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# Detection and attribution of trends in magnitude, frequency and timing of floods in Spain

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SUMMARY

An analysis to detect trends in magnitude, frequency and timing of floods was conducted in Spain through nine flood indicators. A data set of gauging stations where the effect of dam regulation on flow series is negligible was obtained. Annual maximum and peaks-over-threshold series were extracted in three periods: 1942–2009, 1949–2009 and 1959–2009. A pre-whitening procedure was applied to remove serial correlation and the Mann–Kendall test selected to detect trends. A general decreasing trend in magnitude and frequency of floods was detected in the three periods, with more notable evidence in 1959–2009. An increasing trend in the timing (i.e. towards later floods) was also found in the northwest of Spain. In addition, a study to relate detected flood trends to a set of potential drivers was also conducted. Most such trends in flood series could be explained by corresponding and increasing trends in evapotranspiration that increase water losses in soils and decrease soil moisture content before the occurrence of floods.



## 1. Introduction

Reliable flood estimates for a given exceedance probability are crucial for hydrological risk analysis, as extreme flood events may lead to catastrophic effects on the environment, individuals and society. Unfortunately, extreme flood events have become more frequent and harmful in Europe for the last 25 years regarding the duration and extension of affected areas (Kundzewicz et al., 2013). In addition, their economic impact also increased for the period 1971–2008 (Barredo et al., 2012).

Traditional flood frequency analyses usually assume homogeneity, independence and stationarity in observed series (Rao and Hamed, 2000). However, stationarity is under doubt because means and extremes of precipitation and river streamflows could be changing in time, as a consequence of climate change (Milly et al., 2008) or any other driver. Consequently, non-stationarity assumptions question the results of traditional flood frequency analyses, which might lead to catastrophic failures in the case of underestimation and waste of economic resources in that of overestimation (Khaliq et al., 2006).

Several factors can cause changes in flood time series, such as climate change, wildfires, land-use changes, anthropogenic actions, relocation of gauging stations or volcanic eruptions (Yue et al., 2012). The latter entails a factor that can either change the soil properties in the catchment or modify the drainage network and its hydraulic properties by the deposition of erupted sediments. Climate drivers can be distinguished from anthropogenic-induced changes when the study focuses on pristine basins with reduced human interventions (Svensson et al., 2006).

Several flood trend analyses have been carried out recently in Europe. Wilson et al. (2010) analysed trends in annual and seasonal flows in near-natural catchments in Denmark, Finland, Iceland, Norway and Sweden, detecting both a general increasing trend in streamflow magnitude and a trend in the timing of floods in the Nordic countries (except Iceland), given that they tend to arrive earlier in spring. Petrow and Merz (2009) found significant upward trends in flood magnitude and frequency in the south, west and centre of Germany. Significant upward trends in flood magnitude were also found in some Swiss alpine catchments (Castellarin and Pistocchi, 2012). Blöschl et al. (2012) found a general increasing trend in flood magnitude in Austria, especially in catchments of fewer than 500 km$^2$. While Giuntoli et al. (2012) found generalised upward trends in magnitude in the northwest of France, they identified downward trends in the southwest and mixed patterns in the centre. Hannaford and Buys (2012) found heterogeneous patterns in the United Kingdom, with an overall increasing trend in autumn and winter flows, a decreasing trend in spring flows in lowland

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England and a mixed pattern in summer. In addition, a general upward trend in flood magnitude was detected in Wales by Macdonald et al. (2010) and in Ireland by Murphy et al. (2013). Some Pan-European studies have also focused on monthly, seasonal and annual streamflows, as well as various streamflow indices (Stahl et al., 2010, 2012; Hannaford et al., 2013).

Regarding trend studies beyond Europe, Ishak et al. (2013) found more generalised decreasing trends in annual maximum flood series in Australia, at both local and regional scales. Burn et al. (2010) found decreasing trends in both magnitude and timing of annual and spring maximum flows in Canada. Hodgkins and Dudley (2006) detected significant earlier flows in eastern North America. In addition, some studies have provided a global dimension, with Kundzewicz et al. (2005) analysing trends in streamflow series from catchments located around the world by using a subset of data extracted from the Global Runoff Data Centre (GRDC).

Most trend studies in Spain are focused on annual, seasonal, monthly and low flows. Lorenzo-Lacruz et al. (2012), for example, found downward trends in monthly streamflows in winter and spring across the Iberian Peninsula, particularly in the centre and south in the period 1945–2005. These results are in line with the Morán-Tejeda et al. (2011) study that detected a generalised negative trend in winter and spring monthly streamflows in the Douro catchment in the period 1961–2006. Both studies attributed part of these downward trends to the effects of dam regulation and water management strategies on flood regimes. However, a set of near-natural catchments in Spain was considered by Martínez-Fernández et al. (2013), who found negative trends in annual and seasonal streamflows in spring and winter in most catchments in the period 1966–2005. In addition, Coch and Mediero (2014) found a generalised downward trend in low flows in the northern half of Spain in the period 1949–2009. Finally, Stahl et al. (2010) also detected a general decreasing trend in both annual and monthly streamflows in Spain in the periods 1952–2004 and 1962–2004 that could, arguably, be caused by an increasingly positive trend in the North Atlantic Oscillation Index.

Certain local studies have analysed trends in floods in Spain. López-Moreno et al. (2006) analysed daily discharge series in the central Pyrenees on the Spain side for the period 1959–1995, finding a decreasing tendency in the frequency and magnitude of flood events. Since an overall downward trend in rainfall observations was not identified, flood trends were related to land use changes. A general decreasing trend in floods was also found in the Douro catchment in 1961-2005 by Morán-Tejeda et al. (2012).

Some trend studies in precipitation have been also carried out in Spain. López-Moreno et al. (2009) analysed time series of cumulative rainfall in five days in the Ebro catchment in the period 1955–2006 with downward trends being found in the central area of the catchment. These results are consistent with the conclusions reached by Valencia et al. (2012) for the period 1957–2002. Turco and Llasat (2011) analysed the extreme rainfall variability in Catalonia for the period 1951–2003 with no consistent regional trend patterns identified. Acero et al. (2012) carried out a trend study on cumulative rainfall from one to seven days in the Iberian Peninsula for the period 1958–2004, with varying results offered depending on the season. In winter, a general negative trend was detected, except for positive trends at the south-eastern Mediterranean coast. In spring, a general negative trend was also detected, except for some positive trends in the northeast. However, whereas positive trends were detected in the west of the peninsula in autumn, negative trends were highlighted in the east.

In addition, temporal trends can be studied in reconstructed flood series by extending systematic records across several centuries by using historical and palaeoflood information (Llasat and Barriendos, 2001; Llasat et al., 2003). A thorough review and compilation of historical floods in Europe can be found in Brazdil et al. (2012). In Spain, this approach has been applied to the Rivers Ter, Llobregat and Segre in Catalonia, where no homogeneous behaviour has been observed for extraordinary floods from the 14th century to the present (Barriendos et al., 2003).

Summarising, most trend studies in flow series previously developed in Spain were focused on annual, monthly and low flows, which are essential for management of water resources and droughts. However, flood frequency analyses should account for a shorter temporal resolution, either instantaneous or mean daily, to characterise better peak flows. Some of the aforementioned trend analyses recently conducted in Spain have focussed on daily flows. Nevertheless, they focus only on some local regions of Spain, such as the Ebro and Douro catchments.

In this paper, a flood trend analysis is carried out at a national scale in Spain with the aim of filling an existing research gap. The analysis focuses on tendencies in magnitude, frequency and timing of floods through using observed daily flow series. A set of catchments where effects of dam regulation on floods can be neglected is selected from the results of a thorough screening of the Spanish flood data conducted previously by Jiménez-Álvarez et al. (2012). This data set also complements previous research studies regarding long and unaffected flow time series to be used in flood studies in Spain. Nine flood indicators obtained from annual maximum, seasonal maximum and peaks-over-threshold (POT) series are used. Three periods are considered in accounting for larger temporal extension at the expense of poorer spatial coverage and vice versa. A study to link detected significant trends in flood series to different drivers is undertaken through a set of indices based on both daily precipitation and temperature series. The partial Mann–Kendall (PMK) test is used to assess the influence of each climate variable on flood trends.

The paper is organised as follows: Section 2 introduces the methodology; Section 3 summarises the case study and data used; Section 4 presents the results; Section 5 is devoted to the discussion of the results presented in the previous section; finally, conclusions are included in Section 6.

## 2. Methodology

In this section, the method used to detect trends in flood series based on the Mann–Kendall (MK) test is presented. Second, the influence of both the selected period of time and the spatial correlation among sites on detecting significant trends is analysed. Then, a summary of the hydrological variables used is provided. Finally, the methodology to link flood trends to a set of climatic variables used as surrogates of flood drivers is offered.

### 2.1. Detection of monotonic trends

Temporal trends can be classified into step-changes and monotonic trends. The former assumes that the observed data show an abrupt change at a given time, while the latter involves a gradual change in time (Yue et al., 2012).

Temporal trends are customarily detected by statistical tests, which can be also classified into parametric and non-parametric or distribution-free tests. The former requires independent and normally distributed data, while the latter assumes that data are independent and identically distributed. Non-parametric tests are particularly suitable for flood series, as hydrological data are usually non-normal distributed and serially correlated (Kundzewicz and Robson, 2004). Moreover, they are more robust to outliers and do not require any assumption related to the distribution (Hamed and Rao, 1998).

Two common non-parametric tests are used for monotonic trend detection: the MK and Spearman's rho. Both have been