TRENDS ON HIGH FLOWS IN THE CENTRAL SPANISH PYRENEES: RESPONSE TO CLIMATIC FACTORS OR TO LAND-USE CHANGE?

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Abstract This paper analyses the evolution of high flows in the Central Spanish Pyrenees during the period 1955-1995. The method applied makes it possible to assess whether the contribution of the largest daily discharge and rainfall events to the total annual runoff and precipitation remains stationary or shows any temporal trend. The results show a general negative trend in flood intensity in the last decades, together with an increase in the importance of low flows in the total annual contribution. However, a change in the frequency distribution of precipitation events has not been detected. The different behaviour shown by runoff and precipitation could only be explained as being due to the increase in plant cover that is a consequence of the farmland abandonment and reforestation that occurred during the 20th century.

Key words: high flows; trend analysis; plant recolonisation; Central Spanish Pyrenees.

Tendances aux crues dans les Pyrénées Centrales espagnoles: réponse aux facteurs climatiques ou à l´aménagement du territoire ?

Résumé Ce travail analyse l´évolution des crues dans les Pyrénées Centrales espagnoles pendant la période 1955-1995. La méthode appliquée tente de déterminer si la contribution des crues et des précipitations extrêmes est stationnaire ou montre quelque tendance temporelle. Les résultats ont une tendance négative générale dans l´intensité des crues, et un accroissement de l´importance des débits les plus bas en relation avec la contribution annuelle. Cependant, nous n'avons pas détecté de changements dans la distribution de la fréquence des précipitations. La différente dynamique de l´écoulement et des précipitations seulement pourraient être expliquée par l´augmentation de la couverture forestière et arbustive, comme conséquence de l´abandonnement des terres cultivées et la reforestation pendant le 20e siècle.

Mots clefs crues; analyses de tendance ; augmentation de la végétation ; Pyrénées Centrales espagnoles

INTRODUCTION

The study of the frequency of high flows is of paramount importance in assessing the possible risks related to flood events and optimizing the management of water resources. Both issues are extremely important in Mediterranean areas because discharge, as well as precipitation, shows high interannual variability. In this environment, the contribution of high flows is crucial for filling reservoirs (López-Moreno *et al.,* 2002, 2005), but also implies a noticeable risk for infrastructures and settlements located in the floodplains. Thus, managers should take them into account for planning human activities and for analysing the safety of dams.

Previous studies have provided information on the occurrence of extreme precipitation and snowmelt events resulting in high flows in the Pyrenees (Daumas, 1964; García Ruiz *et al.*, 1983, 2000, 2003; White *et al.* 1997). Although floods in the Pyrenees do not usually reach the magnitudes observed on the Mediterranean coast, peakflows can be over 100 times the mean annual river discharge and have catastrophic consequences (Martí Bono and Puigdefábregas, 1983; White *et al.*, 1997; García-Ruiz *et al.*, 2001).

Due to the importance of high flows for risk and water resources management, the detection of changes in the frequency and magnitude of floods is an important research target. The temporal evolution of both magnitude and frequency of high flows is quite difficult to assess, since they are usually related to rainfall events which show a high spatial and temporal variability (García-Ruiz *et al*. 2000). However, several studies have detected changes in low frequency events in different environments, generally related to: i) changes in the occurrence of extreme precipitation events (Kunkel *et al.,* 1999; Groisman *et al.,* 2001); and ii) changes in land cover (Lewis *et al.,* 2001; Changnon & Demissie, 1996; Roo *et al.,* 2003; Ranzi *et al., 2002*; Robinson *et al.,* 2003).

Changes in flood frequency and magnitude induced by changes in plant cover have been frequently studied due to their great importance for risk estimation and territory and water resources management. However, finding statistical evidence about the effect of vegetation on high flows is usually very difficult, given the variability of extremes and the uncertain response of the basins to precipitation (Archer, 2003; García-Ruiz *et al.*, 2005). Although the extent of the hydrological change attributed to vegetation has been discussed frequently in the literature, most studies negatively correlate the occurrence of floods with the surface covered by vegetation (Caissie *et al.*, 2002; Archer, 2003; Gallart & Llorens, 2003; Sullivan *et al.*, 2004; Andréassian, 2004). However, several authors advise caution in the interpretation of this type of results since they can be conditioned by numerous factors such as catchment size, intensity of afforestation, soil depth, vegetation type, rainfall intensity, etc. (Niehoff *et al.*, 2002; Robinson *et al.*, 2003; Lane *et al.*, 2005).

Revegetation was the most important environmental process that occurred in the Pyrenees during the 20th century (Lasanta, 1989; Molinillo *et al.,* 1997). It particularly affected the mid-mountain sectors (below ±1600 m), as a result of farmland abandonment and reforestation activities (García-Ruiz & Lasanta, 1990). The change in plant cover has been responsible for a noticeable decrease in annual runoff (Beguería *et al.,* 2003). However, the effects of the revegetation process on high flows remains unstudied. The main purpose of this paper is to analyze the temporal evolution of high flows during the last decades of the 20th Century and its relation with low frequency precipitation events, using the available precipitation and runoff records.

STUDY AREA

The study area is located between the Aragón and Noguera Pallaresa rivers in the Central Spanish Pyrenees (Fig.1). The relief increases progressively eastward and northward. The highest altitudes are located at the headwaters of the Cinca, Ésera and Noguera Ribagorzana rivers, over 3000 m a.s.l.

Precipitation shows a North-South and West-East gradient depending on relief and the Atlantic and Mediterranean influences. Most of the precipitation falls between October and June (García-Ruiz *et al.* 2001). The summer is relatively dry (with occasional rainstorms), as is the winter, when snowfalls alternate with long anticyclonic periods. Intense precipitation events can occur throughout the year (White *et al.,* 1997; García-Ruiz *et al.,* 2001) although they are more frequent in autumn. Temperature is mainly controlled by the altitudinal gradient, which is around 0.6ºC for every 100 m of increment (Del Barrio *et al.,* 1990). Between November and April the 0ºC isotherm is around 1600-1700 m a.s.l. (García-Ruiz *et al.*, 1986); above that level snow accumulation occurs for a long period. The melting period occurs between April and

June, producing prolonged high discharges and frequent floods which are generally of low to medium intensity (López-Moreno & García-Ruiz, 2004).

Plant cover has been strongly impacted by human activities. Historically, cultivated areas have been located below 1600 m a.s.l., in the valley bottoms, perched flats and steep, south-facing hillslopes, which were managed even under shifting agriculture systems (Lasanta, 1989). Forests remain relatively well preserved on the north facing slopes and everywhere between 1600-1800 m. The subalpine belt (up to 2200 m) was extensively burnt during the Middle Ages to increase the pasture areas (Montserrat, 1992).

During the 20th century, most cultivated fields were abandoned, except in the valley bottoms. Abandoned fields, that represent about 25% of the total area, have been affected by a natural process of plant recolonization (Vicente-Serrano *et al.,* 2005) or have been reforested for land reclamation and to reduce reservoir siltation (Ortigosa et al., 1990).

DATA AND METHODS

Daily precipitation and discharge data were obtained from 18 weather and 18 gauging stations. Both variables show a reasonable spatial coverage of the study area (Fig. 1). The catchments analysed are not affected by human disturbances (reservoirs, water diversions for irrigation, hydropower or urban consumption), or their effect is negligible. The analysis corresponds to the period 1955-1995, depending on the quality (length and completeness) of the data. The few gaps in the precipitation series were filled by means of linear regression with neighbouring stations. The gaps in the discharge series were filled using the SACRAMENTO model from the Ebro River

Hydrographic Administration (www.chebro.es), showing a good agreement with the observed data (López-Moreno, 2005). There are no tests to check the homogeneity of daily precipitation or discharge series. However, the inexistence of inhomogeneities in the monthly series according to the Standard Normal Homogeneity Test (Alexanderson and Moberg, 1997) suggests that weather and gauging stations have not been affected by instrumental or environmental changes.

Following Osborn *et al.* (2000), all days for discharge and all rainy days for precipitation in the period 1959-1995 were sorted in ascending order. The ranked series were then divided into ten classes in such a way that each class added up to 10% of the total accumulated precipitation or runoff. This permitted an analysis of the frequency (in number of days) of each magnitude class for the whole study period.

Moreover, time series showing the contribution of each magnitude class to the annual precipitation or runoff were also obtained. This value can range for a given class above or below 10%, indicating higher or lower importance with respect to the average of the whole period. The Spearman´s rho test was used to detect possible trends in these series. We paid special attention to the observed trends of class ten, representing the heaviest rainfall and most significant discharge events. The analysis was also applied on a seasonal basis.

The evolution of the influence of the different classes on the total amount of runoff or rainfall can be forced by changes in the intensities and/or in the frequency of the events. Changes in frequency were studied from annual time series of the number of days that are over ten times the mean daily runoff (López-Moreno *et al.,* 2003; Múdelsee *et al.,* 2003). The Spearman's rho test was also used to detect the presence of time trends in the series. Changes in the intensity of floods were assessed by comparing the magnitude of the peakflows estimated for different return periods (5 and 25 years) in the period 1955-1974 and 1975-1999. Return periods have been calculated by adjusting the Partial Duration Series over the 97th percentile to a General Pareto Distribution (Madsen *et al.*, 1997).

RESULTS

Fig. 2 shows a high concentration of precipitation and runoff in very few events, whereas most of the days contributed very little to the total amount. On average, 44.3% of the lightest precipitation events were required to make up 10% of the total precipitation during the period 1955-1995 (class one). The number of events in each class decreased progressively, and finally only 1.4% of the heaviest events (class ten) were enough to contribute the final 10% of the total precipitation. Similar results were obtained for discharge. Although the variability between stations was higher than in the case of precipitation, in general a small number of high flow days contributed the greatest part of the annual runoff (on average, class ten included 1.4% of the days).

Fig. 3 shows the observed trend in the contribution of the events designated previously as class 10 on an annual basis. The legend indicates those stations where trends have a high statistical significance ($\alpha<0.05$), low statistical significance ($0.25<\alpha\leq0.05$), and where no trend is detected ($\alpha\geq0.25$). Figure 3A shows that the contribution of the events included in class 10 to total precipitation remains stationary during the study period at most of the weather stations. Low Increases of a low level of significance are observed at only two stations, whereas at others a decrease of a low level of significance is assessed. However, in almost all of the gauging stations the contribution of the high flows to the total runoff decreases in a significant way (Figure 3B).

Similar results were found on a seasonal basis (Table 1). In winter and spring the contribution of the class 10 precipitation events does not show any trend, except for some decreases of a low level of significance, whereas in the gauging stations the highly significant negative trend clearly dominates. In summer, the differences between precipitation and runoff series are smaller. In both cases stations without trend alternate with negative trends of different levels of statistical significance, but the decreases in the contribution of class 10 are more pronounced in the runoff series. Finally, in autumn few highly significant trends are found, but there are differences between precipitation and discharge evolution. Thus, contribution of class 10 precipitation events does not change or increase, whereas runoff series remain stationary or decrease.

A comparison of the evolution of the contribution to total precipitation and runoff of all classes (Fig. 4) confirms the existence of noticeable changes in the frequency distribution of discharge series that cannot be explained by the evolution of precipitation. In the last decades, a clear increase in the importance of low flows to total runoff occurs, especially in classes 2, 3 and 4. Otherwise, the contribution of high flows tends to decrease in most of the stations, especially those belonging to classes 9 and 10. No clear trends exist in any of the classes of precipitation events.

The decrease of torrential behaviour in Pyrenean rivers affects both flood frequency and flood magnitude. Thus, Fig. 5 shows the average number of annual events that are over 10 times the mean discharge of the period 1955-1995 in the study area. The maximum frequency occurred from the end of the 50´s until the beginning of the 70´s. After that, several years did not go beyond this threshold, which was seldom surpassed even in 1.5 events per year, a value that was frequently reached during the first decades. The linear trend shows a significant decrease of 0.03 events per year. Table 2 shows the magnitude of the events expected for a return period of 5 and 25 years at all the gauging stations, considering the period 1955-1975 (A) and 1976-1995 (B). The ratio between both periods indicates a noticeable decrease in the magnitude of the events. The range in the expected reduction oscillates between 8 and 40% for events with a recurrence of 5 years, and between 9 and 46% for events with a return period of 25 years. In both cases the magnitude of the floods decreases 26% on average.

DISCUSSION AND CONCLUSIONS

In this paper the trends in high flows in the central Spanish Pyrenees during the period 1959-1995 have been analysed.

The results obtained have shown a clear decrease in the contribution of high flows to the total runoff, whereas the importance of low flows has increased, especially during winter and spring. A decrease in the frequency and the intensity of flood events has also been found. A similar trend has not been found in the case of precipitation, so we relate the changes in the frequency distribution of runoff to the intense regrowth of vegetation during the 20th century, especially in its second half.

Until the middle of the 20th Century, most of the south facing slopes under 1600 m a.s.l. were cultivated in the Pyrenees, even on very steep hillslopes and with shifting cultivation procedures. The main geomorphic and hydrological consequences were an intensification of soil erosion processes and an increase in the torrentiality of fluvial channels, especially within the Flysch Sector, that is, where the proportion of the cultivated area was higher (Gómez-Villar, 1996). For this reason, most of the rivers showed braided patterns, with unstable channels composed of very coarse sediments (García-Ruiz & Valero-Garcés, 1998). Studies at the "Aisa Valley" Experimental Station confirmed that plots under shifting cultivation (barley crops) and fallow crops yielded high volumes of water and sediment during each rainstorm event in comparison with dense shrub cover and meadow plots (García-Ruiz *et al.*, 1995). Similarly, at a small catchment scale, the hydrological response during rainstorm events is very different in deforested and forest-covered catchments with similar lithological and topographic characteristics. Thus, the Arnas catchment, almost totally deforested and cultivated 40 years ago, reacts to any rainfall event with flash floods that decrease immediately after the rainstorm stops (García-Ruiz *et al.*, 2005). The San Salvador catchment, covered by a dense forest, shows very moderate floods that only occur during very intense rainstorms or under very wet antecedent conditions (Serrano *et al.*, in press). In more humid environments, Boardman (1995) and Sullivan *et al.* (2004) indicated that cereal cultivation amplifies the flood risk due to problems derived from soil erosion and the consequent increase of overland flow.

Farmland abandonment throughout the 20th century resulted in shrub and forest colonization, thus decreasing sediment yield and overland flow. Most probably, a dense forest cover is unable to significantly reduce peakflows during extreme rainstorm events since the interception capacity is quickly “saturated”. This was the case, for instance, of the Biescas campsite disaster, which occurred in the Upper Gállego Valley (Central Spanish Pyrenees) when a rainstorm of about 200-220 mm in 1 hour caused a serious, catastrophic flood in the Arás ravine (9th August 1996), even though the basin was densely covered by pine forest (White *et al.*, 1997). But during more frequent, less intense rainstorms, a reduction in peakflows could be expected due to the effect of both interception (Llorens *et al.*, 1997) and increasing infiltration capacity as a consequence of dryer soil antecedent conditions (Lewis *et al.*, 2001; Caissie *et al.*, 2002; Gallart and Llorens, 2003). Is this the reason why a significant decrease in the intensity of relatively frequent floods has been observed in the Central Spanish Pyrenees? Although the effect of plant cover and land uses on runoff is extremely uncertain, especially during very intense rainfall events (Niehoff *et al.,* 2002; Gallart & Llorens, 2003; Roo *et al.,* 2003; Andréassian, 2004; Lane *et al.,*2005), they may noticeably reduce the frequency and intensity of floods during moderate events. This could explain the change of the role of high flows on Pyrenean hydrology observed in the last decades.

The decrease in the torrentiality of Pyrenean rivers has important consequences in geomorphic processes and in water resources availability and management. Thus: i) a generalized stabilisation of the flood plains has occurred in the last decades: currently, river channels tend to be narrower, and their alluvial plains are more and more stabilised, with an increasing presence of riparian vegetation (García-Ruiz & Valero-Garcés, 1998; Beguería *et al.*, in press); ii) there is evidence of decrease in siltation rates in the Pyrenean reservoirs, implying an important increase of their expected life span (Lopez-Moreno, 2003), most probably due to a reduction in both the frequency and intensity of floods and in sediment yield from hillslopes; iii) the decrease in the occurrence of high flows explain the changes detected in the management patterns of the reservoirs (López-Moreno *et al.*, 2004; López-Moreno, 2005).

At present, at least one third of the old deforested areas still remain without a dense shrub or forest cover (Vicente-Serrano *et al.*, 2005). This suggests that the observed trend in high flows will continue in the near future, affecting more intensively the river regimes and the availability of water resources. This justifies the interest in carrying on further research on this topic at different spatial and temporal scales.

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Table 1. Number of stations with a significant (α = 0.05) trend in the contribution of the events classified as class 10 to the total annual precipitation and runoff.

	Positive (α<0.05)		Positive (α<0.25)		No trend		Negative (α<0.25)		Negative (α<0.05)	
Season	Disch.	Precip.	Disch.	Precip.	Disch.	Precip.	Disch.	Precip.	Disch.	Precip.
Winter	0	0	0	1	2	10	4	6	12	1
Spring	0	0	0	0	2	12	6	5	10	1
Summer	0	0	0	2	5	11	8	5	5	0
Autumn	0	0	1	7	12	9	5	2	0	0

Table 2. Magnitude of the discharge events (m^3s^{-1}) expected for a recurrence of 5 and 25 years for the periods 1955-1974 (A) and 1975-1979 (B).

		Return period: 5 years			Return period: 25 years		
River	**Location**	A	B	**B/A**	A	B	**B/A**
Veral	Zuriza	32	20	**0.63**	49	29	**0.58**
Veral	Biniés	61	52	**0.86**	79	72	**0.91**
A. Subordán	Javierragay	183	132	**0.72**	246	170	**0.69**
Esca	Sigüés	191	163	**0.85**	252	230	**0.91**
Aragón	Jaca	129	99	**0.77**	209	145	**0.69**
Aragón	Inflow to Yesa	432	375	**0.87**	574	545	**0.95**
Ara	Boltaña	367	310	**0.85**	670	533	**0.8**
Ara	Torla	112	103	**0.92**	202	184	**0.91**
Cinca	Escalona	466	381	**0.82**	901	623	**0.69**
Cinca	Lafortunada	196	152	**0.78**	327	287	**0.88**
Cinca	M. Gistaín	41	31	**0.75**	64	44	**0.68**
Ésera	Eriste	110.6	87.6	**0.79**	184	113	**0.61**
Ésera	Graus	370.4	203.1	**0.55**	801	511.8	**0.64**
Isabena	Capella	164	98	**0.6**	311	263	**0.85**
N. Tor	C. Bohí	26	18	**0.7**	50	33	**0.67**
N. Ribagorzana	Ginasté	76	47	**0.62**	138	75	**0.54**
N. Ribagorzana	P. Suert	207	126	**0.61**	446	248	**0.56**
N. Pallaresa	Collegats	293	187	**0.64**	503	414	**0.82**
Mean value				**0.74**			**0.74**

Figure Captions

Figure 1. Study area.

1 River Aragón; 2 River Gállego; 3 River Cinca; 4 River Ésera; 5 River Noguera Ribagorzana; 6 River Noguera Pallaresa

Figure 2. Number of daily events (in %) in each magnitude class for precipitation (A) and runoff (B). The box plots show the median, 1st and 3rd quartiles, and 1st and 9th deciles of the observatories.

Figure 3. Observed trend in the contribution of events classified as class ten to the total annual precipitation (A) and runoff (B).

Figure 4. Observed trend in the contribution to total precipitation and runoff of all classes. A: precipitation, B: discharge.

Figure 5. Average number of annual events that are over 10 times the mean discharge of the period 1955-1995.

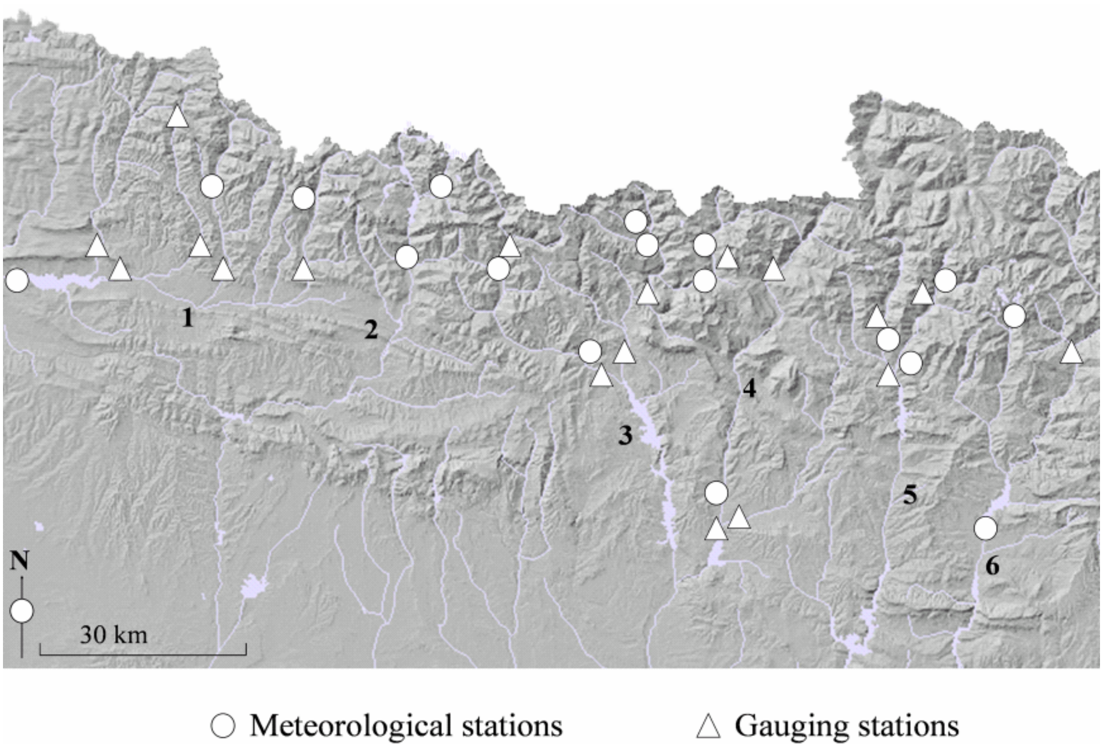
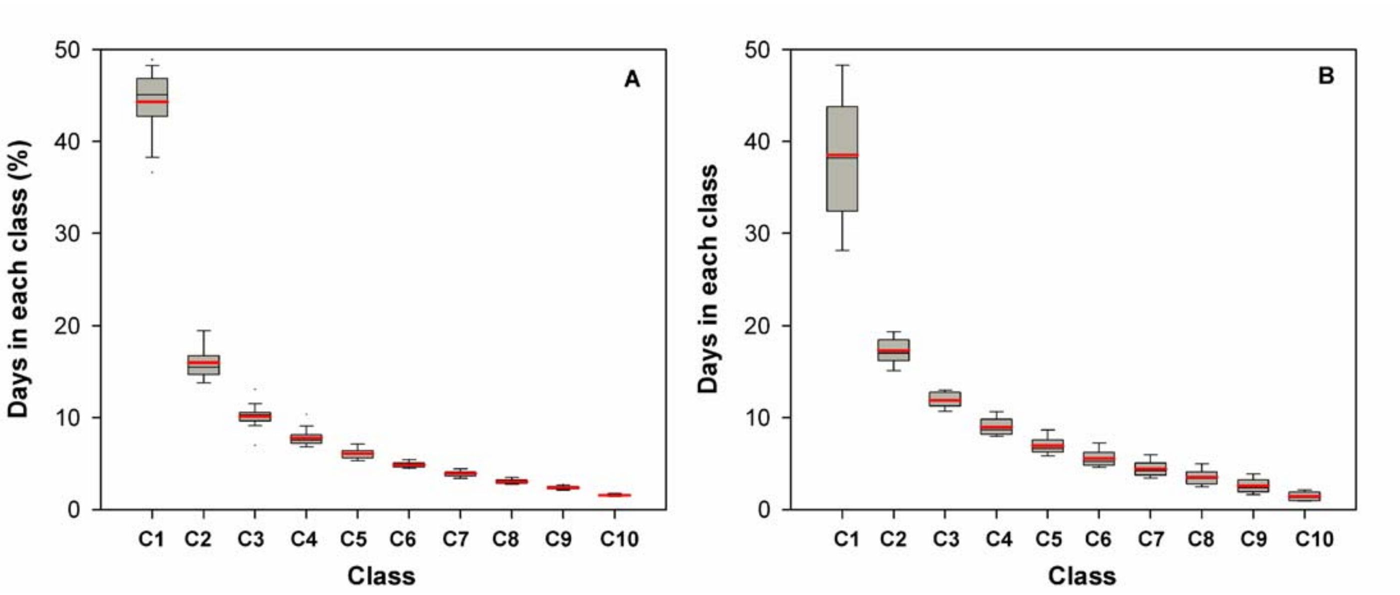


Figure 1



A
Days in each class (%)
50
40
30
20
10
0
C1 C2 C3 C4 C5 C6 C7 C8 C9 C10
Class
B
Days in each class
50
40
30
20
10
0
C1 C2 C3 C4 C5 C6 C7 C8 C9 C10
Class

Figure 2.

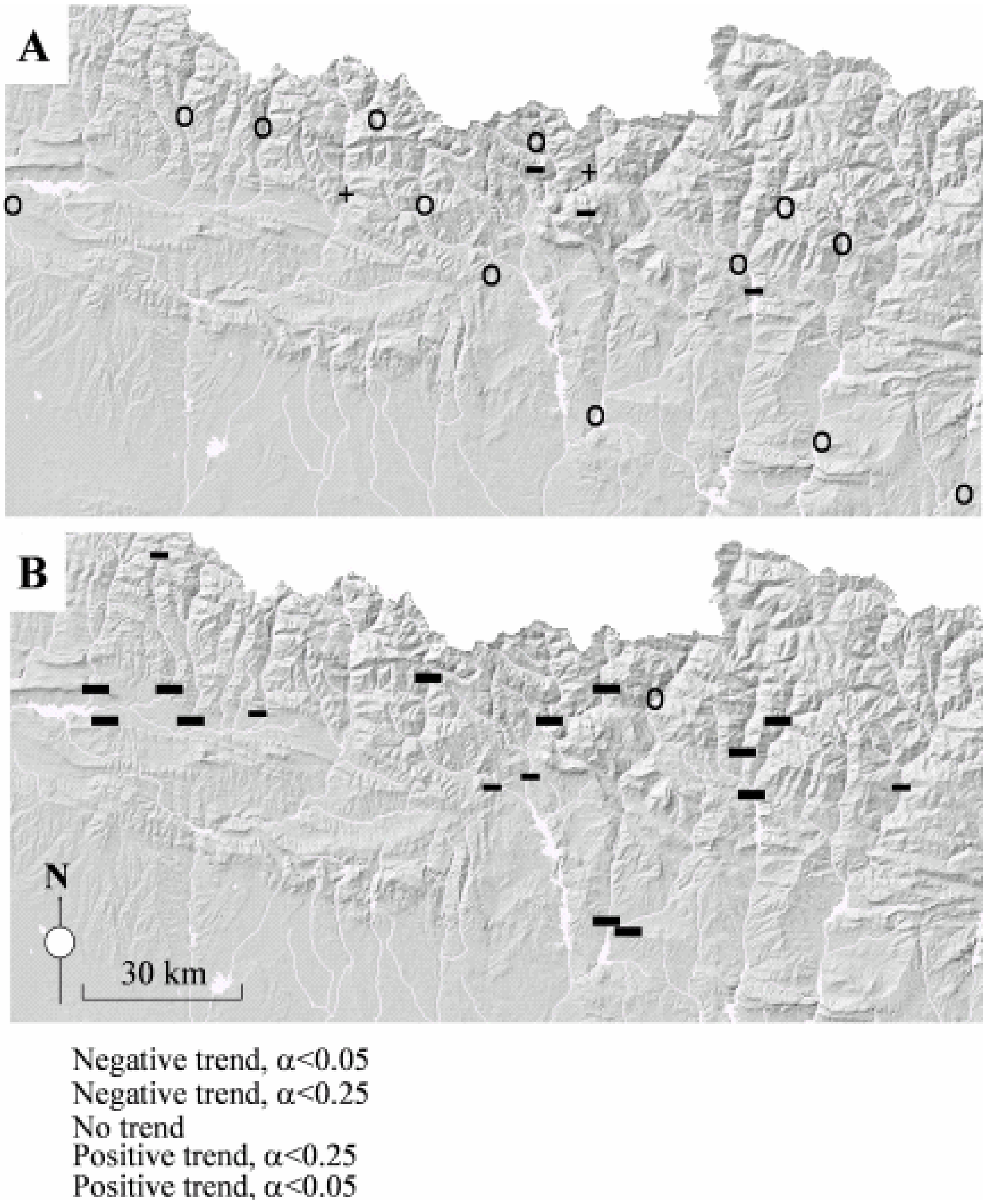

A
B
N
30 km
Negative trend, α<0.05
Negative trend, α<0.25
No trend
Positive trend, α<0.25
Positive trend, α<0.05

Figure 3.

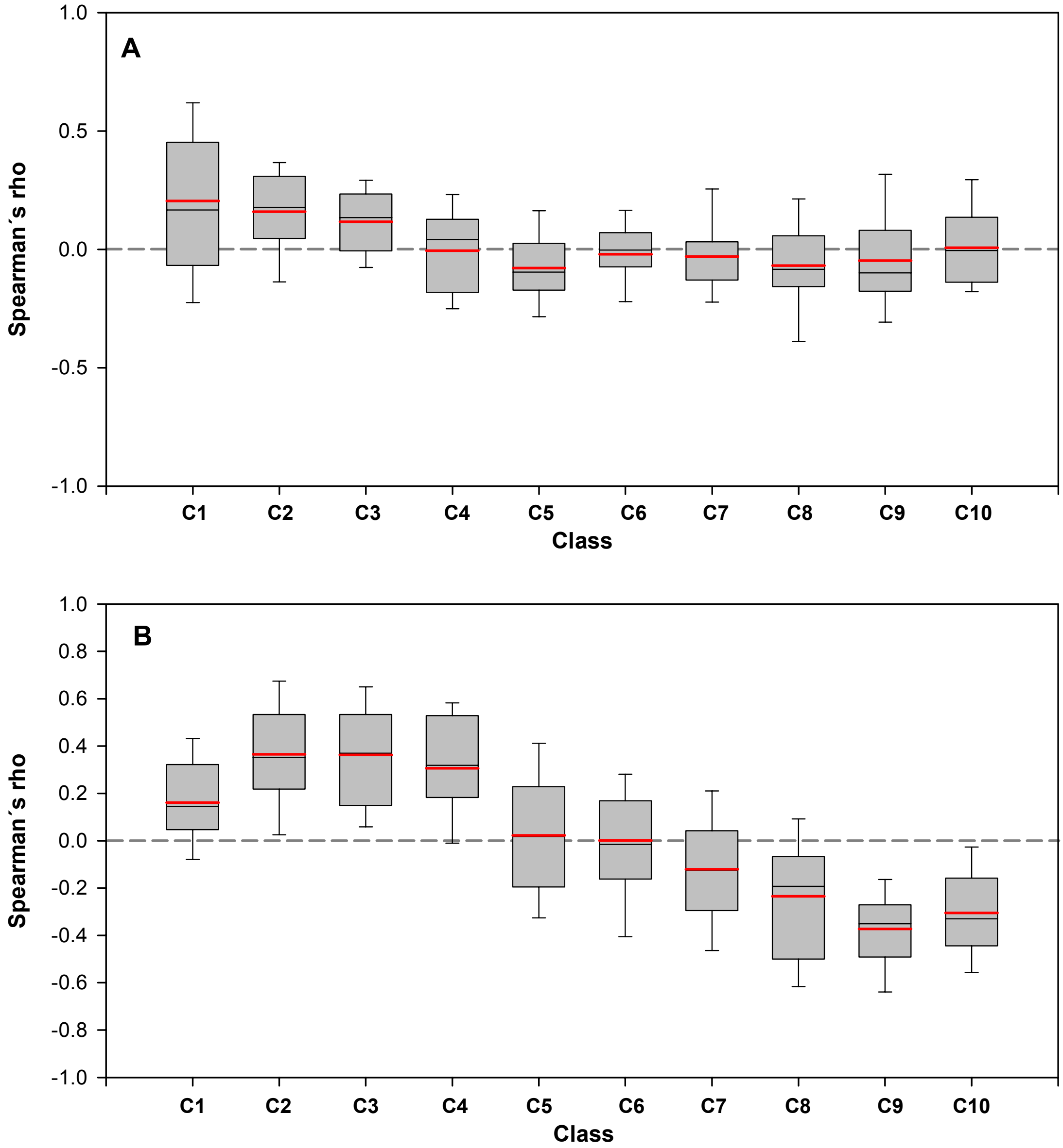

A
1.0
0.5
0.0
-0.5
-1.0
Spearman´s rho
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
Class
B
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
Spearman´s rho
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
Class

Figure 4.

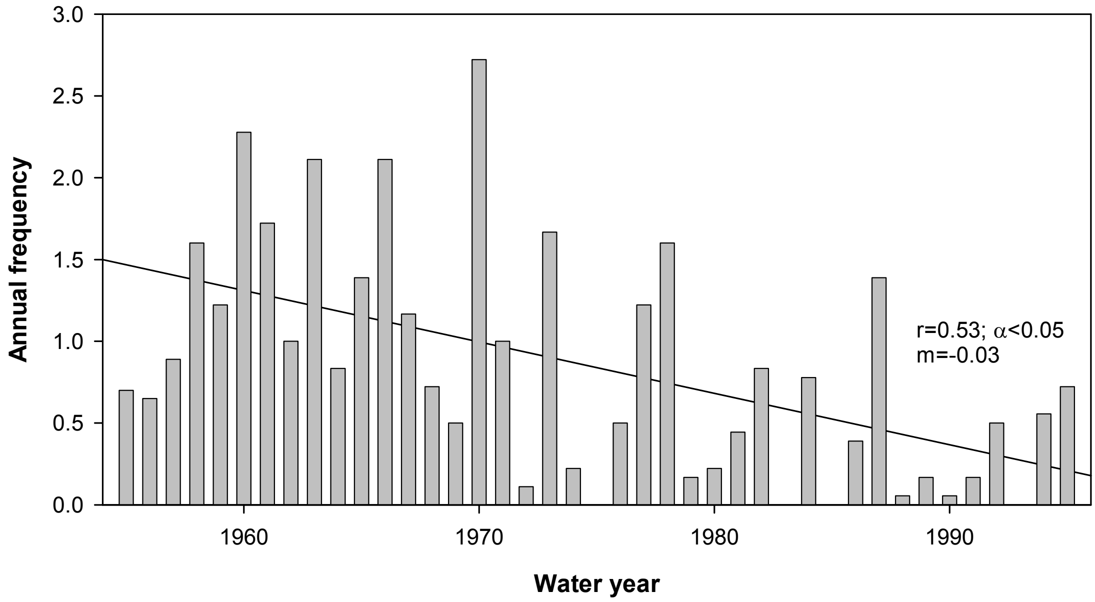

3.0
2.5
2.0
1.5
1.0
0.5
0.0
Annual frequency
r=0.53; α<0.05
m=-0.03
1960
1970
1980
1990
Water year

Figure 5.