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The extreme floods in the Ebro River basin since 1600 CE

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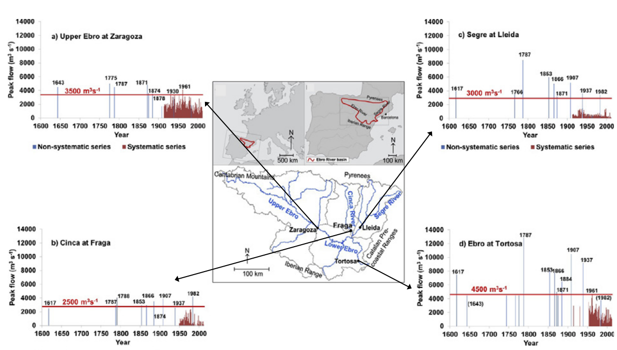
HIGHLIGHTS

- Analysis of the major floods on the Ebro river since 1600.
- Spatial and temporal distribution of the floods in the whole basin.
- Contributions of the different main tributaries at the mouth.
- Patterns and type of precipitation dominating the different subbasins.
- Role of the synoptic and large scale atmospheric systems and climatic variability.

GRAPHICAL ABSTRACT



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ABSTRACT

Reliable and complete knowledge of the historical floods is necessary for understanding the extreme hydrological dynamics of the rivers, their natural variability and anthropic changes. In this work we reconstruct the most important floods of the Ebro basin during the last 400 years in different areas of the basin. The analysis is based on four different areas: the Ebro River at Zaragoza, the Cinca River at Fraga, the Segre River at Lleida, and the Ebro River near its mouth at Tortosa.

Based on a documentary research, we have first obtained relevant information about the initial conditions (rainfall duration and distribution, snow cover influence) and the maximum flood heights that allow to reconstruct the maximum peak flows by using hydraulic models and to calculate the subbasins contributions.

The results show four main types of extreme floods: a) those affecting simultaneously all the subbasins with the highest peak discharges (Ebro at Tortosa in 1787: 0.15 $m^3\ s^{-1}\ km^{-2}$); b) those originated at the western basin, upstream from Zaragoza, with an Atlantic origin, presenting moderate maximum peak flows, caused by persistent winter rainfall and where snowmelt significantly contributes to the flood; c) those originating at the central Pyrenean subbasins, with Mediterranean origin, occurring, with high peak discharges. These mainly occur during autumn as a consequence of rainfalls of different duration (between 3 days and 1 month), and without significant snow thawing and d) finally, less frequent but very intense flash floods events centered in the Lower Ebro area with low peak flows.

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In terms of frequency, two different periods can be distinguished: from 1600 until 1850, the frequency of events is low; since 1850 the frequency of events is clearly higher, due to an increase of the climatic variability during last stages of the Little Ice Age. From the 1960's reservoirs construction modifies discharges regime.

1. Introduction

The European Union regulatory framework for planning flood risk (EU Directive 2007/60/EC) uses information from previous floods obtained from hydrometric series of maximum peak flows and from documentary sources of historical floods.

Sometimes information about the largest peak flows during a flood is scarce for several reasons: they seldom occur; it could be difficult to measure hydraulical variables such as water height and flow speed; and due to the destruction of the instrumentation during the flood. However, determining this type of data with robustness and reliability is most needed for estimating the expected discharge for different return periods.

While the current requirements for the secure design of civil infrastructures must include return periods of 500 years or more, the available series do not cover even 50 years for many rivers and it is very unusual to have continuous series that are longer than 100 years for any river (Macdonald and Sangster, 2017). This clearly reflects the important lack of representativeness of the data.

On the other hand, IPCC (2013) projects an increase in extreme climatic events, including the occurrence of floods. In order to reduce the uncertainty of these projections, it is advisable to collect instrumental and documentary data covering long periods in order to explain the variability of the hydrological systems and to be able to relate flood occurrence to natural or anthropogenic causes: a) climate change, b) land use modifications at the basin scale, and c) changes in the riverbeds and reservoirs (Merz et al., 2014; Kundzewicz et al., 2014). Having broad and centuries-old knowledge of the hydrological data allows us to investigate the long-term temporal variability and the lack of stationarity in the fluvial systems (Milly et al., 2008; Machado et al., 2015).

This new necessity is clearly reflected by some early 21st century reviews of flood series at different rivers being published in journals specializing in historical hydrology and paleohydrology (Benito et al., 2005, 2015b; Gregory et al., 2006; Brázdil and Kundzewicz, 2006). There is currently an extended chronology in Europe (Glaser et al., 2010; Brázdil et al., 2006, 2012; Luterbacher et al., 2012) that allows detecting spatial and temporal changes in the flood regimes (Blöschl and Montanari, 2010; Hall et al., 2014; Kjeldsen et al., 2014; Kundzewicz et al., 2014).

For the Iberian Peninsula (IP), there are historical chronologies that cover most of the basins (Barriendos and Rodrigo, 2006; Benito and Machado, 2012), the Mediterranean coast (Barriendos and Martín Vide, 1998), Catalonia (Barriendos et al., 2003; Llasat et al., 2005; Barrera-Escoda and Llasat, 2015), SE of IP (Machado et al., 2011), the Atlantic rivers (Benito et al., 2003), and some specific areas of the Pyrenees mountain range (Corella et al., 2014, 2016).

Despite the quality of those previous works, we still have a reduced knowledge of the magnitude (maximum peak flow) of some of the floods and this information is very difficult to obtain (Herget et al., 2014; Benito et al., 2015a). During the last decade, several studies have reconstructed the maximum peak flow at a particular location in a particular basin (Thorndycraft et al., 2006; Balasch et al., 2007; Calenda et al., 2009; Elleder, 2010). Considering the whole basin of a river, some historical analysis that cover several centuries have been published (Benito et al., 2003; Naulet et al., 2005; Herget and Meurs, 2010; Balasch et al., 2011; Elleder et al., 2013; Roggenkamp and Herget, 2014), although they do not analyze the role and contribution of the different tributaries, which is fundamental to understanding the different hydrological responses of the subbasins during the floods.

For the particular case of the Ebro River, the analysis of the hydrology regarding the magnitude of the extreme floods before the instrumental period has been quite limited (López-Bustos, 1972, 1981; Ruiz-Bellet et al., 2015b). The main goals of this work are to reconstruct the maximum peak flow of the large floods at the mouth of the Ebro basin (Tortosa) and to study and evaluate the contributions of the main subbasins (Upper Ebro in the west, and Cinca and Segre rivers in the central Pyrenees), specifically at the hydraulic, and hydrological levels. In addition, we seek to qualitatively study the previous soil moisture conditions. This analysis will be performed on the magnitude, temporal evolution (frequency), seasonality, and complementarity of the discharge contributions. With this information we would like to increase our knowledge about the temporal variability of the extreme floods in one of the most important Mediterranean rivers and to improve some aspects of planning flood risk management.

2. Study area: the Ebro river basin

The Ebro is one of the great rivers of the Mediterranean basin, similar in size and mean discharge to the (France and Switzerland) and Po (Italy), but smaller than the Nile and Danube. Within the IP, it is the second longest (930 km), the second in mean discharge (428 $m^3 s^{-1}$), and the most regular in annual discharge volume.

The Ebro River drains the north-eastern part of the IP, which includes most of the southern side of the Pyrenees Range, into the Mediterranean Sea (Fig. 1). It has a NW-SE orientation and a triangular-shaped basin of 85,362 km^2, which approximately matches the Cenozoic foreland basin caused by the Alpine rising of the Pyrenees Range. This range delimits the basin to the N, whereas the Cantabrian Massif delimits it to the NW, the Iberian System Range to the S and SW and the Catalan Pre-Coastal Range to the E.

Regarding its morphology, the main course is divided into three parts: The Upper Ebro, from Peña Labra (Cantabria) up to Miranda de Ebro (250 km, mean slope 7.6 mkm^{-1}); the Middle-Ebro, from Haro up to Mequinenza (565 km, 480 km of them with meanders, and a mean slope 0.66 mkm^{-1}) and the Lower Ebro, between the confluence with the Segre-Cinca system up to the Mediterranean Sea (115 km, mean slope 0.46 mkm^{-1}) (Ollero et al., 2004; Del Valle et al., 2007).

Mean annual rainfall in the whole basin is 622 mm during the period 1920–2000. However, rainfall is very unevenly distributed across the basin: there is a high altitudinal gradient as well as a W-E gradient: 1000–1500 mm in the Cantabrian mountain ranges and the Pyrenees; 400–700 mm in the Iberian System range; and <400 mm in the central course of the Ebro, and in the lower courses of the Cinca and Segre. In the period 1950–2001 a small decrease in the amount of precipitation at the headwaters located at the Pyrenees were observed, and this was especially concentrated during the spring and summer (Vicente-Serrano et al., 2007). Evapotranspiration losses have an opposite gradient to those of rainfall: they are higher in lower areas, with a basin average value of 450 mm. Increasing water use and changes in soil use in mountainous regions have greatly reduced runoff volume at Tortosa, near the outfall: from 18,500 hm^3yr^{-1} in the 1960s to 12,000 hm^3yr^{-1} (García-Ruiz et al., 1995; Gallart and Llorens, 2004). In terms of the runoff coefficient this represents a change from 35% to 22.7%.

Due to the extension and geographical configuration of the Ebro basin, there is a high climatic variability between the headwaters and