Journal of Hydrology: Regional Studies 12 (2017) 13–32

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

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

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A R T I C L E I N F O

Article history:
Received 23 June 2016
Received in revised form 16 January 2017
Accepted 29 January 2017

Keywords:
Droughts
Floods
Segre basin
Hydrological trends
Dams
Reservoir effects

A B S T R A C T

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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http://dx.doi.org/10.1016/j.ejrh.2017.01.004

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 km^2. The basin has three main rivers: the Segre River (8167 km^2; the main tributary of the Ebro River), the Noguera Pallaresa River (2807 km^2), and the Noguera Ribagorzana River (2061 km^2) (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 agricultural 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