The role of forest maturity on hydrological extreme events

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Abstract. Land cover and soil properties largely determine how climatic and hydrological regimes interact and produce hydrological stress in aquatic ecosystems. This study aims to clarify the influence of forests, as well as other majoritarian land cover types, on hydrological extreme events through a land cover gradient design within a similar climatic region. Specifically, we selected 10 catchments within a gradient of forest land cover in which there were 15 years of simultaneous hydrological and meteorological data, and also an additional forest descriptor: forest maturity. The study is developed in a heterogeneous region located in the Cantabrian Mountains (NW Spain) with different vegetation types and a long history of human disturbance and land use change that has produced a gradient in forest cover. This study focuses on hydrological extremes: regular flood and drought events. Specific objectives were to isolate the relative contribution of land cover composition to such flow extremes and to contrast the effectiveness of forest surface, forest maturity and other land cover types to predict them. Partial Correlation and OLS Regression were developed using hydrological indices, obtained from flow records, and hydrological parameters calculated through modelling, using IHACRES and hydrometeorological data. Land cover characteristics showed more ability to predict floods than low flows. Forests were associated with a reduction in flow extreme events (lower intensity and frequency of floods and greater base flows), while shrub formations did the opposite. These results were more evident using forest maturity than using forest surface. This study shows that hydrological modelling might benefit in the future from considering not only the surface of different land cover types but also the conservation status of the different vegetation formations. In the selected study area, forest maturity (associated with the absence of forest disturbances) seems to be a key landscape characteristic that contributes to better explain patterns of hydrological extreme events.

Keywords. Cantabrian Mountains, Native Forests, Maturity, Land cover, catchment hydrology, IHACRES.

1 Introduction

Flood and drought events represent the extreme demonstration of hydrologic variability, which constitutes a primary driver of stream biological communities and ecosystem functioning (Resh et al. 1988; Lake 2000). Such events may cause greater impacts on river ecosystems than changes in flow means averaged along years (Woodward et al. 2016). Their frequency, intensity and duration is expected to increase due to Climate Change (IPCC 2012). But land use changes, which are mostly induced by human activities, also affect hydrological processes such as evapotranspiration (ET) and interception, resulting in alterations of surface and subsurface flows (Wang et al. 2014, Niraula et al. 2015). Therefore, changes in the land cover mosaic may attenuate or exacerbate the hydrological effects of Climate Change on riverine communities and ecosystems.

Recent studies show increasing trends in forest area in Europe over the last decades (Spiecker et al. 2012). Socioeconomic adjustments, such as those linked to the EU Common Agricultural Policy (CAP), 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 et al. 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 and Hewlett 1982). Thus, their expected effect on river flows would be 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, 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. Additional paired catchment studies have been reported in the literature since then and in other reviews (Hornbeck et al. 1993; Stednick, 1996; Vertessy, 1999; Vertessy, 2000; Brown et al., 2005). However, further catchment scale research is necessary to advance our understanding of forest impact on hydrology and, particularly, studies focused on large basins (several tens of km^2), additional descriptors of forest characteristics (besides area) and more than two observed catchments (Andréassian 2004). More complete studies that clarify the relationship between forests and hydrological processes may allow improving 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 Forest Northwest 2010).

Forest maturity may be an important factor to determine forest-river flow relationships, as the long process of native forests formation involves many steps that increase water retention. 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 and Stone 1969; Fisher and Eastburn 1974). 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 is to improve the understanding of how forests and other predominant land cover types influence the occurrence of recurrent floods and droughts using a land cover gradient design. To achieve this we used up to 10 large catchments (between 30 km^2 and 650 km^2) in the Cantabrian Mountains (NW Spain) with a gradient of forest cover generated by human management since the 15th century. Such a forest cover gradient is very difficult to find within a similar climatic condition, especially with more than 15 contemporary years of gauge and meteorological records in all catchments like in this case. This study aims therefore to provide empirical evidence without modelling the underlying biophysical processes. We defined forest cover not only through forest surface but also using forest maturity. Our specific objectives were: (i) to isolate the relative contribution of land cover to hydrological extreme events from the contribution of precipitation and (ii) to compare the effectiveness of forest surface and maturity, as well as other predominant land cover types, to predict such extremes. We expect 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 is expected to be negatively associated with the intensity and frequency of floods and positively related to larger base flows better than forest surface.

2 Material and methods

2.1 Study area

This study has been 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 1160 mm and 9.5 ºC, respectively. Areas located at lower latitudes show sub-Mediterranean characteristics, with higher temperatures and summer droughts (Ninyerola et al 2007). This environmental heterogeneity shelters a mix of tree species with 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 semi-arid 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.

An initial set of 16 catchments, later reduced to 10 due to data quality issues (see Meteorological and hydrological data; Fig. 1, Table 1), was selected to represent a land cover gradient within a similar climatic region. Such 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 dominance of dry heathland communities and extensive pastureland. Only some isolated patches of forest remain in steep hillslopes. On the contrary, the western catchments have not suffered massive deforestation and still present quite well developed mature forests. The presence of brown bear (*Ursus arctos*) and Cantabrian Capercaillie (*Tetrao urogallus cantabricus*) in these catchments, unlike the eastern extreme (González et al. 2016; Blanco-Fontao et al. 2012), evidences 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 makes 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 (USGS). 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 developing high-resolution mapping of our study area. The image was radiometrically and atmospherically corrected using the algorithms available in GRASS (2013). A complementary digital elevation model (DEM) was obtained from LiDAR data (CNIG 2014) and resampled to 30 meters to match the spatial resolution of the image.

Two high-resolution classifications of the study area were developed in order to obtain land cover types and forest maturity in each catchment, respectively. First, a per-pixel classification approach was applied using a Maximum Likelihood algorithm (ML) over a combination of spectral information and topographic layers derived from the 30-m DEM. 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 et al. 2000), generating a ‘hard’ classification. Testing points were used to construct confusion matrices (Congalton 1991), using standard accuracy assessment methods (Stehman and Czaplewsky 1998), in order to detect misclassification errors. Second, a fuzzy k-means classification allowed yielding membership probabilities for each land cover type at the pixel level. The pixels classified as forest by the ‘hard’ classification and 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 the ones selected as training dataset of the forest class). On the contrary, forest pixels with low probability of forest class membership will be those with certain degree of heterogeneity at the pixel level due to forest fragmentation and presence of other land cover types (for more details, see Álvarez-Martínez et al. 2010).

Land cover types with a surface, averaged among catchments, lower than 10% were discarded for subsequent analyses due to their low occurrence at catchment scale (forest plantation, agricultural, denuded rock and urban). The relative surface occupied by the other (the majoritarian) 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. Forest maturity was estimated using the corresponding membership probability obtained through the fuzzy classification, calculating the average per-pixel forest probability in each of the selected catchments. Forest surface refers to the area occupied by the corresponding vegetation formation (trees and undergrowth). Forest maturity refers to the degree of development of forest formations, estimated using an indirect measure (probability). Pixels with a higher forest probability represent dense forest patches that could be interpreted as developed mature forest.

2.3 Meteorological and hydrological data

Meteorological records were acquired from the Spain02 database (version 4), developed by the Agencia Estatal de Meteorología (AEMET, the State Meteorological Agency) and the Universidad de Cantabria (UC, University of Cantabria).

Such database includes gridded datasets interpolated with rainfall and temperature data from over 2500 stations in Spain at different resolutions for the period 1971-2007 (Herrera et al. 2012; 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 in order to verify that the catchments in the study area presented reasonably similar climatic regimes.

Flows recorded by the Red Oficial de Estaciones de Aforo (ROEA, the Official Network of Gauging Stations) were obtained from the Anuario de Aforos database available online at the Centre for Studies and Experimentation on Public Works (CEDEX, 2016). Only the gauging stations located at the outlet of each catchment were retained. After testing flow records in order to detect deficiencies (see details in Peñas et al. 2014), 6 out of the initial 16 stations (and their corresponding catchments) were discarded from the study: one in the Duero Basin (2034; Fig. 1) and five in the Ebro Basin (9092, 9178, 9202, 9203 and 9254; Fig. 1). The flow series of the remaining 10 stations were divided by the mean to remove catchment-size effect and allow comparison among catchments (Poff et al 2006).

2.4 Hydrological analyses

Two sets of hydrologic indicators (indices and parameters) were computed to characterize, respectively, regular floods and droughts (hydrological extremes) and water interception caused by ground vegetation and soils. On one hand (empirical), three hydrological indices were chosen to summarize hydrological extreme events through flow records: (i) the maximum 3-day mean annual flow (M3DMF); (ii) the mean number of high flow events per year using an upper threshold of 9 times the median flow over all years (FRE9) and (iii) the Base Flow Index (BFI, the seven-day minimum flow divided by mean annual daily flow averaged across all years). The latter was used to characterise low-flow conditions, whereas the two others were used to characterise flood regimes (magnitude and frequency), as it has been done in previous studies (e.g. Richter et al. 1996; Olden and Poff 2003; Snelder et al. 2009; Belmar et al. 2011; Peñas et al. 2014). The period selected for computation was 1995-2010, in order to ensure 15 years of records (Kennard et al. 2010) and match the timing of the LANDSAT image taken by the USGS. These indices were also calculated using contemporary precipitation series (P-M3DMF, P-FRE9 and P-BFI).

On the other hand (process-based), we computed 10 independent hydrological models for each of the selected catchments based on a physical model (IHACRES; Jakeman and 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 ºC) 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 for which our data were best (2000-2007). Using this model two hydrological parameters were calculated in each catchment to estimate water interception caused by ground vegetation and soils: the proportional volumes of quick (υq) and slow (υs) flow storage. ‘Slow’ and ‘quick’ flows constitute two components in which flow regimes may be decomposed. The former refers to volumes with high time of concentration (e.g. base flows), defined as the time needed for water to flow from the most remote point in a catchment to the outlet. The latter refers to volumes with low time of concentration.

2.5 Analysis of the effect of climate and land use on hydrological regime

Partial Correlation Analyses and 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. Hornbeck et al. 1993; Gyawali et al. 2015), were employed. The effect of land cover on the selected hydrological indices was isolated from that of precipitation through Partial Correlation. The three hydrological indices (M3DMF, FRE9 and BFI) were predicted through OLS Regression using the three precipitation indices (P-M3DMF, P-FRE9 and P-BFI). Then, by means of a new 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).
In order to contrast the effectiveness of different land cover characteristics to predict recurrent hydrological extremes and water interception, land cover characteristics were used to predict the hydrological indices and the proportional volumes of the quick (υq) and slow (υs) flows through a new 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 volumes of quick and slow flows, as they were proportions (McDonald 2014). All analyses were developed using the R software (version 3.1.3; R Core Team 2015) through the base package “stats”.

3 Results

The ten studied catchments displayed reasonably similar climatic regimes, with only a very subtle gradient from West to East of slightly increasing temperature and decreasing rainfall (Fig. 2). The 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 (majoritarian) types with at least a 10% of surface averaged among catchments. The catchments in the western part of the study area showed larger areas covered by forests and higher values of forest maturity, whereas those in the eastern part presented the lowest values of both descriptors. Shrub surface showed the opposite pattern. Pastureland did not show clear differences across the study area (Table 1).
Only the Base Flow Index showed correlation with precipitation regimes (Table 2). On the contrary, the hydrological indices associated with the magnitude and frequency of floods (M3DMF and FRE9) showed a very low correlation with precipitation. Land cover characteristics, particularly shrub surface and forest maturity, showed a significant relationship with M3DMF and FRE9 after removing the effect of precipitation. In all partial correlations, forest maturity showed higher correlation scores with hydrological indices than forest surface.
Forest maturity and shrub surface showed the highest ability for prediction of hydrological extreme events (Fig. 3). Forest maturity showed a negative relationship with the magnitude and frequency of floods and positive with the base flow, while shrub surface showed opposite trends.

Forest maturity and shrub surface also showed the highest ability for quick/slow flow prediction, as the R^2 values and p-values of the OLS modelling evidenced. Slow flows were positively correlated with forests maturity and negatively with shrub surface (Fig. 4). This output was also supported by the high degree of adjustment obtained by the IHACRES models of the 10 selected catchments, according to their R^2 values (Table 3).

4 Discussion

This study aimed to provide empirical evidence of land cover types on hydrologic extremes without modelling the underlying biophysical processes. The complex land cover mosaic and land cover dynamics of the selected region in the Cantabrian Mountains (NW Spain) allowed obtaining statistically significant results even with a relatively low number of cases (n=10), after discarding catchments with unsuitable data. This study shows that land cover is very relevant to determine the spatial variability of flow extremes in similar close catchments. It also points out the importance of additional land cover descriptors (i.e. forest maturity, more effective than forest surface) and land cover dynamics to explain hydrological extreme events. We consider that such results have implications for water management in areas with 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 for mitigating the effects of Climate Change.

4.1 Precipitation and land cover contribution to flow extremes

The land cover mosaic has different relative contribution to regular floods and droughts 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 modify flow peaks, being unable to overcome the impact of critical reductions in water incomes. However, a moderate influence of land cover on droughts was also observed, as land cover characteristics presented certain ability to predict low flows.

Within the land cover mosaic, forest surface showed a reduced ability to predict hydrological extremes. This contradicts the results of studies in temperate zones that have reported increases in base flows due to reductions in forest surface (Hornbeck et al., 1993). However, our study indicates that mature forests reduce hydrological extreme events in rivers. Catchments with higher forest maturity presented less intense and frequent floods and greater base flows. Additional tests (not showed) using different number of days or times the mean flow provided analogous results but the relationships were clearer using lower number of days for flow magnitude and higher number of times the median for flow frequency. Obviously, this is due to a better characterization of extreme flow rises by minimizing the number of days used to compute their magnitude, as these phenomena take place in short periods, and by increasing the magnitude considered to compute their frequency, as this allows characterizing more extreme flow rises. As expected, this effect of forest maturity seems to be associated with water interception (possibly aided by ground vegetation and the organic content of soils), as forest maturity also predicted the spatial variability of slow and quick flows in the selected catchments. Croke et al. (2004) were able to observe the same pattern between forest surface 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; Perez et al. 2002) with IHACRES. The use of several (and larger) catchments (as Andréassian 2004 suggested) and of estimates both of forest surface 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 surface, the use of forest maturity estimated through fuzzy-logic approaches (see Álvarez-Martínez et al. 2010) may provide a relatively simple catchment descriptor that could assist the assessment of catchment hydrologic responses. This is especially relevant for water research due to the widely spread use of vegetation surface in modelling tools (e.g. Soil and Water Assessment Tool, SWAT; Arnold et al. 1998).

4.2 Implications for forest management

The role that mature forests may play conferring base flows at a catchment scale is unlikely to be accomplished by reforestations. Frequently, reforestation efforts are based on a comparatively small number of fast-growing exotic species. These species have particular environmental preferences and, not surprisingly, many do not always grow as well as expected (e.g. Lamb et al. 2005). Reforestations are then likely to lack a developed ground vegetation cover and a mature soil (at least, during the first decades). They will be less effective in intercepting precipitation, and therefore, in providing base flows. Instead, their water consumption may contribute to water scarcity and aridification (Jackson et al. 2005; Brown et al. 2005; Sun et al. 2006). Consequently, whereas native forest expansion and maturation could constitute a powerful strategy to counteract the effects of Climate Change in the mid- to long-term, the deterioration of native forests due to human land use management in a context of Climate Change will exacerbate its effects and constitute a serious drawback in the short-term.

4.3 The importance of recent past in land cover mosaic

Our results imply that landscape dynamics in previous decades results fundamental for catchment hydrology and water management. Besides the exploitation that forests experienced in the study area since the 15th century, the Cantabrian Mountains have shown a major decline in livestock grazing pressure for the last 40 years (Morán Ordóñez et al. 2011, Álvarez-Martínez et al. 2013). This has resulted in a displacement of shrubs and pastureland by native forests in many different areas (e.g. Poyatos et al. 2003; Álvarez-Martínez et al. 2014). In our case, more than 10% of pixels classified as forest in 2010 were pasture or shrub in 1984 (unpublished data). This involves that new forest surface comprises a mixture of pixels with different degree of forest development, and with different hydrological effect at a catchment scale. Pixels recently occupied by forests present reduced ground vegetation, organic matter decomposition and soil development (Binkley and Fisher 2012) in comparison with those that already presented forests in the 80’s (with mature forests already then). We believe, this is why forest surface had a poorer ability to explain the spatial variability of hydrological extremes, whereas forest maturity performed much better. The former integrates within the same category old and new forest patches that produce very different hydrological responses, while the latter includes only old forest patches that produce a more similar and homogenous hydrological response.

Similarly, the different performance showed by other land cover types not associated with forests also indicates an influence of land cover dynamics on hydrological response. Pastureland was not a good predictor, whereas shrub surface was highly related to hydrological extremes. The lack of relationship between pastureland and hydrological indices could be caused by the reduced surface occupied by pastures in the study area in comparison with the other dominant land cover types (i.e. forests and shrubs). On the contrary, 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 and Fernández-Muñoz 2012; Regos et al. 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; Díaz-Delgado et al. 2002; Gimeno-García et al. 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.

Further research on the long-term impacts of land cover on hydrologic regimes at a catchment scale may provide key guidelines for a sustainable land use management. First, through the development of more complex designs based on land cover dynamics. For example, using data from different years during the last decades. By doing so, the changes in climate, flows and land cover could be quantified and compared in order to determine the relative contribution of landscape dynamics to hydrological change during the selected period (with a complete understanding of the performance of land cover characteristics through the observation of their changes during those years, and some on ground measurements when possible). Unfortunately, such analyses were not possible in our study area due to data availability and quality issues. Second, with hydrologic models based on additional land cover descriptors to extension (such as maturity, for forests). That would allow mimicking land cover-hydrology interactions more accurately. Finally, we consider that understanding the physical mechanisms that may explain the interactions herein observed 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 (for example, a 5 cm thick O horizon in a sub-alpine forest might have a mass of about 5 kg m^{-2} and could retain about 10 litres of water; Golding and Stanton 1972). By doing so, we will 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.

5 Author contributions

OB performed research, analysed data and wrote the paper. JB conceived the study, performed research and contributed to analyses and writing. JMAM performed research, analysed data and contributed to writing. FJP contributed to analyses and writing. MDJ performed research and contributed to writing.

6 Competing interests

The authors declare that they have no conflict of interest.

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Table 1. Topographic and hydrologic (a) and land cover (b) characteristics 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)

Code (Name)	Topographic and hydrologic (1995-2010) characteristics				
	Area (km^2)	Altitude (m)	Slope (%)	Mean runoff (hm^3)	Mean flow (m^3/s)
1296 (Ponga)	34	1277	29	55	2
1295 (Sella)	480	1005	29	627	18
1274 (Cares)	266	1454	31	245	8
2035 (Besandino)	70	1498	19	33	1
1265 (Deva - O.)	296	1185	26	141	4
1268 (Deva - P.)	648	1029	27	415	15
1264 (Bullón)	156	972	25	63	2
1215 (Pas)	358	599	19	270	9
1207 (Miera)	161	563	21	147	5
1196 (Asón)	492	558	20	649	22

b)

Code (Name)	Land cover (2009) characteristics (%)			
	Forest maturity	Forest surface	Shrub surface	Pasture surface
1296 (Ponga)	82	62	33	3
1295 (Sella)	75	41	42	6
1274 (Cares)	72	15	32	9
2035 (Besandino)	52	7	45	17
1265 (Deva - O.)	77	39	35	12
1268 (Deva - P.)	75	38	38	11
1264 (Bullón)	78	56	31	10
1215 (Pas)	55	33	57	7
1207 (Miera)	48	22	64	9
1196 (Asón)	62	32	47	14

Table 2. Squared R-values obtained for regression modelling of hydrological indices (M3DMF: maximum flow, FRE9: high flow events, BFI: Base Flow Index) against the same indices computed using precipitation (left) and partial correlations of hydrological indices with land cover characteristics (fm: forest maturity, fs: forest surface, shs: shrubs surface, ps: pasture surface) (right). Values are expressed in percentage. Significance levels: '·' ≤ 0,1; '*' ≤ 0,05; '' ≤ 0,01.**

	Precipitation indices (regression model)			Land cover characteristics (partial correlation)			
Hydrological index	P-M3DMF	P-FRE9	P-BFI	fm	fs	shs	ps
M3DMF	07	-	-	* 47	10	** 69	03
FRE9	-	05	-	· 36	01	** 65	04
BFI	-	-	* 53	24	10	10	11

Table 3. Models developed using IHACREs for the 10 selected catchments indicating model parameters (c: storage coefficient; tw: time constant for the rate of drying; f: factor that modulates changes in temperature; υs: slow flows; υq: quick flows) and model adjustment (R^2).

Site	c	tw	f	υs	υq	R^2
1196	0,01	27,00	0,00	0,43	0,57	0,86
1207	0,01	17,00	0,00	0,38	0,62	0,83
1215	0,01	17,00	0,50	0,74	0,26	0,83
1264	0,00	2,00	3,00	0,91	0,09	0,84
1265	0,01	2,00	2,00	0,92	0,08	0,81
1268	0,00	22,00	0,00	0,77	0,23	0,78
1274	0,01	7,00	0,00	0,81	0,19	0,51
1295	0,01	7,00	0,50	0,61	0,39	0,76
1296	0,00	27,00	3,00	0,78	0,22	0,65
2035	0,00	2,00	2,50	0,40	0,60	0,82

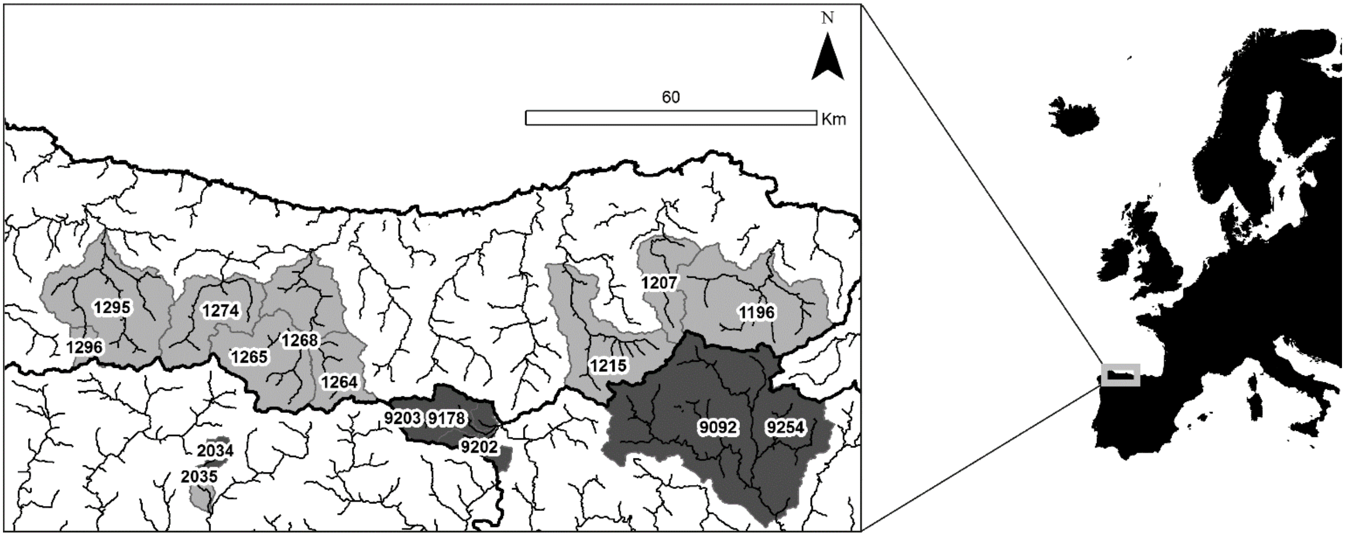

Figure 1. Catchments with hydrological records in the study area of the Cantabrian Mountains. The darkest catchments were discarded due to the poor quality of their data.

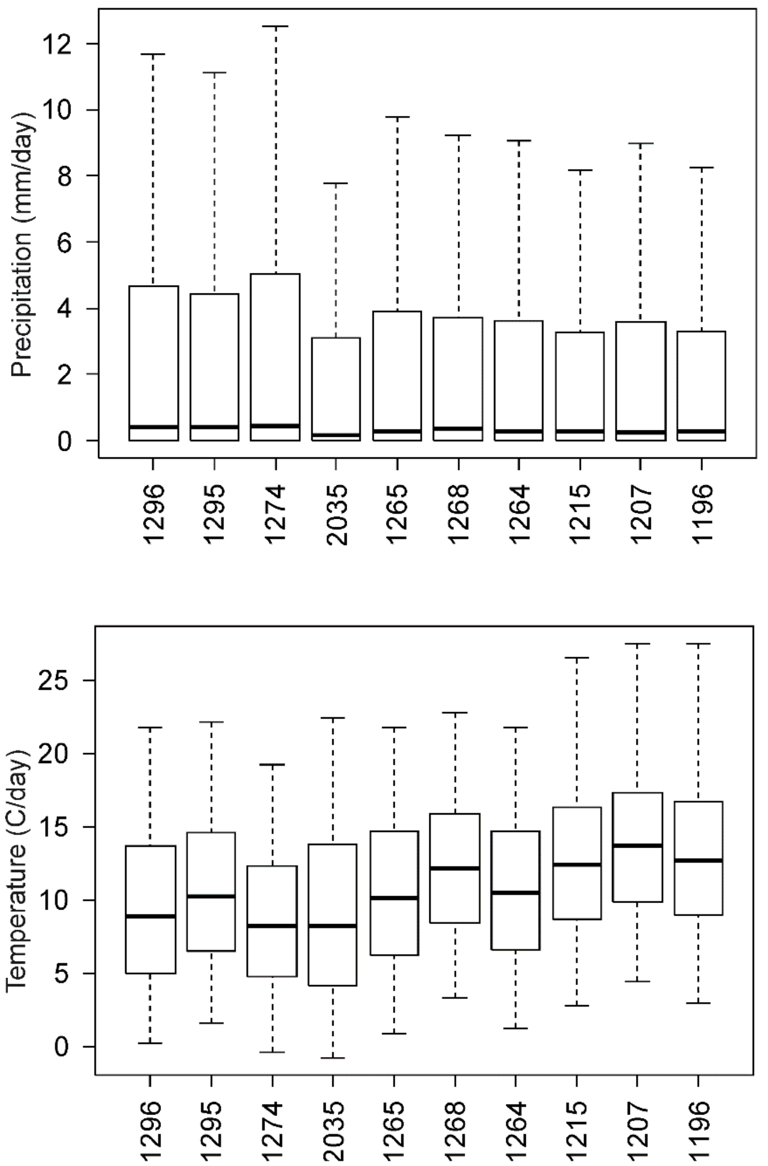

Figure 2. Daily precipitation and temperature variability for the period 1995-2010 in the 10 catchments of the Cantabrian Mountains, ordered from West (left) to East (right). Boxplots show quartiles. Whiskers show maxima and minima (outliers excluded).

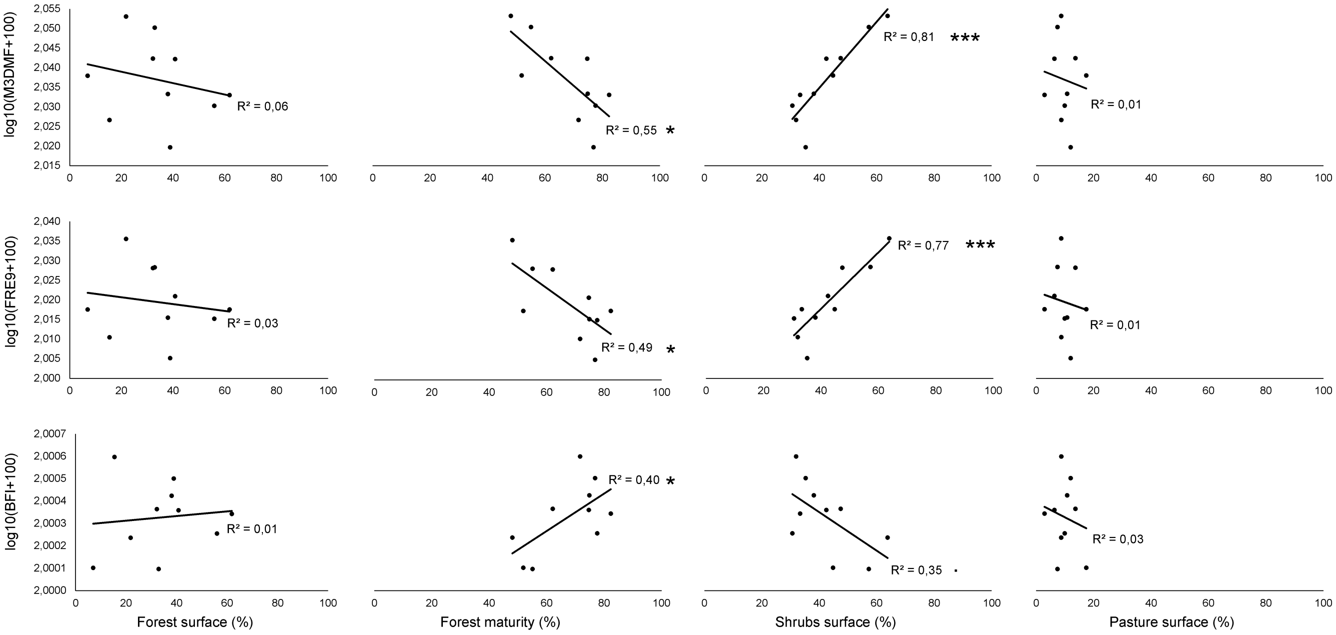

Figure 3. Regression modelling between land use characteristics and hydrological indices for the period 1995-2010 in the 10 catchments of the Cantabrian Mountains. M3DMF: mean 3-day maximum annual flow, FRE9: number of high flow events per year using an upper threshold of 9 times the median flow over all years, BFI: Base Flow Index. Significance levels: '·' ≤ 0,1; '*' ≤ 0,05; '' ≤ 0,01; '***' ≤ 0,001.**

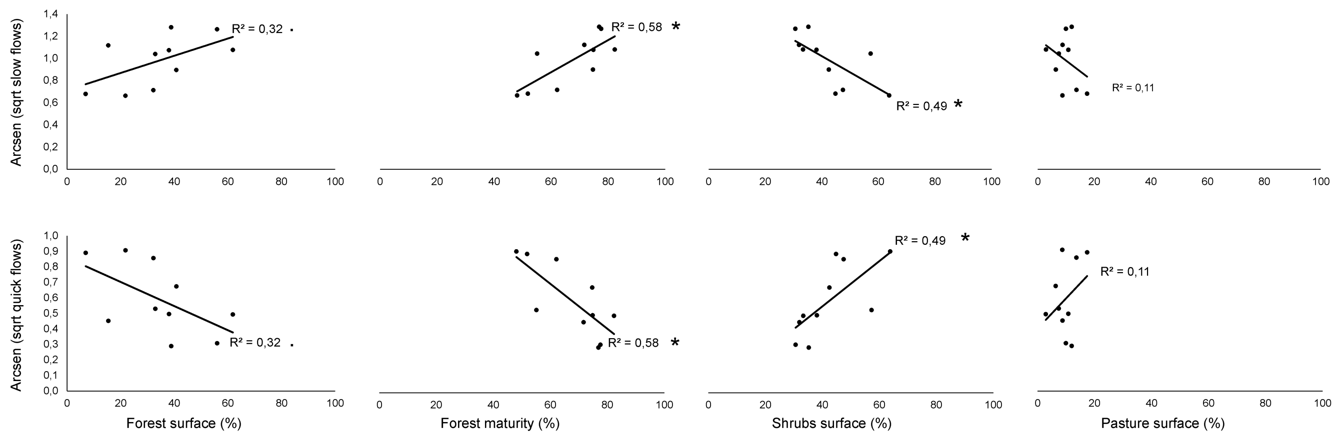

Figure 4. Regression modelling between land use characteristics and the proportion of slow and quick flows modelled through IHACRES for the period 2000-2007 in the ten catchments of the Cantabrian Mountains. Significance levels: '·' ≤ 0,1; '*' ≤ 0,05.