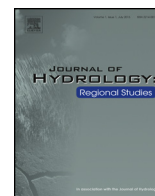




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Extreme hydrological events and the influence of reservoirs in a highly regulated river basin of northeastern Spain



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ABSTRACT

Study region: The Segre basin (northeastern Spain).

Study focus: The Segre basin is extensively regulated, through a dense network of dams, during the second half of the 20th century. This study assessed the impact of river regulation on the evolution of hydroclimatological extreme events across the basin during the past six decades (1950–2013). We assessed whether the occurrence of floods and hydrological droughts has changed, and whether these changes have differed spatially between the headwaters and lower areas of the basin. For this purpose, we employed a set of hydroclimatological indices in order to quantify the evolution of the amount as well as the frequency of quantiles of high precipitation and flood events. Changes in these variables were assessed by means of the nonparametric Mann–Kendall Tau coefficient.

New hydrological insights: Results reveal a general reduction in the occurrence of extreme precipitation events in the Segre basin from 1950 to 2013, which corresponded to a general reduction in high flows measured at various gauged stations across the basin. While this study demonstrates spatial differences in the decrease of streamflow between the headwaters and the lower parts of the basin, mainly associated with changes in river regulation, there was no reduction in the frequency of the extraordinary floods. Changes in water management practices in the basin have significantly impacted the frequency, duration, and severity of hydrological droughts downstream of the main dams, as a consequence of the intense water regulation to meet water demands for irrigation and livestock farms. Nonetheless, the hydrological response of the headwaters to these droughts differed markedly from that of the lower areas of the basin.

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1. Introduction

Determining the occurrence of extreme events in the hydrological cycle is one of the main priorities of hydrologists and water managers, as these events commonly have major economic, environmental, and social impacts (e.g. Kunkel et al., 1999; Van Dijk et al., 2013). Under global warming conditions, the frequency and magnitude of extreme precipitation events are likely to increase (Trenberth, 2012), due to the higher specific atmospheric humidity associated with the Clausius–Clapeyron relationship (Santer et al., 2007; Trenberth et al., 2005; Allan, 2012; Westra et al., 2014). The most recent IPCC report (Hartmann et al., 2013) shows that changes in precipitation extremes are consistent with a warmer climate. Nevertheless, the report also emphasizes that changes in extreme precipitation events show low spatial coherence (Alexander et al., 2006; Westra et al., 2013; Dittus et al., 2015).

Drought patterns are even much more difficult to determine (Vicente-Serrano, 2016). Seneviratne et al. (2012) highlighted major uncertainties in the evolution of climate droughts worldwide. These difficulties are confirmed in a range of studies that assessed drought trends at the global scale (e.g. Sheffield et al., 2012; Dai, 2013; Trenberth et al., 2014), highlighting the need to analyze the evolution of extreme hydroclimatic events at regional scales.

Another important uncertainty is how extreme events propagate throughout the hydrological cycle, as climatic and hydrological extreme events do not typically coincide in magnitude, spatial extent, and time. This feature can be linked to topography (Lorenzo-Lacruz et al., 2013; Barker et al., 2015), previous climate conditions (Mediero et al., 2014), and vegetation cover (Lana-Renault et al., 2012; Serrano-Muela et al., 2015). Other variables (e.g. landscape changes, water regulation and management, etc.) can also complicate the response of extreme hydrological events to extreme climate events, as reported in earlier studies (e.g. López-Moreno et al., 2006; Llasat et al., 2014; Mediero et al., 2014, 2015; Machado et al., 2015; Crooks and Kay, 2015). Furthermore, while extreme rainfall typically occurs at daily or even sub-daily scales, with notable regional or local effects, droughts are usually studied at monthly scales and tend to impact larger areas. Accordingly, it is important to consider the distinct time and spatial scale of these two types of extreme events.

In the western Mediterranean region, there is an evidence of a decrease in the frequency and magnitude of extreme precipitation events over recent decades (López-Moreno et al., 2010; Gallego et al., 2011; Valencia et al., 2012), while there is an increase in the duration and severity of climate droughts (Vicente-Serrano et al., 2014; Spinoni et al., 2015; Lorenzo-Lacruz and Morán-Tejeda, 2016; Coll et al., 2016). River floods have also decreased, as a consequence of changes in precipitation, combined with higher atmospheric evaporative demand (AED) (Mediero et al., 2014) and increased vegetation cover in the headwaters (López-Moreno et al., 2006). Hydrological droughts also showed higher increases in severity and duration compared to meteorological droughts. This feature can be explained by the higher AED (Vicente-Serrano et al., 2014), increased tourism, urban water demands, and the expansion of irrigated areas (Lorenzo-Lacruz et al., 2013).

In the Mediterranean region, the availability of water resources is critical (García-Ruiz et al., 2011). Managing water resources in any Mediterranean reservoir must make balance between the need to store water for different water supplies and uses, and the need to manage floods and their catastrophic effects (López-Moreno et al., 2002). This balance is critical, especially during spring and summer, due to the high water demand and the high probability of extreme precipitation events during these seasons. In this context, albeit with numerous studies investigating the effects of reservoirs on river regimes and streamflows in the western Mediterranean (e.g. Batalla et al., 2004; Piqué et al., 2016; Vicente-Serrano et al., 2016), only few studies have considered the joint effect of damming and reservoir management on the severity of floods and hydrological droughts downstream.

In this study, we investigated the evolution of extreme climate and hydrological events in the past six decades across the Segre basin (northeastern Spain). This basin, whose headwaters are located in the Pyrenees, has been highly regulated by numerous dams during the second half of the 20th century (Vicente-Serrano et al., 2016). The main objective of this study was to determine whether the occurrence and severity of floods and hydrological droughts have changed in recent decades, and whether these changes have differed between the headwaters and lower areas of the basin.

2. Study area

The Segre basin is located in northeastern Spain, and its drainage area covers approximately 13,000 km². The basin has three main rivers: the Segre River (8167 km²; the main tributary of the Ebro River), the Noguera Pallaresa River (2807 km²), and the Noguera Ribagorçana River (2061 km²) (Fig. 1). The elevation ranges from 175 m, where the Segre River enters the Ebro River, to more than 3200 m in the Pyrenees. The relief causes marked climatic and landscape contrasts in the basin. In the Pyrenean headwaters, the precipitation exceeds 1100 mm year⁻¹, but in the southern lowlands the average annual precipitation is <300 mm year⁻¹. Annual reference evapotranspiration in the headwaters is <600 mm year⁻¹, but it exceeds 1100 mm year⁻¹ in the south. Climate and topographic factors are responsible for the remarkable landscape contrasts in the basin. In the north, the dominant landscape units are alpine pastures and subalpine and sub-Mediterranean forests, including *Pinus uncinata*, *Pinus sylvestris*, *Fagus sylvatica*, and *Quercus* sp. In the center of the basin (elevations of 800–1000 m), shrubs and forests dominate in some areas, reflecting successional changes associated with the abandonment of the cultivated slopes during the 20th century (García-Ruiz and Lana-Renault, 2011; Buendia et al., 2015). Irrigated agriculture occurs in the lower part of the basin, facilitated by the construction of dams. The basin has 144,000 irrigated hectares, served by the canals of Urgell, Pinyana, Aragón and Catalunya, and Segarra-Garrigues. Thus, agro-industries and intensive livestock

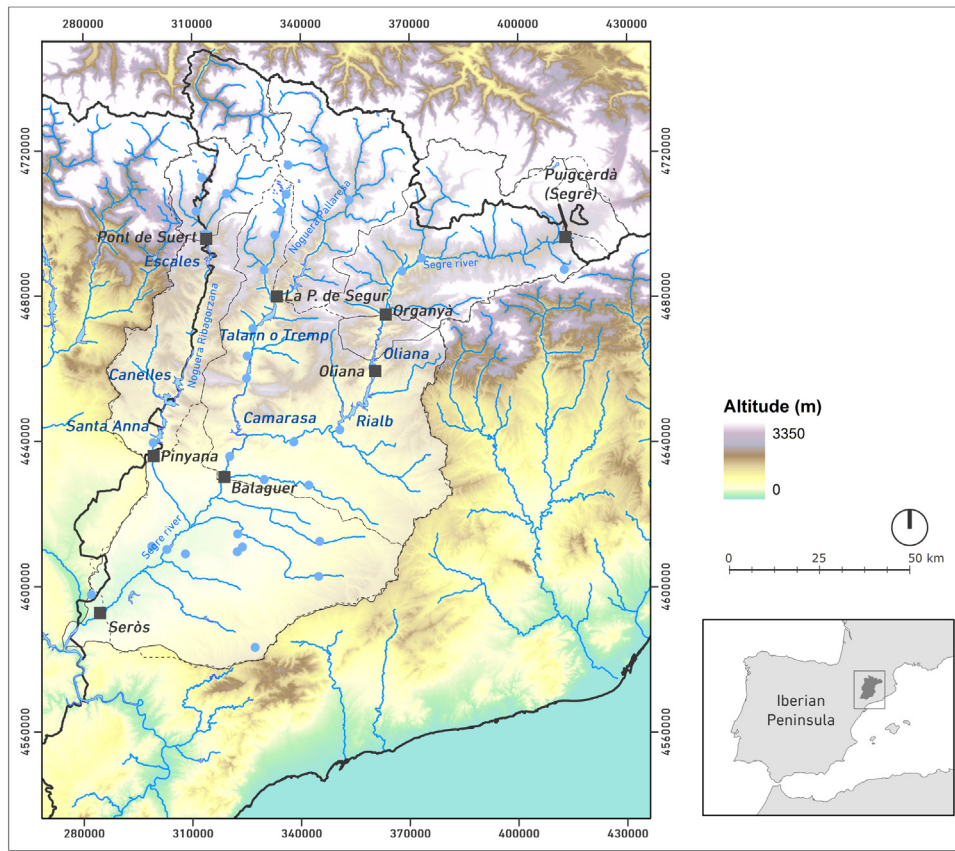


Fig. 1. Spatial distribution of gauge stations (black squares), precipitation stations (blue circles), and reservoirs. Background colors represent elevation. Dashed lines represent the boundaries of the different sub-basins.

production are the main economic activities in the basin. The few remaining natural areas in the arid lands of the basin correspond to the northernmost steppes of Europe (Braun-Blanquet and Bolòs, 1958).

In normal conditions, the Segre River shows a clear seasonal regime, with the main flows occurring during May and June, due to snow melting and high springtime precipitation. However, in the lower part of the basin, the river regime is highly modified, as a consequence of impoundment of the river as well as water management for irrigation uses and urban supplies (Batalla et al., 2004; Piqué et al., 2016). Currently, there are 35 reservoirs in the Segre River basin, providing a total storage capacity of 2084 hm³ (1 hm³ = 1,000,000 m³): a value which is very close to the average annual streamflow recorded close to the mouth of the river (2130 hm³). Most water regulation occurs in the headwaters and the middle reaches of the Noguera Ribagorzana River and the Noguera Pallaresa River, where the Escales (163 hm³), Canelles (687.5 hm³), Santa Anna (236.6 hm³), Talarn (205.1 hm³), and Camarasa (163 hm³) reservoirs are located. The Segre River is regulated by the Oliana (101 hm³) and Rialb (402.8 hm³) reservoirs; the latter was established in 2000. These reservoirs caused a marked decrease (>60%) in the annual streamflow of the Segre River during the past six decades (Vicente-Serrano et al., 2016).

The occurrence of extreme precipitation events is common in the basin (Llasat and Puigcerver, 1997; Beguería et al., 2009). These events are associated with short-lived, isolated, and high-intensity thunderstorms in summer. In autumn, these events are linked to the backward trajectories of the Mediterranean perturbations, which involve the occurrence of low level warm and humid northeasterly and easterly flows, with cold continental air above cut-off lows over the Mediterranean Sea (Ramis et al., 1997). In addition to these atmospheric configurations, extreme precipitation events are enhanced by the complex terrain (Pastor et al., 2001), making some historical floods in the basin catastrophic, with serious environmental, economic, and societal impacts (Arbiol et al., 1984; Barriendos et al., 2003; Thorndycraft et al., 2006; Llasat et al., 2009, 2010, 2013).

In northeastern Spain, climate drought periods occur frequently, due to the occurrence of low flows and hydrological droughts (Vicente-Serrano, 2006; Lorenzo-Lacruz et al., 2013). In particular, some hydrological basins suffered from long, intense and severe droughts over the last three decades, in response to the decreased precipitation and increased AED (Lopez-Bustins et al., 2013; Vicente-Serrano et al., 2014).

3. Data and methods

3.1. Data

The Ebro River Basin Management Authority (Confederación Hidrográfica del Ebro) provided the daily streamflow data for the Segre basin. The daily streamflow data for 11 gauge stations were chosen for this study because these stations had less than 15% of missing data for the period 1950–2013 (Fig. 1). Gap filling was performed using a linear regression analysis, in which the independent series were derived from the same rivers whose data were missing, or from nearby tributaries. The minimum Pearson's correlation coefficient between the series in the model was set to 0.6, following Lorenzo-Lacruz et al. (1945–2005). As depicted in Fig. 1, seven gauge stations are located upstream of the main reservoirs (Puigcerdà, Organyà, Arabó, la Seud'Urgell, Valira, la Pobla de Segur and Pont de Suert), while four are located downstream (Oliana, Pinyana, Balaguer and Seròs). To determine the drainage basin corresponding to each gauge station, we used a digital elevation model (DEM) at a spatial resolution of 100 m, and the r.watershed tool in GRASS (v.6.4). The drainage area of each gauge station was defined as the upstream area from the headwaters to the gauge station. We also used monthly average reservoir storages in the basin from 1950 as well as the reservoir capacity upstream the gauge stations located in the lower bound of the basin.

Daily streamflow records were used to analyze the evolution of flood events, and monthly streamflow series were computed from the daily series to calculate hydrological drought indices. Daily precipitation series were obtained from the Spanish and Catalan meteorological agencies (AEMET and SMC). A total of 432 stations with daily precipitation data were available for the entire basin. The development of complete, quality controlled and homogeneous daily precipitation series is essential for robust climate assessments. There are multiple approaches for gap filling and homogeneity assessment, which were comprehensively revised and compared in Vicente-Serrano et al. (2010) for the entire Ebro basin (NE Spain). Here we follow the recommendations of this research to develop a quality controlled and homogeneous daily precipitation data set in the Segre basin. From the entire dataset ($N=432$), only 52 candidate stations, with more than 30 years of data, were first selected. The other series (reference series) were used to reconstruct and fill gaps in the candidate series. Daily precipitation series were transformed to quantiles, based on their empirical cumulative distribution function. For each candidate series, we selected the nearest reference series (within a maximum distance of 10 km), with at least 3 years of common data. The gaps in the candidate series were filled using the quantile values of the nearest available reference station. In few cases where the candidate series could not be completed using the nearest neighbor series, the existing gaps were filled using both reference and other candidate series up to a maximum distance of 25 km. This procedure provided complete datasets for each of the 52 candidate series. From the daily precipitation series, we calculated the monthly sum to test the temporal homogeneity of the series. For this purpose, we used HOMER (Homogenization in R) (Mestre et al., 2013), which is based on the pairwise algorithm described by Caussinus and Mestre (2004) and a two factor ANOVA model for correction. HOMER facilitates comparison of sets of stations, and estimation of the number and positions of their breakpoints. Few temporal inhomogeneities were identified in the series (68), and the coefficients obtained were applied to those days having precipitation in the month, according to Vincent et al. (2002).

We also used gridded monthly precipitation and monthly reference evapotranspiration (ET_o), at a 500 m grid interval, obtained using the equation of Hargreaves and Samani (1985). These gridded datasets were based on the MOPREDAS and MOTEDAS datasets (González-Hidalgo et al., 2011, 2015), which are the most complete quality controlled and homogeneous monthly climate datasets for Spain. Details of the procedures used to obtain and validate these gridded data have been described by Vicente-Serrano et al. (2016). Using the drainage basin corresponding to each gauge station, we determined the total monthly precipitation and ET_o for the entire basin. This procedure enabled comparison of the average climate series (precipitation and ET_o) corresponding to the drainage area at each gauge station with the monthly streamflow data.

3.2. Analysis

3.2.1. Floods and extreme precipitation events

We quantified the trends in the percentage of annual streamflow corresponding to daily river flows of different magnitudes. For this purpose, we used the method proposed by Osborn et al. (2000), whereby streamflow values corresponding to each 5th quantile unit were extracted from all the daily streamflow data for each gauge station. Using this procedure, we classified the daily streamflow records into 20 categories. Then, we determined the contribution of the daily streamflow in each category to the total annual streamflow, and analyzed the temporal trends in the contribution of each category using the nonparametric Mann–Kendall Tau coefficient. Statistically significant trends were defined as those having p -values <0.05 . We also used this approach to determine changes in the percentage of annual precipitation corresponding to events above the 95th quantile. In addition, we analyzed trends (Mann–Kendall tau coefficient; significance level: $p < 0.05$) in the annual frequency of high precipitation (>95 th, >99 th, and >99.9 th quantiles) and streamflow (>95 th, >98 th, >99 th, >99.5 th, >99.9 th, and >99.95 th quantiles) events. Finally, to account for the possible influence of the reservoir capacity and the reservoir storage upstream the gauge stations located in the lower bound of the basin, we related the annual frequency of days above the 95th, 99th and 99.9th percentiles with the average annual reservoir storage, reservoir capacity and the ratio between the reservoir storage and capacity.

3.2.2. Drought quantification and analysis

Hydrological droughts were quantified using the Standardized Streamflow Index (SSI; Vicente-Serrano et al., 2012), and climatic droughts were quantified using the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) at time scales ranging from 1 to 48 months. The SSI enables comparison of streamflow deficits and surpluses in time and space, regardless of the magnitude of the series and the river regimes involved. The SSI is obtained by transforming the monthly streamflow series into a dimensional series of standardized anomalies. To obtain a reliable SSI that encompasses large variability in the statistical properties of the monthly streamflow data, the series were fitted to the most suitable probability distribution, according to the minimum orthogonal distance between the sample L-moments at site i and the L-moment relationship for a specific distribution, selected from the general extreme value, the Pearson Type III, the log-logistic, the log-normal, the generalized Pareto, and the Weibull distributions. More details on the calculation of the SSI are provided by Vicente-Serrano et al. (2012).

The SPEI is a climatic drought index that can be obtained at various timescales, similar to the Standardized Precipitation Index (SPI) (McKee et al., 1993); this is essential for identifying the complex response of hydrological systems to climate variability (Vicente-Serrano et al., 2011; López-Moreno et al., 2013; Barker et al., 2015). Hydrological droughts usually respond to different timescales of climate drought, as a function of environmental conditions (e.g. lithology, vegetation cover, and management) (Lorenzo-Lacruz et al., 2013). The SPEI is based on precipitation and ETo, and incorporates the sensitivity of drought severity to changes in AED in the multi-temporal nature of droughts based on a monthly climatic water balance (P–ETo), which is adjusted using a three-parameter log-logistic distribution. The values are accumulated at various time scales, following the same approach as is used for the SPI, and converted to standard deviations with respect to average values. For this purpose we used the monthly total precipitation and ETo gridded series corresponding to each drainage basin.

Using the SSI and SPEI, we defined individual drought events. This is commonly done by selecting a threshold in the series (Fleig et al., 2006; Sharma and Panu, 2014). To define drought events, a threshold level that did not vary in time and space was applied to the SSI series for each basin and the SPEI series. Nevertheless, the response of hydrological droughts to the occurrence of climate droughts can be strongly complex. According to the topographic/lithological/management characteristics of the basins, the time-scale of the climatic droughts at which the hydrological droughts are responding can be very different (see for example, López-Moreno et al., 2013; Lorenzo-Lacruz et al., 2013). For this reason, before relating the SSI and SPEI, we analyzed the best SPEI time-scale at which the SSI is responding. The selected threshold for SSI and SPEI was 0; consequently a drought event was recorded when the monthly SSI or SPEI fell below this level. Based on this threshold, each identified drought event was characterized according to the drought duration and magnitude. The duration of a given drought event was defined as a consecutive and uninterrupted time period (one or more months), with a SSI or SPEI value lower than 0. The drought magnitude was the accumulated deficit volume (defined as the sum of the deficit volumes generated during an uninterrupted number of months) delimiting a drought event and expressed as the accumulated deficits

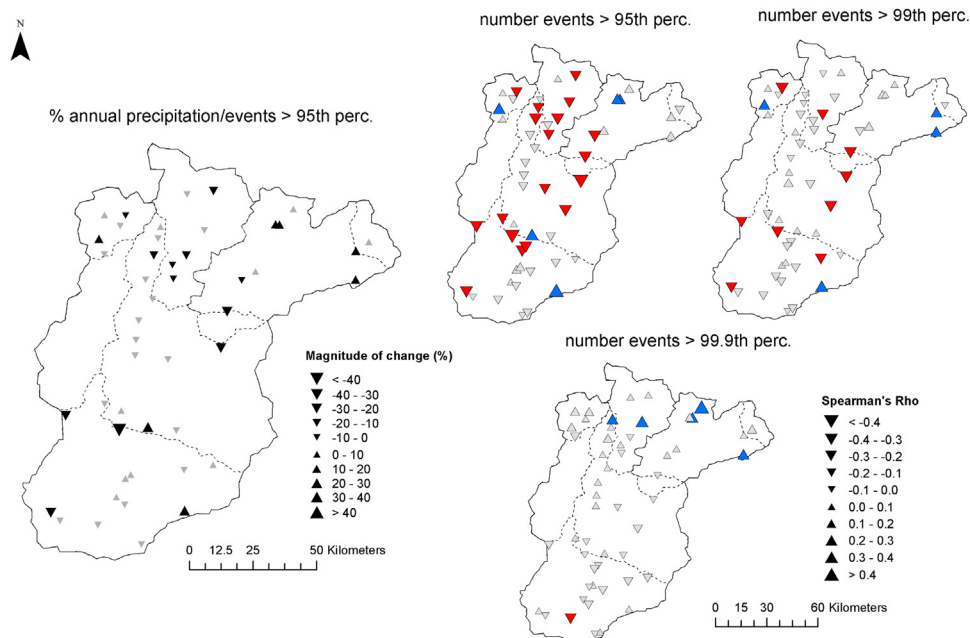


Fig. 2. Left: Evolution of the percentage of annual precipitation corresponding to events exceeding the 95th percentile. Right: Evolution of the number of events exceeding the 95th, 99th, and 99.9th percentiles. Red: Significant negative trends, Blue: Significant positive trends, Gray color: non-significant trends.

of the SSI or SPEI. Annual series of the average drought duration and magnitude were created for each basin following this approach. Here, it noteworthy indicating that a hydrological drought is considered as this period in which the streamflow was below a given threshold quantified in relative terms (i.e. considering the entire streamflow series), independently if it is only driven by climate anomalies, by water regulation and abstraction or both.

Changes in hydrological and climate drought duration and magnitude were also determined by the nonparametric Mann–Kendall Tau coefficient. Statistically significant trends were defined as those having $p < 0.05$. To determine the magnitude (amount) of change, a linear regression model between time (independent variable) and the drought

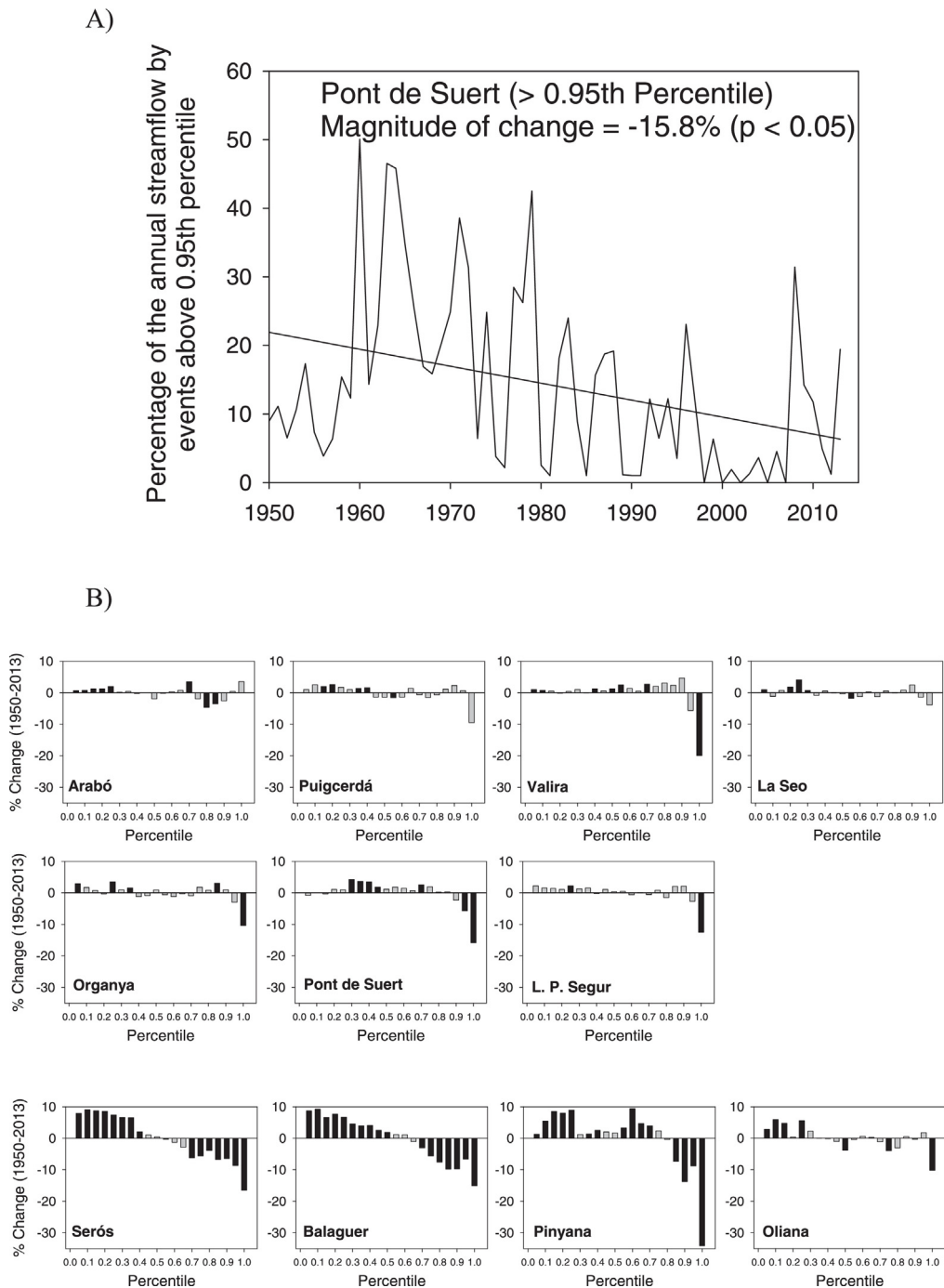


Fig. 3. (A) Example of the amount quantile analysis corresponding to the percentage of the annual streamflow by events above 0.95th percentile in Pont de Suert. (B) Plots showing the magnitude of change in the amount quantiles corresponding to the volume of annual streamflow. Black columns represent significant trends. The four plots at the bottom correspond to the basins located downstream of the main dams.

duration/magnitude was fitted. The slope of each model (m) indicated the magnitude of change. We also analyzed the relationship between the annual SSI (as a measure of the annual drought severity) and the average annual reservoir storage, reservoir capacity and the ratio between the reservoir storage and capacity in the gauge stations located in the lower bound of the basin.

4. Results

4.1. Extreme precipitation events

The evolution of the most extreme precipitation events concurs with the general reduction in precipitation in the region, as reported in previous studies. Trends in the percentage of the annual precipitation corresponding to events exceeding the 95th percentile did not show a clear structure, although stations showing negative trends dominated (Fig. 2, left). However, the number of events exceeding the 95th percentile clearly decreased over most of the basin in the period 1950–2013 (Fig. 2, right). Among the 52 meteorological stations used in this study, only 16 showed a positive trend in the number of events exceeding the 95th percentile, with only 5 stations showing statistically significant trends. Other stations exhibited negative trends, with only 18 of them showing statistically significant trends. As the precipitation threshold increases, the pattern is much less clear. Results indicate that a total of 34 stations showed a decrease in the number of events exceeding the 99th percentile, albeit with only 9 stations exhibiting statistically significant trends. These findings suggest that the pattern changed markedly when the threshold was set to the 99.9th percentile. This can be explained by the notion that the annual frequency of events exceeding this threshold generally increases in the headwaters.

4.2. High river flows

Results reveal a general decrease in the percentage of streamflows associated with daily events exceeding the 90th percentile throughout the entire basin. Nonetheless, this pattern was much more evident in the lower reaches, downstream of the dams (Fig. 3). For the stations located in the headwaters, there was no change in the percentage of streamflow recorded for daily flows with magnitudes less than the 90th percentile. Exceptionally, only 4 stations in the headwaters significant changes in the daily streamflow recorded for events exceeding the 95th percentile. For gauge stations located downstream of the main dams, the percentage of the streamflow associated with daily flows with magnitudes less than the 50th percentile increased, while those exceeding the 50th percentile decreased. This pattern indicates that, in the lower reaches of the basin, there was a general increase in the frequency of low streamflows. Correspondingly, there was a decrease in the total streamflow associated with high flows, mainly linked to events having a magnitude exceeding the 95th percentile.

Although there was a reduction in the frequency of the events exceeding the 95th percentile as well as the total streamflow of these events, there was no change in the frequency of the most extraordinary events (>99.5th percentile). Fig. 4 shows the trends in the annual frequency of events exceeding the 95th, 98th, 99th, 99.5th, 99.9th, and 99.95th percentiles at the various gauge stations. For both the headwaters and the lower reaches of the rivers, there was a reduction in the frequency of

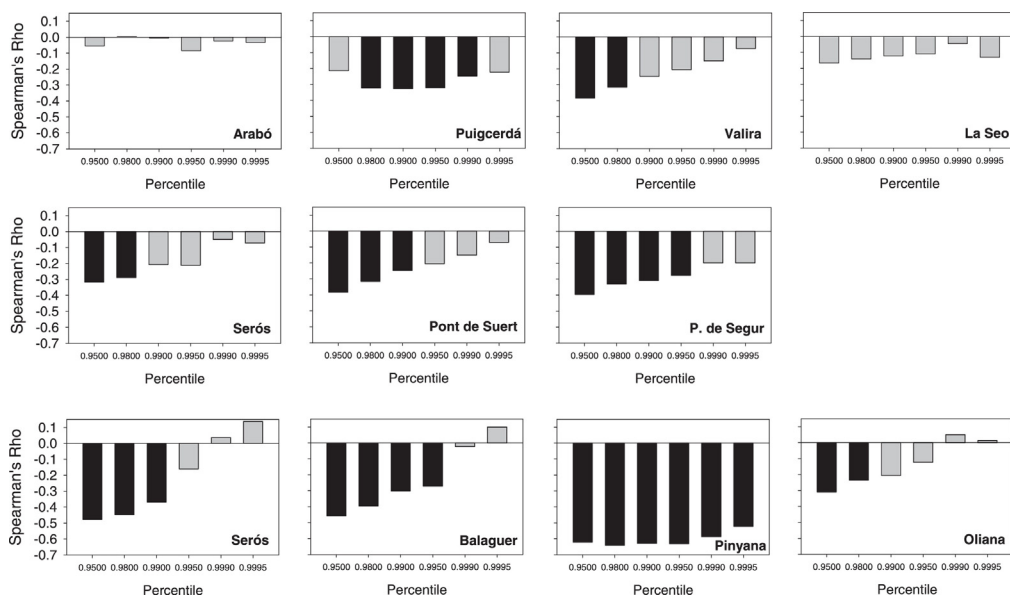


Fig. 4. Correlation between the frequency of events exceeding various percentiles (95th, 98th, 99th, 99.5th, 99.9th, and 99.95th percentiles) and the time series (1950–2013). Black bars represent significant correlations.

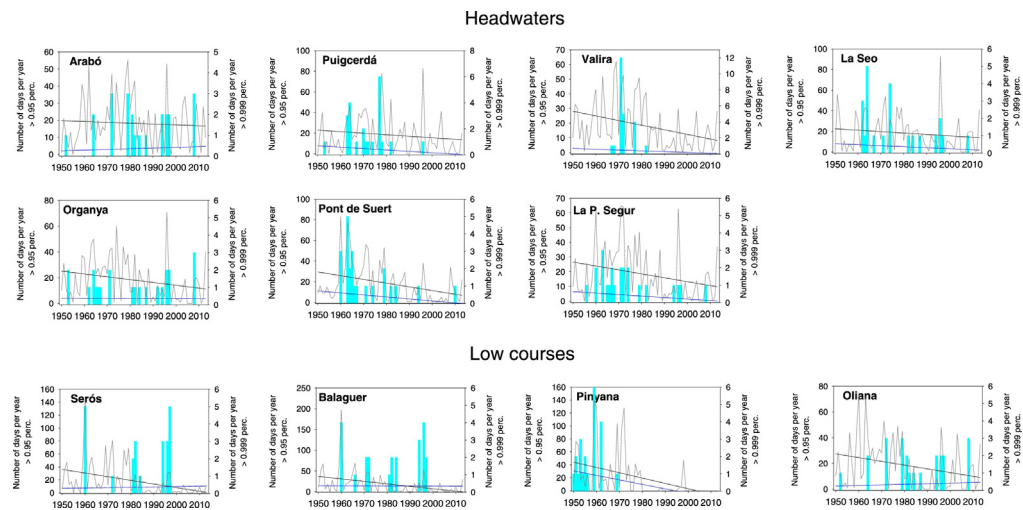


Fig. 5. Evolution of the number of flow events per year exceeding the 95th (gray line) and 99.9th (blue bars) percentiles at each of the two gauge stations located in the headwaters and in the lower reaches. Trend lines are included for events exceeding the 95th (black line) and 99.9th (blue line) percentiles.

daily flows below the 98th percentile. However, there were some exceptions in the headwaters, including the gauge stations of Arabó and la Seud'Urgell. Nevertheless, the analysis of the frequency of the extraordinary floods (i.e. those exceeding the 99.5th percentile) indicates that the magnitude of the decreasing trend is much lower, although assessing trends in the frequency of these events is difficult given their irregular character and uneven sample size. Fig. 5 confirms the same finding for the gauge stations located in the headwaters and the lower reaches of the basin (Seròs and Balaguer). As illustrated, there is a marked decrease in the number of flows exceeding the 95th percentile in the lower reaches of the Segre River (Oliana, Seròs and Balaguer), while the frequency of the extraordinary events (>99.9th percentile) showed no clear temporal pattern. Exceptionally, there is a reduction in the frequency of extreme and extraordinary floods in Pinyana, which can be explained by the very high water regulation and the water transfer to other basins. In any case, in the stations of the Segre River, it is clearly observed that the most extraordinary daily flows showed a low frequency and were usually grouped in the same year. These events mostly occurred prior to the extensive river regulation of the basin that mostly occurred during the period 1960–1970. Nonetheless, other events also occurred in the 1980s and 1990s, following the construction of the main dams in the basin.

The increased regulation in the basin has influenced significantly the frequency of extreme and extraordinary flood events. Fig. 6 shows the evolution of the storage capacity, the ratio between the annual water storage and the storage capacity and the annual frequency of events above the 95th percentile in the gauge stations located downstream the reservoir network. The different gauge stations showed a significant decrease in the frequency of these events, which concurs with the increased storage capacity. In addition, the interannual variability of the events above the 95th percentile is related to the temporal variability in the ratio of reservoir storage/capacity (Table 1). Thus, in the last two decades, only those years with high reservoir levels witnessed some of these events. The pattern of the evolution of events above the 99th percentile is quite similar, albeit with a clear reduction in the most regulated river sectors (Fig. 7). Nevertheless, while Pinyana was exceptionally

Table 1

Pearson's r coefficients between the annual frequency of days with a streamflow above the 95th, 99th and 99.9th percentiles and the average annual values of reservoir storage, total reservoir capacity and the ratio between storage and capacity upstream the gauging stations located in the lower bound of the basin. Statistically significant correlations ($p < 0.05$) are given in bold.

	Pinyana	Oliana	Balaguer	Seròs
Annual frequency (events > 95th)				
Storage	-0.24	0.19	0.03	0.00
Reservoir capacity	-0.31	0.03	-0.26	-0.29
Ratio storage/capacity	0.25	0.19	0.49	0.47
Annual frequency (events > 99th)				
Storage	-0.39	0.31	0.03	0.06
Reservoir capacity	-0.54	0.16	-0.24	-0.19
Ratio storage/capacity	0.46	0.31	0.45	0.39
Annual frequency (events > 99.9th)				
Storage	-0.45	0.17	0.09	0.12
Reservoir capacity	-0.57	0.10	-0.16	-0.14
Ratio storage/capacity	-0.22	0.17	0.40	0.40

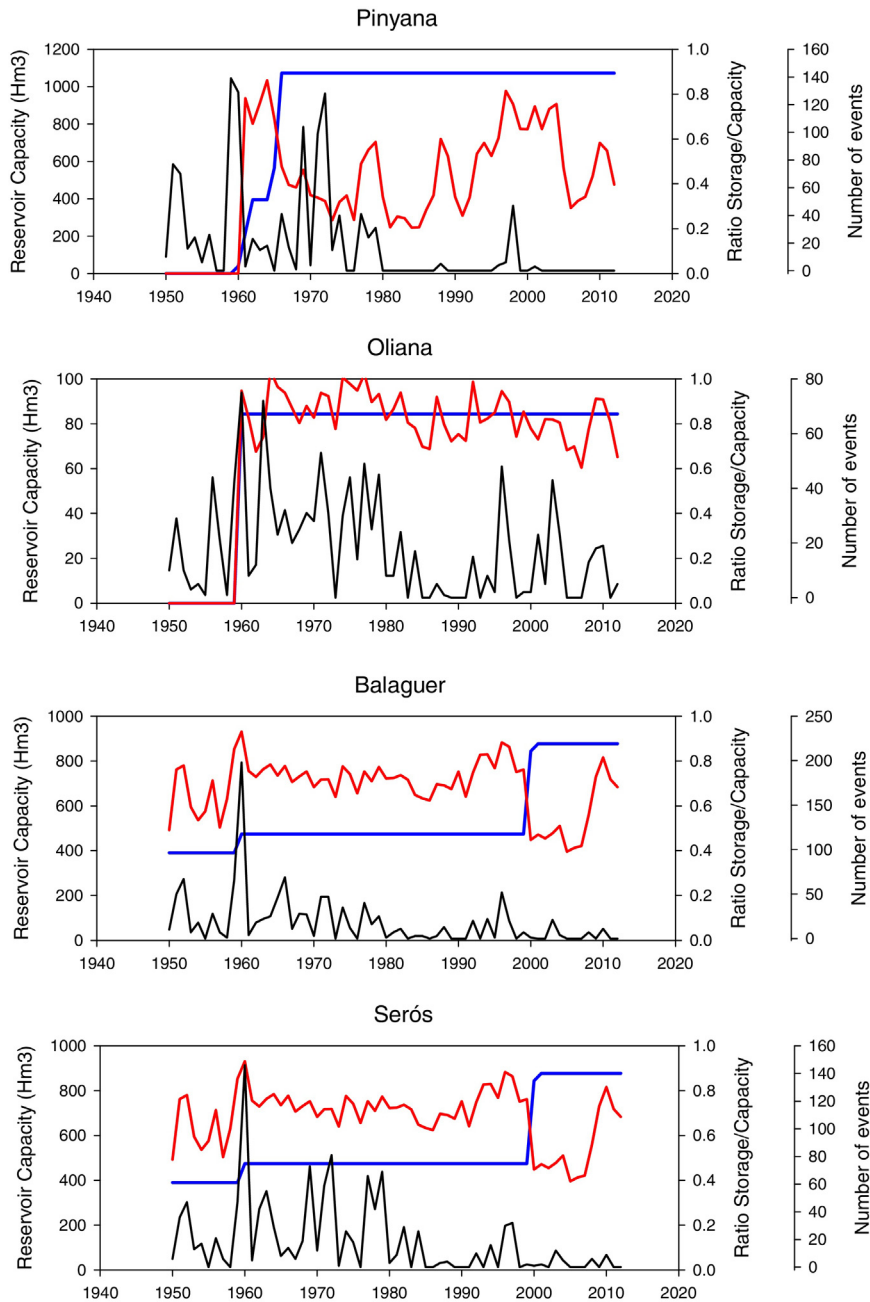


Fig. 6. Temporal evolution of the reservoir storage capacity (blue), the ratio between annual storage and capacity (red) upstream the gauge stations located in the lower bound of the river. Black line represents the annual frequency of events above the 95th percentile.

affected by a strong water regulation and transfer, other gauge stations had a certain frequency of these events during the last two decades. Considering the frequency of extraordinary flood events (>99.9th), the trend was less clear in the stations of Serós and Balaguer (Fig. 8), in which some extraordinary flood events were identified from 1960 to 1990, in spite of the high water regulation from 1950. Since the construction of the Rialb dam in 2000, no events above the 99.9th percentile were identified. This pattern could be related to the strong decrease of relative reservoir storages during the 2000s, which coincided with the most extreme climate drought events in the basin (see below). Overall, Table 1 clearly demonstrates how the frequency of events above the 95th percentile is negatively correlated with the evolution of the reservoir capacity in Balaguer and Serós, although this correlation decreases with the events above the 99th and 99.9th percentiles. On the

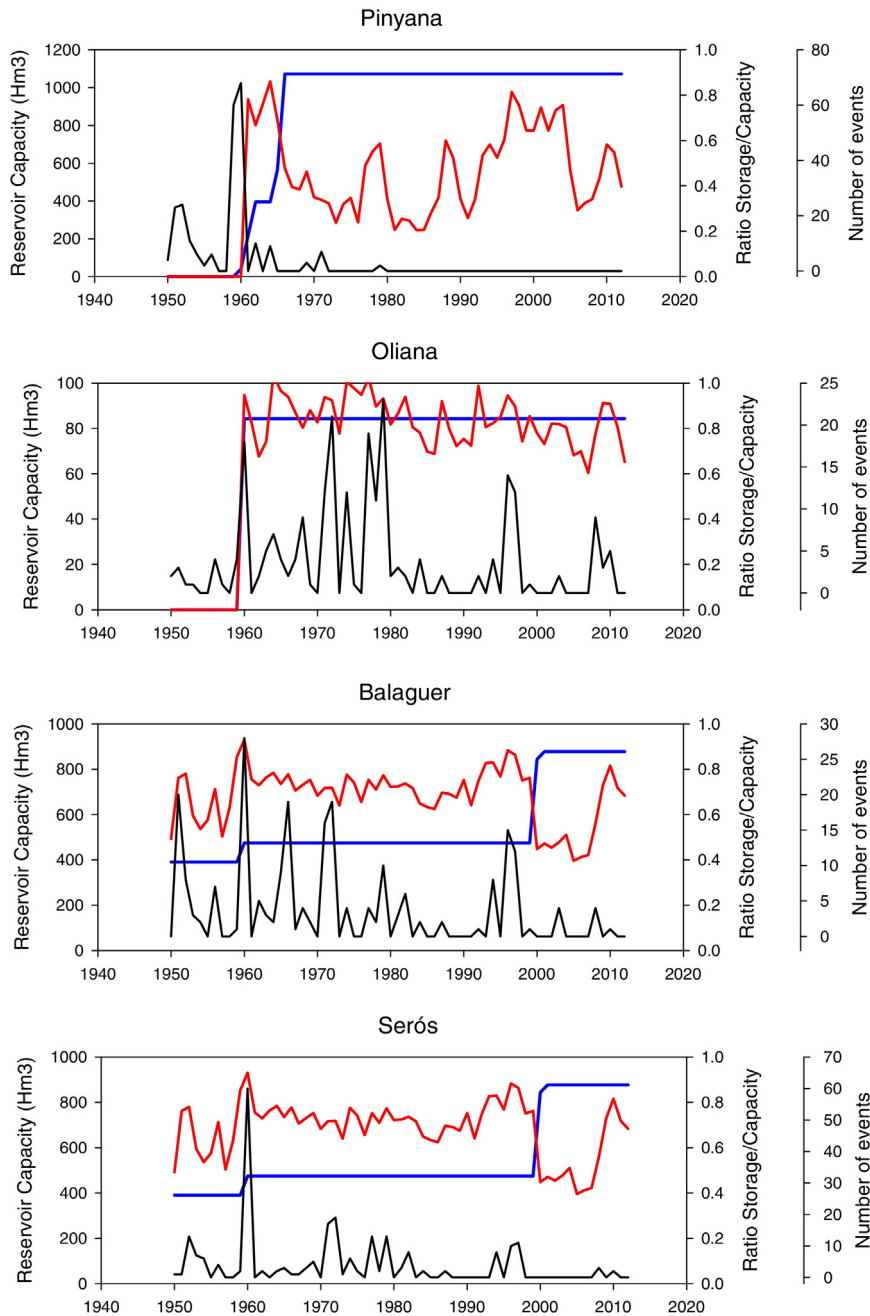


Fig. 7. Temporal evolution of the reservoir storage capacity (blue), the ratio between annual storage and capacity (red) upstream the gauge stations located in the lower bound of the river. Black line represents the annual frequency of events above the 99th percentile.

contrary, the frequency of the three types of events (i.e. 95, 99 and 99.9th percentiles) is significantly correlated with the evolution of the ratio storage/capacity.

4.3. Droughts

Fig. 9 illustrates the evolution of the SSI (hydrological drought index), based on gauge stations in the headwaters of the Segre basin. In general, the series for the majority of stations showed severe drought episodes in the 1950s, although the most extreme episodes occurred during the 2000s. A correlation analysis, calculated at different timescales, between the SSI and the SPEI (climate drought index) reveals that hydrological droughts were correlated with climatic droughts in the headwaters at time scales of 5–8 months. The SPEI series for each sub-basin corresponded to the drought timescale that

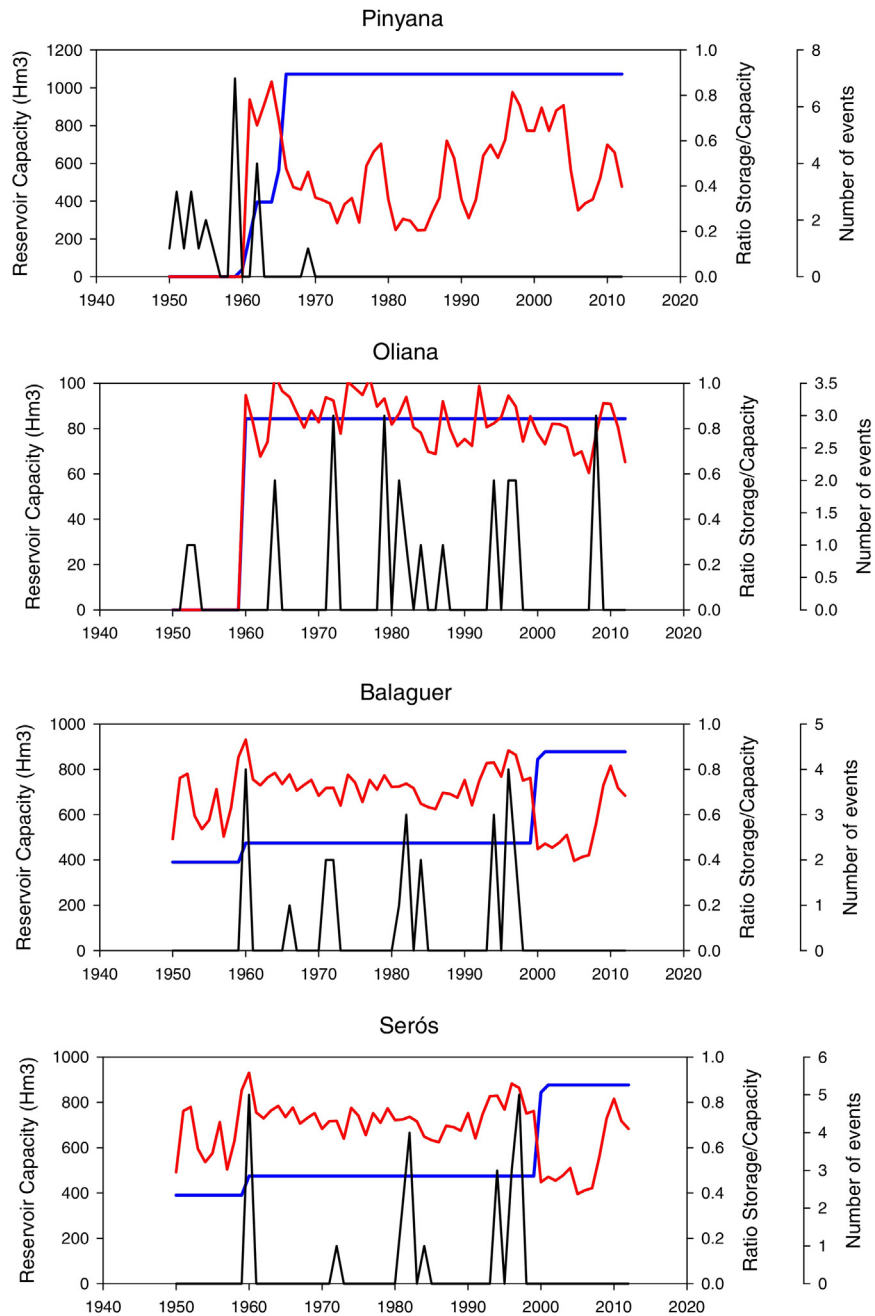


Fig. 8. Temporal evolution of the reservoir storage capacity (blue), the ratio between annual storage and capacity (red) upstream the gauge stations located in the lower bound of the river. Black line represents the annual frequency of events above the 99.9th percentile.

showed the highest correlation with the SSI. Similar to the SSI, the SPEI showed that the most extreme drought episodes occurred in the 2000s, particularly from 2005 to 2010.

Fig. 10 shows the same analysis, but for the gauge stations located downstream of the main dams. At these stations, a marked decrease was observed in the SSI values, which was much more pronounced than that observed for the headwaters during the period 1950–2013. Moreover, the magnitude of the correlations between the SSI and the SPEI decreased at various timescales in the lower reaches. The maximum correlation occurred for longer SPEI timescales. Nevertheless, the behavior of the climate droughts in the lower reaches was quite similar to that observed in the headwaters, with the main drought episodes being recorded in the 2000s; although they showed lower severity and duration relative to the SSI droughts.

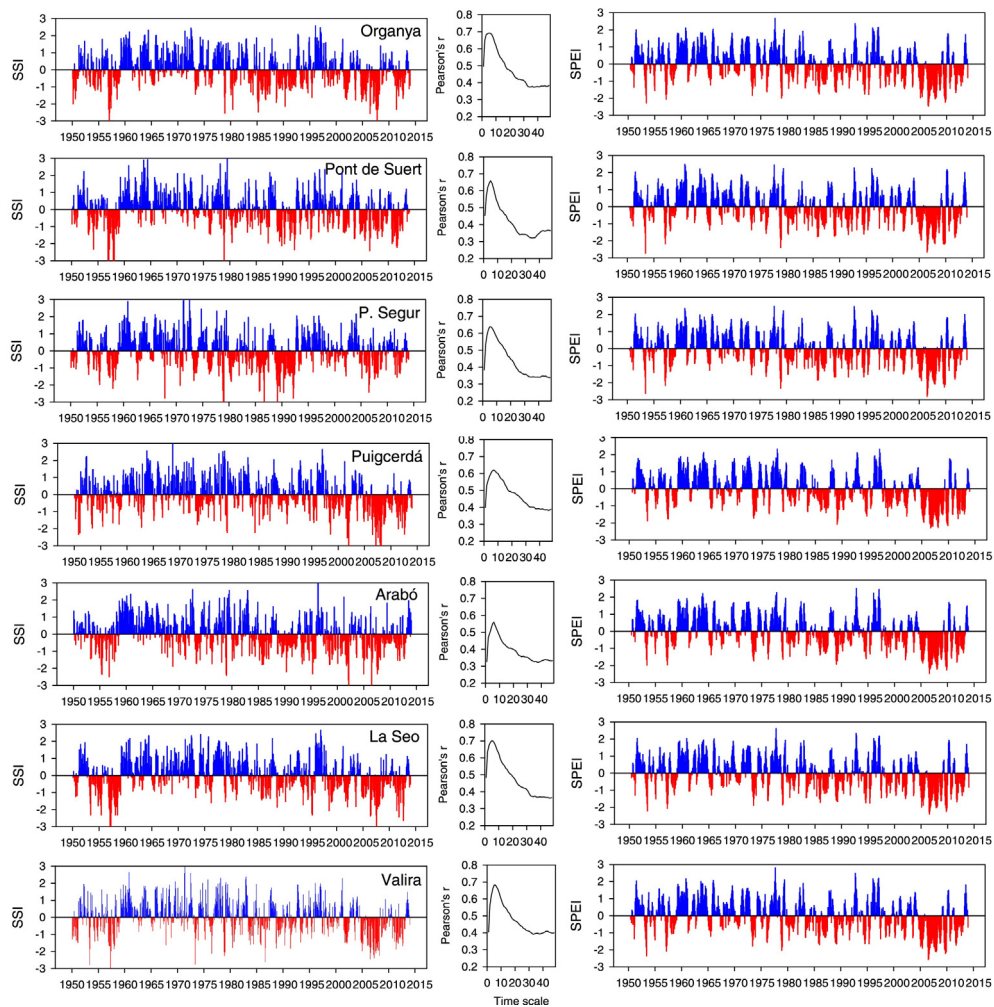


Fig. 9. Left: Temporal evolution of the SSI in the gauge stations of the headwaters. Central: Correlation between the SSI and the 1- to 48-month SPEI time scales. Right: Evolution of the SPEI at timescale with higher correlation.

An interesting response of hydrological droughts to climate droughts was the change in the response of hydrological droughts at the timescales of climate droughts. We found that the magnitude of the change was greater in the lower reaches than in the headwaters. This aspect was detected by applying moving-window correlations between the SSI and SPEI series recorded at different time scales (Fig. 11). In the headwaters, there was no trend toward a decrease in the magnitude of correlations between the SSI and the SPEI at the 5-month timescale, which corresponded to the maximum correlation values in the majority of series. This was clearly evident for the Organyà and Pont de Suert stations, as well as other stations in the basin. In contrast, a comparison of the correlations between the SSI and the SPEI at short and long timescales in the lower reaches suggests a trend toward a lesser response to short SPEI timescales and a greater response to long SPEI timescales.

Trends of droughts of longer duration and greater magnitude were assessed for both the headwater and the lower reach areas. Fig. 12 shows the evolution of the average annual drought duration (in months) and magnitude (in standardized units) for three stations (Puigcerdà, Organyà, and Pont de Suert) located in the headwaters and three (Seròs, Balaguer, and Pinyana) located in the lower reaches. For all these stations, the correlation between the annual average drought duration and magnitude was positive and statistically significant for both hydrological and climatic droughts. Nevertheless, for the headwaters, we found that the trend was stronger for climate droughts than for hydrological droughts, while the opposite occurred for the lower reaches (Table 2). Thus, the evolution of the average annual drought duration and magnitude in the headwaters was positive and statistically significant for both hydrological (SSI) and climate (SPEI) droughts. Nevertheless, for headwater gauge stations, the increase in the magnitude and duration of the climate drought episodes was much greater than that observed for hydrological droughts. In contrast, for the three gauge stations located downstream of the main dams

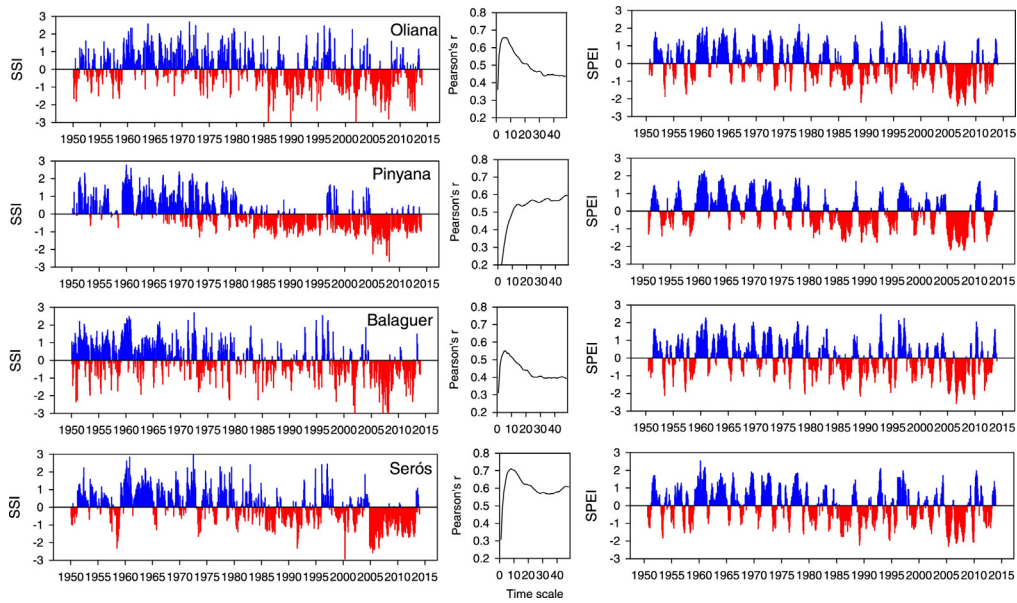


Fig. 10. Left: Temporal evolution of the SSI at gauge stations in the lower reaches. Central: Correlation between the SSI and the 1- to 48-month SPEI time scales. Right: Evolution of the SPEI at timescale with higher correlation.

in the basin (Seròs, Pinyana, and Balaguer), the magnitude and duration of hydrological droughts increased more than that observed for climate droughts.

Fig. 13 shows the temporal evolution of the reservoir storage capacity, the ratio between annual storage and capacity and the annual SSI in the gauge stations located in the lower bound of the river. The most regulated basins (i.e. Pinyana, Balaguer and Seròs) showed a positive and significant correlation with the evolution of the reservoir capacity (Table 3). This finding suggests that drought severity has increased in the lower bound of the basin, as a consequence of river regulation. Results also reveal that reservoir storage is a key driver of streamflow drought severity downstream the reservoirs. In particular, there is a high and significant correlation between the annual reservoir storages and the annual SSI in the most regulated basins, demonstrating a significant influence of the reservoir management on the occurrence of hydrological droughts downstream.

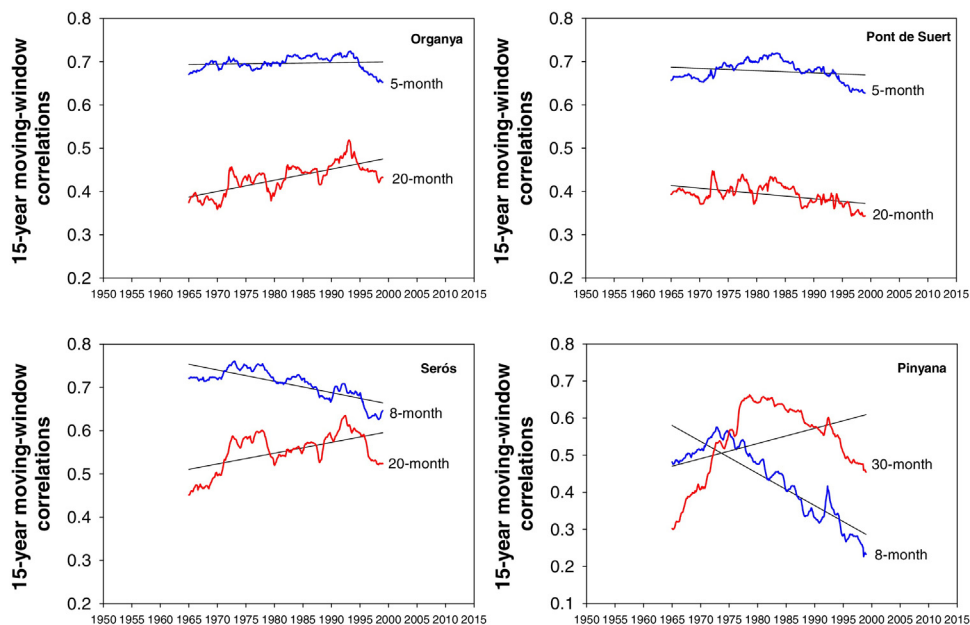


Fig. 11. Evolution of 30-year moving correlations between the SSI and short (blue) and long (red) SPEI time scales at two gauge stations in the headwaters (above) and two stations in the lower reaches (below).

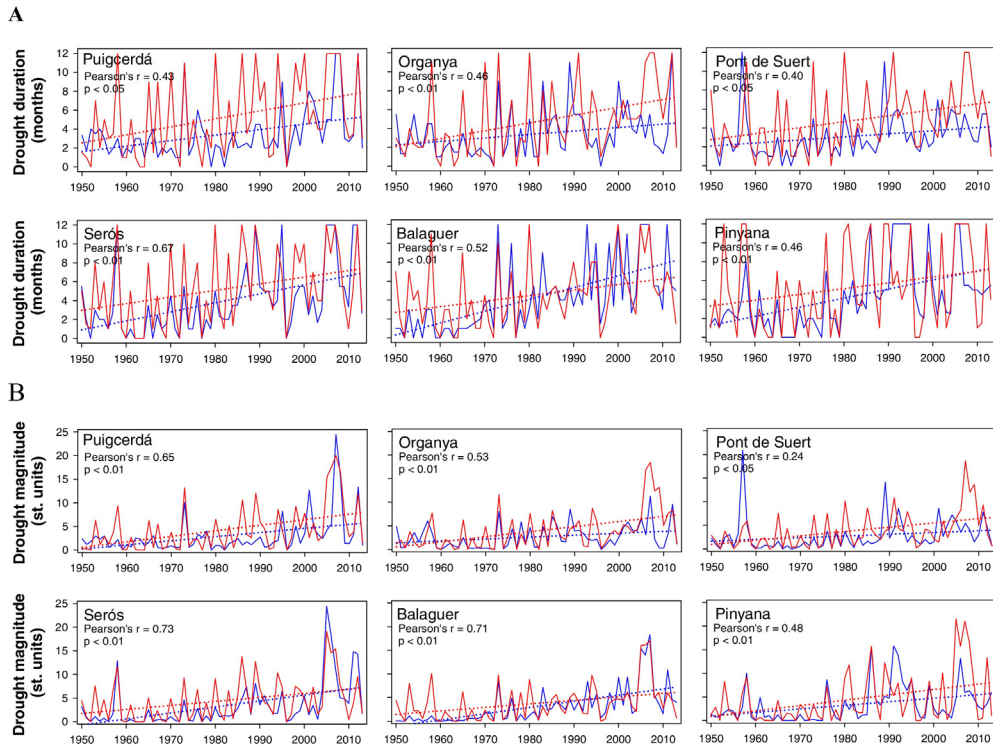


Fig. 12. (A) Evolution of the annual drought duration (blue: hydrological droughts; red: climate droughts) at three gauge stations in the headwaters and three in the lower reaches. (B) Evolution of the annual magnitude (blue: hydrological droughts; red: climate droughts) at three gauge stations in the headwaters and three in the lower reaches.

Table 2

Magnitude of trends in drought duration and magnitude in the headwaters (blue) and lower reaches (orange). Bold: significant trends ($p < 0.05$).

	Duration		Magnitude	
	SSI	SPEI	SSI	SPEI
Puigcerdá	3.3	4.0	4.8	6.1
Organya	2.1	4.0	2.2	5.5
Arabó	0.7	3.4	1.3	5.4
La Seo	0.9	3.9	0.9	5.6
Valira	3.0	3.4	3.4	5.1
Pont Suert	1.4	2.9	1.7	4.6
P. Segur	-0.5	3.0	0.2	4.4
Oliana	3.0	2.8	4.4	4.7
Serós	4.5	2.7	6.7	3.9
Pinyana	4.3	2.1	3.4	5.6
Balaguer	6.1	2.3	7.1	3.5

Table 3

Pearson's r coefficients between the annual SSI and the average annual values of reservoir storage, total reservoir capacity and the ratio between storage and capacity upstream the gauge stations located in the lower bound of the basin. Statistically significant correlations ($p < 0.05$) are given in bold.

	Pinyana	Oliana	Balaguer	Serós
Storage	-0.13	0.18	-0.30	-0.22
Reservoir capacity	-0.31	-0.02	-0.61	-0.55
Ratio storage/capacity	0.28	0.18	0.49	0.56

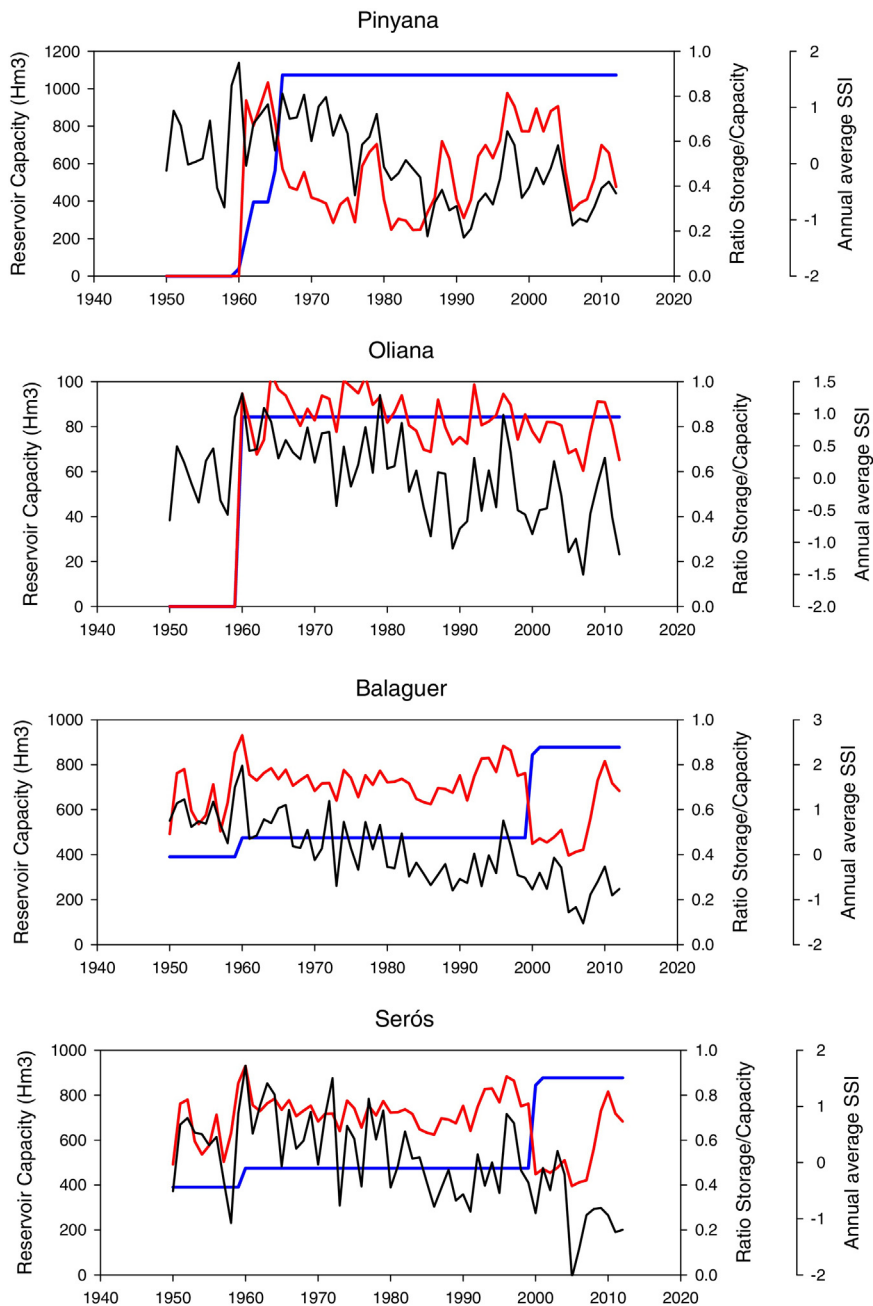


Fig. 13. Temporal evolution of the reservoir storage capacity (blue), the ratio between annual storage and capacity (red) upstream the gauge stations located in the lower bound of the river. Black line represents the annual SSI.

5. Discussion and conclusions

We analyzed the evolution of climate and hydrological extreme events in the Segre basin (northeastern Spain), where streamflows have been highly regulated by a dense network of reservoirs constructed during the second half of the 20th century. Between 1950 and 2013, there was a general reduction in the occurrence of extreme precipitation events in this basin, which this study defined as those exceeding the 95th percentile in precipitation series. This pattern is consistent with previous analyses undertaken at the national (Rodrigo, 2010; Gallego et al., 2011) and regional (López-Moreno et al., 2010; Turco and Llasat, 2011) scales. Thus, the percentage of annual precipitation explained by events exceeding the 95th percentile generally decreased, but with few exceptions where there was a decrease in the frequency of such events. The

trend for the extraordinary events per year (i.e. those exceeding the 99.9th percentile) was not so clear. The analysis of the trend for these events was difficult because they occur very irregularly. Recent studies in Spain focusing on these events have provided no evidence for a generalized trend (e.g. Acero et al., 2011; Beguería et al., 2011). Nevertheless, the headwaters of the Segre basin showed an increase in the frequency of the extraordinary precipitation events, while there has been no significant change in the rest of the basin.

The evolution of the streamflow at the gauge stations in the basin also indicated a general reduction in high flows. There has been a general reduction in the annual streamflow since the 1950s, though being more pronounced in the lower areas of the basin than in the headwaters (Vicente-Serrano et al., 2016). Nevertheless, the pattern of streamflow decrease differed between the headwaters and the lower part of the basin. In the headwaters, there was a general reduction in the streamflow volume associated with events exceeding the 95th percentile. In contrast, there were no major changes in the volume associated with low flows. Following the construction of a dense network of reservoirs in the lower parts of the basin, there was an increase in the streamflow volume associated with the low flow categories, combined with a marked decrease in the high flow categories. This pattern was mainly recorded at the Seròs, Balaguer, and Pinyana gauge stations, which are located in the lower part of the Segre basin.

This study also noted a general decrease in the volume associated with high flows during recent decades, particularly in the northern (Renard et al., 2008; Giuntoli et al., 2013) and southern (López-Moreno et al., 2006) slopes of the Pyrenees. A similar pattern has also been observed in other basins across the Iberian Peninsula (e.g. Silva et al., 2012; Morán-Tejeda et al., 2012; Mediero et al., 2014). This pattern can be explained by the general reduction in precipitation in the Spanish Pyrenees (López-Moreno et al., 2010), and particularly in the Segre basin (Vicente-Serrano et al., 2016). However, the general increase in vegetation activity and cover associated with the abandonment of agricultural practices in these mountain areas during the second half of the 20th century may also have been important (Lasanta et al., 2005; García-Ruiz and Lana-Renault, 2011). Mediero et al. (2014) related changes in climate processes to the general reduction in high flows in several basins of Spain not affected by damming. They suggested that trends in floods could also be related to the evolution of the AED, which has increased markedly in Spain in the last five decades (Vicente-Serrano et al., 2014). In humid areas, including the Pyrenean headwaters, an increase in AED would contribute to greater transpiration in areas having dense vegetation cover, which would contribute to depletion of the soil water content. Thus, studies in experimental basins in the Pyrenees have shown that the generation of floods is highly related to the soil moisture conditions in the basins (Lana-Renault et al., 2007; Serrano-Muela et al., 2015), although a direct connection between particular flood anomalies and air temperature conditions is difficult to establish.

The marked differences between the headwaters and the lower reaches of the basin with respect to the trends in the contribution of low and high flows to the annual streamflow volume are likely to be associated with the intense regulation of water to meet the water supply demands for irrigated areas and livestock farms, which are the main economic activities in the basin. Several studies have indicated that there has been a reduction in the magnitude of high flows associated with the presence of dams (Benke, 1990; Ligon et al., 1995; Thoms and Sheldon, 2000; Song et al., 2015; Bai et al., 2015), but also an increase in the contribution of low flows (Nislow et al., 2002; Cowell and Stoudt, 2002). For example, Magilligan and Nislow (2005) analyzed the impact of dams in 21 river basins in the USA, concluding that, for low flows, the 1- to 90-day minimum flows increased significantly following impoundment.

In the Segre basin, the dams have clearly moderated the floods that occur in the basin. This is evident from the analysis of the frequency of streamflows exceeding certain thresholds each year. Nevertheless, while this pattern is evident for thresholds corresponding to the 95th to 99.5th percentiles, there has been no reduction in the frequency of extraordinary floods. This pattern is particularly evident in the headwaters, where extraordinary precipitation events are random in space and time, mainly contributing to flood generation (García-Ruiz et al., 2000). Thus, there has been a general increase in the frequency of the extraordinary precipitation events (>99.9th percentile) in the headwaters of the basin, which could affect the frequency of the extraordinary floods occurring in this area. An explanation of the absence of a trend in extreme floods is an avenue for future research, particularly with the observed increase in the frequency of the most extreme rainfall events. However, revegetation of parts of the basin, as reported in Piqué et al. (2016), could affect water interception and soil moisture via evapotranspiration, and thus influence the relationship between extreme precipitation events and floods. The results of studies in experimental basins across the western Pyrenees skillfully validated this hypothesis (Serrano-Muela et al., 2015).

Interestingly, r , the observed pattern in the headwaters of the Segre basin was also recorded in the lower reaches. Regardless of the extensive regulation of the basin since the 1950s, extraordinary floods were recorded in the 1980s and 1990s, as a consequence of the reconstruction of the main reservoirs of the basin. This exception is represented in the Pinyana station, which was affected by a high level of water regulation and a water transfer upstream. Based on a temporal perspective of several centuries, Barrera-Escoda and Llasat (2015) suggested that floods in the Segre basin did not decrease during the second half of the 20th century. Our results suggest that the reservoirs of the Segre basin have had a marked influence on the regulation of ordinary and extraordinary floods, but the capacity of the reservoir network to reduce extraordinary floods may depend on a large number of factors, including reservoir capacity and storage and the dam operation rules. Using various case studies based on small reservoirs in Europe, Salazar et al. (2012) analyzed the effectiveness of flood management measures, demonstrating that these reservoirs are effective in reducing the downstream magnitude of small and medium events, but have almost no effect on the largest floods. Similar results have been found in other studies (e.g. Smith et al., 2010). In the Segre basin, it is likely that the reservoirs would reduce the magnitude of extreme floods,

as their storage capacity is very high. Nevertheless, other physiographic and climatic factors could also play important roles.

The basins of northeastern Spain are affected by torrential rainfall in response to various atmospheric mechanisms (Llasat and Puigcerver, 1997). Extreme precipitation events can occur following periods of extensive precipitation, generating large volumes of surface runoff, particularly when soil is saturated (Lana-Renault et al., 2007; García-Ruiz et al., 2005, 2008). Numerous studies have shown that annual and/or seasonal climate conditions can markedly affect the capacity of reservoirs to manage the largest floods. Morán-Tejeda et al. (2012) investigated this issue in the Douro basin (central Spain), concluding that for most reservoirs, the level of alteration to flows was highly correlated with the annual inflow volume. A representative example is the reservoirs, which were not regulated excessively, during years of relatively high levels of water input. Furthermore, López-Moreno et al. (2002) indicated that the influence of the Yesa reservoir on downstream floods in Aragon basin (the western Pyrenees) depends largely on water storage level. Thus, they noted that when the dam was at greater than 90% capacity, there was almost no flood control, and even higher peak flows could occur downstream because of the sudden releases of the water necessary for dam safety. These results highlight the difficulties in flood management in highly complex Mediterranean basins, including the Segre basin, where climate variability overlaps at various temporal scales (from daily to annual) in determining the occurrence of flood events.

This study indicates that reservoir construction and water uses in the Segre basin have impacted the frequency, duration, and severity of hydrological droughts downstream of the main dams. There has been an increase in hydrological droughts associated with the observed evolution of climate droughts, which is consistent with the general pattern found for the Iberian Peninsula (Vicente-Serrano et al., 2014). This study suggests a high level of agreement between the temporal evolution of climate and hydrological drought indices in the Segre basin. Thus, both records indicated that the most severe drought events occurred in the 2000s, in accordance with observations in other basins of northeastern Spain (López-Bustins et al., 2013). Nevertheless, the response of hydrological droughts to climate droughts differed markedly between the headwaters and the lower areas of the basin. In the headwaters, hydrological droughts mostly respond to short timescales of climate droughts, which is a characteristic of areas with limited capacity to water storage as well as a rapid streamflow response to precipitation variability (López-Moreno et al., 2013; Barker et al., 2015). In contrast, in the lower areas of the basin, the response of hydrological droughts occurred at longer climate drought timescales, because of the high water storage capacity upstream. This pattern is also a characteristic of other regions of the Iberian Peninsula, where damming has clearly altered the timescales of response of hydrological droughts to climate variability (Vicente Serrano and López-Moreno, 2005; Lorenzo-Lacruz et al., 2010; López-Moreno et al., 2013). Thus, the increased streamflow regulation in the Segre basin has markedly altered the timescales of response of hydrological droughts to climate droughts. While there has been significant change in the correlation between hydrological and climate droughts at various timescales in the headwaters, there has been a clear increase in the influence of long climate drought time scales in the lower areas of the basin, and accordingly a reduction in the influence of short climate drought timescales; this is consistent with the increased storage capacity in the basin.

Numerous studies had stressed the potential of water regulation to reduce the severity of droughts, based on water storage capacity (Yeh and Becker, 1982; McMahon et al., 2006). This approach is applicable in the Segre basin, where a large reservoir network guarantees the water supply for large irrigated areas in the lower parts of the basin. Nevertheless, in few instances, the Segre basin network failed to adequately meet water demands for irrigation. A representative example is the most extreme drought events occurred during the 2000s.

Nevertheless, from a hydrological perspective, the water regulation system does not appear to be so efficient for managing hydrological droughts. In the headwaters of the Segre basin, the increase in the duration and magnitude of hydrological droughts was less, compared to climate droughts. This was probably because of the capacity of the mountain headwaters to split long duration climate droughts in response to intense short duration precipitation events. In contrast, in the lower areas of the basin, the opposite pattern was observed, with a marked increase in the duration and magnitude of hydrological droughts relative to that of climate droughts. In the Segre basin, there has been a large decrease in streamflow, as a consequence of the recent decrease in precipitation and increase in AED. However, the decrease in streamflow is much more pronounced in the lower areas of the basin, due to the high and increasing demands for different domestic and agricultural uses (Vicente-Serrano et al., 2016).

The high demand for water for agriculture, urban, and tourist uses in the Iberian Peninsula have made the accentuation of hydrological droughts downstream large reservoir systems a common management practice. This feature has already observed in the Douro basin (Morán-Tejeda et al., 2012) and the headwaters (Lorenzo-Lacruz et al., 2010) and lower reaches (López-Moreno et al., 2009) of the Tagus basin. The objective of reservoir management in any basin is primarily to supply water for various uses, besides releasing water to rivers. Because of the need to meet the demands of water users, the base flow in most regulated rivers is much lower in magnitude than that in rivers with natural streamflow (Ibáñez et al., 1996; Batalla et al., 2004). This feature largely explains the observed increase in hydrological droughts downstream of major dams, which in accordance increases water regulation capacity to supply irrigated lands, urban areas and livestock farms. This is exacerbated during extreme climate drought periods, such as those affected the Segre basin in 2007–2009, when the supply of available water resources to the various water users was prior over streamflows. However, the streamflow reduction cannot affect a minimum environmental flow, established by the current environmental laws in Spain.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.ejrh.2017.01.004](https://doi.org/10.1016/j.ejrh.2017.01.004).

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