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The catastrophic floods in the Guadiana River basin since 1500 CE

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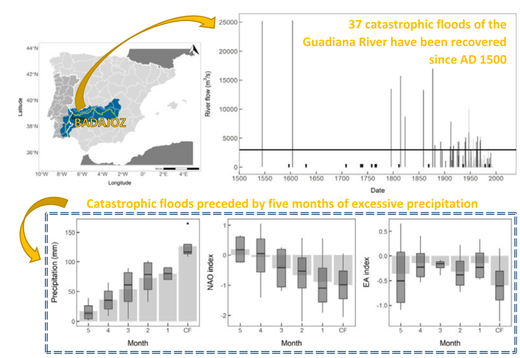
HIGHLIGHTS

- 37 catastrophic floods have been recovered in Badajoz since 1500 CE.
- Newspapers and books are useful to complete the lack of information.
- The decadal distribution of the catastrophic floods is not uniform.
- Values of the NAO and EA indices are negative in previous months of major floods.
- Consecutive months with higher than usual precipitation could cause extreme floods.

GRAPHICAL ABSTRACT



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ABSTRACT

The task of retrieving information about past flood events is very important to reconstruct flood series data. In this work, a wide range of different sources including newspapers, technical reports, and books was consulted in order to recover information about catastrophic flood events in Badajoz (Spain). A set of 37 catastrophic floods of the Guadiana River that occurred in Badajoz in the winter months (DJFM - December, January, February, and March) have been recovered since 1500 CE. This strong seasonality constrain is due to the important influence of the large-scale circulation patterns in winter affecting the climate of the Iberian Peninsula. Moreover, it is found that there is a clear difference between a higher number of floods in the 19th and 20th centuries and a substantial lower value of floods in the 16th–18th centuries. Finally, we evaluated the long-term evolution and inter-annual variability of the precipitation and the main large-scale atmospheric circulation patterns that govern climate variability in Iberia (NAO and EA modes) for the period 1851–1985. This analysis suggests that most extreme floods observed in this period (26 events) correspond to consecutive months with higher than usual precipitation, driven in part by unusual values of both the NAO and the EA modes of variability.

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1. Introduction

Floods are one of greatest disasters of nature. In terms of human and economic losses, climate-related disasters, including floods, have devastating effects on infrastructures. In Europe, floods account for circa 40% of the total direct economic damages for the period 2009–2018 (CRED, 2020). Socio-economics damages caused by floods and climate change will increase by the end of the 21th century (Dankers and Feyen, 2009; Rojas et al., 2013). Jongman et al. (2014) found that the extreme floods losses could be more than double by 2050 under future climate change and socio-economic development. Moreover, it is clear that regions where disasters occur undergo direct socio-economic damages. Other regions can also be affected with indirect damages (e.g. fresh

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food shortages in cities). Koks et al. (2019) have evaluated the indirect economic losses caused by river flooding in Europe. They found that indirect economic flood losses will notably increase in the future with most affected economic sectors in the future corresponding to the commercial services and public utilities (Koks et al., 2019).

In order to reduce direct or indirect losses in civil infrastructures, it is necessary to compute long-term return periods, preferably of at least 500 years. However, most available instrumental series of river flow do not cover the long-periods required, typically beginning in the early 20th century (e.g.: Balasch et al., 2019; Barriendos and Rodrigo, 2006; Benito et al., 2005; Sánchez-García et al., 2019). Some authors recovered historical chronologies of floods in different river basins to extend instrumental series. In Europe, a recent major review work has been undertaken by Blöschl et al. (2020), where the authors have identified nine flood-rich periods in the past half millennium in various regions of Europe. Likewise, Glaser et al. (2010) compiled historical flood data for major European rivers since 1500 CE and found four periods of flood frequency: 1540–1610, 1640–1700, 1730–1790 and 1790–1840. Macdonald and Black (2010) studied flood frequency using historical information for the period 1200–2000 in York. In the Iberian Peninsula (IP), Barriendos and Rodrigo (2006) studied most river basin through documentary sources. More detailed studies of each basin can be found for (i) the Ebro basin (Balasch et al., 2019; Barriendos et al., 2014; Llasat et al., 2005), (ii) the Tagus basin (Benito et al., 2003), (iii) the Andalusian Mediterranean basin (Sánchez-García et al., 2019), and (iv) the Duero basin (Bullón, 2011). For the Guadiana basin, and to the best of our knowledge, very few studies can be found (e.g.: Benito et al., 2005; Ortega, 2007; Ortega and Garzón, 2009). Barriendos et al. (2014) showed the density of flood events in relation to their space and time coverage (see Table 4 of Barriendos et al. (2014) for these values) for all the basins of the IP. These values provided an idea of the density of information related to the floods occurred in the main river basins of the IP. For the case of the Guadiana basin, the density of events obtained is 1.8 events/coverage, where coverage is defined as years of records multiplied by basin area (km^2) and divided by 10^6, corresponding to the lowest density value of the IP basins. This value suggests that the Guadiana basin has been poorly studied and it is quite likely that the real number of flood events per year and per square kilometer in the Guadiana basin is greater.

The task of retrieving information of historical flood events is very important to extend flood series data. Climatological information can be found in many documentary sources, such as technical reports, ecclesiastical manuscripts, books, newspaper or magazines. For example, one of the climate proxies recorded in different documentary sources is related with the rogation ceremonies. Rogations are useful documentary proxies to identify dry and wet extreme events. Information about rogation ceremonies can be found frequently in ecclesiastical manuscripts, books, magazines and newspapers (Bravo-Paredes et al., 2020; Domínguez-Castro et al., 2017; Domínguez-Castro et al., 2012). Therefore, flood events can also be found in these documentary sources. In addition, floods are recorded in technical reports and local government records. Some authors consulted these documentary sources to recover historical floods in Iberia (Sánchez-García et al., 2019; Trigo et al., 2014). In this study, these documentary sources have also been consulted to retrieve information about flood events.

Historical accounts of flood events can be used to associate with information about different topics. Therefore, the analysis of the temporal distribution of floods have been carried out by many authors namely in the IP. The decadal distribution of the number of floods since the 16th century provides generally coherent results, namely: fewer floods in the 16th–18th centuries compared to those retrieved for the 19th–20th centuries (Balasch et al., 2019; Barriendos et al., 2014; Benito et al., 2003, 2005; Sánchez-García et al., 2019). Other authors studied the climatological conditions that have been preferentially associated with floods. One of the principal modes of winter climate variability in the North Atlantic is the North Atlantic Oscillation (NAO) (Hurrell, 1995). In fact, it has been shown that the NAO is the most important mode of variability controlling the IP precipitation (Trigo et al., 2008). When the NAO index is positive, dry conditions appear mainly in the climate of the IP. On the contrary, wet conditions appear in the climate of IP when the NAO index is negative (Gallego et al., 2005; Goodess and Jones, 2002; Queralt et al., 2009; Trigo et al., 2004). The NAO index is often used to analyze climatological conditions that cause floods. Trigo et al. (2014) analyzed the influence of the NAO for the great flood of December 1876 while Benito et al. (2005) studied the effects of climate variability for floods using historical information and the NAO index. Besides the NAO, the second most important large-scale pattern in the North Atlantic sector is the East Atlantic (EA) pattern that is also relevant determining the climate of the Iberian Peninsula (e.g. Jerez and Trigo, 2013; Trigo et al., 2008). Recently the relatively short time series of the EA pattern has been extended until the mid-19th century by Comas-Bru and Hernández (2018).

The main aim of this work is to recover historical catastrophic flood events of the Guadiana River in Badajoz (Spain) since 1500 CE. To reach this objective, flood events of the Guadiana River in Badajoz have been collected from different documentary sources. In addition, we evaluate the role played by the two climate modes of climate variability in the North Atlantic sector (NAO and EA) in terms of major floods frequency.

2. Data

The Guadiana River is the fourth longest river of the IP with 744 km length (Fig. 1, green line). It is located in the southwest of the IP, corresponding to the physical border between Portugal (Algarve) and Spain (Andalusia) before reaching the Atlantic Ocean. The total area of the basin (Fig. 1, blue region) is 67,129.38 km^2, including several regions of Spain and Portugal.

The main course is divided into three parts: (i) the Upper Guadiana (Castilla-La Mancha region, 26,455.55 km^2), (ii) the Middle Guadiana (Extremadura region, 23,443.73 km^2), and (iii) the Lower Guadiana (Portugal and Andalucía regions, 17,230.10 km^2).

In this study, only the Middle Guadiana is considered, specifically, the city of Badajoz (38° 52′ 40.4″ N, 6° 58′ 14.2″ W). Moreover, the Palmas Bridge, a site located inside the city of Badajoz is selected to carry out the study. The Palmas Bridge was built in the 15th century and has suffered damages caused by different floods throughout history. Due to the fact that floods also affected the population of Badajoz, flood marks were placed on the bridge reminding the highest level reached by the water in each occasion. More recently during the 20th century, a metric scale was installed on the bridge to measure the water height systematically. Thus, we would like to stress that there are two important reasons for selecting this place: i) the long period of the water height observations recorded at this location; ii) most of the historical sources describe the impact of the floods on this historical bridge.

The climate of Badajoz is Mediterranean with dry summers and mild winters, with a mean annual accumulated precipitation of 475.4 mm for the period 1851–2009. The mean accumulated precipitation has a strong seasonal behaviour: 162.5 mm in winter (December, January, and February); 135.4 mm in spring (March, April, and May); 28.06 mm in summer (June, July, and August); 149.4 mm in autumn (September, October, and November). The monthly precipitation data used in this study for the period 1851–2009 was provided by the Spanish Agency of Meteorology.[1]

Instrumental river flow data for the Guadiana basin are available in the *Anuario de aforos 2016–2017* of Centro de Estudios y Experimentación de Obras Públicas (CEDEX - https://www.ceh.cedex.es). Specifically, river flow data for the station 4018 (Guadiana basin in Palmas Bridge - Badajoz) is available for the period 1913–1994. In this

[1] The data used can be downloaded at http://www.aemet.es/documentos/es/serviciosclimaticos/cambio_climat/datos_diarios/dato_observacional/series_largas/Series_precipitacion.tar.gz.

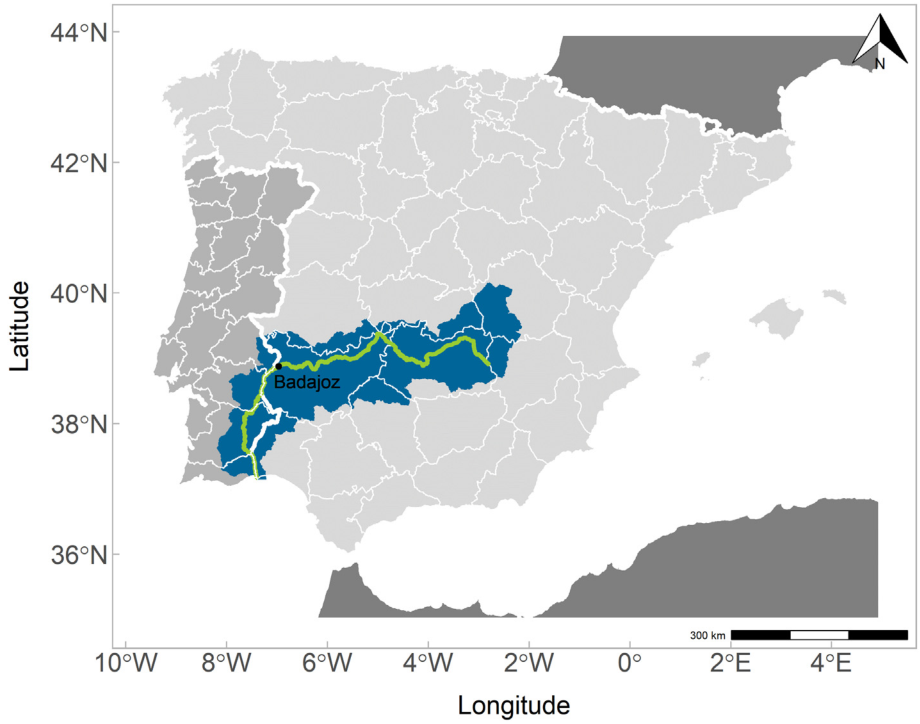

Fig. 1. The location of the Guadiana basin (blue area) and the Guadiana river (green line) in the IP from Confederación Hidrográfica del Guadiana (www.chguadiana.es) and Instituto Geográfico Nacional (www.ign.es). The black point indicates the location of Badajoz.

study, daily river flow data has been used for the period 1943–1994 because there is a gap of 11 years in the period 1913–1943 and many missing values.

Historical river flow data of the Guadiana basin are retrieved from different documentary sources:

- Catalog: National Catalog of Historical Floods made by Comisión Técnica de Emergencias por Inundaciones (CTEI, 1985) has been consulted. Specifically, *Estudio de Inundaciones Históricas y mapa de riesgos potenciales en la Cuenca del Guadiana* has been consulted.

This catalog keeps a record of everything related to the floods in the Guadiana basin. The date and description of each flood is given. The catalog can be found at http://www.proteccioncivil.es/catalogo/naturales/cnih/cnih2014/B6_Document.html.

- Digitized newspapers: different newspapers have been consulted from the virtual newspaper library of the Spanish Government (www.prensahistorica.mcu.es).
  Newspapers record the most important things that happened in a region (in villages and towns), such as floods. Usually, newspapers record important information about floods: damages, deaths, water height, among others.
- Books: sometimes additional relevant information can be obtained from authors that have compiled and recovered information on the history of Badajoz. The monographies by Cruz Franco et al. (2018), González Rodríguez (2019), Hernández Tolosa (1992), Solano de Figueroa (1929), and Díaz y Pérez (1887) have been consulted in this work. In the case of floods, the authors compiled information about the magnitude of floods from different documents. The water height reached by the flood is also presented in some cases. Moreover, some of these authors provide information in what concerns the locations of flood marks in the city.

The magnitude of floods can be classified according to their impact. That is why we resorted to the Floodup project that gives a classification taking into account the individual impact of each flood. The objective of the Floodup project was to increase the information on the impact caused by floods in the northeast of the Iberian Peninsula (Llasat-Botija et al., 2018). This classification, that can be found on the Floodup project website (www.floodup.ub.edu) was considered adequate to characterize the floods of the Guadiana from the documentary sources used in this work:

- Ordinary flood: the river does not overflow. Floods cause little damage.
- Extreme flood: the river overflows. Floods cause major damage.
- Catastrophic flood: the river overflows. These floods cause very important damages, such as the partial destruction of bridges or buildings or the death of animals and people.

Taking into account this classification, the catastrophic floods in Badajoz (Palmas Bridge) have been selected among all the floods (of any magnitude) registered in the documentary sources consulted. The selection was carried out considering two points:

1. An important indicator of the magnitude of the floods is the water height. Only floods with more than 6 m of water height in Palmas Bridge were retrieved.
2. The description of the flood. In the absence of water height, the description of the flood can contribute to infer the magnitude of the floods (e.g.: description of the number of deaths, damages in agriculture, damages in civil infrastructures, such as others).

In total, 37 catastrophic floods have been retrieved from different documentary sources since 1500 CE. Table 1 shows the 37 catastrophic floods and their main data (date, water height and source). There are some catastrophic floods presented in the instrumental and historical series. In these cases, the value of the river flow of the instrumental series has been chosen.

Fig. 2a shows the scale to measure the water height in Palmas Bridge in Badajoz. Fig. 2b shows the flood-marks of the catastrophic flood of

Table 1
37 catastrophic floods recovered from different documentary sources (newspapers are named with the title in italics) since 1500 CE and their main data.

Year	Month	Day (s)	Water height (m)	Documentary source
1545	1	18–28	14.78	(Cruz Franco et al., 2018; CTEI, 1985; Díaz y Pérez, 1887; Solano de Figueroa, 1929)
1596	12			(CTEI, 1985)
1603	12	19–26	14.80	(CTEI, 1985; Díaz y Pérez, 1887; González Rodríguez, 2019; Solano de Figueroa, 1929)
1708	3			(González Rodríguez, 2019)
1736	12			(González Rodríguez, 2019)
1740	2			(González Rodríguez, 2019)
1758	1	5–6		(CTEI, 1985)
1766	12	5–6		(CTEI, 1985; Hernández Tolosa, 1992)
1796	1	29–30	11.34	(Díaz y Pérez, 1887; González Rodríguez, 2019)
1814	3	3–7	12.10	(Díaz y Pérez, 1887; González Rodríguez, 2019)
1823	2	8–11	9.4	(CTEI, 1985; Díaz y Pérez, 1887; González Rodríguez, 2019)
1859	1	24–29	11.26	(Díaz y Pérez, 1887; González Rodríguez, 2019)
1869	2			(González Rodríguez, 2019)
1876	12	6–7	12.50	(CTEI, 1985; Díaz y Pérez, 1887)
1881	1	28	6.69	*La Correspondencia de España: diario universal de noticias*
1892	3	13	7	*El isleño: periódico científico, industrial, comercial y literario*
1895	1	15–16	6	*La lid católica*
1911	1	25		(CTEI, 1985)
1912	2	6–9	9	(CTEI, 1985) and *El popular: diario republicano*
1915	1	5	7	*El pueblo: diario republicano de Valencia*
1916	3	14	6	*El liberal*
1917	2	15	6.5	(CTEI, 1985) and *El norte: diario católico-monárquico*
1924	3	27	6	*La libertad*
1926	2	3–4	7	(CTEI, 1985) and *El pueblo: diario republicano de Valencia*
1927	12	27	7	*Correo extremeño*
1936	2	22		(CTEI, 1985)
1940	1	6	7	(CTEI, 1985) and *El Progreso: diario liberal*
1941	2	1	7.5	(CTEI, 1985)
1947	3	6	8	(CTEI, 1985), *Diario de Burgos: de avisos y noticias*, and daily instrumental data
1951	3	15	6	(CTEI, 1985) and *Diario de Burgos: de avisos y noticias*
1955	12	18	6.75	Daily instrumental data
1962	1	1	7	(CTEI, 1985) and *Diario de Burgos: de avisos y noticias*
1964	2	27	6.7	(CTEI, 1985) and daily instrumental data
1969	3	15	7.1	(CTEI, 1985) and daily instrumental data
1970	1	13	7.1	(CTEI, 1985) and daily instrumental data
1979	2	13	7.11	(CTEI, 1985) and daily instrumental data
1985	1	22	6.4	Daily instrumental data

December 1876 in different locations of Badajoz. Fig. 2c shows the catastrophic flood of December 1927 that occurred in Badajoz recorded in the newspaper *Correo Extremeño*. It can be read in the headline: "The storm in Badajoz. The water height of the Guadiana River is more than six meters covering the 28 portholes of the Palmas Bridge". The text includes a description of the flood, such as the water height measured, and the damages provoked in agriculture, livestock, and civil infrastructures.

It can be seen in Table 1 that all the floods occurred in the core winter months (DJFM – December, January, February, and March). As was aforementioned, the IP winter climate is particularly affected by the two most prominent patterns in the North-Atlantic and European sectors, i.e., the NAO and EA modes of variability (Gallego et al., 2005; Rodriguez-Puebla et al., 1998; Trigo et al., 2008) (Gallego et al., 2005; Rodriguez-Puebla et al., 1998), in particular, recent work has shown that the most intense precipitation events in western Iberia are often triggered by the occurrence of Atmospheric Rivers, associated with the EA pattern (Ramos et al., 2015). So, in order to analyze the climatological variables that trigger catastrophic floods we relied on the longest time series available for the NAO and EA indices besides the precipitation. The NAO index used here is the one by Jones et al. (1997), were calculated from instrumental sea-level pressure data between Gibraltar and Reykjavik since 1821. This index has been widely used in climatological studies over Europe (Gouveia et al., 2008; Trigo et al., 2002) and particularly over IP (e.g.: Gallego et al., 2005; Trigo et al., 2004). For the EA index we used the recently index computed for the period from 1851 to the present (Comas-Bru and Hernández, 2018).

3. Method

The month and the year of occurrence are recovered for the 37 flood events considered. The temporal distribution of the catastrophic floods was analyzed here with the 37 floods events compiled being grouped in two different manners. The first grouping consists of gathering all the floods considered at the monthly scale. The second approach is established considering all the floods distributed at the decadal time scale since 1500 CE.

A useful tool to study flood events is often based on the empirical relationship between the river flow and the water height. From water height data, river flow can be estimated (Breña Puyol and Jacobo Villa, 2006). Therefore, instrumental river flow and water height data recovered from the different documentary sources consulted have been fitted. To stablish this fit, the relatively recent period 1943–1960 was selected for two reasons: (i) the most significant anthropic modifications of the riverbed (particularly new bridges and access roads) were executed after this period, and (ii) there are numerous gaps in the series before this period.

A common method to derive a rating curve is based on the power-law function (Breña Puyol and Jacobo Villa, 2006):

$$Q = a(z - z_0)^b \tag{1}$$

where Q is the flow, z is the height measured, z_0 is the height for $Q = 0$. The parameters a and b are constants to be fitted. In our case, $z_0 = 0$. Several methods can be used to estimate the river flow of the Eq. (1) from the water height data (Chow et al., 1988). Here we have used the logarithmic method (Breña Puyol and Jacobo Villa, 2006):

$$logQ = \ loga + blogz \tag{2}$$

Fig. 3 shows the black linear regression of Eq. (2). The linear regression is obtained from the adjustment of 6207 values (gray dots) of the daily instrumental data of the Guadiana River in the Palmas Bridge of Badajoz for the period 1943–1960. Values are represented by gray open dots to better visualize their density.

The equation of the flow-height curve is obtained from the Eq. (2) and the corresponding fitted parameters are shown in Table 2:

$$Q = 44z^{2.357} \tag{3}$$

Fig. 4 shows in black the flow-height curve (Eq. (3)) for the Guadiana River at the Palmas Bridge in Badajoz for the period 1943–1960. Dots correspond to daily instrumental data and are represented with small gray circles to enable the visualization of their density. The blue point corresponds to the estimation of the 1876 flood of González-Cao et al. (2021).

In addition, the precipitation and the NAO and EA climate modes indices are analyzed for the catastrophic floods in order to better characterize the climatological conditions that helped triggering these events. The NAO index used in this study begins in 1821 while the EA index and the precipitation both start in 1851. Due to this fact, 26 catastrophic floods were analyzed for the concurrent period 1851–1985. In order to assess the climatological conditions prior to the flood events, we considered the six months leading to each flood event. The month in which the catastrophic flood occurred is labelled CF; one month before the

Fig. 2. a) the scale on the Palmas Bridge to measure the water height; b) the two last flood marks of the catastrophic flood of December 1876 in different locations of Badajoz; c) the catastrophic flood in December 1927 that occurred in Badajoz recorded in the newspaper *Correo Extremeño*. It can be read in the headline: "The weather in Badajoz. The water height of the Guadiana River is more than six meters covering the 28 portholes of the Palmas Bridge".

catastrophic flood is labelled 1; and so on up to 5 months. So, the mean precipitation and the mean value of the NAO index are computed for these 26 catastrophic floods in each month (CF, 1, 2, …).

4. Results and discussion

The catastrophic flood events since 1500 CE will be described in this section. From the analysis of the documentary sources consulted and the instrumental data available it was possible to identify 37 catastrophic floods since 1500 CE. The floods and their main characteristics were recorded from different documentary sources: 21 floods were found in technical reports; 10 in books; 14 in newspapers; and 7 in instrumental river flow data (see Table 1). It can be seen in Table 1 that each flood can be described in different documentary sources. In the case that there is missing data in the documentary source that is being consulted, other documentary sources should be consulted to recover that information. Newspapers, for example, are useful documentary sources to complete the lack of information. In these documents, the date is always known, a description of flood is frequently given, and water height is often recorded.

The month and the year of occurrence were recovered for the 37 catastrophic floods, thus allowing the analysis of the monthly distribution. The light gray bars during the winter months (DJFM) in Fig. 5 show the monthly distribution of the 37 catastrophic floods considered. Boxplots show the monthly precipitation distribution in Badajoz for the period 1851–2009. The black line represents the long-term mean monthly

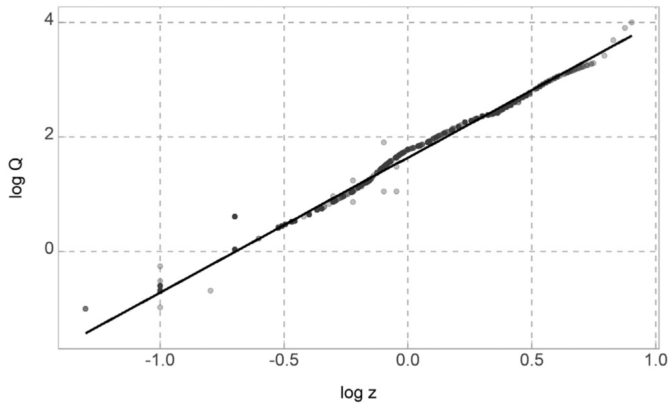

Fig. 3. The black linear regression of Eq. (2). Dots correspond to the daily instrumental data of the Guadiana River in the Palmas Bridge of Badajoz for the period 1943–1960. Values are represented with small gray circles to facilitate the visualization of their density.

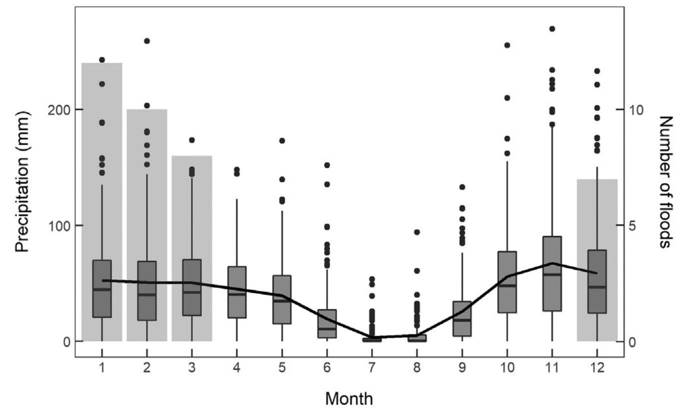

Fig. 5. The monthly distribution of the 37 catastrophic floods (light gray bars) and boxplot showing the monthly precipitation distribution in Badajoz for the period 1851–2009. The black line shows the mean monthly precipitation of Badajoz for this period.

Table 2
The fitted parameters of Eq. (2).

Parameter	Value	R^2
log*a*	1.6410 ± 0.0012	99.42
b	2.357 ± 0.002	

precipitation for Badajoz for this period revealing a marked seasonality with winter months recoding the highest precipitation values (including November).

To characterize the long-term distribution of floods, we computed their decadal distribution since 1500 CE. Fig. 6 shows the distribution of the 37 catastrophic floods of the Guadiana River in Palmas Bridge in Badajoz per decade since 1500 CE.

The number of floods in the 19th and 20th centuries is considerably higher than the number of floods registered in historical sources in the 16th–18th centuries. As refereed by previous authors, the difference between these two periods could be mostly related to the poor preservation of documents in 16th–18th centuries, or the lack of registration of the events (Sánchez-García et al., 2019). In fact, the number of recorded flood events appears to increase with the rise on the available documentary sources, particularly with the appearance of the first newspapers and magazines. Additionally, during the 16th–18th centuries most people used to live inside the city walls while in 19th and 20th centuries, the population increases significantly and the city limits are extended to the outside of the city walls, with people settling near the river. As was aforementioned, floods are recorded when they caused significant human and socioeconomic impacts, including deaths and damages. Therefore, in order to reach the wall and cause damage, the water height that a flood had to reach during the 16th–18th centuries was higher than in more recent times. On the contrary, the water height that a flood had to reach in the 19th and 20th centuries was relatively lower simply as a consequence of the people living near the river. It is possible that all the above considerations have contributed, in one way or another, to explain why the number of floods recorded in the 19th and 20th centuries is higher than what was recorded in the previous centuries. Finally, the number of flood events in the second half of the 20th century is less than in the first half. This is due to the fact that the river flow has been regulated though the construction of reservoirs since the late 1950s (Medina, 2002).

It is also important to put in perspective these long-term changes in flood events with what has been detected in other river basins of the IP. Thus, Sánchez-García et al. (2019) showed a similar distribution of the flood events in Almanzora River in Almería region (Spain) since 1500 CE. According to these authors the number of floods in the 19th and 20th centuries is higher than the number of floods in 16th–18th centuries. Similar distributions of flood events can be found in other studies developed for the IP (e.g. Balasch et al., 2019; Barriendos et al., 2014; Benito et al., 2003, 2005).

Once the temporal distribution of the flood events was analyzed, the magnitude of the catastrophic floods was also studied. One of the objectives of the present work is to estimate the river flow of the catastrophic floods of the Guadiana River in Badajoz. In order to perform this task, the water height reached at each flood event was considered. Non-instrumental river flow was computed for all flood events containing

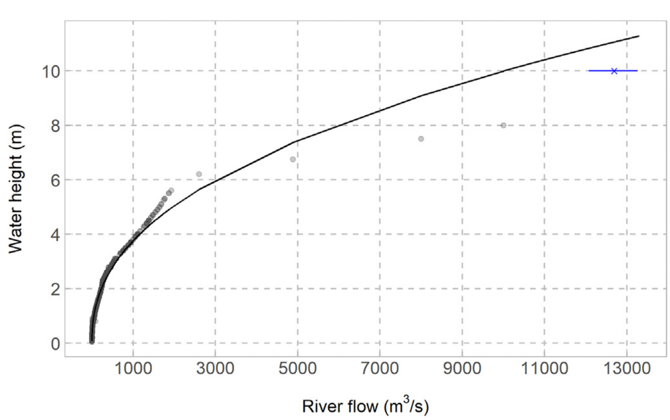

Fig. 4. The velocity-height curve (Eq. (3)) in black of the Guadiana River in the Palmas Bridge of Badajoz for the period 1943–1960. Daily instrumental data are represented by gray open dots. The blue point corresponds to the estimation of the 1876 flood of González-Cao et al. (2021).

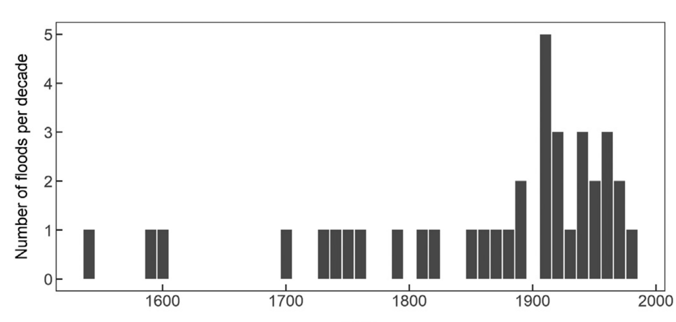

Fig. 6. Distribution per decade of the 37 catastrophic floods of the Guadiana River in Palmas Bridge in Badajoz since 1500 CE.

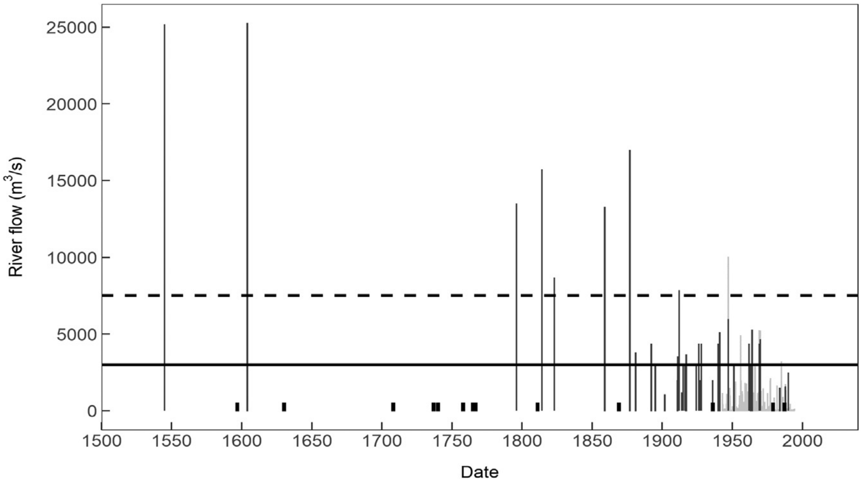

Fig. 7. Instrumental (light gray bars) and non-instrumental (dark gray bars) river flow estimated values at Palmas Bridge in Badajoz. Black bars represent floods with no registered water height. The black horizontal dashed line indicates the value 7500 m^3/s. The black horizontal line indicates the threshold for catastrophic floods. The threshold was estimated taking into account the qualitative descriptions of the damage and impact caused by the floods and the water height of the floods.

water height since 1500 CE with the equation of the flow-height curve (Eq. (3)).

The obtained results are presented in Fig. 7 that shows the distribution of the flood events since 1500 CE indicating river flow using instrumental series (light gray bars) and non-instrumental (dark gray bars) at Palmas Bridge in Badajoz. Black bars denote floods with no registered water height. The black horizontal dashed line indicates the value 7500 m^3/s. Black horizontal line indicates the threshold for catastrophic floods. The threshold was estimated taking into account the qualitative descriptions of the damage and impact caused by the floods and the water height of the floods.

There are 8 floods with estimated flow values falling above the value 7500 m^3/s: 1545, 1603, 1796, 1814, 1823, 1859, 1876 and 1912 and the estimate of the river flow for these 8 floods can be seen in Table 3.

These 8 floods registered the highest values of water height for the entire period analyzed, i.e., between 9 and 14.80 m. All these floods affected the bridge, the city wall, and many nearby houses. Moreover, based in several documentary sources, it can be affirmed that the December 1876 flood corresponds to the largest in recent centuries. The water height value that appears in the documentary sources is 12.50 m (Tables 1 and 3) and the river flow value that appears in the documentary sources is 10^4 m^3/s. The value obtained from Eq. (3) for 10 m is $(100 \pm 2) \cdot 10^2$ m^3/s. González-Cao et al. (2021) have recently reproduced this flood using two different approaches that provide very similar results. The result of their study shows that the water height reached values near 10 m and the peak flow reached values greater than $1.2 \cdot 10^4$ m^3/s (see Fig. 4). Other authors estimated this flood and obtained similar values (Ortega, 2007).

During the 19th and 20th centuries there were 11 catastrophic floods, with water heights between 7.0 and 8 m. The estimated river flow for these floods falls between $(43 \pm 1) \cdot 10^2$ m^3/s and $(592 \pm 13) \cdot 10^1$ m^3/s. These floods affected some neighborhoods, as the water reached the houses but also affected the agriculture and livestock.

Table 3
River flow estimate for the 8 largest catastrophic floods.

Year	Month	Water Height (m)	River flow estimation (m^3/s)
1603	12	14.80	$(252 \pm 6) \cdot 10^2$
1545	1	14.78	$(251 \pm 6) \cdot 10^2$
1876	12	12.50	$(169 \pm 4) \cdot 10^2$
1814	3	12.10	$(157 \pm 4) \cdot 10^2$
1796	1	11.34	$(135 \pm 3) \cdot 10^2$
1859	1	11.26	$(132 \pm 3) \cdot 10^2$
1823	2	9.4	$(87 \pm 2) \cdot 10^2$
1912	2	9	$(78 \pm 2) \cdot 10^2$

Another 9 catastrophic floods in the 19th and 20th centuries were characterized by water heights in the range between 6.0 and 7.0 m. The estimated river flow for these floods varies between $(300 \pm 7) \cdot 10^1$ m^3/s and $(43 \pm 1) \cdot 10^2$ m^3/s. Nevertheless, the information that appears in the documentary sources about the impact on the city and surroundings of these floods is similar to the 11 floods described above with higher water heights. Finally, although the water height for the 1911 flood was not registered, the river flow was recovered (3500 m^3/s). So, the associated water height can be estimated in 6.40 $\pm$ 0.06 m.

In addition, there are 8 catastrophic floods where the river flow could not be estimated. These floods appear in Table 1 without the water height (except the flood of 1911). The impacts of these floods were much stronger. With the exception of the floods that occurred in 1758, 1766, and 1936 all the remaining floods in this group caused structural damage to the Palmas Bridge. The water height of these 6 floods could be inferred to range between the 7 and 15 m. The magnitude of floods occurred in 1758 and 1766 are similar as both floods affected some buildings in the city and also affected many pasture and agricultural fields. So, the water height of floods occurred in 1758 and 1766 could be estimated to fall between 7 and 8 m. The effects of the flood occurred in 1936 are slightly smaller than the effects of the other 8 floods. In any case, this flood (1936) also affected some houses of the city. The value of the precipitation accumulated in 24 h were registered (77.5 mm) for this flood in 22 February 1936, and this value is higher than the mean precipitation registered in February (50.9 mm) for the period 1951–2009. Considering the damage caused by this flood in 1936, the water height could be located between 6 and 7 m.

Once the temporal distribution and the magnitude of the catastrophic flood events were analyzed, large-scale atmospheric circulation conditions were also considered. Besides the precipitation registered, we looked into both the NAO and EA indices for all 26 catastrophic floods between 1851 and 1985. This analysis is summarized in Fig. 8, that shows the mean monthly precipitation of Badajoz with boxplots (on the left), the mean monthly value of the NAO (EA) index with boxplots in the middle (on the right) for 26 catastrophic floods for the period 1851–1985. The label CF (on axis) shows the mean value for the month in which the flood events occurred and the number on the axis indicates the number of month prior to the month of the flood events. It should be noticed that the month in which these 26 catastrophic floods occurred is different: 9 in January, 8 in February, 6 in March, and 3 in December.

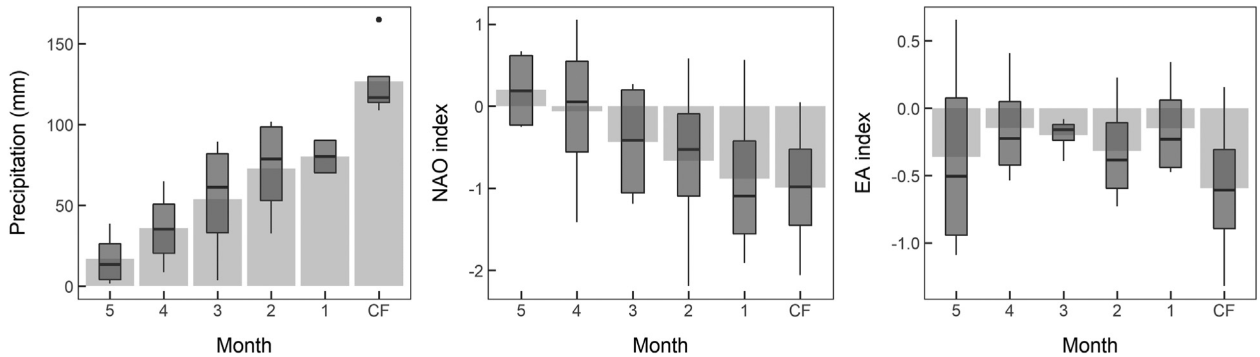

Fig. 8. Mean monthly precipitation of Badajoz with boxplots (on the left), mean monthly value of the NAO index with boxplots (in the middle) and the mean monthly value of the EA index with boxplots (on the right) for 26 catastrophic flood events for the period 1851–1985. Gray columns show the mean precipitation or the month in which the flood events occurred (CF) and also for the months before the flood events.

The mean precipitation in Badajoz for the 26 catastrophic floods for the month in which these events occurred (CF) is 126.75 mm. The mean precipitation in months prior to the floods occurred is also relevant and can be quantified as follows: 1 month before – 80.18 mm; 2 months before – 72.9 mm; 3 months before – 53.75 mm; and 4 months before – 35.93 mm. The mean precipitation in January, February, March, and December for the period 1851–2009 is between 50.7 mm and 58.9 mm (see Fig. 5). Taking into account these values, the mean precipitation for the 26 flood events for the month in which these events occurred (CF) is more than double the typical monthly precipitation. Moreover, the mean precipitation in previous months is slightly higher than the normal conditions. An increase in precipitation is found from the 3 previous months to the month in which floods occurred (CF).

The mean value of the NAO index for the 26 catastrophic floods for the month in which these events occurred (CF) is −0.994. As was aforementioned, negative values of the NAO index are associated to wet conditions in the IP (e.g. Gallego et al., 2005; Queralt et al., 2009). The mean value of the NAO index in months before the floods occurred is also relevant as they might be related to the above average precipitation registered. Thus, the NAO average value in the months before the CF events are as follows: 1 month before −0.86; 2 months before −0.67; 3 months before −0.44; 4 months before −0.07. Therefore, we confirmed that all values of the NAO index are negative, and the lowest value is found in the month in which floods occurred (CF). A decrease in the value of the NAO index is found from the 3 previous months to the month in which floods occurred (CF).

A similar analysis was then performed with the EA index. The mean value of the EA index of the 26 catastrophic floods for the month in which these events occurred (CF) is −0.794. The mean values of the EA index in months before CF events are: 1 month before −0.24; 2 months before −0.49; 3 months before −0.37; 4 months before −0.05. All values of the EA index are negative. The lowest value of the EA index is found in the month in which floods occurred (CF).

Abundant precipitation in one month can trigger a flood of low magnitude. However, If the precipitation registered in the following month is scarce or normal it is likely that the river flow evolves to more normal conditions. On the other hand, if the weather conditions in the next month are equally conductive of more precipitation, then the river flow continues to enlarge and the probability of further (and large) floods increases. According to our results, it appears that most extreme flood events observed correspond to situations of consecutive months with higher-than-usual precipitation, driven in part by unusual values of the two main large-scale patterns that govern climate variability in Iberia, i.e. the NAO and the EA modes of variability. So, regarding Fig. 8, the consecutive increase (or decrease) in climatological conditions could be partially responsible for some of these catastrophic floods.

5. Conclusions

Different newspapers, technical reports, and books have been consulted to carry out the task of retrieving catastrophic flood events. A set of 37 catastrophic floods of the Guadiana River, occurred in Palmas Bridge in Badajoz, have been recovered since 1500 CE. Newspapers, books and government records have been consulted in other studies to retrieve information about flood events (Sánchez-García et al., 2019). In this study, newspapers and books have been useful documentary sources to complete the lack of information presented in technical reports.

The monthly distribution of the 37 catastrophic flood events presents a strong seasonal cycle. In fact, the 37 floods considered occurred in the four main winter months (DJFM). The decadal distribution of the 37 catastrophic floods is not uniform. There is a clear difference between the number of floods in the 19th and 20th centuries and the number of floods in the 16th–18th centuries, with the former showing significantly higher values than the latter. The same distribution can be found in other studies. The difference between the number of floods in the different centuries could be associated (at least partially) with the poor preservation of the documents in the 16th–18th centuries and/or with the urban changes produces in the city of Badajoz.

In order to better frame the large scale climatological conditions that favored the catastrophic flood events, the monthly mean precipitation and the monthly values of the NAO and EA indices were analyzed for 26 catastrophic floods for the period 1851–1985. An increase (decrease) in the mean precipitation (mean NAO index) is found from the 3 previous months to the great flood event. On average, values of the NAO and EA indices are negative during the month of the flood event, as well as during the 5 months prior leading to the major floods. Therefore, according to our results, it appears that most extreme flood events observed occurred when there are consecutive months with higher than usual precipitation, driven in part by unusual values of the two main large-scale patterns that govern climate variability in Iberia, i.e., the NAO and the EA modes of variability.

It should be empathised that direct comparison of available sources with descriptions of flood impacts are difficult to establish, as these events took place during different historical periods, with variable city limits and constructed area has changed. Our analysis provides a relatively consistent framework by considering the same location and therefore comparable metrics for all the floods. The main metric is the maximum height of the river attained in each event and the estimated maximum river flow, allowing, among other possibilities to compare with some of the most well-known episodes (e.g., 1876). Finally, all the analysis presented here on the 37 catastrophic floods in the river Guadiana, registered since 1500 CE in the Palmas bridge, Badajoz requires further investigation, namely the need to disentangle the impact of anthropogenic changes in the city from decadal climate variability and, if possible, climate change.

CRediT authorship contribution statement

N.B.-P. wrote the first draft of the manuscript. M.C.G and J.M.V. initiated the idea and collaboration. R.T., J.M.V. and M.C.G. wrote and reviewed the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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