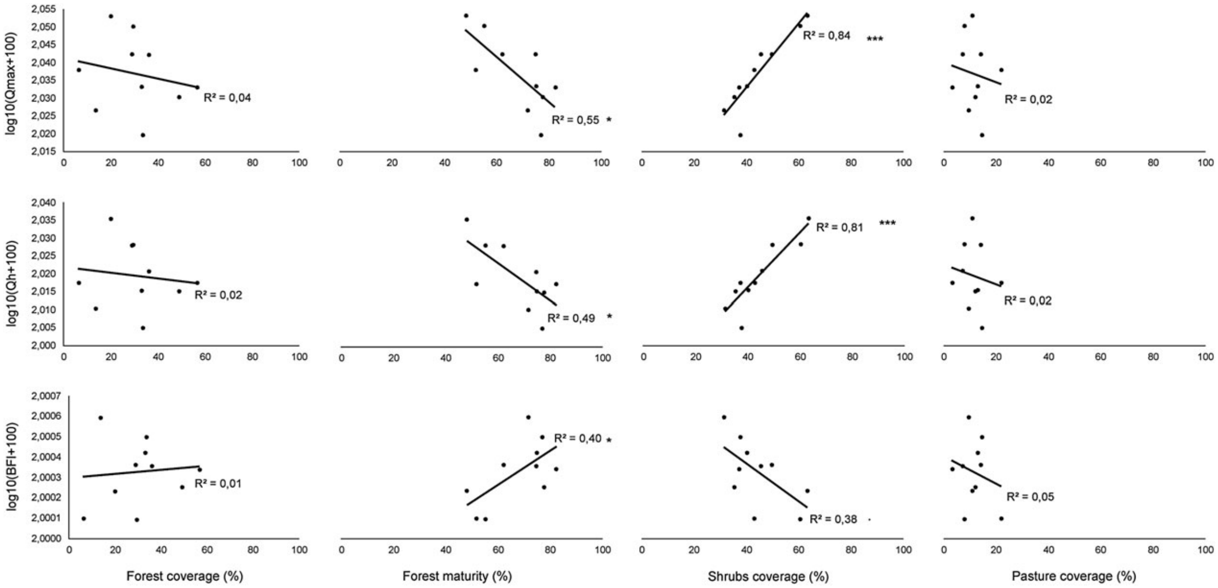

FIGURE 5 Regression modelling between land use characteristics and hydrological indices for the period 1995–2010 in the 10 catchments of the Cantabrian Mountains. Qmax = mean 3-day maximum annual flow; Qh = number of high flow events per year using an upper threshold of 9 times the median flow over all years; BFI = base flow index. Significance levels: "·" ≤ 0,1; "*" ≤ 0,05; "**" ≤ 0,01; "***" ≤ 0,001

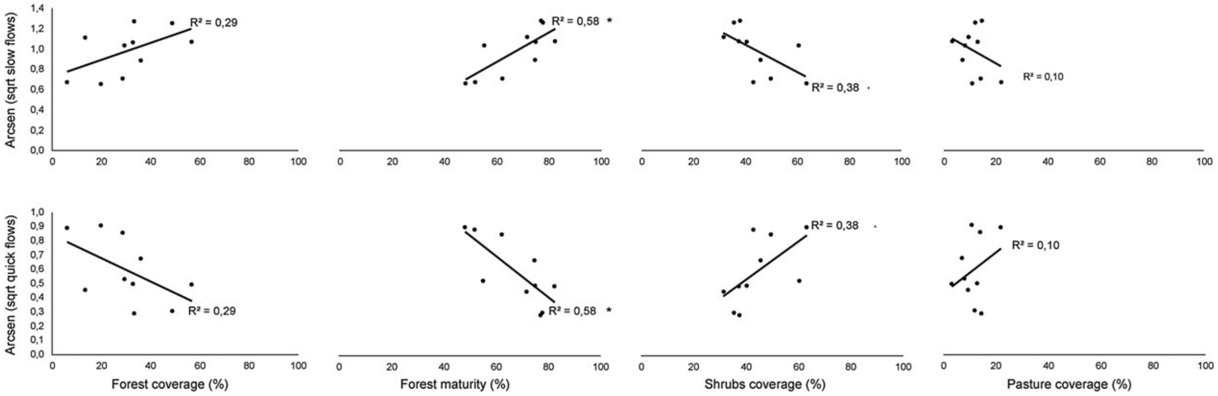

FIGURE 6 Regression modelling between land use characteristics and the proportion of slow and quick flows modelled through IHACRES for the period 2000–2007 in the 10 catchments of the Cantabrian Mountains. Significance levels: "·" ≤ 0,1; "*" ≤ 0,05

4 | DISCUSSION

This study aimed to provide empirical evidence of how forests and other predominant land cover types influence the occurrence of recurrent floods and low flows without modelling the underlying biophysical processes. The complex land cover mosaic and change in time of the selected region in the Cantabrian Mountains (NW Spain) provided statistically significant results using 10 catchments. Whereas paired-catchment studies generally use two catchments, we were able to obtain a set of catchments with a gradient in land cover characteristics and empirical data that allow regression modelling techniques to find patterns in the relationship between land cover characteristics and hydrology. Such patterns, supported by statistically significant *p* values, show that land cover is very relevant to determining the spatial variability of flow extremes in similar close catchments. They also indicate the importance of additional land cover descriptors (i.e., forest maturity, more effective than forest coverage) and changes in land cover with time to explain extreme hydrological events. We consider such results to have implications for water management in areas with a similar climate, land cover types and land uses (i.e., in temperate Atlantic catchments) and possibly in other climatic regions. These implications are relevant for environmental management and planning to mitigate the effects of climate change.

4.1 | Precipitation and land cover contribution to flow extremes

The land cover mosaic has varying abilities to influence regular floods and low flows at a catchment scale. As partial correlations showed, the spatial variation of floods is determined mainly by land cover characteristics. This means that land cover characteristics have the ability to intercept flow peaks. On the contrary, the ability of this interception to provide flows during low precipitation and flow events is more limited, as land cover characteristics presented a reduced ability to predict low flows (water interception and release takes place in hours). This is coherent with the results obtained by Zhang et al. (2016), which found that base flows are less sensitive than high flows to forest disturbance.

Within the land cover mosaic, forest coverage showed a poor ability to predict hydrological extremes. This contradicts the results of studies in temperate zones that have reported that reductions in forest coverage magnify peak flows and alter base flows (Hornbeck et al., 1993; Li et al., 2017). Our study indicates that mature forests reduce extreme hydrological events in rivers. Catchments with higher forest maturity presented less intense and frequent floods and greater base flows. Additional tests (not shown) using different numbers of days or times the mean flow provided analogous results. The relationships were even clearer using fewer days for flow magnitude and a higher number of times the median for flow frequency.

As expected, the performance of forest maturity seems to be associated with water interception, as forest maturity also predicted the spatial variability of slow and quick flows in the selected catchments. Croke et al. (2004) observed the same pattern between forest coverage and the proportional volume of quick and slow flow storage. However, they obtained their results in a small catchment through simulation by combining a generic crop model (CATCHCROP; Pérez, Ardlie, Kuneepong, Dietrich, & Merritt, 2002) with IHACRES. The set of 10 catchments presented in this study constitutes an important advantage in comparison. Previous literature showed that the response of two basins to forest disturbances may differ, for example, in terms of low flows (Zhang et al., 2016). Therefore, the use of several (and larger) catchments (as Andreassian, 2004 suggested) and of estimates both of forest coverage and maturity in this study, based on empirical ("real") flow data, provides more reliable results. Given the good performance of forest maturity in this study in comparison with forest coverage, the use of forest maturity estimated through fuzzy-logic approaches (see Alvarez-Martinez et al., 2010) may provide a relatively simple catchment descriptor that could assist in the assessment of catchment hydrologic responses. Thus, forest maturity may be a first step to addressing to the need for indicators alternative to the use of forest coverage highlighted by Zhang et al. (2017). Although its estimation through forest probability using a Landsat image involves the risk of obtaining erroneous results during the classification processes, the accuracy obtained for the different land cover types indicates a satisfactory performance and suggests that it is a reliable indicator. This is especially relevant for water research due to the widespread use of vegetation coverage in modelling tools (e.g., the Soil and Water Assessment Tool or SWAT; Arnold, Srinivasan, Muttiah, & Williams, 1998).

Given the likely mediation of water interception in flow extremes and the role that ground vegetation and the organic content of soils plays, recent changes in land cover may allow a better understanding of the performance of the land cover types and indicators used in this study.

4.2 | The importance of the recent past in the land cover mosaic

Our results imply that landscape changes in previous decades are fundamental to catchment hydrology and water management. In addition to the exploitation of forests in the study area since the 15th century, the Cantabrian Mountains have seen a major decline in livestock grazing pressure for the past 40 years (Alvarez-Martinez, Gomez-Villar, & Lasanta, 2013; Morán-Ordóñez, Suarez-Seoane, Calvo, & de Luis, 2011). This has resulted in a displacement of shrubs and pastureland by native forests in many different areas (e.g., Alvarez-Martinez, Suarez-Seoane, Stoorvogel, & Calabuig, 2014; Poyatos, Latron, & Llorens, 2003). In our case, the Landsat image taken in 1984 also revealed that more than 10% of the pixels in our study area classified as forest in 2010 had been pasture or shrub. Therefore, anthropogenic pressures typically based on deforestation linked to advancement of shrubs appear to be absent in our study area (it is actually the opposite), and new forest coverage comprises pixels with forest patches of different degrees of development (maturity) that will have different effects on hydrology at a catchment scale. Pixels recently occupied by forests should present reduced ground vegetation, organic matter decomposition and soil development (Binkley & Fisher, 2012) in comparison with those that had presented forests in the 1980s (with more mature forests currently). We believe this is why forest coverage was less able to explain the spatial variability of hydrological extremes, whereas forest maturity performed much better. Forest coverage integrates, within the same category, old and new forest patches, which produce different hydrological responses. Given that our methodology integrates the changes in land coverages that occurred during the period with data records (1995–2010), even with a relatively low maximum annual variation rate (less than 1% for forest land cover type and similar to that obtained by Alvarez-Martinez et al., 2014), our conclusion regarding forest maturity versus forest coverage as an indicator is reliable. There is no larger error in the use of forest coverage in comparison with forest maturity that may be associated with the inherent ability of the latter to encompass previous land cover characteristics.

Similarly, the different performances shown by other land cover types not associated with forests also indicate an influence of land cover change with time on hydrological response. Pastureland was not a good predictor, whereas shrub coverage was highly related to hydrological extremes. The lack of a relationship between pastureland and hydrological indices could be a result of the smaller proportion occupied by pastures in the study area in comparison with the other dominant land cover types (i.e., forests and shrubs). The better performance of shrubs may be related to land use management, which makes shrub lands a dominant land cover type through the extensive and recurrent use of fire (Pausas & Fernandez-Munoz, 2012; Regos, Ninyerola, More, & Pons, 2015). Commonly, the shrub formations in the study area present a pattern of degraded vegetation and poor soil structure associated with recurrently burnt areas (cycles of 3 to 5 years; Diaz-Delgado, Lloret, Pons, & Terradas, 2002; Gimeno-Garcia, Andreu, & Rubio, 2007). In this context, the development of additional land cover descriptors, such as maturity for forests, remains necessary to explore the effects of land cover mosaics on hydrological response at a catchment scale.

4.3 | Implications for forest management

The role that mature forests may play in providing base flows at a catchment scale is unlikely to be emulated by reforestation programs if they are based exclusively on tree plantation. Frequently, reforestation efforts are developed using a comparatively small number of fast-growing exotic species. These species have particular environmental preferences, and not surprisingly, many do not grow as well as expected (e.g., Lamb, 2005). Reforestation is thus likely to lack developed ground vegetation cover and mature soil (at least during the first decades). It will thus be less effective to infiltrate precipitation, and therefore, provide base flows. On the contrary, the water consumption of these trees may contribute to water scarcity and aridification (Brown et al., 2005; Jackson et al., 2005; Sun et al., 2006). Therefore, it is necessary to ensure the development of ground vegetation and organic soils.

Further research on the long-term impacts of land cover on hydrologic regimes at a catchment scale may provide key guidelines for sustainable land use management. First, analyses using Landsat images taken in different years during the last decades should be carried out. The changes in land cover (with on-ground measurements), climate and flows could be quantified and compared to determine the relative contribution of changes in land cover to hydrological variations. Unfortunately, such analyses were not possible in this study, as processing additional Landsat images requires additional training datasets for each image (as stated). In addition, more good quality hydroclimatic series were unavailable. Second, using other land cover descriptors based, for example, on forest species (Zhang et al., 2017) would be informative. The use of such descriptors would allow the enhancement of hydrologic modelling. Finally, we believe that understanding the physical mechanisms that explain the interactions observed herein is mandatory. The influence of tree physiological conditions (e.g., basal area, live biomass or leaf area) deserves special attention, considering the impressive water holding capacity of O horizons (e.g., a 5-cm-thick O horizon in a subalpine forest may have a mass of about 5 kg m^{-2} and could retain about 10 L of water; Golding & Stanton, 1972). By doing so, we would be able to better assess the contribution of forests and their soils to flow regimes at a catchment scale, as well as the contribution of other land cover types.

CONTRIBUTORS

O. B. performed research, analysed data and wrote the paper. J. B. conceived the study, performed research and contributed to analyses and writing. J. M. A. M. performed research, analysed data and contributed to writing. F. J. P. contributed to analyses and writing. M. D. J. performed research and contributed to writing.

DECLARATION OF INTERESTS

The authors declare that they have no conflict of interest.

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