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A 500-year flood history of the arid environments of southeastern Spain. The case of the Almanzora River.

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Abstract

The study of flood events, especially analyses of flood magnitude and flood frequency, is crucial for the planning and management of settlements and infrastructure located near river channels. This work studies the historical floods of the Almanzora catchment, in southeastern Spain, one of the driest regions in Europe. We compile, describe and statistically process flood data that extend back to the year 1500 AD. The data were collected from historical sources held in both local and regional archives. The analysis of the flood record shows that the most destructive events occurred in 1550, 1729, 1879 and 1973, the last of these being the most catastrophic event on record. The synoptic configurations of the four most destructive floods in the time-series were explored and found to present the same type of pattern (cold drop). Historical flood discharges were estimated by calibrating historical flood magnitudes with instrumental data. This assessment was undertaken using a cumulative function applied to flood episodes that exceeded the threshold of magnitudes ≥3. The flood frequency analysis performed by combining instrumental and historical data shows that catastrophic events, such as the 1973 flood with a discharge of 5600 $m^3 s^{-1}$, occur with a return period of less than 100 years. We also estimate that high magnitude floods with a discharge between 684 and 3081 m^3 s^{-1} can occur every 10-50 years. During recent decades, several municipalities and, above all, the coastal area of the Almanzora catchment have experienced significant urban growth and land use changes, as a result of the development of both tourism and extensive agricultural. This, in turn, has contributed to an increase in flood exposure.

Keywords: Historical floods; Flood Frequency Analysis; Discharge estimation; Natural Hazards.

1. INTRODUCTION

Floods are the natural hazard that affects the greatest number of people worldwide (Bouaakkaz et al., 2018) and which causes the highest global economic losses (Benfield, 2016). In recent decades, exposure to floods has increased dramatically in certain regions (Tanoue et al., 2016), due to an increase in world population but also to human occupation of and inadequate land use in floodplains and alluvial fans. Yet, in other regions, flood activity during the 20th century fell thanks to effective mitigation measures (Schulte et al., 2019a). Given the threat they pose, it is crucial we improve our knowledge of flood events, especially as regards flood frequency and magnitude, flood triggering mechanisms, and different types of forcing.

The study of historical floods allows us to extend the flood series further back in time and so enhance our understanding of the influence of climate change on flood dynamics (Pfister, 1999; Glaser et al., 2010). Studies of this nature depend mainly on historical records of casualties and of damage suffered by buildings and infrastructure and descriptions of the affected areas. Many such studies have focused their attention on the rivers of Central Europe and Great Britain, where handwritten archives stretch back to the Middle Ages (Brázdil et al., 1999, 2006; Glaser and Stangl, 2003; Glaser et al., 2010; Wetter et al., 2011; Elleder et al., 2013; Schulte et al., 2015, Macdonald and Sangster 2017; Schulte et al., 2019b). In Spain, too, many studies of historical floods have been undertaken. Some examined catchments of the Mediterranean basin (Capel Molina, 1987; Barriendos and Martín-Vide, 1998; Machado et al., 2011; Pino et al., 2016 and Balasch et al., 2018), while others studied catchments of the Atlantic basin (Barriendos and Coeur, 2004; Barriendos and Rodrigo, 2006 and Santos et al., 2018). Although the results of these studies are indisputably relevant to our knowledge of the historical floods of the Iberian rivers, an exhaustive analysis of the historical databases of various basins in the arid southeastern region has yet to be undertaken (Barriendos et al., 2014).

This study reconstructs the flood events of the Almanzora River. Few historical flood studies have been conducted in this area (but see Ferre Bueno, 1979; Capel Molina, 1987), due, in the main, to its remote rural history, located some distance from Spain's main cities and production centers. As a result, few instrumental flood series are available and most of the extant data are either recent or discontinuous, for example, low-frequency aggradation pulses in the flood plains, reconstructed by the geomorphological studies undertaken by Schulte (2002). Despite this lack of information, historical flood data can be found in municipal historical archives and local newspapers (Brázdil et al., 2006; Barriendos et al., 2014). Moreover, in the early 1990s, the local government began to take a growing interest in the area's flood hazard, which led to an increase in the amount of flood data and to studies of the occurrence of floods and the vulnerability of urbanized areas and infrastructure. This interest was spurred by the development of tourism in the region and an increasing awareness of the hazardous location of hotels and apartments on the area's floodplains.

An examination of the historical evolution of settlements in the southeastern Iberian Peninsula shows that most of its older towns were located on higher ground, including Pleistocene fluvial and marine terraces, the paleosurfaces of alluvial fans, pediments, hills and slopes (Schulte, 2002). For this reason, most of its historical settlements have not been seriously affected by floods.

In recent decades, however, the regions have rather undergone land use changes with its traditional dryland-farming being replaced by tourism and intensive agriculture, exposing a larger part of the population to the risk of flooding. This process has been characterized by a lack of awareness – intransigence, even – on the part of local real estate developers, making it necessary to improve knowledge of local floods and their main triggering factors. In this regard, the historical study of the Almanzora catchment, with one of the highest number of catastrophic flood events in the region, is of particular interest.

Our paper aims to gather historical flood data for the Almanzora catchment and, moreover, we seek to estimate the flood frequency of its most catastrophic events. In order to improve our knowledge of the triggering patterns of catastrophic floods, we also undertake an analysis of the synoptic configurations of high magnitude events over the last 450 years.

2. REGIONAL SETTING

The Almanzora catchment is considered one of the main catchments in the eastern Andalusian region, in terms of its fresh water resources. The catchment occupies an area of 2,611 km^2 and is 105 km long. It runs from west to east, along the northern flank of the Filabres Range that reaches a maximum height of 2,168 m a.s.l. (Calar Alto peak). The river is fed mainly by precipitation and snowmelt from the Filabres, Estancias and Almagro ranges (see Fig. 1).

The basin's geology is dominated by rocks from the Pennibetic basement and from Neogene and Quaternary basin infill. The lower catchment forms part of the Vera basin, a wider accumulation comprising interbedded layers of marine and continental origin (Völk, 1966; Schulte and Julià, 2001). The catchment landscape is highly diverse, shifting from steep slopes in the main mountain ranges to an almost flat surface in the tectonic basins and coastal plain where the river flows into the Mediterranean Sea (Fig. 1). In these areas, we find pediments, alluvial fans and sequences of fluvial terraces (Schulte and Julià, 2001; Schulte et al., 2008).

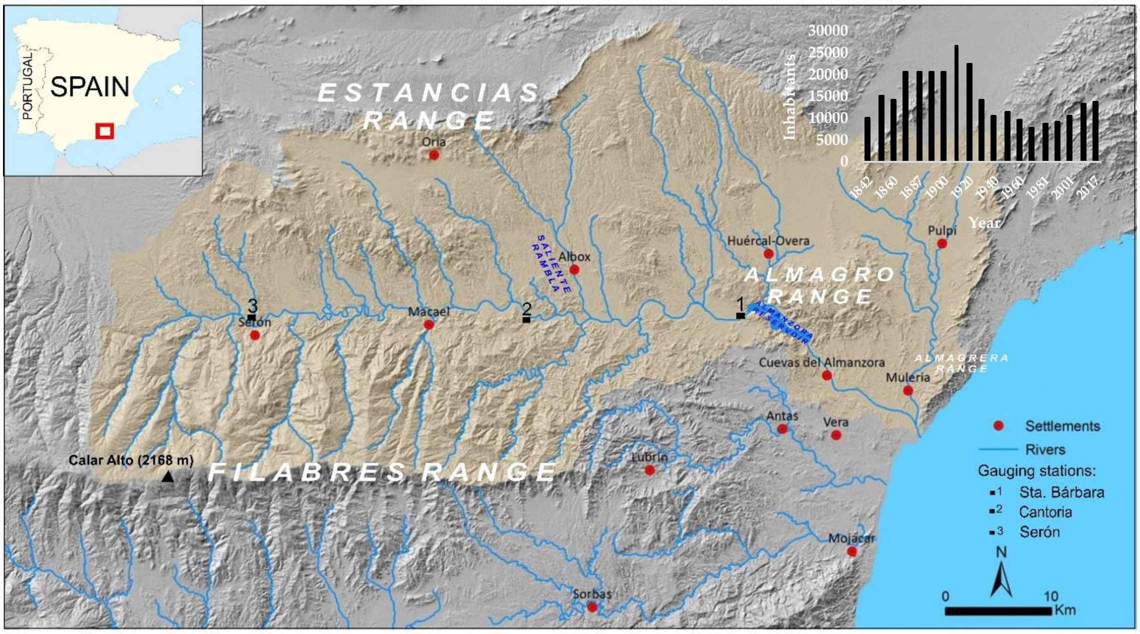


Figure 1. Location of the Almanzora catchment and the region's main settlements and the demographic evolution of the town of Cuevas del Almanzora.

The headwater catchment of the Almanzora River has a seasonal flow that is affected mainly by precipitation events during the fall and winter months. The mean precipitation of the Almanzora valley on the northern slopes of the Filabres range (SAIH Hidrosur, 2018) ranges between 312.2 mm yr^{-1} at the Oria meteorological station (located near the southern slopes of the Estancias range) and 325.6 mm yr^{-1} at the Tahal meteorological station. The lower catchment is marked by a drier climate, due to higher temperatures and lower annual precipitation (Vera mean annual precipitation: 312 mm yr^{-1}), contributing to an ephemeral flow regime. River flow is only appreciable during winter or during torrential rainstorms during summer and autumn, as was the case during the flood event of September 28th of 2012, when a precipitation of 240.4 mm/24 h was recorded in the Almagro range (SAIH Hidrosur, 2012).

Land cover and land use in the study area are categorized as disused and are typical of the dryland of southeastern Spain. Traditionally, the land cover is dominated by semi-desert open woodland and shrubland. On glacis surfaces, fluvial terraces and valley floors, there is a prevalence of agricultural land. Agricultural land use in recent decades has seen a dramatic change towards an intensification of cropping, with cultivated land occupying an area of 30,873 ha (Vera-Rebollo et al., 2016), representing 11.8% of the lower Almanzora catchment. This has meant the introduction of intensive irrigation cropping. In contrast, the catchment's upper basin is dedicated to extensive farming, which occupies an area corresponding to approximately 47% (Taguas et al., 2008).

Traditional dryland irrigation river management has been adopted at various points along the main valleys, a practice that dates back at least to the Moorish occupation (from the 8th until the end of the 15th century) and probably even earlier, to the Roman period (Bermúdez, 2014). Historical hydraulic interventions on the river channel consisted mainly of a complex system of agricultural channels, terraces and small dams that were used to divert and store the river sediment (normally floods) in the agricultural plots. Modern hydraulic interventions include the construction of a reservoir in the lower Almanzora course, built between 1986 and 1993, to meet the increasing demand for crop irrigation in the region. The last 15 km of the Almanzora River have been channelized since 1994, in order to protect settlements and agricultural land from flooding.

3. MATERIAL AND METHODS

In order to reconstruct flood frequencies in the Almanzora catchment, we compiled flood data from documentary sources, including municipal historical archives and old newspapers, photographs and research papers (Capel Molina, 1987; Paprotny et al., 2018). Instrumental data from the Santa Bárbara and

Cantoria gauging stations were also used for purposes of calibration, but these data series are relatively short term. For example, the gauging record at the Santa Bárbara station began in 1962, but the series are not continuous. There is a gap between 1973 and 1975, coinciding with the 1973 flood event that damaged the gauging station. Meteorological data are used to link high intensity precipitation events with flood episodes. The oldest meteorological station opened in 1945 and is located at Albox, a historical settlement on the *Rambla del Saliente* valley floor, a northern tributary of the Almanzora River.

3.1. Historical data

Extreme flood events recorded by the government and published in the "*Catálogo de Inundaciones Históricas*" (National Historical Floods Catalog; DGPCE, 2011) were first identified. This information was then compared and validated to publications describing flooding in the Almanzora catchment (Capel Molina, 1987) and nearby regions (Machado et al., 2011). Likewise, information about flood events retrieved from the municipal proceedings (see details below) were first classified, then validated and classified again according to a flood magnitude index (Table 1). We identified several inconsistencies in the flood data drawn from the National Historical Floods Catalog. For example, the figures for some dates had been transposed, affecting not only days and months, but even years (e.g. instead of 11/09/1891, the catalog recorded 11/09/1819).

The most accurate sources used in this study were the aforementioned municipal proceedings (local government records) from the secular settlements of Cuevas del Almanzora and Vera. The documents from Albox were not well conserved and could not be integrated into the flood series.

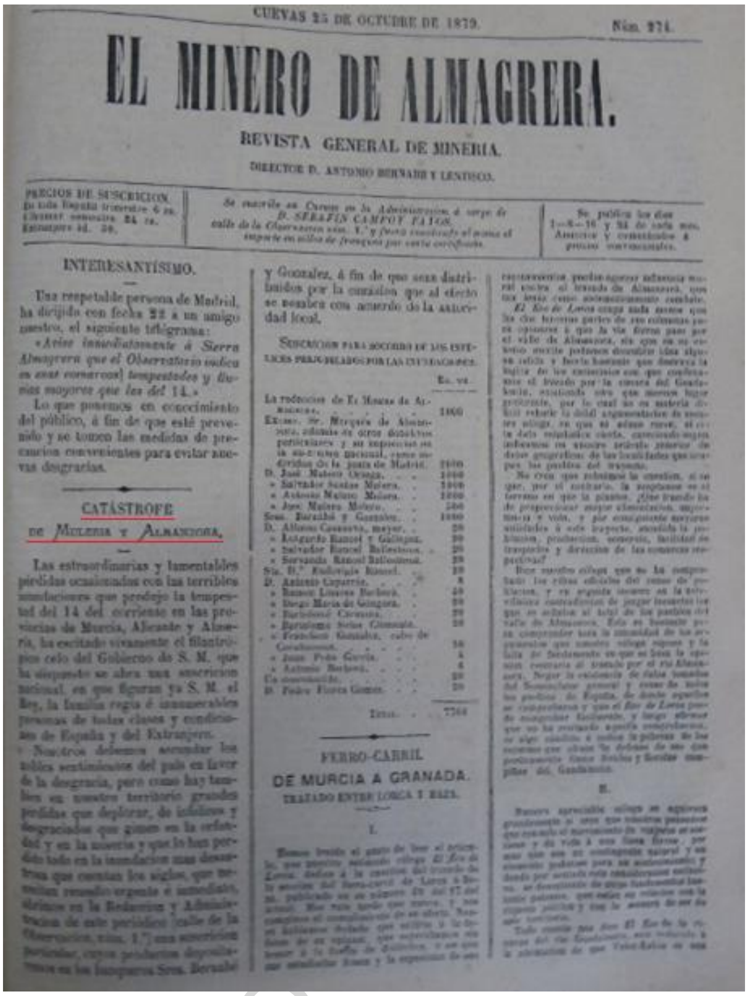
The Cuevas del Almanzora archive is well preserved and includes municipal proceedings that date back to the 16th century. Descriptions of flood events were found in documents from the 17th century onwards. Most of the events are described in detail and provide information about the number of fatalities, the areas flooded, the destruction of roads and the damage caused to buildings. Older written sources were in a poorer state of conservation. Pages were missing from several books from the 16th century, pages were also ripped and entire years were missing from the record.

One of the most important periods in the demographic history of Cuevas del Almanzora occurred during the second half of the 19th century. During this period, Cuevas del Almanzora became the main settlement for the region's mining activities, which centered on the Almagro Range and the west of the Almagrera Range. This mining activity attracted many people in search of work and prosperity (Fernández-Bolea, 2006). Indeed, the town's population rose to reach 26,000 inhabitants in 1900, more than twice its present-day population of 12,000. Thanks to this activity, the newspaper *El Minero de Almagrera* was founded in 1870. The paper kept local inhabitants informed about events in the mining industry, but also recorded other daily events of note.

The Vera municipal archive lies outside the Almanzora catchment and, although the town does not lie close to a major river floodplain, we found several descriptions of floods on the Almanzora River from local inhabitants that owned buildings or agricultural plots in flood-prone areas. The documents held in this archive are the oldest of all the archives in this region, dating back to the 15th century. From these records, it is possible to identify and obtain descriptions of flood events from the beginning of the 16th century.

In addition, we consulted the Albox municipal proceedings. However, the descriptions of flood events were much poorer than in the other primary sources described above. The documents available in these archives did not contribute to increase the number of flood events, nor was it possible to extract more information about the events already identified from the other primary and secondary sources.

Old newspapers proved to be one of the most important sources of information. Local newspapers included reports from the last 150 years and, so, provided a considerable amount of flood information for the 19th and 20th centuries. The oldest local newspaper in the region is the *Crónica Meridional* and dates back to 1866. The *El Minero de Almagrera*, one of the most important and best-known newspapers in the region, was founded a couple of years later. Publication of this newspaper stopped in 1910 (Fernández-Bolea, 2014) but it includes several descriptions of flood events (e.g. the 1879 flood reported on its front page, as shown in Fig. 2). Many of the descriptions of flood events in these two local newspapers are accurate and the flood information was taken into consideration for the classification of flood magnitudes. Other sources of information included letters to the editor and first hand reports from local inhabitants affected by the flood event. These letters are typically very detailed because, as well as informing the readers of the flood damage suffered, a primary objective of the sender was to obtain monetary relief from the national or regional authorities, therefore they are largely credible and accurate, but perhaps prone to exaggeration to secure more relief (Wetter et al., 2011; Macdonald et al., 2014).



CUEVAS 25 DE OCTUBRE DE 1879.

EL MINERO DE ALMAGRERA.

REVISTA GENERAL DE MINERIA.

DIRECTOR D. ANTONIO BERNABÉ Y LENTISCO.

INTERESANTÍSIMO.

CATÁSTROFE

FERRO-CARRIL

DE MURCIA A GRANADA.

Figure 2. Front page of the historical newspaper El Minero de Almagrera, 1879. The left-hand column (highlighted in red) describes a flood event on October 14th of 1879.

3.2. Classification of flood magnitudes

The magnitude of each flood event was determined according to its social-economic impact and field observations conducted in the floodplain areas. This impact ranges from the loss of human life and the destruction of buildings and infrastructure to damage to agricultural plots and infrastructure adjacent to the river channel. Flood magnitudes were grouped into four classes: magnitude 1 – ordinary floods; magnitude 2 – extraordinary floods; magnitude 3 – catastrophic floods; and magnitude 4 – flood events that caused significant impact on more than one river stretch (see Table 1 for a detailed description of each magnitude class).

Information about the flood events obtained from the municipal proceedings included the following details: the event date, number of fatalities and/or damage to buildings, infrastructure and agricultural plots affected, water levels reached during the flooding, number of agricultural fields affected, and the coordinates of the recorded flood-data. However, this characterization was not entirely homogeneous given that the event description varied from year to year, being highly dependent on the individual responsible for recording the event. Moreover, some flood events (mostly of low magnitude), which only caused damage to agricultural fields, were not as exhaustively described as other higher magnitude events that caused fatalities and damage to buildings and infrastructure. These low magnitude events also tend to be overlooked, as people, it has been shown, typically forget non-catastrophic events (Wetter, 2017; Schulte et al., 2019b, this issue). It appears, therefore, that when these low magnitude events are being documented the memory of the facts and the area affected is often blurred and, on occasion, even lost in the mist of time (Barriendos et al., 2014).

In addition to classifying the flood magnitudes, a matrix of flood damage categories was also constructed. To do so, we adhered to the methodology described in Brázdil et al. (2012) and Schulte et al. (2015). To validate poorly reported events we also followed the methodology proposed by Barriendos et al. (2014).

Table 1. Classification of historical floods according to the magnitude.

Flood magnitude	Classification	Primary Indicators	Secondary Indicators
1	Ordinary floods	-Flooding, erosion, damage to crops next to the riverbank	-Short event duration
2	Extraordinary floods	-Agriculture plots affected at some distance from the riverbank. -Damage to buildings and hydraulic infrastructure	-Severe damage to fields close to the river -Loss of livestock
3	Catastrophic floods	-Fatalities -Partial or complete destruction of settlements	-Flood event is recognized by name (common in very important foods) -Population migration -High economic impact
4	+1 Added when the event was recorded in more than one stretch of the river.		

3.3. Discharge estimation and flood frequency analysis

In order to estimate the recurrence of flood events, a flood frequency analysis (FFA) was performed on the Almanzora flood series. FFAs have been widely used in similar studies employing historical data (Leese, 1973; Stedinger and Cohn, 1986; Salinas et al., 2016) and requires a knowledge of the peak discharge reached in each flood event. Instrumental discharge data were obtained from three sites: the Serón, Cantoria and Santa Bárbara gauging stations (see Fig. 1). Discharge values for events with no instrumental readings were calculated as follows: i) flood magnitudes were assigned to all historical and 20th century flood events, according to the flood damage classification presented above in section 3.2.; ii) median values were assigned to each flood magnitude based on the measured flood data obtained at the Santa Bárbara gauging station, and extrapolated to all historically documented floods (Salinas et al., 2016).

To calculate the return period, we applied the cumulative function described in Bayless and Reed (2001, p. 34) and Macdonald et al. (2006).

Equation 1:

$$Pi = \frac{k}{n} + \frac{n-k}{n}\,\frac{i-k-\ \alpha}{ns-e+1-2\alpha}$$

where k is the total number of extreme floods above the threshold (≥M3); *e* is the number of extreme floods during the systematic (instrumental) record; *h* is the length of the historical (pre-instrumental) period (years); *s* is the length of systematic records (years); *n* represents the combined number of years in the records (*h* + *s*); and α is the 0.44 plotting position constant introduced by Cunnane (1978).

The choice of a augmented distribution is justified by the fact that this is today a well-established method that provides a good fit for humid mid-latitude rivers (Macdonald et al., 2006) and the rivers of the Mediterranean basin (Barrera et al., 2006; Barriendos et al., 2014). The flood data used to calculate the return period include all available instrumental data from the Serón, Cantoria and Santa Bárbara gauging stations, the estimated river discharge in hydraulic reports (flood events of 1888 and 1924) and the estimated discharge for each magnitude class. We established a bottom threshold (3600 m^3s^{-1}) so as to only consider floods of a higher magnitude and avoid the potential errors attributable to lower magnitude floods.

Because of the uncertainties associated with the interpretation of historical descriptions, large error ranges need to be considered when classifying floods. However, to reduce these errors to a minimum, we applied the method described by Neppel et al. (2010) and Salinas et al. (2016), which calculates the error associated with each flood magnitude separately (Fig. 7).

3.4. Analysis of the meteorological trends from major flood events

In order to understand the meteorological trends that trigger extreme flood events, we analyzed the synoptic patterns of the four major flood events that occurred over the last 450 years (namely, March 20th of 1550, November 9th of 1729, October 14th of 1879 and October 19th of 1973).

The synoptic configurations of the floods from the pre-instrumental period (1500-1850) were simulated from the sea level pressure (in hPa; SLP) composite of the 13 runs of full forcing simulation taken from the daily values of the Last Millennium Ensemble Project Atmosphere Post Processed Data developed by the Community Earth System Model-Last Millennium Ensemble (CESM-LME). The CESM-LME's mission is to produce weather map simulations for the period from 850 to 2005 onwards with a horizontal spatial resolution of 2°. The CESM-LME employs version 1.1 of CESM with the Community Atmosphere Model version 5 (Hurrell et al. 2013).

The LME project used a ~2-degree atmosphere and land, ~1-degree ocean and sea ice version of CESM-CAM5_CN (1.9x2.5_gx1v6). The following ensemble members were chosen for the transient evolution of paleoclimate from AD 1500 to 1849: solar intensity, volcanic emissions, greenhouse gases, aerosols, land use conditions, and orbital parameters.

Quantile-quantile mapping transformation (Amengual et al., 2012) was used to correct the paleoclimate SLP grid. The procedure involves calculating the changes, quantile by quantile, in the cumulative frequency distribution (CFD) of daily SLP of LME outputs and the observed data. The statistical adjustment is based on the relationship between the ith ranked value of the corresponding CFD for the past calibrated model (AD 1500-1849), the control instrumental or baseline (AD 1850-2006), and the raw control simulated model (AD 1850-2006).

The analyses of the two most recent events were based on the synoptic sequence from the day of the flood plus six days prior to the event. In this way we are able to analyze the evolution of meteorological conditions before the flood event.

The synoptic patterns were reconstructed from a reanalysis of the grids of SLP, the 850 hPa temperature (T850) and the 500 hPa geopotential (Z500). The grid-data were taken from the 20th Century V2 Reanalysis Project (20CRP), provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado (Compo et al., 2011) and the extended temporal coverage from the NCEP/NCAR Reanalysis Project (Kalnay et al., 1996). The 20CRP data begin in 1871 and have a horizontal spatial resolution of 2°.

In addition to the synoptic patterns, we include an analysis of flood trends based on temperature and precipitation data. Temperature data were obtained from a composite of three air temperature series recorded at Almería Airport (1951-2018), Alicante (1901-2018) and Oran-Algeria (1852-2012). The meteorological station at Almeria Airport provides the longest continuous temperature record in the region and, as such, is the reference station for our composite temperature series (Figure 9). The other two meteorological stations are located some distance from the study area, but show a good correlation with the temperatures recorded at Almeria Airport (correlation coefficients of 0.9 for Alicante and 0.8 for Oran-Algeria). The precipitation series was collected from the Albox station (1945-2018), located in the Almanzora catchment (Fig. 1).

4. RESULTS

4.1. Distribution of flood events

From our analysis of documentary sources and the instrumental discharge data, we were able to identify the occurrence of 53 flood events over the last 500 years. Of these events, 44 were described in historical sources (municipal records, technical reports and letters to newspapers) while references to the other 13 were found in more recent newspaper sources (years or centuries after the flood event itself).

The distribution of flood events in Figure 3 shows a significant difference between the number of flood events M<3 occurring between the 16th and mid-19th centuries, compared to the number of floods after 1850. This difference can be attributed to the poor preservation of documents from the 16th to the 18th centuries and to the omission from these records of lower magnitude events. Neither the newspapers nor scientific papers provided further information on the flood events of these centuries. We also observe a marked increase in the number of flood events since the appearance of the first newspapers.

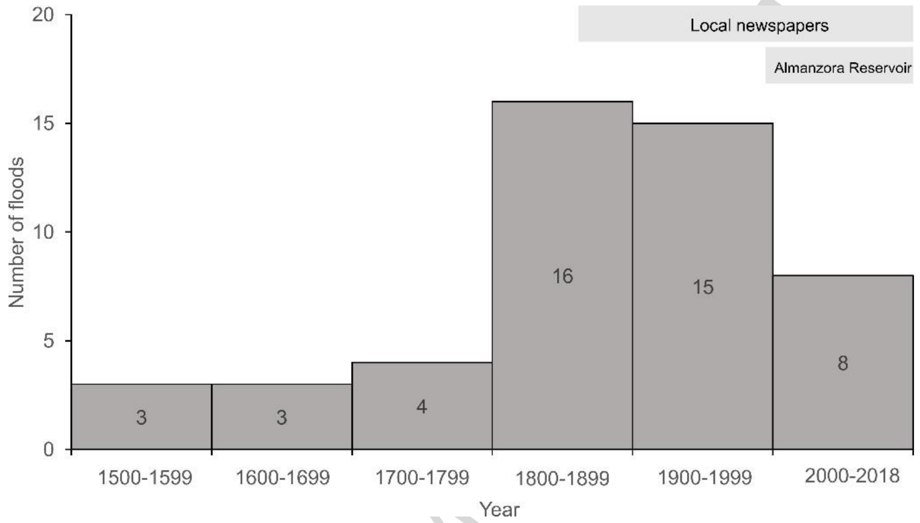


Figure 3. Distribution of flood events of the Almanzora catchment since the 16th century.

The seasonality of flood events presents a clear predominance of flooding during the summer and autumn months. Thus, 63% of floods occurred during the autumn months, above all in September and October, whereas 21% occurred during the summer months (JJA). These seasons are prone to the occurrence of short episodes of intense precipitation that contribute to the occurrence of catastrophic flood events. The triggering of these flood events is usually associated with cold drops, a synoptic situation that is common in the western Mediterranean Sea (Llasat and Ramis, 1996). For example, the catastrophic flood events of 1729, 1879 and 1973 (magnitude M=4) occurred in the months of September and October, because of such cold drops. Floods in the other seasons are much less frequent: 9% in spring and 7% in winter.

4.2. Historical flood series

Figure 4 shows the frequency of floods of the Almanzora catchment since the year 1550, classified according to the four magnitude classes described above in section 3.2. The majority of flood events (37) are classified as magnitudes 1 and 2, twelve flood events are classified as magnitude 3, while four events are classified as magnitude 4 (the floods of 1550, 1729, 1879 and 1973). As highlighted in section 4.1, there is a marked difference in the distribution of flood events between the periods 1500 until 1870 and the more recent period (1870 to 2018). In this first period, there are no records of small floods, due in all probability to the lack interest on the part of the local government and the fact that fewer records have been conserved from those years. This may explain in part the marked surge in flood events – above all M1 and M2 events – recorded from the mid-19th century onwards. Flood clusters of these magnitudes can be identified between 1647 and 1676, 1750 and 1780, 1870 and 1900, 1966 and 1977 and 1989 and 2018.

Taking into account all the flood events in the Almanzora catchment since 1500, five high frequency clusters of flood magnitudes M2 to M4 can be identified. The first cluster occurs between 1647 and 1676, and comprises four flood events, one extraordinary (M2) and three catastrophic flood events (M3). A further three flood events occurred in this period, but no detailed descriptions were found in the written sources.

The second cluster begins in 1750 and ends in 1780. During this period, flood events were less frequent than in the first cluster. Despite there being fewer flood events, the historical sources from this period describe it as being hydrologically very active in terms of flood magnitudes and from the point of view of the behavior of the river, with various high discharge events being recorded.

The third cluster occurs between 1870 and 1900 with a total of 14 flood events: 8 extraordinary floods (M2), 2 catastrophic flood events (M3) and 1 magnitude 4 event. The descriptions of the flood events of this period are considerably more detailed, benefitting from the reports published in the local press, most notably *El Minero de Almagrera* (Fig. 2). Moreover, many of these flood events caused considerable damage to the settlements located near the river’s main channel, including the town of Cuevas del Almanzora. This occurred despite the construction of several retention walls (continuous or discontinuous) – given the name of the *Malecón del Pilar* – in Cuevas del Almanzora by the local government, in order to keep buildings, infrastructure and agricultural fields safe from floods. However, the M3 and M4 flood event levels all rose above this protective wall and caused severe damage to agricultural fields and the urbanized area closest to the riverbed.

The fourth cluster occurs between 1966 and 1977, a period marked by a very high frequency of floods, and with an eight-year subperiod in which six flood events took place. It was during this period that the 1973 flood event (M4), one of the most catastrophic events in this catchment, occurred, with severe consequences for the settlements located in the main valley floor. Indeed, this is one of the few well-documented examples of a magnitude 4 flood in the Almanzora catchment.

The fifth and last cluster began in 1989 and has continued to the present day. During these last 27 years, in which flood events have reached magnitudes of 1 and 2 only, there have been significant changes to the main channel and the natural river dynamics. The construction of the Cuevas del Almanzora dam and the channeling of the last 15 km of the Almanzora River have contributed to a reduction in flood risk in the lower river.

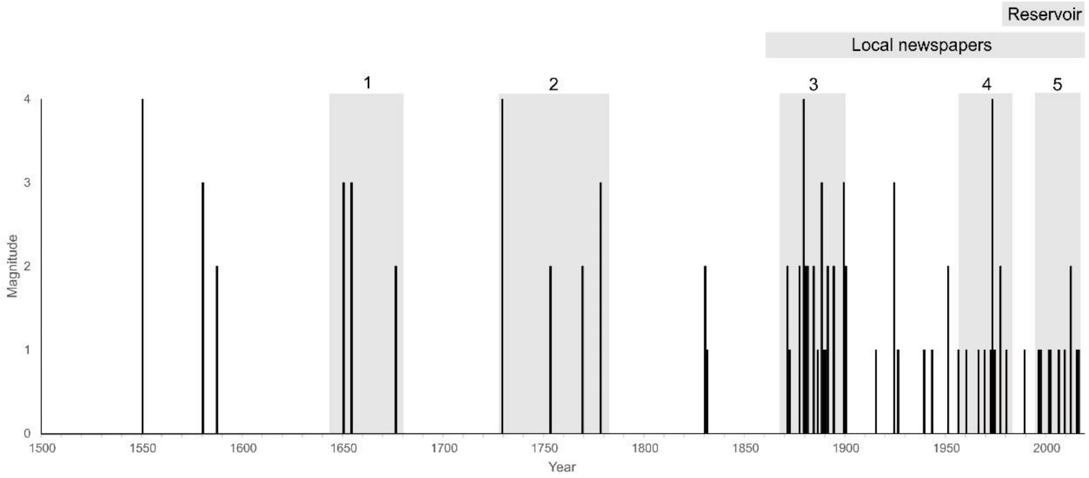


Figure 4. Frequency of flood events of the Almanzora River since the year 1500. Events are classified according to four classes of magnitude.

4.3. Flood discharge and return period

The flood peak at the Santa Bárbara gauging station (1962-2018) reached a maximum of 5600 $m^3 s^{-1}$ during the 1973 flood event (17/10/1973), while minimum peak discharges ranging between 45 and 800 $m^3 s^{-1}$ were recorded during magnitude 1 events.

Based on the calibration of the 20th century flood magnitudes (all levels of magnitude) using the measured annual peak discharges at the St. Bárbara gauging station (1962-2018), estimated discharges could then be extrapolated to the flood magnitudes reconstructed in the documentary sources for the period 1550 to 1962. Figure 5 shows the distribution of the instrumental data from the Santa Bárbara gauging station, together with each category of historical flood magnitude described in section 4.2. From this distribution, we obtained the median discharge of each magnitude class, which was used as the estimated value for the historical flood events (Salinas et al., 2016; Bösmeier et al., 2017). Figure 5 also shows that the median discharge is closer to the lower discharge values and that, in each class, the discharges included in the 3rd and 4th quartiles are less frequent. According to these results, ungauged events of magnitude 1 correspond to a discharge of 138 m^3 s^{-1}; those of magnitude 2 correspond to a discharge of 1300 m^3 s^{-1}; those of magnitude 3 correspond to a discharge of 3600 m^3 s^{-1}; and, those of magnitude 4 correspond to the maximum peak discharge of 5600 m^3 s^{-1} as recorded during the 1973 flood event.

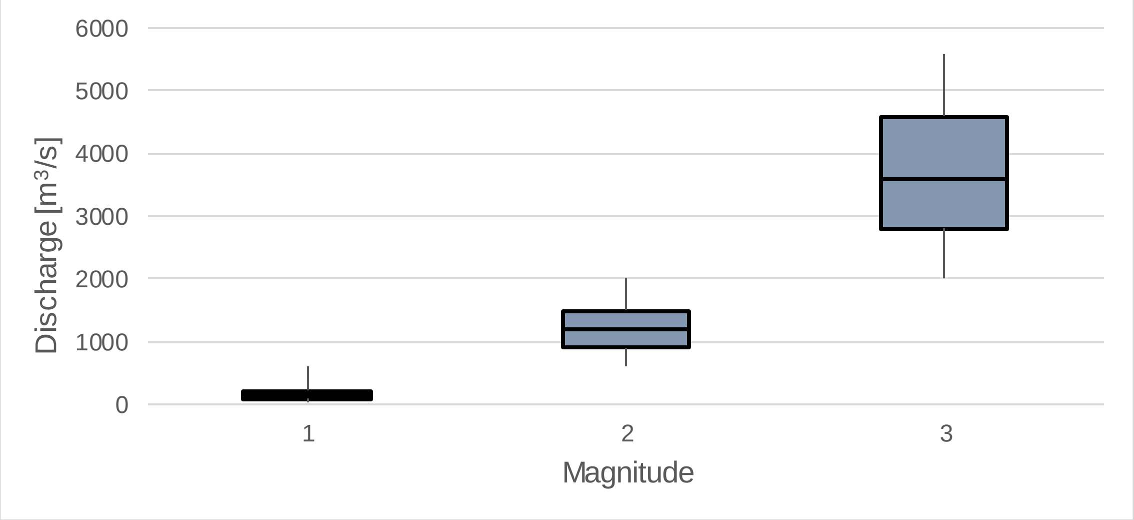


Figure 5. Flood distribution according to flood magnitudes. Discharges are related to real peak discharge data recorded at the Santa Bárbara gauging station.

The frequency of flood events, together with the instrumental and estimated discharges (Fig. 6), shows that there were at least three extreme events (1550, 1729 and 1879), which probably reached a maximum peak discharge comparable to that attained by the 1973 flood event. An analysis of Figure 6 highlights the variability in discharge recordings obtained from instrumental data, thus, illustrating the variability in the annual peak discharge over the last 50 years. The few high magnitude flood events during this period (1973 and

2012) had a discharge greater than 1000 m^3 s^{-1}, which is indicative of the type of flow that can occur in this catchment during flash flood events.

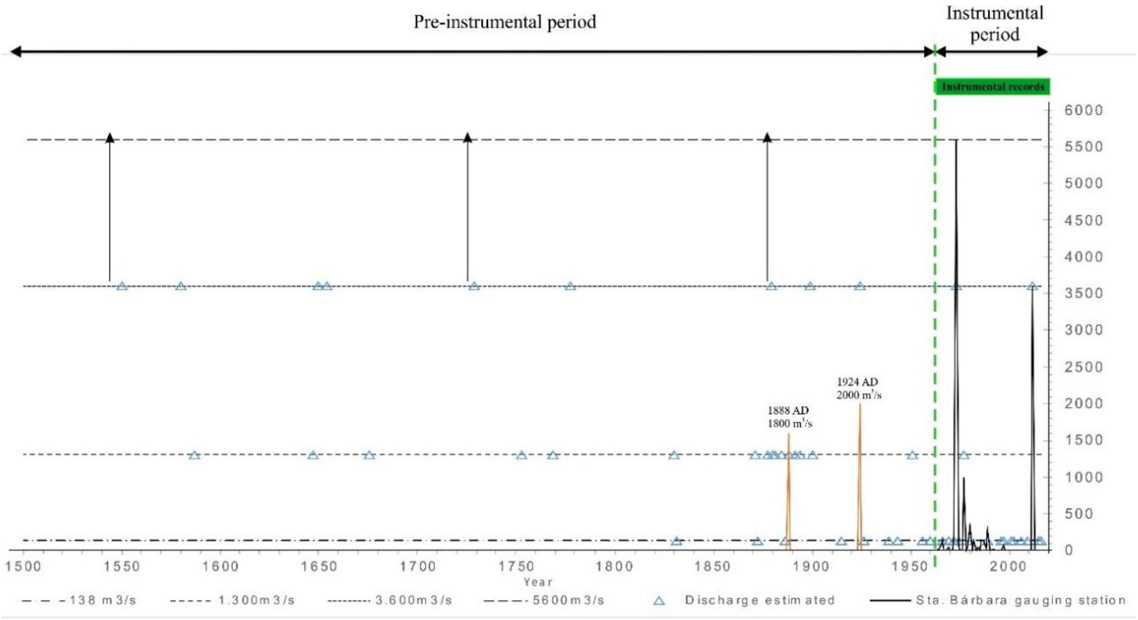


Figure 6. Instrumental and estimated flood discharges of the Almanzora River. The 1888 and 1924 flood events are shown in orange, their respective discharges being estimated from secondary sources (Agencia Andaluza del Agua, 2009).

The calculation of the return period based on the augmented distribution of instrumental and estimated historical flood discharges (see Fig. 7 and Table 2) shows that magnitude 1 events can occur every 1 to 5 years; magnitude 2 events every 10 to 15 years; and, magnitude 3 events every 50 years. Finally, events such as the 1973 flood, with a peak discharge of 5600 m^3 s^{-1}, can occur approximately every 100 years. A comparison of our calculations with the return period estimated by the Andalusia Water Agency (Table 2) indicates that the latter significantly underestimates the flood risk. Our return periods are shorter because our calculations incorporate historical information about extreme flood events. The return period (Fig. 7) for higher peak discharges is associated with a considerably larger uncertainty than that of low magnitude floods. This can be attributed to the fewer events with peak discharges over 2000 m^3 s^{-1} (here, just 10 floods).

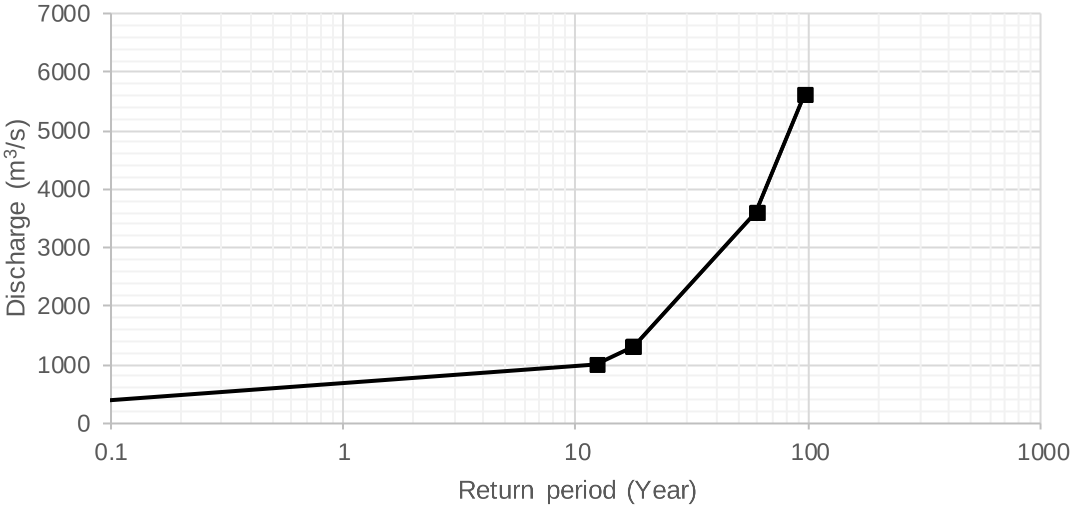


Figure 7. Return period and discharge of instrumental and historical flood events in the Almanzora catchment. Instrumental data measured at the Santa Bárbara gauging station.

Table 2. Flood return periods and peak discharge estimations of the Almanzora River according to this paper (column 2 and 3) and the Andalusian Water Agency (AWA or Agencia Andaluza del Agua, 2009).

Return period [yrs]	**Instr. and hist. data 1500-2018 discharge [m^3 s^{-1}]**	**Instr. and estim. data 1879-2018 discharge [m^3 s^{-1}]**	**Instr. data AWA 1962-2009 discharge [m^3 s^{-1}]**
5	385	250	65
10	684	809	
50	3082	4010	661
100	6076	>10000	

4.4. Meteorological characterization of major flood events

In general, the synoptic patterns linked to large floods in the semi-arid catchments of southeastern Spain are characterized by low-pressure systems that advect warm, wet air in the low levels of the troposphere from the

Mediterranean Sea. Configurations of this type can produce severe convective systems at the mesoscale.

4.4.1. March, 1550.

According to the 13 runs of full forcing simulation from the CESM-LME model, the meteorological conditions in 1550 (Fig.8) were characterized by an anticyclonic blocking over the European continent that provoked a persistent southeastern flux advecting a warm, wet mass of air from the Mediterranean Sea. The configuration was enhanced by the presence of a low-pressure area in the southwest of the Iberian Peninsula.

4.4.2. November 9-10, 1729.

The atmospheric configuration in 1729 (Fig.8) was characterized by a strong low-pressure system over the Atlantic Ocean to the northwest of the Azores Islands and, furthermore, by a high-pressure over the Mediterranean Sea. This configuration provoked a wet, warm flux from the south over the study area.

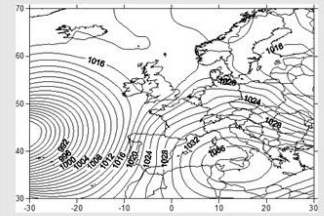
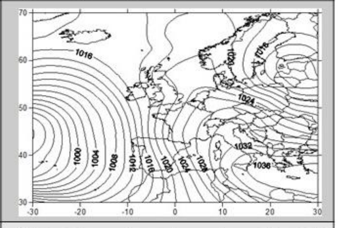
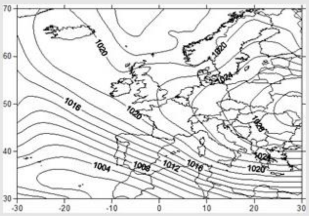
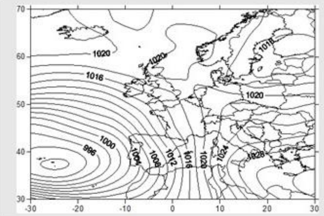
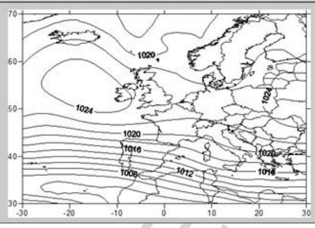
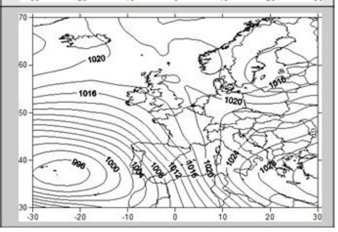
SLP reconstructed fields from LME project (hPa)			
Composite |Date	***March, 1550***	**Composite |Date**	***November 9-10, 1729***
		2-day composite • Strong low-pressure over the Atlantic Ocean in the north-west of the Azores Islands. • High-pressure over the Mediterranean Sea. • Wet and warm flux from south.	
		7-day composite • Low-pressure over the Atlantic Ocean in the north-west of the Azores Islands. • High-pressure over the east part of the Mediterranean Sea. • Wet and warm flux from south-east.	
15-day composite • Reverse quasi-zonal disposition of the action centers. • Low-pressure in disposition west-east over the north of Africa. • West -east high-pressure over Europe. • Wet flux from east.		15-day composite • Low-pressure over the Atlantic Ocean on the Azores Islands. • High-pressure over the east part of the Mediterranean Sea. • Wet and warm flux from south-east.	
1-month composite • Reverse zonal disposition of the action centers. • Low-pressure in disposition west-east over the north of Africa. • West -east high-pressure over Europe. • Wet flux from east.		1-month composite • Low-pressure over the Atlantic Ocean in the east of Azores Islands. • High-pressure over the east part of the Mediterranean Sea. • Wet and warm flux from south-east.	

Fig. 8. Left panel. March, 1550 flood. Synoptic simulation of composite SLP fields (in hPa) of the 13 runs of full forcing simulation from the CESM-LME. Right panel. As left panel but for November 9-10, 1729 flood.

4.4.3. October 14, 1879

The analysis included a 7-day time sequence to investigate the meteorological conditions prior to the occurrence of the flood event. The meteorological conditions associated with the flood event that occurred on October 14th of 1879 were characterized by an anticyclonic blocking over the European continent that generated a persistent southeastern flux, transferring advecting warm, wet air masses from the Mediterranean Sea into the catchment (Fig. 9A). The flow was enhanced by the presence of a low-pressure area, located in the southwest of the Iberian Peninsula. In addition, cold air dominated the 850 hPa level, between the second and fourth day of the 7-day time sequence. In contrast, the middle levels of the troposphere did not present convection conditions.

4.4.4. October 18-19, 1973.

The 7-day synoptic configuration sequence associated with the 1973 flood event (Fig. 9B) was characterized by a low-pressure area centered over the northwest of the Iberian Peninsula, in conjunction with a cold front. The passage of this front generated a cut-off configuration on the fifth day of the 7-day time sequence, coinciding with a warm-wet eastern flux that entered the study area in the low levels of troposphere. The dynamic of this configuration was strengthened by the presence of cold air at the 850 hPa level and negative anomalies of the geopotential in the middle levels of the troposphere. This atmospheric pattern caused severe convective instability, with large amounts of precipitation in the study area.

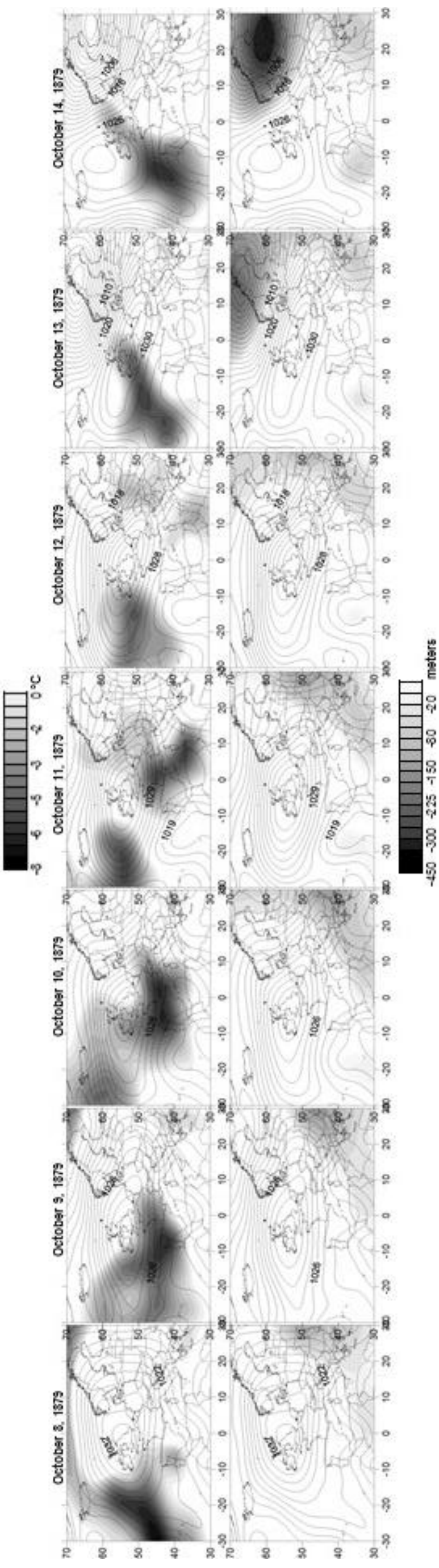


Fig. 9A October 14, 1879 flood. Synoptic configuration. Up panel: sea level pressure in hPa (lines) and standardized anomalies of temperature at 850 hPa in °C (contours). Bottom panel: sea level pressure in hPa (lines) and standardized anomalies of geopotential at 500 hPa in meters (contours).

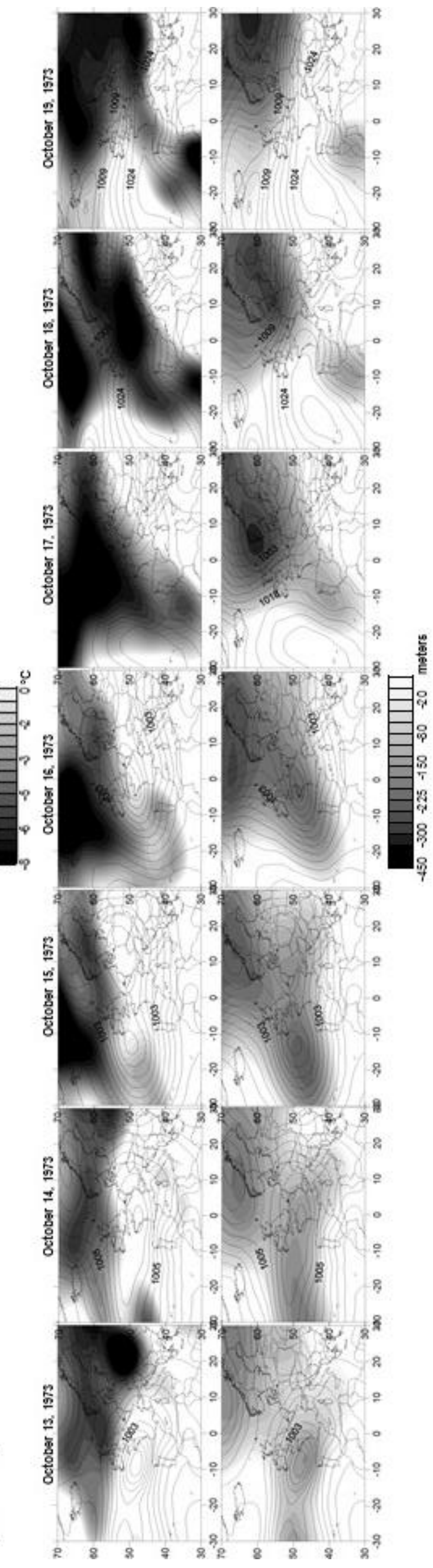


Fig. 9B As Fig.9A but for October 18-19, 1973 flood.

5. DISCUSSION

5.1. Historical flood trends

To interpret the flood data series for the Almanzora catchment over the last 500 years requires that we consider two different periods of data density: the first extends from 1500 until 1870; the second from 1870 to the present day (Fig. 4). Periods marked by socio-economic instability, such as the constitutional reign of Alfonso XIII (1902-1923) and the Spanish Civil War (1936-1939), present fewer flood events.

The differences between these two periods are not related to climate variability, but rather to i) flood perception, ii) recording and iii) the conservation of local documentary sources referring to lower magnitude floods. The publication of local newspapers contributed notably to the increase in flood data over the last 150 years. This increase went hand-in-hand with the increase in human occupation of the catchment (exposure) and of flood-prone areas, making local communities more vulnerable to floods. The growth in human occupation at the end of the 19th century was related to an expansion in the area dedicated to farmland, which in turn contributed to an increased concern among local inhabitants for the effects of smaller floods, which could damage the agricultural plots located closest to the river channel. During the recent decades of urbanization (tourism) and construction of infrastructure, local government awareness of flood risk and flood losses has grown significantly (Macdonald and Sangster, 2017).

On the understanding that the past flood data series (from the 16th to mid-19th centuries) could be biased by the lack of records for low magnitude floods (specifically M1 and M2 events), we can only effectively analyze the trends of high magnitude events (M3 and M4 events). The occurrence of these events increased towards the end of the 19th and the beginning of the 20th centuries, with three M3 events and one M4 event being recorded in a relatively short period of time (50 years). The earlier flood series, from the 16th to the 18th centuries, presents a maximum of two high magnitude events in a 50-year interval, with the exception of the decade of the 1650s when two M3 events were recorded in less than a 10-year interval. The increase in high magnitude events at the end of the 19th century is almost certainly associated with the rise in population and increased flood vulnerability. Moreover, it might also be related to the cool climate associated with the end of the Little Ice Age and the advance of fluvial terraces and glaciers in Sierra Nevada (Schulte, 2002), a change in the atmospheric patterns over this region (Machado et al., 2011), and an increase in the precision of flood records. Indeed, Schulte (2002) has dated the aggradation of flood deposits in the Aguas River, using ^{210}Pb and ^{14}C dating techniques, to the onset (15th century) and end (19th century) of the Little Ice Age. However, it should be stressed that what increased is not the flood magnitude in itself, but rather the magnitude of the damages recorded.

If we focus on the periods without any flood events (i.e. the flood gaps), the majority of gaps occurring between the 16th and mid-19th centuries can be attributed to the lack of M1 and M2 events. An analysis of recent data (last 100 years) shows, however, that while flood gaps may occur, they are never longer than one or two decades. Were we to compare flood gaps in recent periods to precipitation data for last 65 years (Fig. 10), we find evidence to show they are associated with periods of severe drought and low precipitation during the summer and autumn seasons (Estrela et al., 1999). Indeed, when temperature and precipitation series are plotted against the flood series for the last 150 years (Fig. 10), we are able to identify some patterns related to the frequency of high magnitude floods. Thus, on the one hand, the largest flood pulses occurred during periods of cooler temperature, periods that are also prone to the occurrence of high magnitude flood events (M3 and M4); while, on the other hand, the warmest temperature pulses seem to correlate only with secondary flood pulses in the catchment, related mainly with low magnitude floods. According to the precipitation series from the Albox station (1945-2018), major floods correlate well with positive precipitation trends (see Fig. 9). This correlation is highly significant in the cases of the 1973 and 2012 flood events.

It should also be stressed that after a long dry period the damage attributable to flood events can be much greater. This reflects the fact that, in this region, after a long period of drought, the soils become more compact and capillaries become narrower, contributing to a lower soil permeability during high intensity precipitation events, which means that the majority of rainfall turns into surface run off (Nadal-Romero et al., 2018).

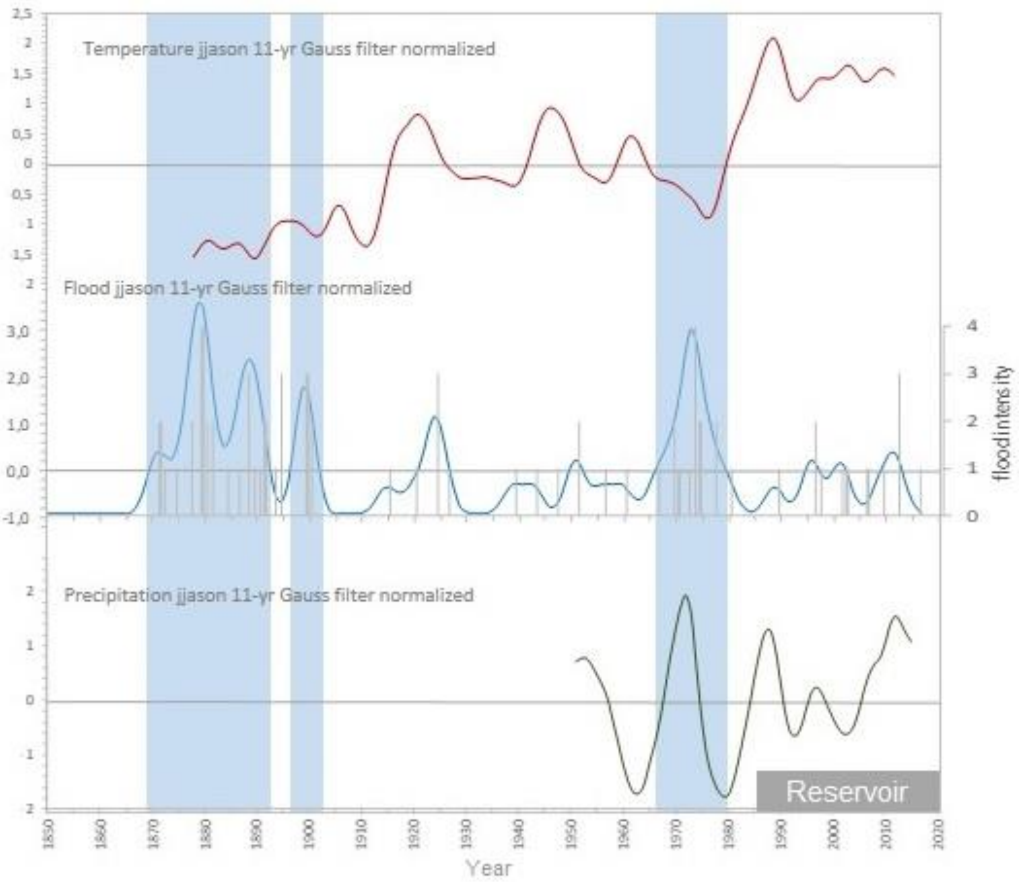


Figure 10. Comparison of the flood series for the Almanzora catchment (1850-2018) and its summer-autumn temperature and precipitation data. Temperature data were obtained as the composite of three air temperature series from Almería Airport (1951-2018), Alicante (1901-2018) and Oran-Algeria (1852-2012). Precipitation data come from the Albox station (1945-2018). Temperature and precipitation data correspond to the period from June to November (JJASON), the predominant flooding months. Blue bars highlight the main flood periods in this series. The data were normalized and smoothed using an 11-year Gaussian filter.

A comparison of our flood series (1500-2018) with other historical flood series (Barriendos et al., 2004; Machado et al., 2011) shows no close correlations for the period between the 16th and 18th centuries. This can be attributed to differences in historical human occupation rather than to different climatic patterns. More recently (the last 150 years), the flood data for the Segura River (Machado et al., 2011), located to the north of the Almanzora catchment, show similar trends. Some flood periods identified by Machado et al. (2011) coincide with those identified in our series, the period between 1870 and 1900 (cluster 3 in Fig. 4) being the one that presents the strongest similarities. A comparison of our series with the flood database built by Barriendos et al. (2014) for the rivers of the NE Iberian Peninsula also shows considerable similarities during the period from 1870 to 1900. This lends weight to the argument that this flooding period was a response to the combination of the climatic variability experienced at the end of the Little Ice Age and the growth in human occupation in the Mediterranean region. The flooding period identified in our series from 1965 to 1980 (cluster 4 in Fig. 4) is also apparent in that of the rivers of the NE Iberian Peninsula. This similarity may be attributed to an increase in human occupation across the whole of the coastal Mediterranean region; however, the precipitation data from our catchment (Fig. 10) show that it was also closely related to a period of increased rainfall during a cooler climate period caused by fronts and cyclones that moved over the Mediterranean basin to the east.

The impact of extreme climate events, including floods, on constructions associated with the tourism sector is more than apparent (Kellens et al., 2012; Yang, 2016). In Spain, several cases have been documented in recent decades, including, for example, in Vendrell in NE Spain in 2000 (Milelli et al., 2006), and along the entire east coast of the Almeria Province (Benito et al., 2012).

5.2. Analysis of high magnitude flood events

The flood data for the Almanzora catchment point to four events – those of 1550, 1729, 1879 and 1973 – that can be considered as being the most destructive and which affected the largest areas (Fig. 6). Here, we focus our discussion on the 1879 and 1973 flood events, given that the 1550 and 1729 events are less extensively documented.

The 1879 flood caused severe damage to buildings and infrastructure as well as fatalities in the settlements of Cuevas del Almanzora (30 victims) and Muleria (50). The event was of such destructive force that the area received financial aid from the Spanish State as well as from private entities in nearby areas and Madrid. The newspaper, *El Minero de Almagrera*, considered this event a major natural catastrophe and published references to it in all its articles addressing subsequent floods. This flood event occurred within a period of clustered floods (cluster 3 in Fig. 4), which coincided with the climatic transition from the end of the Little Ice Age and the beginning of 20th century warming (Xoplaki et al., 2005), marked by lower than average temperatures in summer and autumn (see Fig. 10).

The 1973 flood event is perhaps the best-documented high magnitude event in the catchment, with information available not only in written sources but also in the photographic and documentary film records. It is, moreover, the only event of this magnitude (M4) for which a maximum peak discharge was reconstructed by hydraulic estimation (Vallejos Izquierdo et al., 1994). The flood, with a maximum discharge of approximately 5600 $m^3 s^{-1}$, affected several settlements along the Almanzora main channel and also those on some of its tributaries, including the settlements of Albox and Huércal-Overa. There were 10 fatalities and extensive damage to communication infrastructure (mainly bridges). As a consequence of this flood event, the Spanish State eventually decided to channelize the lower river stretch so as to mitigate flood damage in the town of Cuevas del Almanzora and in the area's agricultural fields. Like the 1879 flood, the 1973 flood event also occurred within a period of clustered floods (cluster 4 in Fig. 4). Likewise, the temperature trends associated with both clusters were lower than average (Fig. 10). Moreover, the recent cluster (1989 to 2018) shows a strong relationship with increased precipitation in the catchment (Fig. 10).

During recent decades, river management has played a major role in the attenuation of flood magnitudes, especially in the lower catchment. Since the end of the 1980s, the majority of the Almanzora River discharges are retained in a reservoir, with a maximum capacity of 161 hm^3. This, together with the channelization of the lower river stretch, has contributed to a considerable reduction in flood magnitudes and in the flood vulnerability of the downstream settlements and infrastructure. By way of example, during the 2012 flood event, the reservoir retention capacity played a crucial role in protecting the town of Cuevas del Almanzora. The initial reservoir volume on the morning of September 28th was 19 hm^3; by the end of the day it had reached 51 hm^3 (SAIH Hidrosur, 2012). It should also be noted that the reservoir reached this maximum volume three hours after a rainfall of 240.4 mm was recorded in the nearby Almagro Range. This is a clear indication of the immediate response in the discharge rate to a torrential rainstorm in dryland.

If we consider the discharge associated with high magnitude events, we can compare the instrumental and estimated data for the Almanzora catchment with the data recorded in similar catchments nearby. Here, the comparison is made with the data reported by Benito et al. (2012) for the 2012 flood event. Although classified in our series as a M2 event, the 2012 flood reached a peak discharge of 3600 $m^3 s^{-1}$ (as measured at the Cuevas del Almanzora Reservoir, SAIH, 2012). In the absence of the retention capacity of the reservoir in the lower

Almanzora, the impact of this flood event on the downstream settlements would have certainly be catastrophic and would probably have reached a flood magnitude of 3 (see other M3 events with similar estimated discharge in Fig. 6). Benito et al. (2012) estimate that some neighboring ephemeral flow rivers (*Ramblas*) reached lower peak discharges than that verified for the Cuevas del Almanzora Reservoir. They estimate that during the day of September 28th of 2012 the *Rambla Nogalte,* with a catchment area of 140 km^2, reached a peak discharge of 1500 m^3 s^{-1}; and that the *Rambla Guadalentín* and the *Rambla Guadalhorce,* with catchment areas of 1389 km^2 and 3158 km^2, respectively, reached similar peak discharges of around 1200 m^3 s^{-1}. These estimates are, therefore, lower than those associated with our M3 events (3600 m^3 s^{-1}) and reflect the fact that the catchments of *Rambla Nogalte* and *Rambla Guadalentín* are considerably smaller than that of the Almanzora River.

As for the meteorological characterization of the four high magnitude events of 1550, 1729, 1879 and 1973 (section 4.4), we assume that these floods were characterized by low-pressure systems that contributed to the advection of warm, wet air into the low levels of the troposphere, coming from the Mediterranean Sea into the coastal region of the Almeria Province. This atmospheric pattern triggered the occurrence of severe mesoscale convective systems. These meteorological configurations can be compared to the dynamics of other flood events in the Mediterranean region. Martin-Vide and Llasat (2018) analyzed the 1962 flash-flood event in the northeastern Iberian Peninsula and report a similar synoptic mechanism as those that triggered the 1879 and 1973 flood events. Likewise, Capel Molina (1989) described the 1989 flood event that affected the eastern Iberian Peninsula, triggered also by a similar synoptic situation.

5.3. Flood frequency analysis

The FFA performed in this study emphasizes the importance of extending the flood database further back into the past by combining historical flood sources with instrumental data. Indeed, the inclusion of these historical data, together with discharge estimates for each flood magnitude class, significantly reduces the return periods for high magnitude events compared to the results published in the Andalusian Water Agency (AWA) study (see Table 2). The main reasons accounting for this difference reside in the statistical methods used and in the fact that the AWA only considered instrumental data from the Santa Bárbara gauging station (1962-1992), which significantly reduces the number of flood data included in the calculations. Our results point to the significant limitations associated with the use of 30-year gauging data when undertaking FFAs of catchments such as the Almanzora basin, where flood occurrence is highly variable and discharges show a wide range of values.

Other studies have likewise highlighted the importance of using historical flood series to correct underestimated FFA calculations based on short-term instrumental measurements (Balasch et al., 2010; Barriendos et al., 2014; Salinas et al., 2016). FFAs that incorporate historical series benefit from a greater number of flood data covering a longer observation period, which includes low-frequency extreme events. In other words, when using a shorter time series there is less chance of finding an event with extraordinary discharge (Baker, 1987; Balasch et al., 2010). This means the use of longer time series should be mandatory to ensure more accurate FFAs (Himmelsbach et al., 2015).

The problem of employing short time periods is also illustrated by our data for M1 and M2 flood events. However, here, in the case of our low magnitude flood events (M1 and M2), it might be that the return periods from our historical flood series tend to overestimate values. This is probably due to the limited inhomogeneous data distribution in our 500-year series. Our complete series comprises 53 flood events, of which 30 have instrumental discharges and the remaining 23 have estimated discharges. This number of events would appear to be insufficient to carry out correctly a FFA of low magnitude events. This problem is caused primarily by the lack of M1 and M2 events between the 16th and mid-19th centuries. If we only take into consideration the period for which we have the most complete record of M1 and M2 events (1870-2018), the return period changes dramatically, and now corresponds to discharges of 250 $m^3 s^{-1}$ in a 5-year, 809 $m^3 s^{-1}$ in a 10-year and 4010 $m^3 s^{-1}$ in a 50-year return period (see, Table 2).

Stokes et al. (2012) used the instrumental data of Sta. Bárbara gauging station to estimate the return periods of the Almanzora river. The 1973 flood would represent an extreme event with a return period of more than 1000 years, according to Stokes et al. (2012), while for Álvarez (2009) represents an event with a return period of 500 years. In both cases, as with the results of the Andalusian Water Agency, the fact that they only use instrumental data and the period of these is so short, makes flood frequencies overestimate. Once the historical data are included, it can be observed that the flow of the 1973 flood was extreme but not exceptional.

Finally, we should stress that other uncertainties in the FFA are likely to be influenced by changes to the flood magnitude dynamic reflecting recent land-use changes that have modified the catchment’s run-off. Such uncertainties are further exacerbated by the estimation and attribution of discharges to flood magnitudes classes. Finally, the FFA is also affected by the incomplete nature of the historical records and by discontinuities in the discharge data, as discussed in sections 4.2, 4.3 and 5.1.

The land use changes introduced over the last two decades play a key role in the area’s exposure and vulnerability to flood risk. It is clear that a regional flood risk management plan needs to be adopted and that a concerted attempt has to be made to control and restrict the construction of buildings and infrastructure near or on the floodplains, as has occurred in recent decades. The incorporation of historical flood series into the local government and civil defense action is mandatory to ensure adequate flood mitigation strategies, river management and risk assessment (*Real Decreto* 903/2010, of July 9th, Assessment and management of floods).

6. CONCLUSIONS

Our analysis of the 500-year long flood record for the Almanzora catchment shows that there were five periods of high flood frequency: from 1647 to 1676, 1750 to 1780, 1870 to 1900, 1966 to 1977, and 1989 until the present day. Moreover, we detect a marked difference in the flood data corresponding to the period from the 16th to the mid-19th centuries, on the one hand, and those corresponding to the period covering the last 150 years, on the other. This difference is characterized by a significant increase in flood data for the later period and can be attributed to the increase in flood information available in written sources as well as to the increased perception among local communities and governments of the risk of smaller flood events.

The historical record shows that there have been four high magnitude events in the catchment resulting in fatalities and severe destruction in the settlements located near the floodplain. These events occurred in 1550, 1729, 1879 and 1973, the most recent being the most catastrophic flood event on record.

Our return period calculations, when using an augmented series (1500-2015), show a periodicity of approximately 100 years for the 5600 m^3 s^{-1} maximum flood peak, as registered during the 1973 flood event. In contrast, discharges of around 684 m^3 s^{-1} and 385 m^3 s^{-1} have a return periodicity of approximately every 10 and 5 years, respectively.

Our analysis of the historical flood record suggests, moreover, that high magnitude events are not associated with recent global warming and have in fact occurred at various moments over the last 500 years. Indeed, the flood clusters over the last 150 years show a significant correlation with cooler climatic trends (1870 to 1900 and 1970 to 1975). However, the recent growth in human occupation and recent land use changes appear to have modified the magnitude of flood damage and increased economic losses. These effects, moreover, appear to be aggravated by low magnitude flood events, thus increasing the challenges faced in reducing flood vulnerability in the catchment. This said, the construction of the Cuevas del Almanzora reservoir and the channelization of its lower river stretch have proved to be effective flood mitigation measures, having drastically reduced the impact of flood events in the lower catchment of the Almanzora River.

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Highlights:

- 500-year long flood record shows five clusters of high flood frequency.
- Historical record show that there were four high magnitude events.
- Flood Frequency Analysis show a periodicity of approximately 100 years for a 5600 $m^3 s^{-1}$ flood peak.
- Flood clusters from the last 150 years show a significant correlation with cooler climatic trends.