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Effect of reservoirs on streamflow and river regimes in a heavily regulated river basin of Northeast Spain

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ABSTRACT

Dams modify downstream hydrology because they alter natural river regimes and divert river flows. The Segre Basin is one of the main tributaries of the Ebro River in Northeastern Spain, and has a drainage area of 13,000 km^2. In this study, we used data on long-term (1951–2013) river flows and climatic series to analyze the downstream cumulative effect of dams on natural river regimes and the disassociation between changes in climate and runoff in the Segre Basin. The headwaters of this basin are in the Pyrenees Mountains, and water flow has been highly regulated since the second half of the twentieth century due to the construction of numerous dams. We compared long-term monthly averages of upstream and downstream sectors, and assessed the relationship between the climatic and hydrological time series. Our results show that the progressive increase of the impounded ratio index (reservoir capacity) increased the disassociation between climate and runoff. This markedly exacerbated the negative trend in downstream runoff, so this decline that cannot be solely explained by climatic changes. Our results provide evidence that reservoirs can cause a significant decline in downstream runoff and significant alterations of natural river regimes.

1. Introduction

Water is an essential resource for agriculture, urban residents, and the natural environment of the Mediterranean region (García-Ruiz et al., 2011). This region has strong inter-annual climatic variability (Lionello, 2012), with a summer dry period in which there is great water demand (Iglesias and Minguez, 1997; García-Ruiz et al., 2011). The mismatch between water availability and demand has led to the creation of many dams, which store water during rainy periods and supply irrigated fields and urban areas during the dry season (Döll et al., 2009; Aus Der Beek et al., 2010). Water from these dams is also used for hydropower (López-Moreno et al., 2008).

Dams have significant effects on downstream hydrology because they alter natural river regimes and divert river flows for different uses (López-Moreno et al., 2004). Thus, the ability to store water in reservoirs has strongly increased water demands in recent decades because it has led to significant increases in irrigated areas (Batalla et al., 2004; Kilic et al., 2006). In Spain, there has been a general decrease in streamflow in the last five decades, and this decrease has been more intense in the most regulated river basins (Lorenzo-Lacruz et al., 2012) because they provide water to different economic sectors. Dam regulation and water transfers between basins have also decreased streamflows and exacerbated droughts in downstream regions (López-Moreno et al., 2009; Lorenzo-Lacruz et al., 2010, 2013).

In parallel, increasing water regulation and demand in Spain during recent decades (Duarte et al., 2014) has occurred together intense climatic and hydrologic changes. These changes include a general reduction of precipitation (González-Hidalgo et al., 2011), more frequent and severe droughts (Hoerling et al., 2012; Vicente-Serrano et al., 2014a), and strong increases of atmospheric water demand (Vicente-Serrano et al., 2014b) due to higher temperatures (Brunet et al., 2007) and decreased relative humidity (Vicente-Serrano et al., 2014c, 2014d). This changes have been especially acute in the Northeast Iberian Peninsula, which suffered from significant droughts in the last decade (Lopez-Bustins et al., 2013) and experienced a general shortage of water resources (Martin-Ortega et al., 2012; March et al., 2013).

The Segre River Basin, with a drainage area of 13,000 km^2, is located between the regions of Aragon and Catalonia, in the Northeast Iberian Peninsula. This region is characterized by strong climatic and hydrological diversity (Sacasas, 2007), and has been greatly affected by floods and droughts in recent centuries (Barriendos et al., 2003; Thorndycraft

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et al., 2006). Studies of the headwaters of the Segre Basin have documented a general decline of water resources over the last five decades. Buendía et al. (2015a) showed that the Noguera Pallaresa River (the main tributary of the Segre River) has undergone a notable reduction in streamflow during late spring and summer. In addition, natural vegetation in this region has dramatically expanded because of the abandonment of traditional agricultural activities and the marginal productivity of the slopes (García-Ruiz and Lana-Renault, 2011). Afforestation is also linked to the declining runoff in the headwaters of the Segre Basin (Buendía et al., 2015a, 2015b), as in other basins of the Spanish Pyrenees (Beguería et al., 2003; Gallart and Llorens, 2003).

Although changes in climate and land cover may explain many of the changes in streamflow during recent decades, the increased river regulation by dams in the last century has also had a major impact on the Segre River Basin. Irrigated agriculture has significant economic importance in this region (Pascual et al., 2006; Matas, 2015), but the consequences of increased irrigation and water regulation on streamflow are unknown. Given the complex interactions of climate change, land cover changes, and water management, it is difficult to determine the role of agricultural water demand on changes in streamflow in the Segre River.

In this study, we used long-term data (1951–2013) on river flows and climatic series to analyze the cumulative downstream effects of dams and agricultural water demands on natural river regimes and on the disassociation of climate from runoff in the Segre Basin. The objective is to analyze changes in the availability of water resources throughout the Segre Basin and to identify interactions between changes in climate and streamflow due to dams and changing water demands.

2. Study area

The drainage basin covers 13,000 km^2, and includes 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 to >3200 m in the Pyrenees. The average precipitation is approximately 814 mm year^{-1}, although there are large differences between the Pyrenean headwaters (>1100 mm year^{-1}) and the southern lowlands (<400 mm year^{-1}). Annual reference evapotranspiration in the headwaters is <-600 mm year^{-1}, but exceeds 1100 mm in the south, near the mouth of the Ebro River (Vicente-Serrano et al., 2007). Under a natural regime, the river has a notable seasonality, with the main flow during May and June due to snowmelt and high precipitation during spring. Nevertheless, significant precipitation from storms can occur during the summer months (De Luis et al., 2011).

The population of the basin has increased 60% from 1900 to 2010. Total population in 2010 was 422,000 inhabitants Agroindustry on irrigated lands and intensive livestock management are the main economic sectors. The basin has 144,000 ha with irrigation, based on the canals of Urgell, Pinyana, Aragón y Catalunya, and Segarra-Garrigues. Currently there are 35 reservoirs in the Segre Basin, an increase from 15 in 1951 (Fig. 2) and the total storage capacity is 2084 hm^3. Despite the large number of dams, seven reservoirs account for 94% of the total water storage capacity. Most water regulation is in the headwaters and middle reaches of the Noguera Ribagorzana River and the Noguera Pallaresa River, with the reservoirs of Escales (163 hm^3), Canelles (687.5 hm^3), Santa Anna (236.6 hm^3), Talarn (205.1 hm^3), and Camarasa (163 hm^3). The Segre River is regulated by the Oliana Reservoir

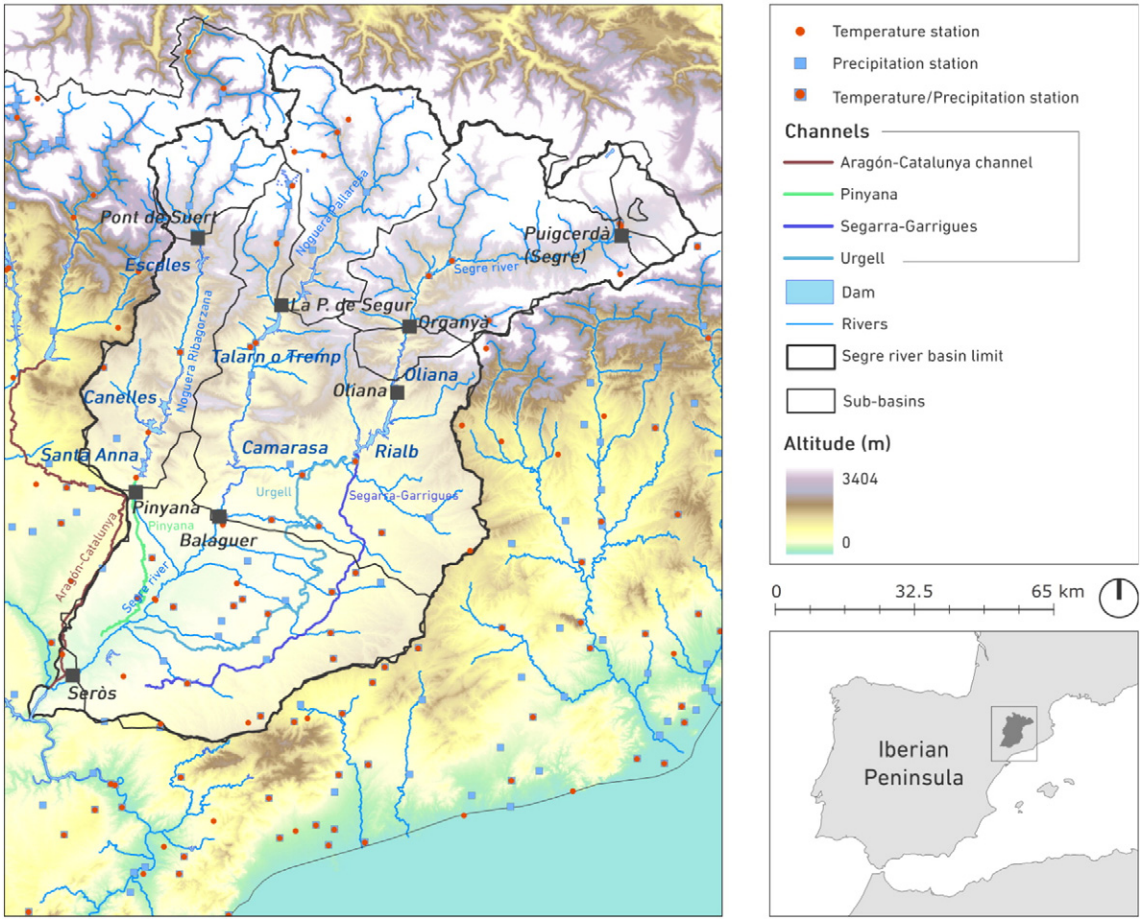

Fig. 1. Location and topography of the Segre River Basin. The main reservoirs are in blue and the black squares indicate the locations of gauging stations used in this study.