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Impact of climate evolution and land use changes on water yield in the Ebro basin

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Abstract

In this study the climatic and hydrological trends across 88 sub-basins of the Ebro River basin were analyzed for the period 1950–2006. A new database of climate information and river flows for the entire basin facilitated a spatially distributed assessment of climate-runoff relationships. It constitutes the first assessment of water yield evolution across the whole Ebro basin, a very representative example of large Mediterranean rivers. The results revealed a marked decrease in river discharges in most of the sub-basins. Moreover, a number of changes in the seasonality of the river regime was found, resulting from dam regulation and a decrease in snowpack in the headwaters. Significant and positive trends in temperature were observed across most of the basin, whereas most of the precipitation series showed negative coefficients, although the decrease in magnitude was low. The time evolution of the residuals from empirical models that relate climate and runoff in each sub-basin provided evidence that climate alone does not explain the observed decrease in river discharge. Thus, changes in water yield are associated with an increase in evapotranspiration rates in natural vegetation, growth of which has expanded as a consequence of land abandonment in areas where agricultural activities and livestock pressure have decreased. In the lowlands of the basin the decrease in water yield has been exacerbated by increased water consumption for domestic, industrial and agricultural uses. Climate projections for the end of the 21st century suggest a reduced capacity for runoff generation because of increasing temperature and less precipitation. Thus, the maintenance of water supply under conditions of increasing demand presents a challenging issue requiring appropriate coordination amongst politicians and managers.

1 Introduction

Mountains play a critical role in water resources availability in lowland areas of drainage basins. Altitudinal gradients in temperature and precipitation ensure that headwaters

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receive more precipitation and have lower evapotranspiration rates than adjacent lowlands (Viviroli et al., 2004; De Jong et al., 2009). Moreover, in mountain regions at high and mid latitudes a large amount of precipitation falls as snow, which is stored frozen in winter. The melting of snow during spring causes high river flows, even in areas where climate exhibits high interannual variability (López-Moreno et al., 2004; Barnett et al., 2005).

In Mediterranean areas there is great dependence on water from mountains, representing a between a 20 and a 90% of the total runoff (Viviroli et al., 2007). Basins with headwaters covered by snow in winter produce high flows in spring and early summer, which helps to meet agricultural and water availability needs independently of the spring climate. Nonetheless, water management in the Mediterranean region is difficult as water is a scarce resource but a key element in ensuring the development of irrigation agriculture, increased populations, improved living standards, industry and tourism activities (Cudennec et al., 2007). In this context water resources generated in mountains are under increasing pressure because of constantly increasing demand. For instance, the expansion of irrigated areas and urbanization in dry parts of Spain has increased water supply difficulties and caused associated political and social conflicts (Ibáñez and Prat, 2003). Under such conditions the rising demand for water is met by increasingly expensive and complex infrastructure necessary to store seasonal or annual water surpluses in reservoirs, to transfer the water from storage sites, generally in the mountains, to areas of demand, and to pump groundwater reserves (Croke et al., 2000). Unfortunately, large infrastructure developments during the 20th century were built on the basis that water availability would remain roughly stationary over time, despite the occurrence of short-term oscillations in supply. However, there is clear evidence of a change in long-term climatic trends that is affecting the environment of Mediterranean mountains (Giorgi and Lionello, 2008), and changes in land cover have produced marked alterations in hydrological responses at the basin scale (Andréassian, 2004).

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Climate projections for the coming decades point to warmer conditions over most of the Mediterranean mountains region (Giorgi, 2006), a marked decrease in snow accumulation and the duration of snow cover (López-Moreno et al., 2009a), and a generalized decrease in precipitation (Ragab and Prudhomme, 2002; Giorgi and Lionello, 2008), although the latter prediction is associated with large spatial and seasonal variations (López-Moreno et al., 2008a, and references therein; Nogués-Bravo et al., 2008) and substantial uncertainty. Moreover, large areas are likely to continue to be subject to major land use and land cover changes, which in the Mediterranean region are mostly characterized by increasing vegetation in headwaters, as a consequence of land abandonment during the 20th century (Debussche et al., 1999; Beguería et al., 2003; Lasanta et al., 2005).

Increasing efforts are being made to quantify and understand the consequences of environmental change for the hydrological response of mountain areas, and to assess its impact in the lowlands. This may improve the capacity to optimize water use and enhance preparedness for future challenges in water management. In this study climatic and hydrological trends across the Ebro basin (northeast Spain) were analyzed. Changes in the runoff coefficients of 88 sub-basins of the Ebro River were used to investigate the evolution of water yield since 1950, which enabled assessment of whether trends in runoff are driven by climatic factors, by the land cover changes that have occurred in the basin, or both. The Ebro basin is representative of Mediterranean basins that depend on water generated in mountain areas (mainly the Pyrenees), and are subject to enormous pressure on water resources because of the development of large irrigation areas and industrial zones, and the growth of major urban settlements. Previous studies have identified climate variations and revegetation in headwaters as causes of decreasing river flows in Pyrenean rivers (Beguería et al., 2003; López-Moreno et al., 2008b).

The availability of newly developed climate and river flow databases for the Ebro basin enabled us to conduct the first spatially distributed analysis to climate-runoff relationships, and to identify those sectors for which environmental change may have the most significant consequences for water availability in the basin. The results are discussed in the context of climatic and environmental projections for the region in coming decades.

2 Study area

The study area comprises about 83 000 km^2 in the northeast of Spain and has very contrasting relief (Fig. 1a). The main unit is the Ebro Valley, which is a depression surrounded by high mountain ranges including the Cantabrian Range and the Pyrenees to the north (maximum elevations above 3000 m a.s.l.), the Iberian mountains to the south (maximum elevations 2000–2300 m), and the Coastal Range to the east (maximum elevations 1000–1200 m a.s.l.). The latter parallels the Mediterranean coast and abruptly encloses the Ebro Valley.

The heterogeneous topography, contrasting influences of Atlantic and Mediterranean conditions, and the influence of various large scale atmospheric patterns (Vicente-Serrano and López-Moreno, 2006) generate a complex spatial distribution of climate parameters. Large variations in precipitation and evapotranspiration occur throughout the region (Ninyerola et al., 2005; Vicente-Serrano et al., 2007), and annual precipitation varies from 307 to 2451 mm yr^{-1}. Most of the precipitation falls in autumn and spring, although in some areas the maximum precipitation occurs in winter and summer (López-Moreno et al., 2008b). Average annual temperature varies from 0.8 to 16.2 °C.

The humid conditions in these mountainous areas, especially the Pyrenees, are in stark contrast to the dry characteristics of large areas of the Ebro River valley, emphasizing the importance of hydrology and water resources throughout the study region. For example, the headwaters of Pyrenean rivers considered in this study (Fig. 1; the Irati, Aragón, Gallego, Cinca, Ésera, Noguera Ribagorzana, N. Pallaresa and Segre rivers) occupy 11% of the surface of the Ebro valley, but generate 56% of the total runoff (mean value for the period 1950–2005). The relative abundance of water in the area led to the construction of numerous dams to regulate the main rivers, which markedly altered river regimes and reduced flood occurrence (López-Moreno et al., 2002). Most of the dams were built between the 1950s and the 1980s, leading to an increase in storage capacity from 500 to 3000 hm^3; this represents approximately half of the mean annual runoff of the Pyrenean rivers. This capacity enables the diversion of 1947 $hm^3 yr^{-1}$ to irrigate 295 748 ha of land (77% of the irrigated area of the Ebro basin) and the generation of 62% of the hydropower produced in the region (López-Moreno, 2006).

Until the middle of the 20th century most of the south facing slopes below 1600 m a.s.l. were cultivated. The main hydrological and geomorphological consequences of this were an intensification of soil erosion processes and an increase in the torrential nature of fluvial channels (García-Ruiz and Valero-Garcés, 1998). For this reason most of the rivers are braided and have unstable channels. The subsequent abandonment of farmland, associated with depopulation, has been the most outstanding feature of the Spanish Pyrenees (Beguería et al., 2003; Lasanta et al., 2005; López-Moreno et al., 2008), and by 1970 all the fields on hillslopes had been abandoned. These areas were then recolonized by shrubs, and induced afforestation took hold in many areas that were previously cultivated and grazed (Vicente-Serrano et al., 2004). As in the Pyrenees, generalized land abandonment and subsequent revegetation processes have occurred in all the mountainous areas that enclose the Ebro basin (Lasanta et al., 2006). Indeed, based on estimates of the evolution of the spring normalized difference vegetation index (NDVI), derived from NOAA satellite imagery (8 km spatial resolution) since 1981, more than 45% of the surface area has been affected by a statistically significant increase in the vegetation index, which is related to the increase in vegetation cover and its physiological activity (Nogués et al., 2010).

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3 Data and methods

Climate trends were analyzed from monthly series of precipitation (429) and temperature (55) from observatories located within the Ebro basin or in its immediate surroundings. The series were obtained through a process that included reconstruction, gap filling, quality control and homogenization testing with independent reference series (see González-Hidalgo et al., 2009).

The river flow evolution at 88 gauging stations managed by the Ebro Water Management Agency (Confederación Hidrográfica del Ebro, CHE) was analyzed. In terms of climate data there is a reasonable spatial coverage with respect to hydrological observations across the entire Ebro basin (Fig. 1b). The criteria for selection of a gauging station was that the series had commenced by 1950, encompassed at least 30 complete years, and any data gaps were able to be filled using data from neighboring gauging stations with which there was a Pearson-correlation coefficient of at least $r=0.80$.

To assess the evolution of temperature and precipitation in a spatially distributed fashion, monthly distributed layers from 1950 to 2006 at a resolution of 1 km^2 were created by interpolating values from the various observatories. For this purpose we used multiple linear regression, in which a number of geographic (latitude and distances to the Mediterranean Sea and the Atlantic Ocean) and topographic (elevation) parameters were used as predictors of monthly temperature and precipitation (Daly et al., 1994, 1997; Agnew and palutikof, 2007). The residuals (the difference between the climatic variable measured at each weather station and the value predicted by the model) were subsequently obtained for each observatory and interpolated over the study area using local techniques (see Ninyerola et al., 2000, for more details).

The distributed monthly layers obtained were aggregated into annual and seasonal series, and trend analyses for the period 1950–2006 were conducted in two ways: i) for each 1 km^2 cell of the study area, and ii) for the sum of precipitation and average temperature for the area drained at each of the 88 gauging stations. Trend analyses for

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the same period were also conducted for annual and seasonal river discharges and the runoff coefficient (water yield), which was defined as the ratio of precipitation to river discharge in each sub-basin. We used the nonparametric Mann-Kendall (MK) test to assess the sign, strength and significance of the evolution of the hydroclimatic series. This test has been widely used to detect trends in climatic and hydrological series (e.g. Hirsch et al., 1982; Sneyers et al., 1990; Yue et al., 2002a). Autocorrelation in the data series was removed prior to application of the MK test; the occurrence of serial correlation can increase the probability that the MK test detects a significant trend (von Storch, 1995). Although most studies assume that climatic data are serially independent, it has been shown that some hydrological variables, including mean and minimum streamflows, can exhibit significant serial correlation (Yue et al., 2002b). To remove serial correlation the TFPW (trend-free pre-whitening) procedure developed by Yue et al. (2002b) was applied to our monthly river discharge series. The MK test was then performed on the correlation-free series. Based on the sign of the trend (MK's tau) and the level of significance (α; probability of rejecting the null hypothesis i.e. no trend in the data) we classified the series into 5 groups, following the procedure of Westmacott and Burn (1997):

- SIT (strong increasing trend): tau≥0 and $\alpha \leq 0.05$
- MIT (moderate increasing trend): tau≥0 and $0.05 > \alpha \leq 0.10$
- NST (non significant trend): $\alpha > 0.10$
- MDT (moderate decreasing trend): tau<0 and $0.05 > \alpha \leq 0.10$
- SDT (strong decreasing trend): tau<0 and $\alpha \leq 0.05$

The methodology proposed by Beguería et al. (2003) was used to infer the potential impact of land use changes on runoff generation in the various sub-basins of the Ebro basin. The method is based on removing the influence of the two most influential climatic parameters (temperature and precipitation) from the annual river discharge series. This was done using stepwise linear regression models for each sub-basin. The

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independent variables were the sum of annual precipitation and mean temperature of the area drained at each gauging station. The annual runoff in each sub-basin was the dependent variable. Series of residuals were evaluated to assess whether they exhibited significant trends. The occurrence of a significant trend suggested that water yield had changed in time independently of the evolution of climatic conditions. Given that most of the factors that explain hydrological evolution (except climate) remain stationary in time (e.g. lithology) or change slowly (e.g. soil depth or soil characteristics), only changes in land cover and vegetation can explain potential trends in water yield. This premise is only valid in basins where human activities are moderate and do not affect interannual hydrological behavior (pluriannual reservoirs, or diversions to agricultural areas or large urban settlements). Hence, this premise will apply in headwater catchments, whereas in the lower reaches of the Ebro River the trends in residuals may also be due to water consumption by cities and for agricultural activities.

The potential impacts of climate change in the Ebro basin where analyzed using simulations of temperature and precipitation for the period 1960–2080 under emissions scenario A1B1 (moderate greenhouse gases emissions) from the HIRHAM5 model (Danish Meteorological Institute) at a spatial resolution of 25 km^2. Simulations were downloaded from the ENSEMBLES EU-funded project (http://ensembles-eu.metoffice.com/). Changes in annual and seasonal temperature and precipitation were calculated by subtracting the long-term means of the time slice 1960–1990, to 2020–2050 and 2051–280. Selection of this model was based on its ability to reproduce temperature and precipitation over the Pyrenees and the center of the Ebro valley. Moreover, it was compared with a set of regional climate model projections from the PRUDENCE dataset, as this model is representative of the mean sign and magnitude of the multi-model ensemble average (López-Moreno et al., 2008a).

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4 Results

4.1 Trends in climatic and hydrological variables

Figure 2 shows the trend of annual and seasonal precipitation across the Ebro basin during the studied period (1950–2006). The evolution of precipitation shows that annual precipitation was generally stable across most of the basin. In general, negative MK tau coefficients dominate, but only very small areas exhibited a statistically significant decrease, and any place has shown an upward trend. Only two small sub-basins in the northwest of the Ebro basin showed a moderate but significant decrease. Autumn was associated with a significant increase in precipitation in the east of the basin, with many sub-basins affected by moderate or large increases. However, the total precipitation for the area draining to the outlet gauging station did not show a significant trend, which indicates a stationary situation for the entire basin. Negative but generally nonsignificant coefficients were found for broad areas during winter and summer. Only a few sub-basins, generally to the west, showed significant trends. A relatively stationary behavior was observed for spring precipitation.

The trends in temperature are shown in Fig. 3. Annual temperature showed a significant increase over most of the Ebro basin. The majority (86/88) of the areal sub-basin averages exhibited moderate or large increases (a mean increase of 0.2 °C per decade for the entire basin). The MK tau values indicate that warming has been more intense in the north of the study area (more than 0.3 °C per decade), severely affecting most of the Pyrenean basins and the westernmost sectors. On a seasonal basis, temperatures in summer showed the largest increase (average 0.34 °C per decade). The winter temperature has increased across most of the Pyrenees, affecting all of the headwater basins, but has remained stationary or has become slightly colder in some areas in the center of the Ebro valley. Spring temperatures have increased markedly in the northeast of the study area, and significant increases have also occurred throughout the Pyrenees and in large areas of the Ebro Depression. In the southernmost areas temperature has remained practically stationary. In autumn, smaller areas and fewer

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basins have been affected by warmer temperatures. However, the temperature in some basins of the Pyrenees has increased substantially.

The temporal evolution of river discharges (Fig. 4) is in stark contrast to that of precipitation. Thus, a large decrease ($p < 0.05$) was observed at the majority of gauging stations (55/88), five stations showed a moderate decrease, and 23 had negative but nonsignificant coefficients. Only at two sites was an upward trend recorded, possibly as a consequence of human interference with the river flows. Discharges at observatories at the outlet of the basin showed a large decrease, indicating that a statistically significant decrease in river flows has occurred in the Ebro basin. Although there was no clear pattern in the spatial distribution of stationary hydrological records, most of the gauging stations without significant trends are located in the lower reaches of several tributaries in the eastern Pyrenees.

Winter differed from the other seasons in terms of temporal evolution. Many of the gauging stations in the headwaters in the Pyrenees and the Iberian mountain showed a stationary behavior, suggesting an increase in the ratio of rainfall to snowfall. Most of the negative trends were found to the west and south of the Ebro basin. The evolution of discharges during summer also differed from the evolution observed on an annual basis, and also from the climatic evolution. Thus, a stationary behavior was observed at several gauging stations in the east of the basin, and also in the lower reaches of the Pyrenean tributaries and the main stream of the Ebro River. The evolution during spring and autumn exhibited a similar trend to annual values, with negative and statistically significant MK tau coefficients at the majority of gauging stations.

4.2 Trends in water yield and its relationship to climate and land cover evolution

Figure 5 shows the results of application of a stepwise linear regression to prediction of annual runoff from annual temperature and precipitation over the 88 sub-basins analyzed in the Ebro basin. Figure 5a shows the coefficient of determination for each regression, which indicates the variance explained by each climatic variable. As expected, there was large variability (12–73%) across the basin with respect to the

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influence of climate on the interannual evolution of discharge. Headwaters typically exhibited the greatest explained variance, being this punctually reduced in gauging stations located in lower reaches of the Pyrenean tributaries and in the south and west of the basin, mainly due to dam operations and flow diversions for agricultural purposes. Nonetheless, the large scale nature of this study explained the occurrence of numerous exceptions as a consequence of uncertainties inherent in modeling monthly climatic layers, the regression model, and the unique circumstances of the various gauging stations (potential water diversions or inflows). The coefficients of regression (data not shown) indicated that precipitation is a much more influential driver of runoff variability, explaining 8–72% of the variance for the 88 gauging stations (mean value r^2=0.46); temperature explained a maximum of 18% of the variance (mean value r^2=4%). In 40 sub-basins, temperature was not included as a significant variable. Figure 5b shows the signs and magnitude of the trend in the series of model residuals, i.e. the evolution of runoff series after the influence of climate had been removed. In 70 sub-basins there were large or moderate negative MK tau coefficients.

Based on the results presented above it is evident that the runoff coefficient has declined significantly in most of the sub-basins of the Ebro River. A generalized decrease in river flows during a period when precipitation levels have remained largely stationary can only be explained by a decrease in the water yield in the basin. Thus, the runoff coefficient reflects a spatial pattern of river discharge evolution that is even more marked than that observed for discharge (Fig. 6), involving a generalized decrease in water yield across the Ebro River basin (55 strong trends and 7 moderate trends). The seasonal patterns were practically identical to those found for trends in river discharges.

Although a decrease in river discharge and water yield has affected large areas of the Ebro basin, the consistent changes observed in the majority of the Pyrenean basins is of particular concern. These are the main contributors to the total discharge of the Ebro River and, although not statistically significant, were shown to have received decreased precipitation and undergone a marked increase in temperature and water yield.

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Figure 7 shows the annual runoff from Pyrenean headwaters (between the Iraty and Segre rivers, see Fig. 1), the Ebro discharge in its lower reaches (Tortosa station) very close to the Mediterranean Sea (lower panel), and the evolution of the ratio between both series (upper panel). The annual series for the Pyrenean basins and the lower Ebro River showed statistically significant decreases, but it was more pronounced in the latter. Thus, there has been a marked increase in the ratio between the series. At the beginning of the analyzed period the Pyrenean discharges represented approximately 40% of that of the lowest gauging station of the basin, but during the last 20 years this has consistently exceeded 60%. The lower Ebro River reflects the effects of a marked loss in water yield capacity in the Pyrenees, the major consequences of climate trends and land cover changes in other mountain areas including the Iberian mountains and the Cantabrian range, and an increase over time in the water consumed by large urban settlements (i.e. Zaragoza) and the irrigation areas of the Ebro Depression. Thus, the Ebro basin has an increasing dependence on the Pyrenees for water supply, but the latter is showing a decrease in its water yield capacity.

4.3 Climate change projections for the Ebro basin

Figures 8 and 9 show the changes in temperature and precipitation, respectively, projected by the HIRHAM5 model under the A1B emissions scenario for two time slices (2021–2050 and 2051–2080) compared with the 1960–1990 period. Figure 8 shows that a generalized increase in temperature is expected for the Ebro basin during this century. On an annual basis, warming is expected to be more intense in the Pyrenees and Iberian mountains, especially in the central and eastern areas where temperatures may increase 1.5–2 °C in the 2021–2050 time slice and up to 4 °C in the 2051–2080 period. The greatest increase in temperature is projected for spring and summer. In all seasons the mountainous areas (Pyrenees and Iberian mountains) will be most affected by warming, which may reach 2.5 °C and 5 °C in each of the time slice periods, respectively. Warming trends in autumn are lower, and winter is projected to be the period with the smallest temperature increase, which in the Pyrenees will be 1–1.5 °C

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in the 2021–2050 time slice and 2–2.5 °C in the 2051–2080 time slice. Nonetheless, such changes have been shown to be sufficient to significantly alter snow accumulation patterns in the Pyrenees (López-Moreno et al., 2009).

A moderate decrease in precipitation is expected to occur in the basin (Fig. 9), and to be particularly pronounced in the east of the study area. For the 2021–2050 period the changes are expected to be small and largely involve areas in the west of the basin, which may receive a slight increase in precipitation. For the period 2051–2080 a decrease that may occasionally exceed 30% in the eastern part of the basin is predicted to occur; further westward the decrease will be progressively less pronounced. The greatest seasonal decreases in precipitation are expected to occur in autumn and spring, and to show the same eastward spatial pattern to that of annual precipitation values. Summer precipitation is expected to undergo small changes for the period 2021–2050, but is projected to decrease more rapidly by the end of the century. The greatest changes are projected to occur in the center of the Ebro valley. The changes in winter precipitation are expected to be small and to lack a defined spatial pattern, exhibiting trends with opposite signs in adjacent regions. In general, the model projects stable or slightly increasing precipitation in the western Pyrenees and most of the Ebro basin, and a slight decrease in precipitation in the eastern Pyrenees and broad sectors of the Iberian mountains.

5 Discussion

This study provides evidence that runoff has declined in most of the Ebro basin since the second half of the 20th century. In this context the hydrological role of the mountains, in particular the Pyrenees, is increased. Thus, runoff generation in the Pyrenees is decreasing, but the pressure on its water resources has increased as its contribution to the Ebro River has gained in importance in recent decades.

The occurrence of significant and positive trends in temperature was confirmed; however, the capacity of this variable to explain temporal evolution of river discharges is

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very limited. For precipitation, trends show negative coefficients, but they were generally not significant. Thus, we can confirm that climate alone does not explain the magnitude of the decrease in river discharges. The likely explanations are: i) an increase in water consumption by urban areas, agriculture, industry and tourism in recent decades; and ii) an increase in water consumption by natural vegetation, which has expanded in areas where grazing and traditional agriculture have disappeared. Given that most of the runoff is derived from the mountainous river headwaters, which are practically unregulated, revegetation appears to be the most plausible explanation for the magnitude and spatial dimension of the hydrological changes that have occurred. The effect of vegetation on runoff generation is not fully understood, as it changes markedly among sites in response to the specific climatic conditions, vegetation type and the structure of the landscape (Andréassian, 2004; Cosandey et al., 2005). However, it is generally accepted that afforestation causes a decrease in runoff generation and an attenuated response to rainstorm events (Ranzi et al., 2002; Beguería et al., 2003; Gallart and Llorens, 2003; Andréassian, 2004), which is directly attributable to changes in evapotranspiration and infiltration rates (Calder, 1992; Fohrer et al., 2001).

In addition to changes in the annual amount of water, marked changes were detected in the seasonality of river flows. The reported decrease in snow accumulation during winter and spring in the Pyrenees (López-Moreno, 2005) apparently influenced the results presented here. In view of the climate evolution during winter (Figs. 2 and 3), the stationary or upward evolution of river discharges in headwaters in the north of the basin (the Pyrenean area) may be associated with the increased temperature recorded in that area, which could negatively affect the ratio of snowfall to rainfall and result in less water being stored during winter (López-Moreno, 2005). Spring had amongst the largest decreases in river flows and runoff coefficients, which is consistent with less flow from snowmelt. A similar shift in the seasonal distribution of water resources has been detected in many mountainous areas where snow cover has declined in recent decades (Barnett et al., 2005; Birsan, 2005). However, it is noteworthy that in areas where the density of vegetation is increasing, the greatest evapotranspiration demand

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occurs in spring and summer, which may exacerbate the hydrological changes associated with changes in snow cover. Decreases in runoff coefficients also affect numerous sub-basins where snow plays a secondary role, which suggests an increase in actual evapotranspiration. The evolution of discharges during summer differed from the annual pattern and the climate evolution. Thus, in many sub-basins a marked decrease in runoff was detected, but several gauging stations in the east of the basin, the lower reaches of the Pyrenean tributaries and the main stream of the Ebro River showed a stationary evolution. Such contrasting evolutions may be associated with dam regulation designed to maintain ecological discharges, even in areas were precipitation has decreased and temperatures have markedly increased (López-Moreno et al., 2004; López-Moreno and García-Ruiz, 2007).

The prospects for the future are quite uncertain, as the climate scenarios point to a reduced capacity for runoff generation as a consequence of increased temperature (which affects evaporation rates) and less precipitation. Moreover, revegetation is far to conclude. Large areas covered by shrub are prone to evolve toward forest, and abandonment of grazing in the subalpine belt, together with warmer conditions, may result in the tree line shifting to a higher altitude (Cheddadi et al., 2001; Gaucherel et al., 2008).

The findings for this region reinforce the need (noted during the Göschenen workshop and in this special issue) to increase our understanding of changes occurring in mountain hydrology. Research on environmental change and hydrological functioning conducted in the Pyrenees over several decades has advanced knowledge of hydrological changes at various spatial scales, including in experimental plots, experimental catchments, and at the basin scale (Beguería et al., 2003; Lasanta et al., 2006; García-Ruiz et al., 2008). However, there are many components of the hydrological system that remain poorly understood as a consequence of the lack of hydrometeorological data (especially in the high mountain belt) and the difficulties associated with estimating actual evapotranspiration, snow water equivalents and groundwater recharge at a basin scale. We concur with the view expressed in the introductory article to this

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special issue (Viviroli et al., 2010), that there is also a lack of basic information necessary to conduct appropriate hydrological modeling of factors including soil depth, and to reconstruct the land cover evolution during the 20th century.

Management of the Ebro River to meet increasing demand in the very likely scenario of decreasing water availability will be difficult. The large storage capacity in the basin and a complex system of hydraulic infrastructure have so far enabled water supply to be maintained or increased, even during dry years. Only under severe drought conditions has the imposition of water restrictions been necessary. However, previous research has demonstrated that adjustments to reservoir management will not remain a solution for much longer, as the outflows from dams have already been reduced to the minimum ecological levels in most of the big reservoirs (López-Moreno et al., 2004, 2008). The creation of new reservoirs does not appear to be a solution as the existing dams already occupy the most appropriate locations, and the flooding of valleys, especially if it involves population displacement, is firmly opposed by the broad community (Ibañez-Prat, 2003). In this context, water managers must seek to optimize the available water resources and improve the dam management schemes, many of which were designed under hydrological conditions very different from the current ones. Towards this goal, the implementation in 1996 of a real-time hydrologic information system at the basin scale (SAIH: http://195.55.247.237/saihebro/index.php) represented a significant advance in optimizing management capacity under extreme hydrological events (droughts and floods). A combination of this system with reliable seasonal climatic forecasts could be crucial in improving the management of hydraulic infrastructure. In recent years substantial effort has been devoted to the accurate prediction of seasonal climate and river flows using numerical models and statistical approaches, and significant advances have been achieved (Rodwell and Doblas-Reyes, 2006; Gamiz-Fortis et al., 2008). However, the predictions are still associated with a high degree of uncertainty, which hinders their full application in management.

Politicians also have an important role to play in supporting the work of scientists and managers, by promoting reduced water consumption and strengthening the legal and

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institutional frameworks related to water management. They must realize that obvious water-related problems are very likely to occur in the basin, and appreciate the effect that human activity in the region has on water resources availability. Changing water resources and demand will require investment in improved management, water economy and water recycling policies. Maintenance and improvement of climate, hydrology and land cover monitoring networks is necessary to enable adjustment of water management strategies and water demand to the temporal variability of water resources. An increase in periods of water scarcity in the Ebro basin could result in conflicts among different water uses, territories and administrations responsible for control and use of the available water. Strong institutional frameworks will be necessary to coordinate socially, economically and environmentally sustainable water management.

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References

Agnew, M. D. and Palutikof, J. P.: GIS-based construction of base line climatologies for the Mediterranean using terrain variables, Clim. Res., 14, 115–127, 2007.

Andréassian, V.: Waters and forests: from historical controversy to scientific debate, J. Hydrol., 291, 1–27, 2004.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438, 3003–309, 2005.
Beguería, S., López-Moreno, J. I., Lorente, A., Seeger, M., and García-Ruiz, J. M.: Assessing the effects of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees, Ambio, 32, 283–286, 2003.
Birsan, M.-V., Molnar, P., Burlando, P., and Pfaundler, M.: Streamflow trends in Switzerland, J. Hydrol., 314(1–4), 312–329, 2005.
Calder, I. R., Swaminath, M. H., Kariyappa, G. S., Srinivasalu, N. V., Srinivasa Murthy, K. V., and Mumtaz, J.: Measurements of transpiration from Eucalyptus plantations, India, using deuterium tracing, in: Growth and Water Use of Forest Plantations, edited by: Calder, I. R., Hall, R. L., and Adlar, P. G., John Wiley & Sons Ltd., Chichester, Inglaterra, 196–215, 1992.
Cheddadi, R., Guiot, J., and Jolly, D.: The Mediterranean vegetation: What if the atmospheric CO2 increased?, Lands. Ecol., 16, 667–675, 2001.
Cosandey, C., Andreassian, V., Martin, C., Didon-Lescot, J. F., Lavabre, J., Folton, N., Mathys, N., and Richard, D.: The hydrological impact of the mediterranean forest: A review of French research, J. Hydrol., 301, 235–249, 2005.
Croke, B., Cleridou, N., Kolovos, A., Vardavas, I., and Papamastorakis, J.: Water resources in the desertification-threatened Messara Valley of Crete: estimation of the annual water budget using a rainfall-runoff model, Environ. Model Softw., 15(4), 387–402, 2000.
Cudennec, C., Leduc, C., and Koutsoyiannis, D.: Dryland hydrology in Mediterranean regions – A review, Hydrol. Sci. J., 52, 1077–1087, 2007.
Daly, C., Neilson, R. P., and Phillips, D. L.: A statistical-topographical model for mapping climatological precipitation over mountainous terrain, J. Clim. Appl. Meteor., 33, 140–158, 1994.
Daly, C., Taylor, G. H., and Gibson, W. P.: The PRISM approach to mapping precipitation and temperature. Proceedings of the 10th Conference on Applied Climatology. Reno, NV, American Meteorological Society, p. 10–12, 1997.
De Jong, C., Lawler, D., and Essery, R.: Mountain hydroclimatology and snow seasonality and hydrological change in mountain environments, Hydrol. Processes, 23, 955–961, 2009.
Debussche, M., Lepart, J., and Dervieux, A.: Mediterranean landscape changes: Evidence from old postcards, Global Ecology Biogeography, 8, 3–15, 1999.
Fohrer, N., Haverkamp, S., Eckhardt, K., and Frede, H. G.: Hydrologic response to land use changes on the catchment scale, Phys. Chemis. Earth (B), 26, 577–582, 2001.
Gallart, F. and Llorens, P.: Observations on land cover changes and water resources in the

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headwaters of the Ebro catchment, Iberian Peninsula. Phys. Chem. Earth, 29, 769–773, 2003.
Gámiz-Fortis, S., Pozo-Vázquez, D., Trigo, R. M., and Castro-Díez, Y.: Quantifying the Predictability of Winter River Flow in Iberia. Part II: Seasonal Predictability, J. Climate, 21, 2503–2518, 2008.
García-Ruiz, J. M., Valero-Garcés, B. L.: Historical geomorphic processes and human activities in the central Spanish Pyrenees, Mount. Res. Develop., 18(4), 309–320, 1998.
García-Ruiz, J. M., Beguería, S., López-Moreno, J. I., Lorente-Grima, A., and Seeger, M.: Los recursos hídricos superficiales del Pirineo aragonés y su evolución reciente, Geoforma Ediciones, Logroño, 191, 2001.
García-Ruiz, J. M., Regüés, D., Alvera, B., Lana-Renault, N., Serrano-Muela, P., Nadal-Romero, E., Navas, A., Latron, J., Martí-Bono, C., and Arnáez, J.: Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees, J. Hydrol., 356, 245–260, 2008.
Gaucherel, C., Guiot, J., and Misson, L.: Evolution of the potential distribution area of french mediterranean forests under global warming, Biogeosciences Discuss., 5, 573–603, 2008, http://www.biogeosciences-discuss.net/5/573/2008/.
Giorgi, F.: Climate change hot-spots, Geophys. Res. Lett., 33, L08707, doi:10.1029/2006GL025734, 2006.
Giorgi, F. and Lionello, P.: Climate change projections for the Mediterranean region, Glob. Planet. Change, 63, 90–104, 2008.
Gonzalez-Hidalgo, J. C., Lopez-Bustins, J. A., Stepánek, P., Martin-Vide, J., and de Luis, M.: Monthly precipitation trends on the Mediterranean fringe of the Iberian Peninsula during the second-half of the twentieth century (1951–2000), Int. J. Climatol., 29(10), 1415–1429, 2009.
Hirsch, R. M., Slack, J. R., and Smith, R. A.: Techniques of trend analysis for monthly water quality data, Water Resour. Res., 18(1), 107–121, 1982.
Ibáñez, C. and Prat, N.: The environmental impact of the Spanish national hydrological plan on the lower Ebro river and delta, Water Resour. Develop., 19(3), 485–500, 2003.
Lasanta, T., Vicente, S., and Cuadrat, J. M.: Mountain Mediterranean landscape evolution caused by the abandonment of traditional primary activities: A study of the Central Spanish Pyrenees, Appl. Geogr., 25, 47–65, 2005.
Lasanta, T., Beguería, S., and García-Ruiz, J. M.: Geomorphic and hydrological effects of

HESSD
7, 2651–2681, 2010

Impact of climate evolution and land use changes on water yield

J. I. López-Moreno et al.

traditional shifting agriculture a mediterranean mountain, Central Spanish Pyrenees, Mount. Res. Develop., 26(2), 146–152, 2006.

López-Moreno, J. I., Beguería, S., and García-Ruiz, J. M.: Influence of the Yesa reservoir on floods of the Aragón River, central Spanish Pyrenees, Hydrol. Earth Syst. Sci., 6, 753–762, 2002, http://www.hydrol-earth-syst-sci.net/6/753/2002/.

López-Moreno, J. I. and García-Ruiz, J. M.: Influence of snow accumulation and snowmelt on streamflow in the central Spanish Pyrenees, Hydrol. Sci. J., 49, 787–802, 2004.

López-Moreno, J. I.: Recent variations of snowpack depth in the Central Spanish Pyrenees, Artic. Antarc. Alp. Res., 37(2), 253–260, 2005.

López-Moreno, J. I. and García-Ruiz, J. M.: Hydrological effects of reservoirs in the Central Spanish Pyrenees, in: Managing water resources in a changing physical and social environment, edited by: Robinson, P. J., Jones, J. A. A., and Woo, M.-K., IGU Home of Geography Publication Series, Società Geografica Italiana, Rome, 177 pp, p. 103–114, 2007.

López-Moreno, J. I., Goyette, S., and Beniston, M.: Climate change prediction over complex areas: spatial variability of uncertainties and expected changes over the Pyrenees from a set of regional climate models, Int. J. Climatol., 28(11), 1535–1550, 2008a.

López-Moreno, J. I., García-Ruiz, J. M., and Beniston, M.: Environmental Change and water management in the Pyrenees. Facts and future perspectives for Mediterranean mountains, Global Planet. Change, 66(3–4), 300–312, 2008b.

López-Moreno, J. I., Goyette, S., and Beniston, M.: Impact of climate change on snowpack in the Pyrenees: horizontal spatial variability and vertical gradients, J. Hydrol., 374, 384–396, 2009.

Mitasova, H. and Mitas, L.: Interpolation by Regularized Spline with Tension, Mathem. Geol., 25, 641–655, 1993.

Ninyerola, M., Pons, X., and Roure, J. M.: Objective air temperature mapping for the Iberian Peninsula using spatial interpolation and GIS, Int. J. Climatol., 27(9), 1231–1242, 2007.

Nogués-Bravo, D., Lasanta, T., López-Moreno, J. I., and Araújo, M.: Climate warming in Mediterranean mountains during the XXIst century, Ambio, 37(4), 280–285, 2008.

Ragab, R. and Prudhomme, C.: Climate change and water resources management in arid and semi-arid regions: Prospective and challenges for the 21st century, Biosyst. Eng., 81, 3–34, 2002.

Nogués-Bravo, D., Vicente-Serrano, S. M., and López-Moreno, J. I.: Climate change and

HESSD
7, 2651–2681, 2010

Impact of climate evolution and land use changes on water yield

J. I. López-Moreno et al.

Mediterranean mountains (ed. Vogiatzakis), Mediterranean mountain environments, Willey-Blackwell, accepted, 2010.
Ranzi, R., Bochicchio, M., and Bacchi, B.: Effects on floods of recent afforestation and urbanisation in the Mella River (Italian Alps), Hydrol. Earth Syst. Sci., 6, 239–254, 2002, http://www.hydrol-earth-syst-sci.net/6/239/2002/.
Rodwell, M. J. and Doblas-Reyes, F. J.: Medium-Range, Monthly, and Seasonal Prediction for Europe and the Use of Forecast Information, J. Climate, 19, 6025–6046, 2006.
Sneyers, R.: Use and misuse of statistical methods for detection of climate change, in: Climate Change Detection Project, Report on the Informal Planning Meeting on Statistical Procedures for Climate Change Detection, WCDMP, (20), J76–J81, 1992.
Vicente-Serrano, S. M., Lasanta, T., and Romo, M.: Analysis of spatial and temporal evolution of vegetation cover in the Spanish central Pyrenees: Role of human management, Environ. Manag., 34, 802–818, 2004.
Vicente-Serrano, S. and López-Moreno, J. I.: Influence of atmospheric circulation at different spatial scales on winter drought variability through a semiarid climatic gradient in Nort-east Spain, Int J. Climatol., 26(11), 1427–145, 2006.
Vivirioli, D., Weingartner, R., and Messerli, B.: Assessing the hydrological significance of the World's mountains, Mount. Res. Develop., 23, 32–40, 2004.
Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M., and Weingartner, R.: Mountains of the world – water towers for humanity: typology, mapping and global significance, Water Resour. Res., 43(7), W07447, doi:10.1029/200, 2007.
Von Storch, V. H.: Misuses of statistical analysis in climate research, in: Analysis of Climate Variability: Applications of Statistical Techniques, edited by: von Storch, H. and Navarra, A., Springer-Verlag: Berlin, 11–26, 1995.
Westmacott, J. R. and Burn, D. H.: Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin, J. Hydrol., 202, 263–279, 1997.
Yue, S., Pilon, P., and Cavadias, G.: Corrigendum to "Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series" [J. Hydrol., 259 (2002) 254–271], J. Hydrol., 264(1–4), 262–263, 2002a.
Yue, S., Pilon, P., Phinney, B., and Cavadias, G.: The influence of autocorrelation on the ability to detect trend in hydrological series, Hydrol. Proceses, 16, 1807–1829, 2002b.

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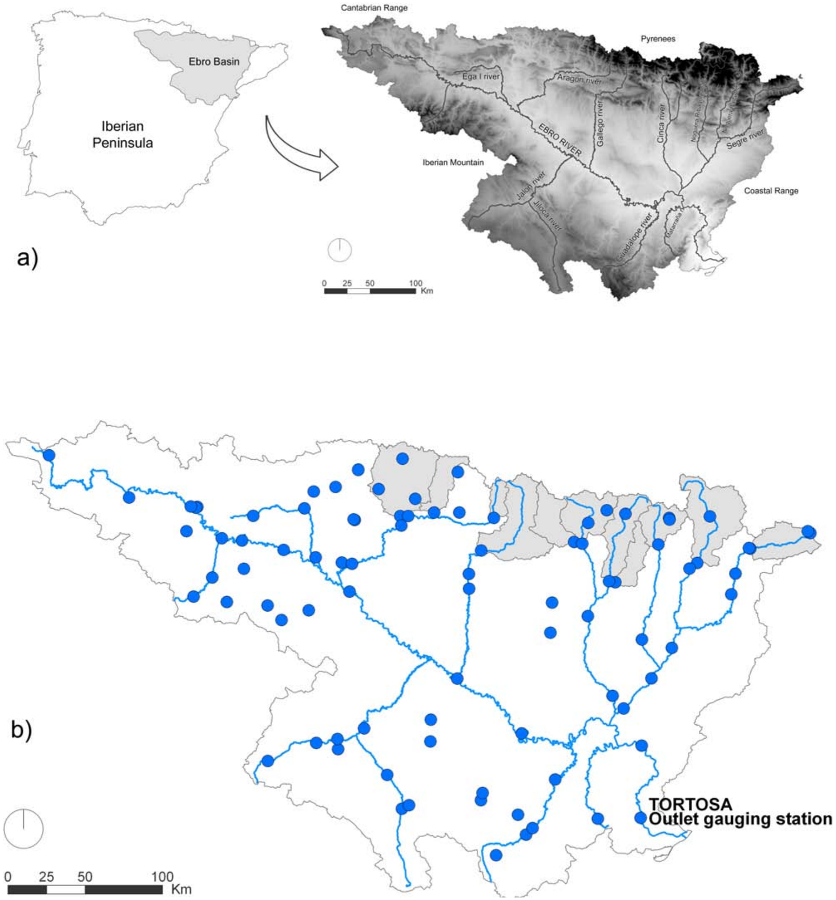

Fig. 1. Study area. **(a)** relief of the Ebro River basins and main tributaries of the Ebro River. **(b)** Gauging station network, and areas included as Pyrenean headwaters (in grey color).

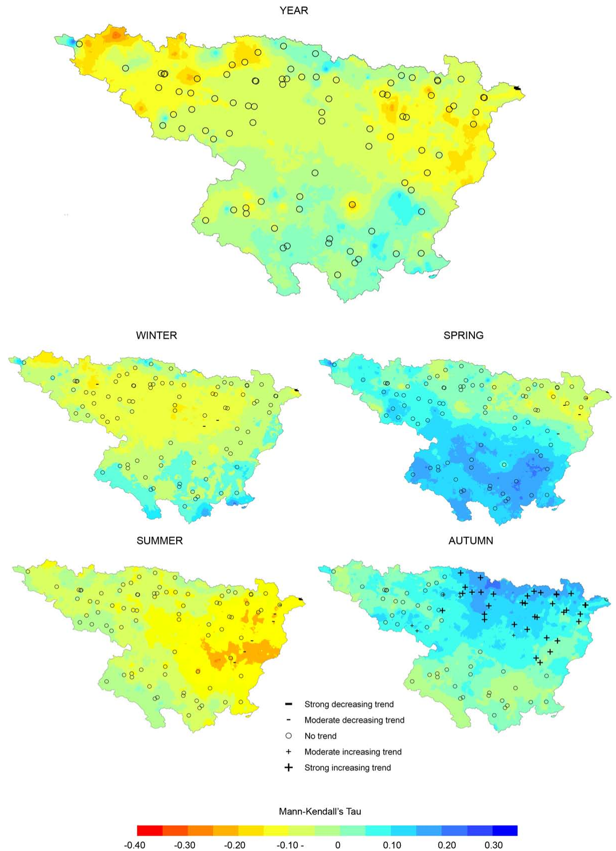

Fig. 2. Trend of annual and seasonal precipitation for the Ebro basin during the studied period (1950–2006). The color scale shows the Mann-Kendall tau coefficients for each 1 km^2 cell. The symbols show the sign of the trend for total precipitation in the area drained at each of the 88 gauging stations.

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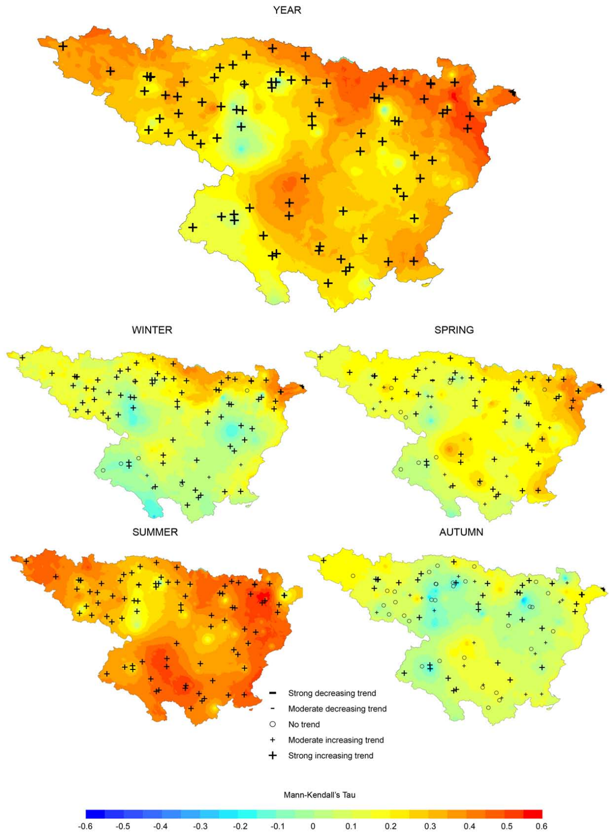

Fig. 3. Trend of annual and seasonal temperature for the Ebro basin during the studied period (1950–2006). The color scale shows the Mann-Kendall tau coefficients for each 1 km^2 cell. The symbols show the sign of the trend for the average temperature in the area drained at each of the 88 gauging stations.

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Fig. 4. Temporal evolution of river discharges.

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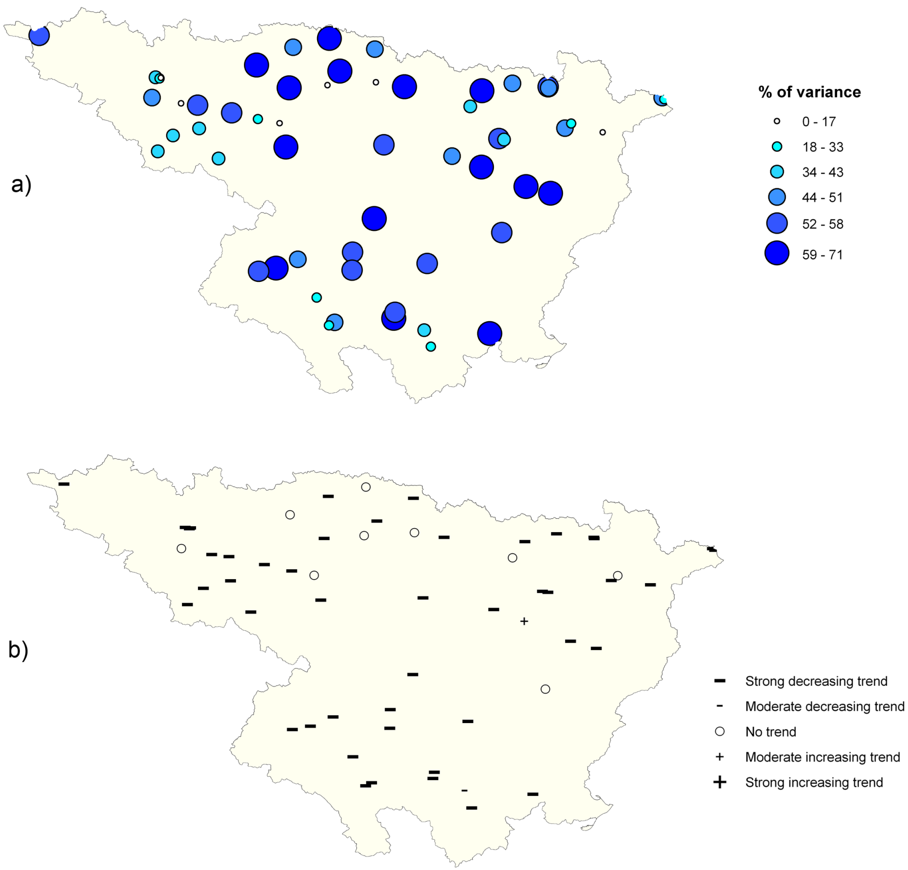

Fig. 5. Results of the application of a stepwise linear regression for predicting annual runoff from annual temperature and precipitation over the 88 sub-basins analyzed in the Ebro basin. **(a)** the coefficient of determination for each sub-basin. **(b)** trends in the evolution shown by residuals in each sub-basin.

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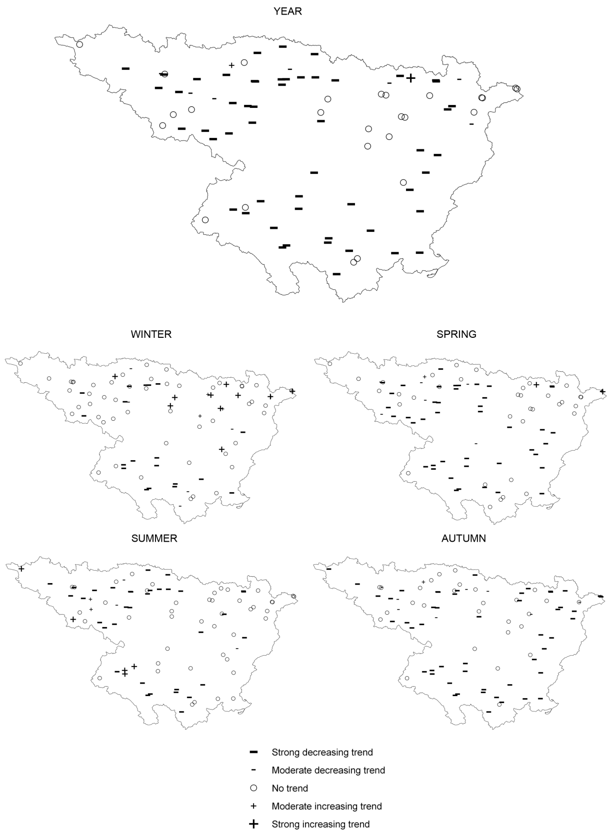

Fig. 6. Temporal evolution of runoff coefficient (water yield).

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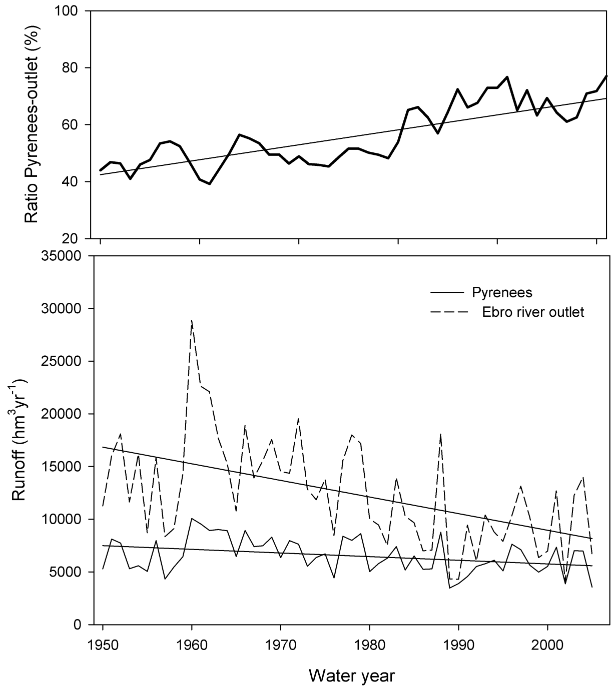

Fig. 7. Annual runoff from Pyrenean headwaters and the discharge of the Ebro River in its lower reaches (lower panel). Evolution of the ratio between the series (upper panel).

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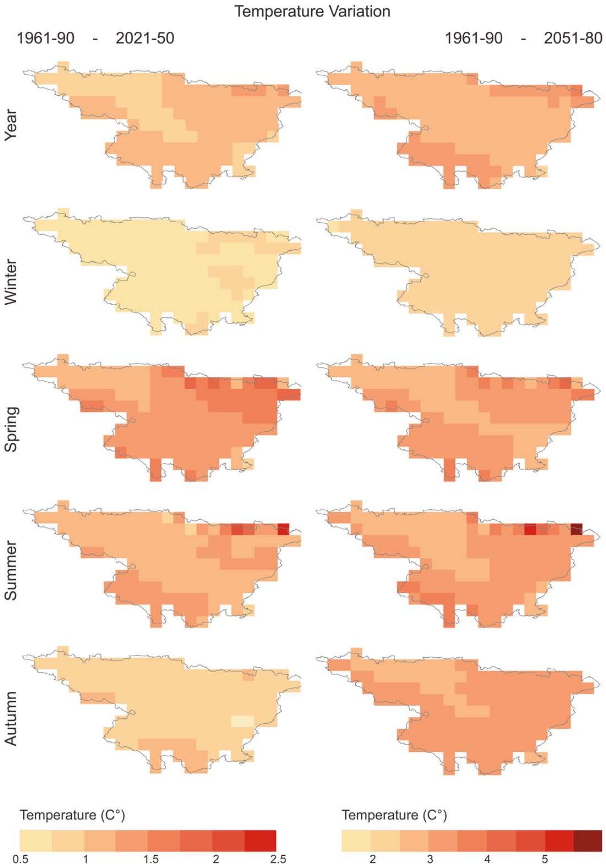

Fig. 8. Projected changes in temperature under the HIRHAM5 model (A1B emission scenario) for the time slices 2021–2050 and 2051–2080 compared with the 1960–1990 period.

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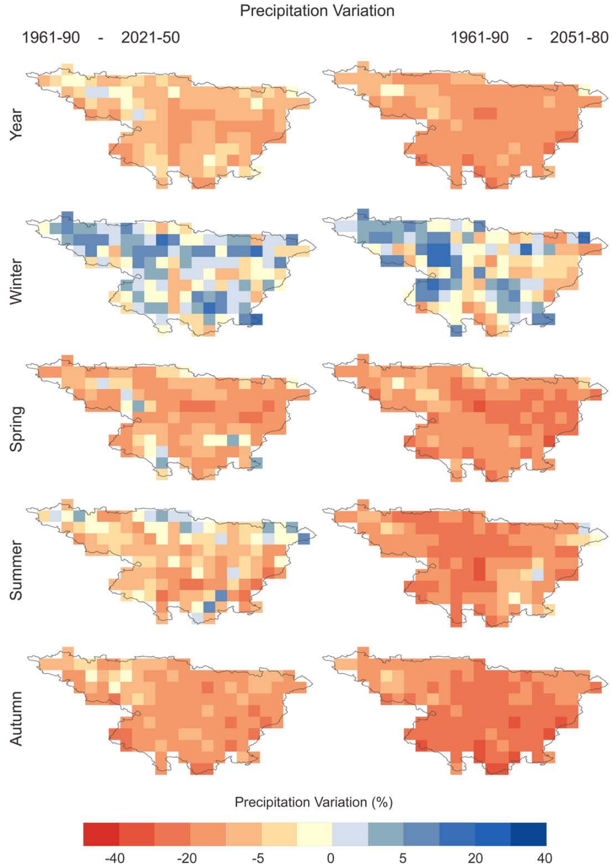

Fig. 9. Projected changes in precipitation under the HIRHAM5 model (A1B emission scenario) for the time slices 2021–2050 and 2051–2080 compared with the 1960–1990 period.

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