



Historical floods in the southeastern Iberian Peninsula since the 16th century: Trends and regional analysis of extreme flood events

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ABSTRACT

Studies related to historical floods have generated much knowledge about flood patterns and frequencies in recent years. Extending the series of floods to a longer range of time allows society to clarify what has happened in the past, and thus know what may happen in the future. From the descriptions of primary and secondary sources, a classification of historical floods has been carried out following a method specifically adapted for the study area. The southeastern Iberian Peninsula is the last region to compile historical floods in the Mediterranean Iberian Peninsula. Therefore, the main objective of the present study is to extend the flood series of historical events for four river basins: the Almansora, Antas, Aguas and Andarax. First, flood events are classified according to their descriptions, generating a dataset of all flood events from 1500 to the present day for each basin. Second, we analyze the trends in the historical series, identifying four trend periods linked with the availability of records: 1500–1850, 1850–1900, 1900–1955 and 1955–2000. Notably, the trend in recent decades has broken with normality because of the large number of lower magnitude events. Lastly, we compare our dataset with seven historical series from different rivers elsewhere in the Iberian Peninsula. The results show a high correlation with all southeastern basins and less with the northern and Atlantic basins. For the purposes of the analysis, we considered only the extraordinary and catastrophic floods in all basins, that is, the floods of magnitude 3 or 4 (M3 or M4), and we identified two flood gaps in 1500–1540 and 1660–1720; two flood-poor periods in 1790–1845 and 1955–1970; and five flood-rich periods in 1540–1560, 1610–1654, 1720–1745, 1860–1891 and 1970–1990 in relation to the four river basins in the study area and the other seven Iberian basins, the last century is highly biased by the construction of reservoirs in all basins. The analysis of historical floods shows a link between the flood-gap periods and negative phases of NAOi and TSI. From 1970, lower flood magnitudes occurred during periods of highest amounts of information, an increase in tourism areas. Consequently, the last flood-rich period clearly stands out because of the disparity of the data, and the consequences are biased, for example, by surface runoff in urban areas where non-irrigated agricultural areas were traditionally located, resulting in an increase in economic damage.

1. Introduction

Floods are the natural hazard that affect the greatest number of people worldwide (UNISDR, 2017; Blöschl et al., 2020). Since the earliest civilizations, there has been an interest in documenting information about rivers, hydraulic dynamics and extreme events, including both floods and droughts, which affect land use in river basins (Brown and Chanson, 2012). The use of hydraulic energy from rivers in agricultural activities has been a key factor in the social and cultural evolution of humankind (Mumford, 1979). Close river–human interaction

has inspired people to focus on the behavior and changes of hydrological systems (Corella et al., 2016; Ballesteros-Cánovas et al., 2020). As a result, many actions of river management have been recorded in written documents and stored in historical archives for as long as they have existed (Brázdil et al., 2006; Barriendos et al., 2014; Barriendos et al., 2019; Gil-Guirado et al., 2021).

Reconstruction of flood-series chronologies from historical data has increased worldwide in the past 30 years (Pfister, 1999; Rodrigo, 1994; Benito et al., 2003; Brázdil et al., 2006; Glaser et al., 2010; Benito et al., 2015a; Elleder, 2015; Barriendos et al., 2019; Sánchez-García et al.,

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2019; Blöschl et al., 2020; Bravo-Paredes et al., 2021) to perform comprehensive flood records for different watersheds and regions. These series contribute to the understanding of characteristics of extreme peak discharges, climatological causes of flooding and flood trends (Barriendos et al., 2019). Indeed, as early as the 18th century, systematic and instrumental data of extreme events have been recorded in Central Europe. Thus, some of the earliest examples include the discharges series for Germany (Pötzsch, 1784) and Austria (Pilgram, 1788). Since the second half of the 20th century, several chronologies of historical floods in Europe have been published (Girgus and Strupczewski, 1965; Jones et al., 1984; Kotyza et al., 1995; Barriendos and Martín-Vide, 1998; etc.), appearing in studies that use a collection method established and systematized in both Barriendos et al. (2003) and Brázdil et al. (2006), at the beginning of the 21st century.

Since the beginning of the 21st century, a host of studies have been carried out on the historical flood chronologies of European rivers (Glaser et al., 2010; Hall et al., 2014) and some meta-analyses have been performed (Blöschl et al., 2020). Regional studies have focused on events in Austria (Strömmer, 2003), the Czech Republic (Brázdil et al., 2005), Germany (Mudelsee et al., 2004; Glaser and Stangl, 2004; Toonen, 2015), the Netherlands (Tol and Langen, 2000), Switzerland (Pfister, 1999; Wetter et al., 2011; Schulte et al., 2015; Wetter, 2017), and the United Kingdom (Macdonald, 2013; Macdonald and Sangster, 2017). In southern Europe, studies have also been carried out based on the descriptions of specific historical events, such as in France (Naulet et al., 2005) and Italy (Alessandroni and Remedì, 2002).

For the Iberian Peninsula, there is a relatively large amount of historical research through the end of the 20th century, but it is not continuous (Barriendos, 1996; Barriendos and Rodrigo, 2006). Since the beginning of the 21st century, by contrast, the research has focused primarily on expanding the time series at the level of specific Spanish rivers such as the Atlantic Iberian Peninsula and, therefore, likely to behave similar: Tagus (Machado et al., 2015), Duero (Benito et al., 2021), also in small stream flows from mountainous regions in Central Spain (Ballesteros-Cánovas et al., 2015), and Guadiana (Bravo-Paredes et al., 2021); and the Mediterranean Iberian Peninsula: Ebro and Segre rivers (Balasch et al., 2019), Guadalquivir and Segura rivers (Rodrigo et al., 1999), Llobregat and Besòs rivers (Barriendos and Martín-Vide, 1998; Llasat et al., 2005; Barrera et al., 2006), and the Almanzora river in the province of Almería (Capel Molina, 1987; Sánchez-García et al., 2016, 2019). The present paper closes the research gap regarding floods in river basins in the arid southeastern Spain. Furthermore, we focus on the linkage between climate variability and a regional flood frequency in different regions of the Iberian Peninsula.

In the southern Iberian Peninsula, extreme hydrological events have been studied using sediment proxies and reconstructed fluvial geomorphology from the Pleistocene and Holocene (Schulte, 2002a, 2002b, 2003; etc.). In addition, two moments of sediment aggradation, which have been detected during the Little Ice Age (LIA), can be related to the higher trend of extreme historical events in the area (Sánchez-García et al., 2019). In the present study, we seek to expand the area of study adopted in Sánchez-García et al. (2019).

The present study focuses on the southeastern Iberian Peninsula, specifically the province of Almería. This area represents a gap region in the available historical flood series (Balasch et al., 2019; Barriendos et al., 2019). Therefore, the aim of the work is to reconstruct the series of historical floods for the main rivers in the province, adding new information on the Almanzora (Sánchez-García et al., 2019) and publishing the very first flood series for the Antas, Aguas and Andarax rivers covering the period from 1500 CE to the present day. To achieve this objective, documentary records from the historical archives in the study area have been consulted and analyzed. Finally, the results from the resulting flood series have been compared with several Mediterranean rivers elsewhere in the Iberian Peninsula to look for any spatial pattern of flood periods and frequencies.

2. Study area

The main rivers in the province of Almería cover 5611 km², encompassing the catchment areas of the Almanzora, Antas, Aguas and Andarax rivers. The geomorphology is characterized by mountain ranges and tectonic depressions, with the main divides being in the Sierra de los Filabres, which separates the Almanzora, Aguas and Antas watersheds from the Andarax watershed, and the Sierra Nevada, which separates the basin of the Andarax and the sub-basin of the Nacimiento, a tributary of the Andarax. Altitudes stand at between sea level and 2000 m in the Sierra de los Filabres (Calar Alto at 2168 m), Sierra Nevada (Chullo at 2611 m) and Sierra de Gádor (Morrón at 2236 m.). Fig. 1 shows the hydrography of the four basins with the main tributaries of the rivers.

The climate of the province of Almería is strongly influenced by the proximity of the Mediterranean Sea, but a semi-arid climate is dominant in the interior, which is considered the most arid region on the European continent (Hooke and Mant, 2000). Humid air masses and precipitation are blocked by the high ranges of the Sierra Nevada and Sierra de los Filabres (Capel Molina, 1981), so that the province remains isolated from humid air masses. Therefore, the inner basins of the rivers are located in an area where the average annual rainfall does not exceed 200–300 mm. On the other hand, at the top of the Almanzora and Andarax catchments, the annual precipitation can rise to as high as 700 mm per year. Although the rainfall regime of the study area is Mediterranean with precipitation throughout the months of autumn, winter and spring, any rainfall is mostly torrential and usually caused by cold drop synoptic conditions (Llasat et al., 2005). Temperatures range from 15 °C in January to 32 °C in August, and the annual mean temperature at the Almería airport weather station stands at 18 °C.

The tectonic units of the Betic Range stretch across the region, and the lithology is formed of Paleozoic complexes around Neogene and Quaternary depressions. The geomorphology is divided between depressions, such as Vera and Sorbas, the Almanzora Valley, the Almería basin and the Andarax Valley, and mountain ranges, such as the Sierra de los Filabres and Sierra Nevada, which rose from west to east in alignment with the Nevado-Filábride Complex during the Alpine orogeny (Andersen, 2008), even as the tectonic depressions remained under marine influence during the Miocene. The valleys and depressions are made up of conglomerates, sandstones, marls, travertine, sands and volcanic rocks (Völkl, 1979; Schulte, 2002a; Schulte et al., 2008a; Andersen, 2008). During the Late Pliocene and Early Quaternary, the basin was uplifted and the landscape was shaped by fluvial systems into pediments, alluvial cones, glaciais and fluvial terraces (Schulte, 2002b).

2.1. Almanzora Basin

The upper and middle Almanzora catchment area drains the northern slope of the Sierra de los Filabres and the southern slopes of the Sierra de las Estancias, and it is also the largest drainage basin in the study area at >2600 km². The headwater catchment is located in the highest peaks of the north face of the Sierra de los Filabres, at 2168 m (Calar Alto). The Almanzora River is characterized by steep slopes until it reaches the middle stretch, where it runs in an inside meander practically all the way to the Sierra de Almagro. From there, the channel narrows until it reopens onto a very broad floodplain at the town of Cuevas del Almanzora. Finally, it flows into the Mediterranean Sea, specifically in a district of Cuevas del Almanzora called Los Villaricos.

2.2. Antas Basin

The Antas River, which is 40 km long, is the shortest river in the study area with a basin of 261 km². The headwater of its catchment is located in the first eastern foothills of the Sierra de los Filabres, and it flows into the Mediterranean Sea. From top to bottom, the Antas river catchment is markedly abrupt with a high average slope. In its first few

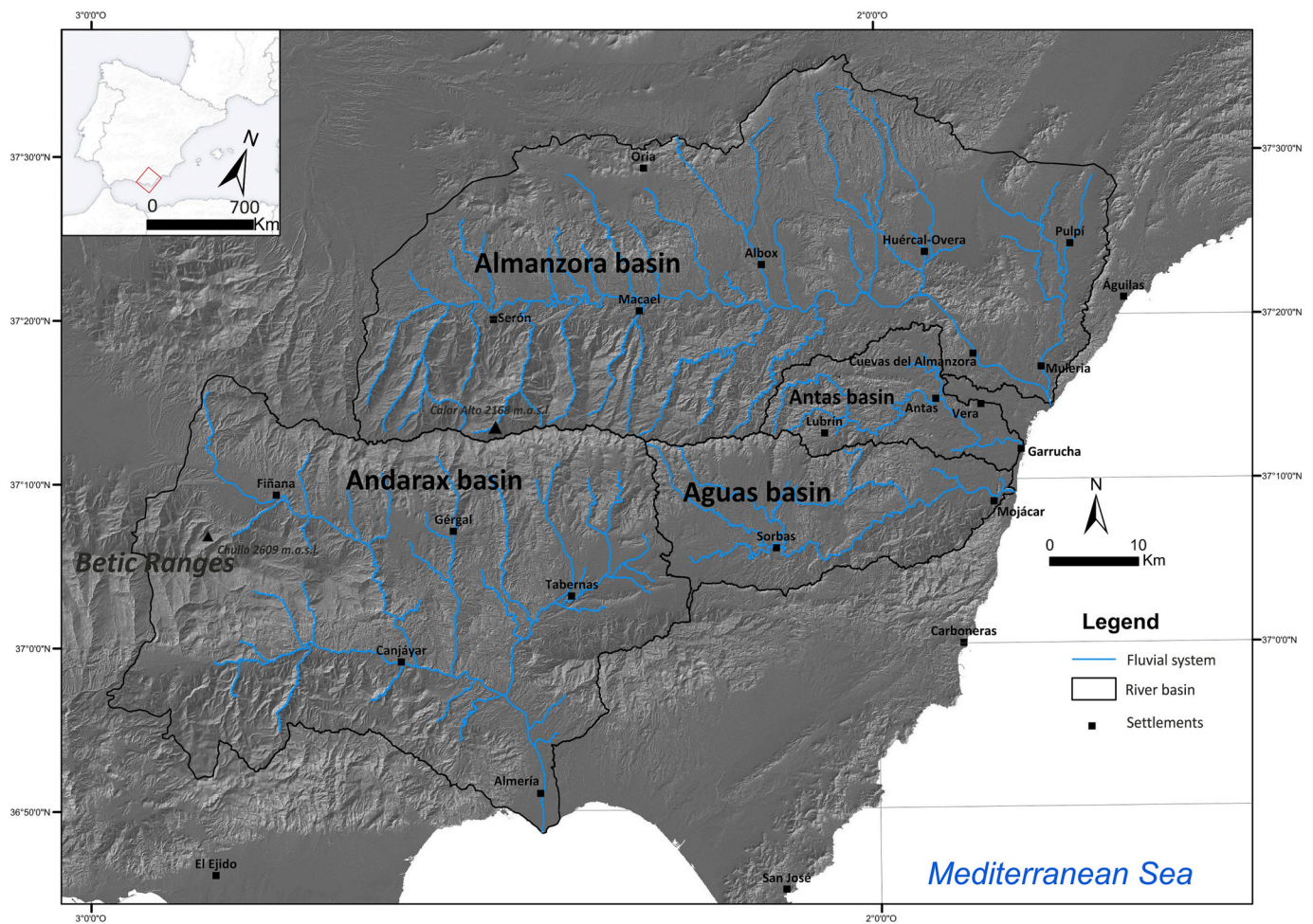


Fig. 1. Map of the study area featuring the Almanzora, Antas, Aguas and Andarax rivers and the main population centers in the province of Almería.

kilometers, the main channel of the Antas flows along the Sierra de los Filabres, delimited by steep slopes. The river topography remains abrupt until the municipality of Lubrín, reaching the western end of the Vera depression where three ramblas (Ballabona, Pocico and Hinojo) converge. From that point on, it becomes a more rectilinear river, draining from west to east across the entire central part of the Vera depression, which is characterized predominantly by low-angle slopes, until the river reaches the Mediterranean Sea.

2.3. Aguas Basin

The Aguas River is the southernmost of the eastern Almería rivers. The river is 75 km long with a basin of 539 km². The headwaters of the Aguas River are also found in the Sierra de los Filabres, specifically in the extreme southeast, at an altitude of 1301 m (Pico Monteagudo), although it is not considered a river until the main channel reaches Molinos del Río Aguas, where the river shows continuous discharge over several kilometers. From the town of Los Gallardos, it becomes more rectilinear and drains the southern part of the Vera depression until it reaches the Mediterranean Sea at the town of Mojácar after several large meanders.

2.4. Andarax Basin

The Andarax river basin is located in the southwestern part of the province, and it reaches to the east of the city of Almería. The Andarax River is the second largest and longest catchment in the study. The main river is 66 km long and the basin covers an area of 2200 km². The

headwater of the basin is located in the Sierra Nevada at an altitude of 2519 m. The Andarax River has three important tributaries, the Rambla de Gérgal, the Rambla de Tabernas and the Nacimiento River, the latter being the most important at a length of 60 km. The three tributaries present a torrential regime as a result of their longitudinal profile, which is marked by a steep slope, and the consequent precipitation regime. The three converge in the Andarax River practically in the same fluvial section. In this way, the last section of the Andarax River, that is, from the descent of the Tabernas Desert gullies, is characterized by a wide valley bottom that continues to the river mouth. In its last section, the Andarax River is confined by defenses and embankments.

3. Material and methods

3.1. Historical data

To obtain information on historical floods, we spent three campaigns (2016, 2017 and 2018) exploring primary sources (first-hand chronicles) and secondary sources (old local newspapers) that describe fatalities and damage to crops, infrastructure, buildings and roads. The flood episodes were recorded in local proceedings, technical reports, church archives and books of minutes of extraordinary meetings held by the local government. Since 1860, local newspapers have published reports of flood events, letters to the editor, and calls to raise money to recover from flood damage. Some of the secondary sources include citations of primary reports and precise copies of municipal proceedings. All documented flood episodes have been cross-checked with different primary sources to verify their authenticity and also, from 1860, with the

secondary sources as well, following the recommendation of Pfister (1999) and Barriendos et al. (2003).

All accessible municipal historical archives and regional historical archives in the study area have been visited. There were a total of 16 local archives, 1 church archive (Almería Cathedral) and 1 regional archive (Archive of the Province of Almería). In addition, interviews have been conducted with local public officials (the mayors of the towns of Antas and Vera) and private agents (Fernández Bolea, a citizen of Cuevas del Almanzora) to gather detailed information on the flooding process, the extent of the flooded areas, any specific damage and the highest stage of floods in relation to flood events that have occurred in the last 50–60 years.

3.1.1. Historical archives

As noted above, visits were paid to 16 historical archives during three field campaigns in February 2016, 2017 and 2018. Table 1 shows the location of the archives, the period covered by the municipal records and the year of the visit(s) to the archives. It is worth noting that the lack of data in some municipalities is a result of looting during and after the Spanish Civil War (1936–1939). Also, the paper on which the municipal records were stored was sometimes used for personal issues, owing to a lack of other products for daily tasks (this is the case for all archives in which the records start at the end of the 19th century). Other archives were destroyed as a result of fire (Pulpí, 1910 and Huércal-Overa, 1912) or flooding (Zurgena, 1973).

For example, Mojácar had a continuous archive until the Spanish Civil War according to documents found in the archive. However, as a result of depopulation, economic and social poverty, and the misuse and destruction of paper documents that occurred in the 1940s, all documents before 1845 have been lost. The documents of Sorbas were analyzed for the period after 1920 because earlier textual sources could not be viewed owing to their poor state of conservation. The municipalities of Garrucha, Bédar, Lubrín and Los Gallardos became independent in the late 19th and early 20th centuries, and therefore most of the information about flood damage was kept in other historical archives in towns such as Vera and Antas.

In addition to the municipal books that contain minutes and proceedings, technical reports on flood damage and subsequent reconstruction plans have been consulted. Archives located in the provincial

administrations, such as the Instituto de Estudios Almerienses in the city of Almería, have also been analyzed. In the latter archive, the descriptions of damage focus on items of general infrastructure such as roads and small dams. In addition, historical photographs of the impact of flooding in the late thirties have been obtained from the same institution.

3.1.2. Secondary historical sources

Once all first-hand information from the municipal archives had been consulted, the local newspapers were examined. For this purpose, the historical press database of the Almería Provincial Council was consulted (Dipalme, <http://prensahistorica.mcu.es/>; last accessed on 25 May 2021).

The first historical newspaper in the region was *La Crónica Meridional de Almería*, which dealt with local affairs such as property disputes and new building projects. Of interest to the general public, *La Crónica Meridional* was first published in 1862 and did not cease operations until 1936.

El Minero de Almagrera is another newspaper that described most of the events that occurred in the eastern part of the study area from 1874 to 1910. Extensive and very detailed information about the 1879 flood, for example, was provided in several accounts because of the flood's major impact on local mining infrastructure and the catastrophic damage sustained by the population of Cuevas del Almanzora. The flood event in 1879 was so important across southeastern Spain that a special edition was published in Paris under the name *Murcie-Paris* to raise money in aid of the victims. Indeed, the flood, which affected the whole of southeastern Spain (Alicante, Murcia and Almería) was commemorated for up to 10 consecutive years and then again 20 and 30 years after the event, until the closure of *El Minero de Almagrera*.

The disaster was also described extensively in the previously mentioned *La Crónica*, although the newspaper focused more on the city of Almería. In 1891, the Andarax River suffered one of the most catastrophic floods in the series, and articles did place greater emphasis on the consequences of that event.

In addition to local newspapers, national newspapers based in Andalusia were also consulted (such as *ABC*, *El País* and *El Mundo*), as were regional newspapers such as *El Ideal de Almería*, *La Voz de Almería* and *Diario de Almería*.

To complete the database, newspapers from the province of Murcia were analyzed, since the study area is adjacent to Murcia in the north and the flood dynamics, climatic conditions and regional climate of Murcia are very close to the Almanzora and Antas river catchments and also, but less so, to the Aguas and Andarax river catchments (Sánchez-García et al., 2016).

3.2. Classification of flood events

Once all flood descriptions had been compiled, flood events were put into four different categories (by magnitude) which appear in Table 2. The method of classification, which is explained in Sánchez-García et al. (2019), draws on the methodology put forward by Barriendos et al. (2003), Brázdil et al. (2012) and Schulte et al. (2015). Table 2 also sets out the key primary and secondary indicators.

Because of the geomorphological, climatological and hydrological settings of the region, particularly in relation to the torrential rainfall regime (Rodrigo, 2010), the methodology was adapted. Accordingly, it was decided to give priority to damage to crop fields, either near or far from the channel, and to human and economic losses (Barriendos et al., 2003). Urban land use is traditionally located far from river courses or on small hills (e.g. the towns of Mojácar and Vera), and the former land use of such areas was non-irrigation agriculture or extensive irrigated systems, which are two geographical characteristics that were taken into account when choosing the specific descriptors. To differentiate the primary indicators of ordinary and extraordinary floods, a geomorphological analysis of every point of damage was carried out. If any damage

Table 1

List of municipal historical archives, period of records, and reasons for gaps in the data.

Municipality	Period covered by data	Year of analysis	Reason for any gaps
Almería	1425–2018	2017–2018	–
Vera	1500–2016	2016	–
Cuevas del Almanzora	1525–2016	2016	–
Antas	1750–2016	2016	–
Huércal de Almería	1750–2018	2018	Date of Independence of the town from Almería
Mojácar	1845–2017	2017	War ^a
Laujar de Andarax	1875–2018	2018	War
Fiñana	1880–2018	2018	War
Turre	1895–2017	2016–2017	War
Tabernas	1895–2018	2018	War
Gérgal	1901–2018	2018	War
Albox	1902–2016	2016	War
Pulpí	1910–2017	2017	Fire
Huércal-Overa	1912–2017	2017	Fire
Sorbas	1920–2017	2017	Archives poorly preserved before 1920
Zurgena	1973–2016	2016	Flooding destroyed the building where the archives were stored

^a The paper held in the archives was used for personal matters owing to the poverty of the people.

Table 2

Description of flood classification factors according to the resulting damage (Sánchez-García et al., 2019).

Flood magnitude	Classification	Primary indicators	Secondary indicators
1	Ordinary floods	Flooding, erosion, damage to crops along the riverbank	Short event duration
2	Extraordinary floods	Affecting agricultural plots far from the riverbank. Damage to buildings and hydraulic infrastructure	Severe damage to fields near the river, loss of livestock
3	Catastrophic floods	Fatalities Partial or complete destruction of settlements	Flood event is recognized by a name (common in major floods); population migration; high socio-economic impact
4	+1 added when the event was recorded in more than one river stretch.		

was documented near the river, at roughly 10 m or less, and there is a low slope, the flood is ordinary. On the other hand, if any damage is documented far from the river or in an area with a high slope, the flood is considered extraordinary or catastrophic, depending on other indicators.

Whenever a flood has affected houses as a consequence of the distance between the riverbed and buildings, the events are classified as extraordinary or catastrophic floods (magnitudes 2 and 3), because in most cases houses are located far from the riverbed or in elevated areas. Only the town of Cuevas del Almanzora is relatively close to the Almanzora River, whereas the rest of the towns are located far away or on Late and Middle Pleistocene river terraces (Schulte et al., 2008a).

Finally, the most catastrophic events are recorded in different basins in the case of the Antas and Aguas basins or in different sub-basins in the case of the Almanzora and Andarax basins. When a flood is recorded in three of the study basins, a point is added to its magnitude, e.g. the 1879 flood is magnitude $3 + 1 = 4$. On the other hand, the flood of 1891 is magnitude 3 according to the descriptions, but it only affected the main river of the Andarax basin and therefore no point is added.

3.3. Trend analysis, Poisson test and seasonality

Lang et al. (1999) provided guidelines for choosing an appropriate threshold. The guidelines include a stationary test based on the computation of the tolerance interval of the number of floods (mt) within an interval $[0; t]$. The null hypothesis H_0 is to assume that the flood process can be described by a homogeneous Poisson process. The 95% tolerance interval of the cumulative number of floods above a threshold, or censored, level is computed. Stationary flood series are those remaining within the 95% tolerance interval (Naulet et al., 2005). To perform the analysis, we used PAST software (Hammer et al., 2001). In the discussion section, we compare our study area with seven historical flood series from river basins elsewhere in the Iberian Peninsula. For the purposes of comparison, only extraordinary and catastrophic floods have been selected from the other basins and they are compared to the M3 and M4 floods from the study area. The aim is to avoid any missing M1 and M2 floods owing to the lack of information in the earlier centuries of the series. We have defined a certain threshold, in this case 0.3, to assess flood-rich periods, which is calculated based on the standard deviation of the 11-year average for each series and the sum of those values (Schulte et al., 2015), and therefore, each value above the threshold is considered part of a flood-rich period. The total dataset has been compared to regional climate variability using the North Atlantic Oscillation index (NAOI) (Luterbacher et al., 2001) and total solar irradiance (TSI) (Steinhilber et al., 2009) in order to assess any possible

triggering of extreme floods. In this case, the correlation between climate patterns is based on the 11-year average for NAOI and TSI, and the flood regional pattern variability (Fig. 12). Schulte et al. (2015) suggest that Summer NAO (SNAO) during positive phase impact on floods related to cyclones of Mediterranean origin that cross central Europe, and during negative SNAO, the extreme events are associated with cold fronts originating over the Atlantic in central Europe (Peña et al., 2015). Furthermore, in the Iberian Peninsula Bravo-Paredes et al. (2020) observed this relation as well, particularly during drought phases of the last 450 years. However, Benito et al. (2015b) postulated performing a meta-analysis of >2000 radiometrically dated European flood units, which at multi-centennial scale Western Mediterranean regions show synchrony of flood episodes associated with negative phases of the North Atlantic Oscillation. Regarding the possible influence of TSI on floods, the literature suggest a relation between temperature, flood events and droughts in central Europe (Büntgen et al., 2006; Schulte et al., 2015; Peña et al., 2015). Inferring from Mediterranean river sediments Benito et al. (2015b) reported anomalous periods of high flood frequency mainly during periods of increased solar activity. In the present study we will analyze if these relationships can be confirmed by flood series compiled from historical sources in the southeastern, central and western and northeastern Iberian river basins.

4. Results

In total, the historical archives record 105 floods. This section presents the database on the flood descriptions found in the archives. We divide the results section according to the different basins, pointing out the most relevant descriptions recorded in the historical archives for each basin. Lastly, we show the results for the seasonality, the trend analysis, the different patterns and the correlation with other basins.

4.1. Almanzora basin flood series

4.1.1. Flood descriptions

The very first document on the Almanzora basin is a description of the landscape and the hydrological dynamics written by Ibn Al-Khatib, who was in charge of the Almeria and Murcia regions under the Arab Nasrid dynasty, during the Caliphate of Granada. Al-Khatib wrote: "Another Nile in its rise and fall after reaching its limits". This statement could indicate that the Almanzora River had quite a few floods between the 11th and 13th centuries, following a different regime than it has today (Bermejo, 1972).

The first catastrophic flooding recorded in the Almanzora basin is an event that affected several towns in 1550 CE. One description of the 1550 flood focuses on the number of fatalities (>20). By contrast, the material and economic damage is not mentioned. A month later, however, the council met again and the minutes of its meeting contain descriptions of the flood's aftermath. Then, almost 200 years later in 1729, the first extensive description of losses appears in file 6 of the Chapter Book of the Council for the year in question, concerning the town of Albox. The translation of the entry is as follows:

[A]fter a great storm of lightning, thunder and hail and water, it came. God willing, a downpour of turbid water ruined nearly forty houses of the neighborhood of this town that were immediately on its Rambla, and among the many others that were filled with water was one belonging to Gines Oller Navarro, in which there was a large portion of wheat (...) after the water carried away a lot of wheat from under the doors of said house, it became much wetter, [with] a great deal of refuse and water deposited from which the waters of said flooding were introduced.

Cuevas del Almanzora was a city of major economic activity at the end of the 19th century because of the mining industry in the Sierra Almagrera. The mining boom gave rise to a dramatic increase in population in the eastern part of the province of Almeria (Fernández-Bolea,

2006). The local newspaper, *El Minero de Almagrera*, published numerous descriptions of floods that affected the miners. This may have an influence on the number of recorded floods, which includes up to eight events catalogued as M3 and M4. Indeed, there is a cluster of extreme events at the end of 19th century that may be biased by the extra information that has been found.

The 1879 flood is considered one of the largest natural disasters in the history of the Iberian Peninsula owing to its extensive damage, not only in the Almanzora basin, but throughout many catchments of the southeastern peninsula (Sánchez-García et al., 2019). The event was captured in a large number of articles (Capel Molina, 1987), poems (personal communication, Juan Grima, 2018) and even a newspaper that was edited in Paris to raise money in aid of the victims.

A book entitled “Memory of the Flood of Murcia, Alicante and Almería: Occurred on October 14 and 15, 1879”, which was published by the Junta de Socorros de los vecinos de Madrid in 1882 (Junta de Socorros de los vecinos de Madrid, 1882), contains the following description of the event:

During the summer and early fall there was a strong drought, from October 12 vertically developing clouds began to be seen in Sierra de los Filabres, Sierra Cabrera, Sierra de Las Estancias and Sierra de Almagro. On the 14th the situation changed, a strong wind from Levante took hold. At two in the afternoon the sky took on a greenish colour never before seen, and from then a sudden bolt of lightning was followed by a boom of thunder that resonated incessantly (...) But this had another cause as well, which could better explain the phenomenon; since we have said that one of the ends of the cloud rested on Sierra Cabrera, whose foot is lapped by the sea; and an enormous spout of water rose from its surface into the cloud, thus coming to increase its flow.

Capel Molina (1987) notes that the torrential waters in the Almanzora basin and all its ramblas rose up to five meters above their riverbeds, according to the descriptions of the affected citizens, exceeding a kilometer and a half in width on each side of the riverbed in the middle basin, close to the Santa Bárbara Bridge. The newspaper *El Minero de Almagrera* reported the same flood in the Rambla de Canalejas, remarking as follows:

Known as the “Santo Negro” (Black Saint) (...) 3000 m³/s at the Cuevas Bridge. 23 dead (the majority in La Muleria) (...) The water rose to the threshing floor of D. Manuel Márquez, a height never before reached according to the men of the time. (...) It flooded mines in the Sierra Almagrera: Santa Matilde, Huerta and Herminia. (...) The Pilar promenade is almost destroyed, the retaining walls of Pago de Campos were knocked over. (...) The new road has been turned into a heap of ruins, the irrigation dams cracked and collapsed, the country estates located to the N. of the road are covered with thick layers of infertile sand...

In 1888, the Almanzora River again suffered another flood, which interrupted construction of the Santa Bárbara Bridge located at the inflow of the Sierra Almagrera gorge. On 11 September of that year, *La Crónica Meridional* published the following report:

The waters of the Almanzora reached heights never before seen at eight o'clock in the evening, flooding the fertile plain of its entire basin, covering a multitude of points from hill to hill on both banks (...) The height of the waters reached 17 m above their ordinary level, causing the total devastation of properties and the riverbank and the total destruction of seven flour mills.

El Minero de Almagrera provides even more information on the flood:

The “Naranjo” (...) 3 dead in Cuevas del Almanzora (...) The draining of the mines and Sierra Almagrera had to be stopped (...) The Minister of Development D. José Canalejas visited the town (...)

The road to Aguilas is closed at the crossroads that marks the entrance to the town.

Indeed, until the major flood of 1973, which once again affected most of the rivers of the southeastern Iberian Peninsula, no flooding with similar magnitudes of material and personal damage had been observed. The flood that occurred on 18 and 19 October 1973 was the most catastrophic on the Almanzora River in the 20th century. According to the hydraulic assessment of Vallejos Izquierdo et al. (1994), the maximum discharge recorded at the Santa Bárbara Bridge was $\pm 5600 \text{ m}^3/\text{s}^{-1}$. The estimated discharge and the height of the bridge indicate that the flood was likely higher than the flood of 1888. The Santa Bárbara Bridge itself was destroyed during the flood of 1973.

The event was also exceptional in terms of rainfall, registering extraordinarily torrential rain in the municipality of Zúrgena, where >700 mm was recorded in one day. The suburb of La Muleria, located near the bed of the Rambla de Canalejas, a tributary of the Almanzora River in its lower course, also suffered significant economic damage and two deaths of people working in the fields (*Diario de Almería*, 1973, consulted on 14 March 2016). As Fig. 2 shows, the flood stage of the Almanzora River can be observed as it passes through the town of Zúrgena, where the building with the local historical documents was destroyed.

4.1.2. Flood series 1500–2020

Fig. 3 shows the complete historical flood series for the Almanzora river basin since records have been kept in the historical archives. The four largest floods (all magnitude 4 in 1550, 1729, 1879 and 1973) show a more or less regular frequency. The recurrence period of the last two modern floods is <100 years (between 1879 and 1973), whereas the difference between 1550 and 1729 (179 years) and between 1729 and 1879 (150 years) is greater. The trend, therefore, is negative for magnitude 4 floods (179–150–96). Notably, the 2012 flood might have reached magnitude 4 without the effect of the canalization and the reservoir built on the final stretch of the Almanzora River.

In terms of floods of magnitude 3, seven catastrophic events have been recorded that meet the characteristics required. These events were recorded in the following years: 1580, 1650, 1654, 1778, 1888, 1899 and 1924. The distribution of the floods is quite heterogeneous in time, with >100 years passing in some cases before another flood of the specific characteristics is recorded, e.g. in the periods 1654–1778 and 1778–1888, whereas the gap is only four years in another case (1650–1654). However, if we add the floods of magnitude 4 to the analysis, it can be concluded that only between 1778 and 1879 do >100 years go by without a catastrophic flood.

Floods of magnitude 2 are distributed throughout the series in a fairly homogeneous way. These floods are constant at the beginning of the series, although they become more frequent with the appearance of local newspapers. In total, there are 16 events, the first recorded in 1587 CE and only a few more recorded until the late 19th century. The cluster in the period 1870–1900, however, consists mostly of floods of magnitude 2. During the latter period, there were actually seven floods of magnitude 2, all very close together in time. For instance, there were two floods of magnitude 2 in 1894 and there were five more between 1880 and 1994. The increase in the proportion not only of floods of magnitude 2, but of floods of all magnitudes in general, is due to the appearance of graphic and written documents in local newspapers. Since 1870, the number of floods and the quality of the descriptions that have reached the present day are much higher.

In addition, these factors have an even greater effect on the floods of magnitude 1. Floods of this type are the most numerous in the last 140 years. However, if the complete series is observed, there are no records of floods with the necessary characteristics until 1831. In the case of floods of magnitude 1, the predominant factor is the lack of information in the records and the poor conservation of the sources. The distribution of floods of magnitude 1 in the Almanzora basin show that most are



Fig. 2. Almanzora River as it passes through Zurgena. According to hydraulic modeling, the maximum discharge is estimated at $5600 \text{ m}^3/\text{s}^{-1}$. (Photo courtesy of the Cuevas del Almanzora City Council).

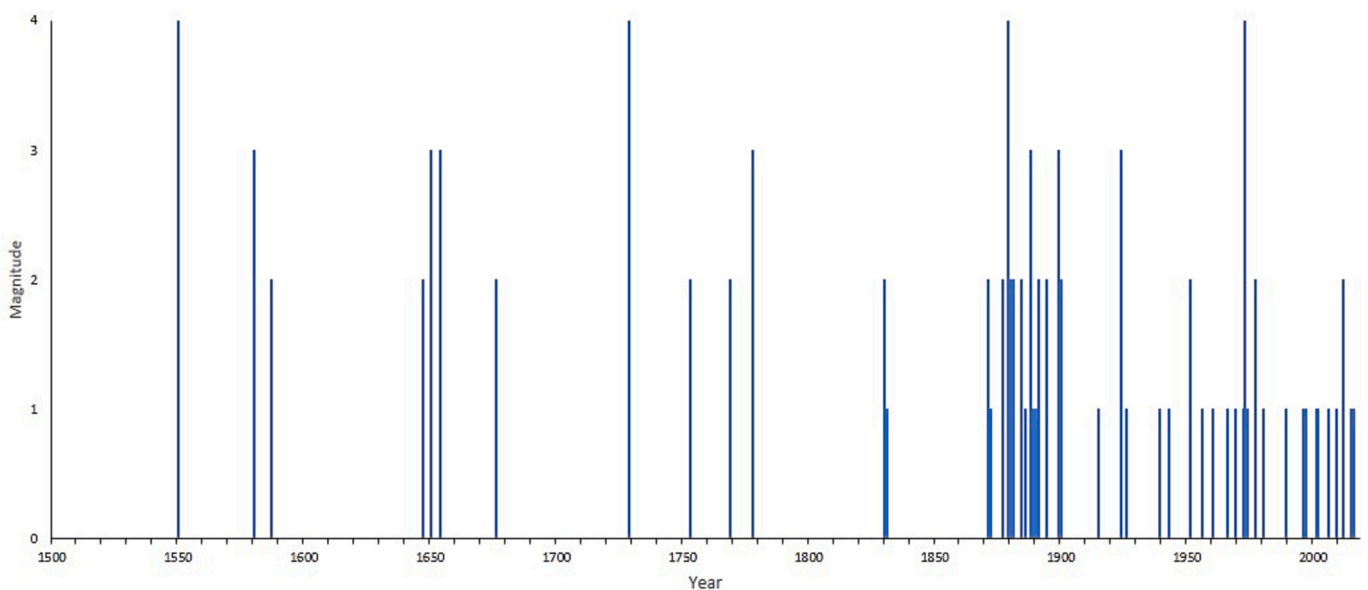


Fig. 3. Series of historical floods for the Almanzora River from 1500 CE to the present, classified by orders of magnitude.

recorded in new urban areas over the last 100 years (Viglione et al., 2023). In addition to building new urbanizations in areas near the river, the traditional type of irrigation was abandoned, at which point the magnitude of floods became greater. In total, 22 events of magnitude 1 have been recorded, most of them in the last 100 years.

4.2. Andarax basin flood series

4.2.1. Flood descriptions

Many of the events that have affected the city of Almeria throughout history come from the rambla of the Sierra de Gádor and pass through the old town. However, the one that caused the most damage was produced by the flow of the Rambla de Belén. The first flood, which was documented in 1550, proved truly destructive. According to a file from the Municipal Archive of Almeria that is echoed by Capel Molina (1987):

Don Carlos (...) To you, our mayor or judge of residence of the city of Almeria and your lieutenant in the Holy Office, health and thanks: that Juan Perez, juror and resident of the city and on behalf of the city council [...], said that the main owner and farmer that the residents of said city have are estates that border the neighborhood they call Larrambla that passes by said city and because of the many large floods that have come to be taken and eaten up much of the said lands and trees as well as those near them, for the remedy of which the council, justice and councillors have made a certain ordinance...

From the file we can draw very concise information on how the flooding of the rambla affected an entire neighborhood of the city (Larrambla). Years later, the Andarax River was the one that caused catastrophic floods. As recounted in file 918 of the Municipal Archive of Almeria, the flood corresponds to the year 1619 and unusually it occurs

in April. According to a portion of the file that has been transcribed and translated below:

Bernabe Nabarro, resident of Benadux (...) says that the flooding of the river that came fourteen days ago with the great force and strength of water flowing down a mountain range and the ditch arrived at the said hill through which the water flows and the heirs of Benadux and Quercal irrigate the other places, leaving them so narrow that water cannot come down or come through them [...] since it was a fortuitous event and that it could not be foreseen or repaired [...] In the city of Almería, on the twenty-sixth day of the month of April in the year one thousand six hundred and nineteen.

The 18th century is very active from a hydrological point of view: there are up to five major floods in 1725, 1729, 1769, 1787 and 1799. The flood of 1769 was the most severe in terms of damage. Taken from file 1 of the Archive of the Cathedral of Almería and report no. 1 of the Archive of the Cathedral of Almería, the extract of a description is transcribed below:

... that having carried away the impetus and torrent of the last flooding of the river, the first dam composed merely of mud through which the mother ditch takes its water, which serves to irrigate the valley and lower fields and that its upkeep is a common obligation, it would be very opportune and useful to replace said dam with a mine, about 20 yards that would facilitate at all times the due course of the waters and the proportion [needed so] that its mill could grind...

From this fragment it is clear that the flood destroyed a dam on the Andarax River, which performed an important function even if it was not built of very resistant materials. Therefore, they were asking for help to rebuild the Andarax River dam.

In the following century, as with the Almanzora River, events are better described and there are also a large number of floods towards the end of the century. The floods that Capel Molina (1987) considers to be the most destructive of the 19th century are those that occurred in 1814, 1829, 1830, 1871, 1888, and 1891. For the Andarax River, the most catastrophic of the century is considered to be the flood of 1891, which was described in *La Crónica Meridional* as follows:

Since the day before yesterday, dense clouds have covered our horizon, keeping the barometer a few millimetres above normal, coinciding with the eastern wind that has persisted for days in this region. At night the barometric column began to descend, anticipating the intense electrical storm that yesterday poured down on

this capital, which coincided with the lower pressure of 756 mm recorded yesterday, four below normal. (...) As a detail, it is enough to point out that in the flood of 1888, the rain gauge dropped a total of 63 mm, less than half of yesterday's measurement. The height reached by yesterday's rain corresponds to the three hours in which the maximum atmospheric disturbance occurred. This is an important fact that proves the horror of the catastrophe that occurred.

This story compares the flood of 1888 and the flood of 1891. The rains of 1891 were much more torrential and caused more damage to the population than the previous flood. In the 20th century, the most important floods in terms of damage occurred in the 1970s. It was precisely in 1970 and 1972 when two floods are recorded in the Andarax river basin. By contrast, the great flood of 1973, which affected the Almanzora, Antas and Aguas rivers, did not cause any significant damage on the Andarax. In recent years, the final section of the Andarax River has been canalized and the streets that pass through the old city are protected by underground channels.

4.2.2. Flood series 1500–2020

Taking into account all the descriptions of floods that have affected the Andarax river basin, Fig. 4 shows the series of historical floods. The series was mainly prepared by Carla Brembilla (Brembilla, 2016).

As can be seen in Fig. 4, the series of floods for the Andarax river basin is quite discontinuous in the earlier centuries and, as occurs in the series of floods for the Almanzora River, there is an increase in the proportion of recorded floods with the appearance of local historical newspapers in 1850.

In the historical series, it can be observed that there are no floods of magnitude 4 until the already mentioned flood of 1891. This is likely because of the geographical properties of the Andarax basin. To be magnitude 4, a flood has to be recorded in more than one sub-basin. In this case, however, there are no data on floods in any of the sub-basins of the Andarax basin (Nacimiento, Gérgal and Tabernas). In terms of damage, however, some of the previous recorded floods of magnitude 3 are quite similar to magnitude 4 floods in the Almanzora basin. Subsequently, there have been two more floods of similar characteristics, in 1989 and in 2006. In the case of the latter two floods of high magnitude, changes in land use might be regarded as an essential factor in understanding the material damage that resulted.

Regarding floods of magnitude 3, it can be seen how the distribution is more continuous throughout the historical series. Since 1500 CE, there have been seven events of similar characteristics. The first one coincides

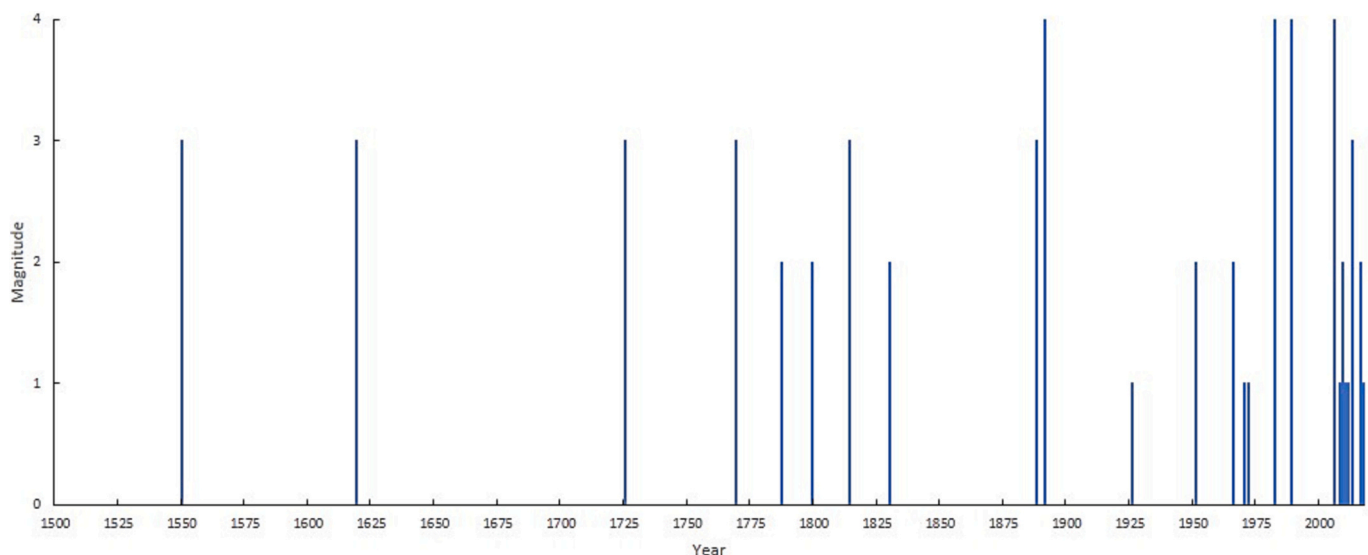


Fig. 4. Series of historical floods for the Andarax river basin. (Adapted from Brembilla (2016)).

with the great flood of 1550 in the Almanzora basin. This event was more serious in the north of the province, but it did cause some structural damage to important streets in the city of Almería.

The lack of data in the archives of the towns in the Andarax basin is quite significant. As a consequence, it may be assumed that some of the floods noted above may have been more catastrophic or that there is a flood that could not be found owing to the loss of documentation.

Floods of magnitude 2 do not appear in the series of historical floods until the end of the 18th century. This is likely due to the lack of data in the historical archives, much as occurred for the Almanzora River. Since then, however, seven floods of similar characteristics that are considered magnitude 2 have been recorded. The same occurs with floods of magnitude 1. The first one was recorded in 1921 and subsequently there have been five more. Of the latter five, two have occurred in the last twenty years and are strictly related to changes in land use and the increased exposure of some neighborhoods to the risk of flooding.

The series of floods for the Andarax River is characterized by data whose distribution is scattered, but frequent over time. There is only one period with few floods, which spans from 1920 to 1950. During the 30 years in question, only three floods were recorded. Subsequently, the increase in mass media has made it possible to register more floods up to the present day.

4.3. Antas and Aguas basin flood series

4.3.1. Antas and Aguas flood series characteristics

The Antas and Aguas rivers are the shortest two rivers in the study area. They pass through few municipalities along their routes, so the number of historical archives is small. However, the documented flood incidence is quite high owing to the exposure of built areas to flooding. In the case of the Antas basin, it crosses four urban centers along its entire length: Lubrín, Antas, Vera and Garrucha, the latter two at the mouth. In this respect, two floods were recorded in 1989 and 2012, and they occurred in the first coastal neighborhoods of Mojácar in the case of the Aguas River and in Vera and Garrucha in the case of the Antas River. The geomorphological map provided by Schulte (2002a) shows clearly that tourism infrastructure was built on river channels that were reactivated by the 2012 flood ten years after the end of the mapping project.

On the other hand, the Aguas River, for its part, crosses three urban centers: Sorbas, Turre and Mojácar, with only the latter at the mouth. In all cases, the municipalities are located far from the riverbed or in an elevated position, unreachable by the river in extraordinary floods.

For both the Antas and the Aguas rivers, the series of historical floods start relatively late in comparison to the series of floods for the Almanzora and Andarax rivers. The scarcity of data before 1870 is the result of several factors. First, there is a lack of historical records dating back to before 1870. The historical archive for Vera does go back to the 16th century, but the contributions made in the years prior to 1870 years are for the Almanzora River and not for the Antas River. Second, the historical fortunes of the towns are a determining factor. Specifically, the lack of historical archives is a direct consequence of the Spanish post-war period. Only the documents that go back to the date of birth of the oldest person living in the municipalities at the time have been preserved.

Despite the reports of floods from several centuries ago in the historical archives of Antas and Vera, such as the flooding in 1550 or in 1729, the floods in question did not affect the Antas River or the Aguas River, but rather the Almanzora River. To find the earliest floods that affected land within the basins of the former two rivers, it is necessary to go back to 1783 in the case of the Antas River and to 1871 in the case of the Aguas River. On the other hand, the available descriptions of the time are usually quite specific in terms of the resulting damage.

For example, the technical report on the 1888 flood that affected the Antas River not only contains a description of the flood and the damage that it caused in the fields, but also identifies in detail who should take charge of the repairs. Something similar happened in 1924, when they

did not agree on who should pay for the improvement works in the main ditch between the municipalities of Vera and Antas.

Additionally, there are several extraordinary reports in the Antas historical archive, two of which focus on the floods of 1877 and 1899. The documents describe the damage caused by both floods. Another extraordinary report focuses on the torrential rains of 1986, but the damage caused by the flooding of the river is not specified in as much detail as the damage caused by the torrential rains themselves. Finally, the last extraordinary report describes the 1989 flood, an event that caused significant damage to the agricultural fields in the municipality of Antas and to the first line of apartments on the seafront in the neighborhoods of Vera Playa and Puerto Rey.

Regarding the Aguas river basin, little data have been found in the historical archives of the visited towns. For instance, the Municipal Archive of Sorbas is under reconstruction and has hardly been explored. Nor could the Turre Municipal Archive be consulted, although it was possible to conduct an interview with Juan Grima, a historian and scholar from Turre who has consulted the historical documents from the archive. Historical flood descriptions provided by Grima have helped in obtaining a consistent flood series for the final stretch of the Aguas basin.

The most important historical flood of the Aguas River is the one that devastated the entire basin in 1899. The 1899 flood is known as “El Señor”, and it was especially destructive because the crops had been harvested and stacked in the fields, only days before the waters of the Aguas River carried the crops away.

In the 20th century, the most important flood took place in 1924 and affected the entire basin of the Aguas and Antas rivers. The Antas River also registered floods in 1956, although it would not be until 1973 when it would register another flood as destructive as the flood of 1888. As for the Aguas River, it registered floods in 1943, 1970, and 1973, but the latter did not affect it as much as it affected neighboring basins. The last major flood, which took place in 2012, was an event that caused considerable material damage in the two basins in the eastern part of the province of Almería and also resulted in personal injuries, claiming two lives in the municipality of Mojácar and another two in the municipality of Vera.

4.3.2. Aguas flood series 1750–2020

The first recorded flood in the Aguas river basin affected several municipalities in 1871 (see Fig. 5). The two floods that are considered the most catastrophic and are classified as extreme events of magnitude 4 occurred in 1899 and 2012. The 1899 flood occurred on 1 June, an unusual date for extreme events to occur. This event affected all the fields that had their crops stacked, but not yet harvested. The next flood of magnitude 4 occurred in 2012. This event affected not only the Aguas River, but also the Antas and Almanzora rivers, as well as the entire southeastern coast of the Iberian Peninsula and the coast of Málaga and Granada.

Floods of magnitude 3 are mostly concentrated at the end of the 19th century. Indeed, the period was very active, marked by three M3 floods that affected the Aguas River in 1879, 1884, and 1888, followed by the next catastrophic flood in 1973. The 1973 flood affected the entire southeastern Iberian Peninsula and was very catastrophic in some towns. On the Aguas River, it affected the towns of Mojácar and Turre and, to a lesser extent, Sorbas.

Taking into account that this series of historical floods covers a short period of time, only seven floods of magnitude 2 have been recorded. As in the previous case, most are included in the cluster in the late 19th century. Subsequently, the next M2 floods occur in 1924, which coincides with the other study basins, and then again in 1977, 1980 and 2006.

Finally, four floods of magnitude 1 have been recorded. The number of low-intensity floods is so small because most of the towns are far from the flood area, and neither the adjacent fields nor the few houses or infrastructure nearby have been affected by small flows.

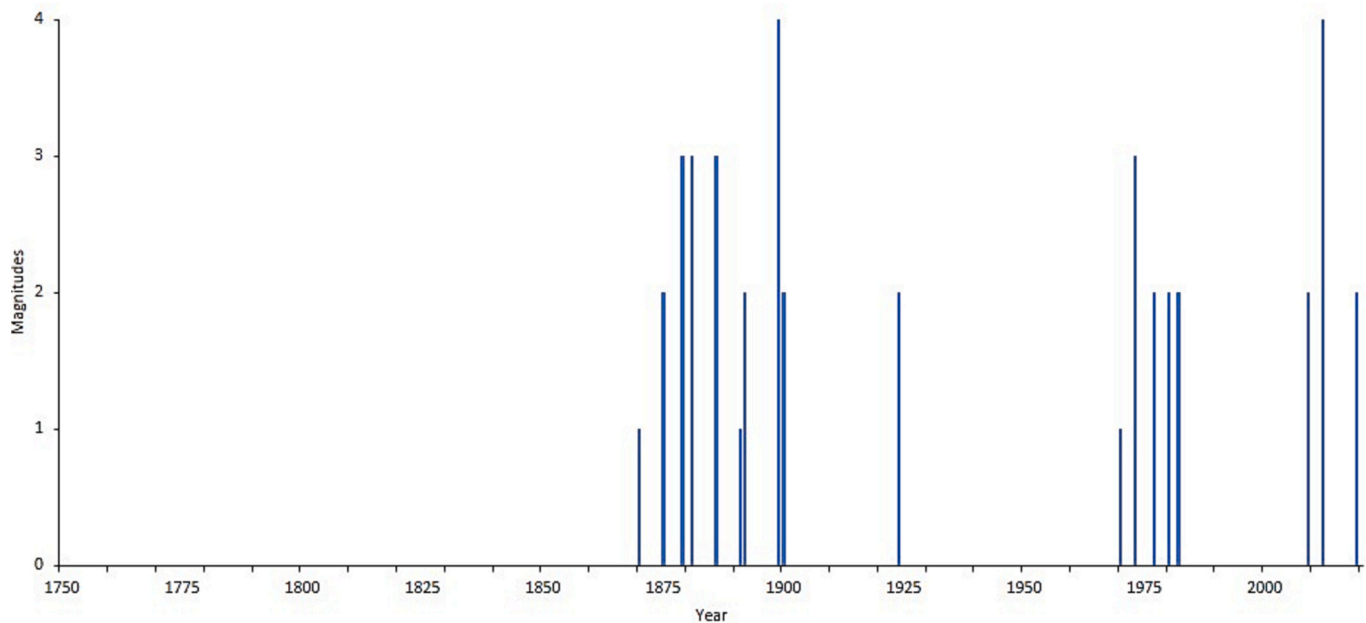


Fig. 5. Series of historical floods for the Aguas basin.

4.3.3. Antas flood series 1750–2020

Floods with a higher order of magnitude have affected the fields and populations of the Antas river basin in 1884, 1973 and 2012 (Fig. 6). Each of the three floods produced very high levels of damage. In the first two cases, the flood damage was linked to traditional irrigation, impacting and destroying ditches, dams and weirs. In the third and final case, the most important damage was recorded in the urbanizations located near the sea and in flood zones.

The floods of magnitude 3 occurred in 1879, 1888, 1924, 1943 and 1989. The catastrophic floods are fairly spread across the entire series and have a certain periodicity. In addition, the first two coincide with the cluster of floods affecting the Almanzora River. The first flood in the series is of magnitude 2 and was recorded in 1780, but it was not until 1870 when the next floods of magnitude 2 appear in the records. In total, there have been seven floods of magnitude 2, four of which complete the cluster of floods at the end of the 19th century.

Finally, the least severe floods, of magnitude 1, start appearing in the records in 1980. As can be seen, their appearance is very late compared to the other three study basins. This fact is a consequence of the limited infrastructure that previously existed along the entire Antas River. At the time when land uses began to change, however, floods of lesser magnitude did start to appear in the records. These are represented by seven events, five of which occur in the last 20 years.

4.4. Seasonality and flood trend analysis

Detailed written evidence of floods for the four river basins enables us to compile flood series according to their dates. Fig. 7 shows the seasonality of the 106 flood events recorded in the Almanzora, Antas, Aguas and Andarax watersheds, expressed as the number of floods per season.

Out of the total of 106 flood events, 55 have occurred in autumn from

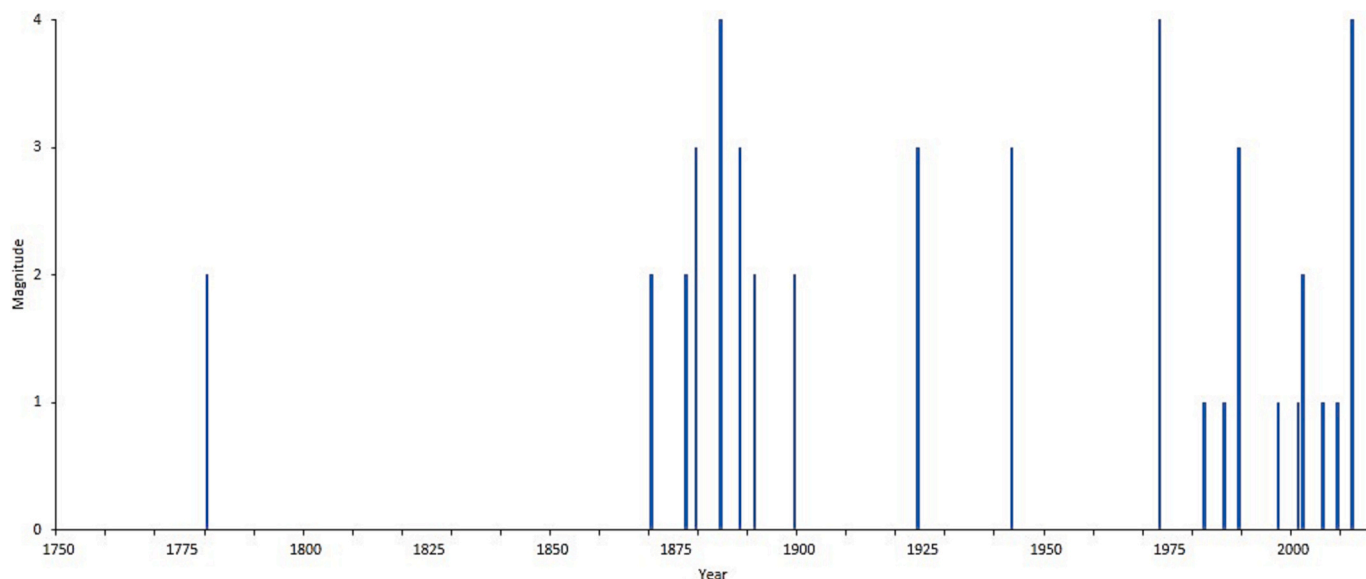


Fig. 6. Series of historical floods for the Antas basin.

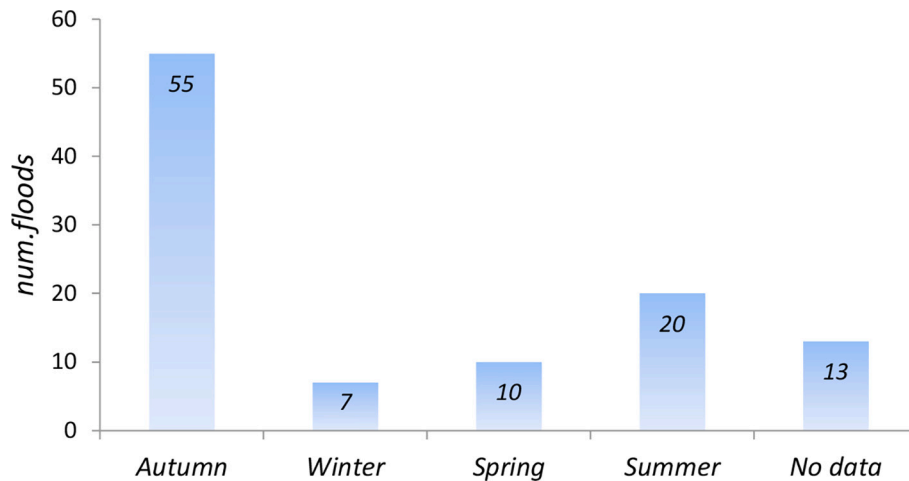


Fig. 7. Seasonal distribution of floods recorded in the Almanzora, Antas, Aguas and Andarax basins.

late September to late December. Most, however, are concentrated in the last weeks of September and the first weeks of October (i.e. the floods of 14–15 October 1879 in all basins and of 28 September 2012 in the Antas, Aguas and Almanzora basins). Additionally, the smallest number of floods are recorded in winter, when there are just 7 events, most of them (4) happening in the Almanzora basin. On the other hand, the number of summer floods is 20 and they are mainly concentrated at the end of the season in the first weeks of September, although one of the most destructive floods in the Aguas and Antas basins occurred on 1 June 1899. Furthermore, there are 10 events recorded in the months of spring and they are distributed throughout the whole period. Finally, there are 13 events in the database for which we do not have an exact date, undoubtedly because of the loss of information in the archives.

Given the diversity of the dataset, the origin of the documentary sources and the impact of the events on the population, several periods

have been identified using the Poisson test. Fig. 8 displays the trend. The main results are divided into four periods: 1500–1870, 1870–1900, 1900–1955 and 1955–2000. These categories depend on the origin of the data and the confidence of the test. All periods have a p -value < 0.05 and, therefore, fall within the threshold of confidence (95%). On the other hand, the last 20 years (2000–2020) are biased by the impact of events on the population and, because of the high number of M1 floods, they do not fall statistically within the threshold of confidence. Based on the Poisson test, the data are reliable when the p -value < 0.05 , but the trend in this context can be either positive (second and fourth periods) or negative (first and third periods).

5. Discussion

In the Section 4, historical floods in the province of Almeria have

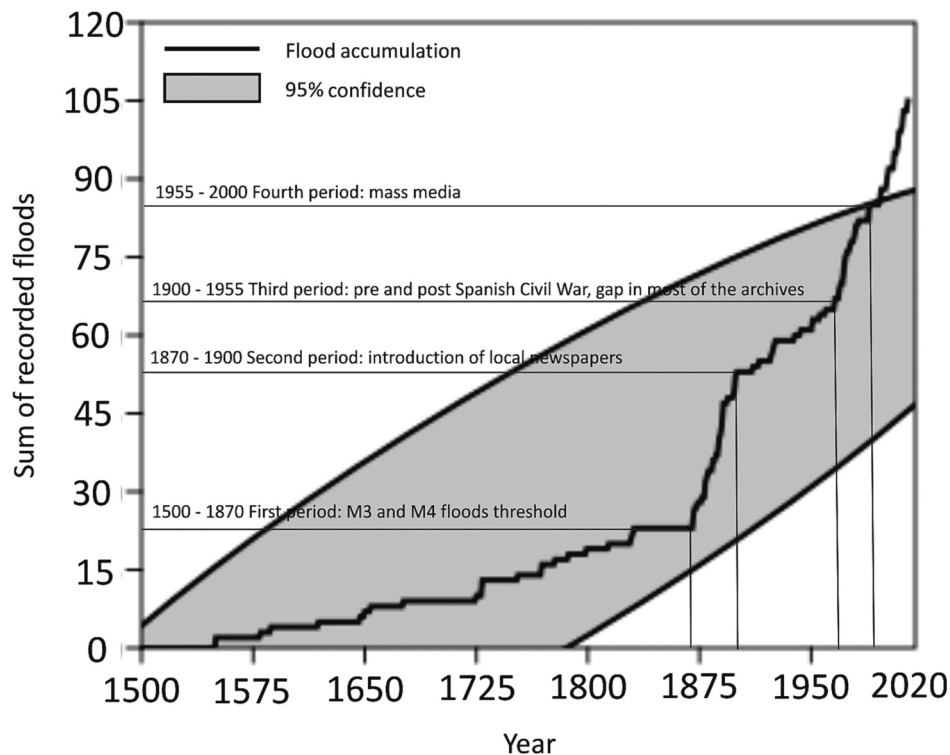


Fig. 8. Poisson test for the floods (M1-M4) in the Almanzora, Andarax, Aguas and Antas river basins. The four different trends are explained in the figure and separated by a black line.

been reconstructed, analyzed and compared since 1500 CE to disentangle flood trends in the context of the Iberian Peninsula. Therefore, the spatial impact of the floods is discussed below in Section 5.2 and Fig. 9. Then Section 5.3 examines the flood frequencies for the Almanzora, Antas, Aguas and Andarax rivers and for several rivers elsewhere in west-central, southeastern and northeastern Spain.

5.1. Analyses of flood trends

The positive trend periods correspond to 1870–1900 and 1955–2000, while the non-positive trend periods correspond to 1500–1870 and 1900–1955. The selected threshold of significance was 95%, and the data indicate that p -values above 0.05 should lead to rejecting the hypothesis of a trend in the series. Therefore, the last two decades (2000–2020) have been rejected according to the trend analysis.

The differences within the flood series, which show changes in flood frequencies and the number of floods, may correspond to natural, low-frequency variations in the climate–hydrological system or to non-stationary dynamics related to anthropogenic changes (Barriendos et al., 2003; Machado et al., 2015).

The first period corresponds to floods of high magnitudes, mainly M3 and M4. Even though the documentary sources for the first period are

scarce and the exposed populations near the rivers were too modest in size to register M1 and M2 events (Barriendos et al., 2019), the numbers of M3 and M4 events are consistent.

Following 1870, the frequency of extreme events doubles, especially during the period 1880–1890. This could be explained by one of three factors. The first factor would involve an increase in atmospheric instability that produced severe precipitation at the end of the LIA (Barriendos et al., 2023). During this period, most of the cases date to the months of September, October and November and were triggered by low pressure in the Gulf of Lion (Llasat et al., 2010). The second factor would concern the increased exposure of the population in the flooded areas, which is tied to an increase in agricultural activity and to population growth, mainly in the Almanzora river basin as a result of the mining industry (Sánchez-Picón, 1981). Lastly, the third factor would relate to the improvement in information resulting from the appearance of the first local newspapers in 1860.

The third period (1900–1955) is a low-frequency period. Few events were registered in the period, with the total reaching 10 across all basins. This lack of events may be due to a steady climatic situation, common in other parts of Europe (Blöschl et al., 2020; Merz et al., 2021), and to a lack of first-hand documents, which were destroyed after the Spanish Civil War, although the destruction did not occur in all historical archives, just in small or recent towns and remained in the big cities



Fig. 9. Physical map of Spain with the location of rivers, cities with historical flood archives and the principal reservoirs in the catchments.

(Almería) and historical cities (Vera) (Table 1).

The last period from 1955 to 2000 is characterized by a high number of floods. However, these events are linked to high-frequency floods of M1 and M2. Furthermore, population growth and the coastal urban boom that began in the 1990s in the eastern part of the study area (in the Antas and Aguas basins) have led to a significant increase in ordinary floods from the end of 20th century to the present. In this case, the trends since 1994 are pronounced in the coastal areas and they were triggered by the urban boom (Olcina-Cantos et al., 2016; Pérez-Morales et al., 2018). On the other hand, the records for the Andarax basin show a higher number of M1 events, probably because of the increased runoff produced by pluvial floods (Llasat et al., 2010), which are becoming more frequent with ongoing climate change (Llasat et al., 2005; Millán, 2014; Sánchez-García and Francos, 2022). Similar to the period 1870–1900, most of the events in the last period are recorded in late summer and autumn, again because of torrential rainfalls caused by low pressure in the Gulf of Lion (Llasat et al., 2010; Millán, 2014).

Broadly speaking, the urban and demographic growth of the analyzed basins is not reflected in an increased number of M3 and M4 floods. However, the higher vulnerability of coastal areas (López-Martínez et al., 2017) does play a determining role in the exponential increase in the number of M1 and M2 floods in the Almanzora, Antas and Aguas catchments that has occurred over the past twenty years, based on the data with 95% confidence in the Poisson process.

To sum up, therefore, the non-positive periods are caused by (i) the lack of information on floods in the first period (1500–1870) owing to the non-description of M1 and M2 events in the historical documents, and (ii) the looting and destruction of documents pre-, during and post-Spanish Civil War in most of the historical archives.

5.2. Flood series in the Iberian Peninsula context

The flood occurrences in the Andarax, Aguas, Antas and Almanzora basins have been compared to other Spanish flood records with continuous data series of five centuries in length from three larger regions, namely the west-central, southeastern and northeastern basins

(Fig. 9). As Fig. 10 shows, the frequencies of extraordinary floods range between 9 (Guadalentín basin) and 32 (Segura basin), although the methodology applied by the research teams is the same. However, the different exposure and vulnerability of land use systems, such as intensive irrigation, farming (Segura River – Vega of Murcia), and dry farming in the tectonic corridor of Lorca (Guadalentín basin), are important factors that influence the incidence and frequency of flood damage.

The large river basins (9 out of 11) have long flood series, whereas the Aguas and Antas series are short. In fact, the long series are associated with cities that are located close to flood-prone areas (Almería near the Andarax; Badajoz near the Guadiana; Tortosa near the Ebro; Zamora near the Duero; Murcia near the Segura; Cuevas de Almanzora near the Almanzora; and Lleida near the Segre). By contrast, the short series of small catchments are related to small towns in rural areas (Vera near the Antas; Mojácar near the Aguas). That said, however, the long records of large rivers are often affected by hydraulic infrastructure like reservoirs (Fig. 9). Indeed, a part of the Andarax river basin witnessed the construction of reservoirs in the early to mid-20th century. Accordingly, the buffering of reservoirs has affected peak discharges and there is a striking lack of extraordinary events in the second half of the 20th century and the early 21st century (Machado et al., 2011, 2015; Balasch et al., 2019; Benito et al., 2021; Bravo-Paredes et al., 2021). As a result, the shorter flood series of small basins may well complement the longer historical series. Despite the implementation of mitigation measures in the Guadalentín, Almanzora and Ebro basins, extraordinary events keep being recorded because the reservoirs affect only the lowest stretch of the river basins. Furthermore, the torrential flow regime in drylands can cause massive destruction, not only along the main rivers but also along tributaries, and/or they can overwhelm any structural mitigation measures. A similar trend is reported from humid regions elsewhere in Europe (Aare River, Rhine River and Maas River), where flood gaps are observed after mitigation measures (Wetter et al., 2011; Schulte et al., 2015, 2019a; Toonen, 2015).

To understand the temporal and regional variability of severe floods, Fig. 10 compares the flood frequencies of 13 Iberian river systems. Five

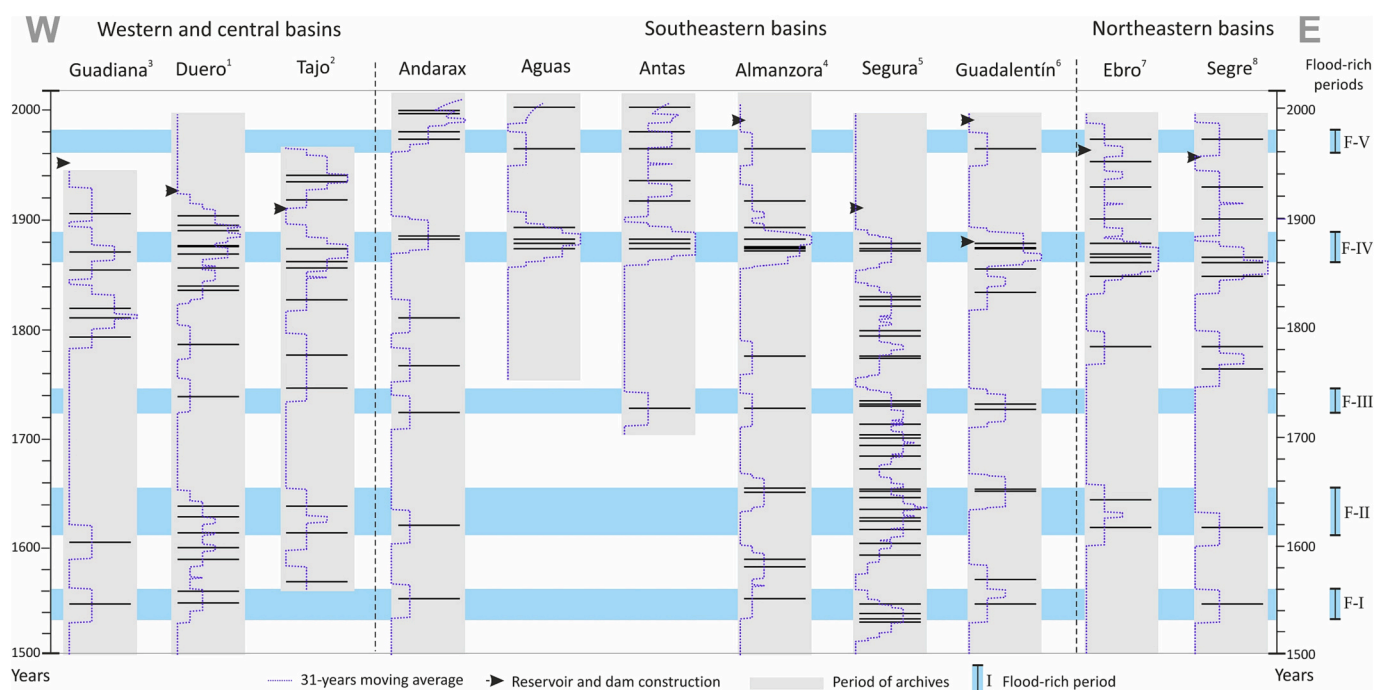


Fig. 10. Historical series of floods for several rivers in the Iberian Peninsula. Flood-rich periods are shaded in blue, while historical flood series appear in grey. (1. Bravo-Paredes et al., 2021; 2. Benito et al., 2021; 3. Machado et al., 2015; 4. Sánchez-García et al., 2019; 5 and 6. Machado et al., 2011; 7 and 8. Balasch et al., 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

flood-rich periods were identified (shaded blue in Fig. 10): 1540–1560, 1610–1654, 1720–1745, 1860–1891 and 1970–1990. The flood periods I, II and IV show flood events in all basins. Period III does not record severe flood damage in the Guadiana, Ebro or Segre river basins (Bravo-Paredes et al., 2021; Balasch et al., 2019). Finally, period V records severe flood events in the southeastern and northeastern basins, but not in west-central Spain. The river systems in southeastern and west-central Spain show mostly synchronous flood patterns from 1540 to 1620 and from 1735 to 1910. The flood-rich period IV from 1860 to 1895 is recorded in many flood series across Europe (Blöschl et al., 2020). The flood frequencies may have been triggered by climatic factors (Peña et al., 2015) or are, in some cases, a consequence of increased information (Schulte et al., 2019b; Wetter, 2017).

In southeastern Spain, the reason for the increase in information is associated with the publication of historical newspapers, as well as the exposure and vulnerability of mining infrastructure in the 19th century in several ranges, especially in the Almanzora basin (Gómez-Díaz, 1992; Sánchez-Picón, 1981; Navarro Flores, 2019). Industry become an important factor that attracted many people to urban areas, and capital cities such as Zamora (Duero), Aranjuez (Tajo) and Badajoz (Guadiana) witnessed an increase in the number of inhabitants, who required new urban areas (Dobado González, 2006). The new inhabitants settled near rivers and transformed many floodplains. Communities implemented new hydraulic infrastructure and policies against the risk of flooding. Ultimately, the resulting changes are very likely to have influenced the flood records of the last 150 years (Viglione et al., 2023).

Each flood-rich period has its own characteristics, which are presented in the following sections.

5.2.1. Flood period I (1540–1560)

From 1540 to 1560 CE, the first severe flood-rich period (F–I) is recorded in the Guadiana, Duero, Segura, Guadalentín, Segre, Andarax and Almanzora basins. In the study area, severe flooding occurred in the Andarax and Almanzora basins and had an impact on the towns of Almería and Muleria near the river mouth (Fig. 10).

In period I, there are two years when the events were supraregional. First, an event in 1545 was recorded in the Duero and Guadiana basins in the west-central basins, in the Segura and Guadalentín basins in the southeastern basins, and in the Segre basin in the northeastern basins.

Second, the 1550 event that occurred five years later has been recorded in the Almanzora and Andarax river basins. This regional event caused damage in the Segura and Guadalentín river basins as well. Moreover, the rest of the rivers behaved quite similarly to our study area with one or two events during the whole period, except the Ebro river basin (Balasch et al., 2019).

5.2.2. Flood period II (1610–1654)

The second flood-rich period (1610–1654 CE) is identified in almost all basins, with a range of one to seven flood episodes in each. Only the Guadiana did not record any flood event in the period. In the Segura river basin, seven severe flood episodes occurred, while the flood activity in the other basins is lower, ranging between one and three events. The simultaneous events are recorded in almost all basins, and also the incidence in our study area (Fig. 10).

Flooding was recorded in 1611 in the Duero and Tajo basins; in 1617 in the Ebro and Segre basins; in 1626 in the Duero and Segura rivers; in 1636 in the Duero and Tajo basins; and in 1651 and 1653 in the Segura and Guadalentín basins. In this case, however, only the event in 1626 can be considered a supraregional event because the records coincide nationwide, stretching from southeastern Spain (Segura River) to west-central Spain (Duero River).

5.2.3. Flood period III (1720–1745)

The third flood-rich period from 1720 to 1745 (Fig. 10) is documented in the Duero, Tajo, Andarax, Antas, Almanzora, Segura and Guadalentín river basins. The 18th century starts with the 1725 flood in

the Almanzora, Antas and Andarax river basins. In the Segura river basin (Fig. 10), three extraordinary floods occurred in 1728, 1735 and 1750 (Machado et al., 2011), and they correlate with the rivers in the study area. On the contrary, the Ebro river basin recorded only one flood in Tortosa (Balasch et al., 2019). Therefore, during flood period III, the southeastern and west-central basins showed a synchronous response, whereas the northeastern basins did not.

In 1729 an event was recorded in the Almanzora and Antas basins; and in 1733 an event was recorded in the Segura and Guadalentín basins. Therefore, there is no simultaneous regional flood pattern in the nearby basins.

5.2.4. Flood period IV (1860–1891)

During the fourth flood-rich period IV (1860–1891), flooding occurred in all of the west-central, southeastern and northeastern basins. In the Guadiana, Tajo, Andarax and Segre river basins, there are two M4 events recorded, while in the other basins there are five M4 events recorded (e.g. the Almanzora river basin recorded five M3 and M4 events).

From 1870 to 1900, biannual flooding was recorded in the Almanzora and Aguas river basins, resulting in >30 events in total across all magnitudes, whereas the flooding in the Antas and Andarax river basins was less frequent (specifically, three in the Antas river basin and two in the Andarax river basin).

These floods coincide with many events in the Segura and the Guadalentín river basins (Machado et al., 2011). In the northeastern basins, the period was also particularly active, especially in the Ebro river basin. Machado et al. (2015) highlighted the period as quite active in the upper basin of the Tagus and in the Duero river basin. Furthermore, the Guadiana river basin shows a flood pattern that is similar to the Andarax and Antas river basins (Fig. 10).

During the period, nine events were recorded in more than one basin. In 1860, flooding was recorded in the Duero and Tajo basins in west-central Spain and in the Guadalentín basin, making it a supraregional event. In 1866, there was an event in the Ebro and Segre basins and the Tajo basin. In 1871, there was an event in the northeastern basins (in the Ebro and Segre basins). In 1877, there was an event in the Almanzora and Segura basins. In 1879, there was an event recorded in the Antas, Aguas, Almanzora, Segura and Guadalentín basins, and it was a very catastrophic event in southeastern Spain (Sánchez-García et al., 2019). The 1880 episode was recorded in the Guadalentín and Almanzora and in the Duero. In 1884, there was an event recorded in the Antas, Aguas, Segura and Guadalentín basins and in the Ebro basin, while lastly, in 1888, there was an event recorded only in the province of Almería.

5.2.5. Flood period V (1970–1990)

During the second half of the century and especially from 1965 onwards, the number of floods recorded in the study area basins increases significantly. That is why the fifth and last flood-rich period falls between 1970 and 1990. Over the two decades in question, floods are recorded in the Segre and Ebro (Balasch et al., 2019), Guadalentín (Machado et al., 2011) and in the river basins of the study area (Fig. 10).

While several flood events coincide in the period, most of the basins had mitigation measures in effect. As a result, the number of the catastrophic events is lower. In 1973, a very destructive flood affected the Antas, Aguas, Almanzora and Guadalentín basins, but not the Andarax and Segura basins. In 1982, an event was recorded in the Ebro and Segre basins in northeastern Spain and in the Andarax basin, but they are likely not well connected because of the lack of records for the remaining southeastern basins. Finally, an event is recorded in 1989 in the Andarax and Antas basins, but it was a highly localized event as a result of extreme rainfall caused by local storms.

5.2.6. The influence of flood mitigation measures

The records of damage from floods of M3 and M4 magnitudes in the Guadiana, Duero, Tajo and Segura river basins cease in the mid-20th

century after the construction of dams and reservoirs on the main rivers (Bravo-Paredes et al., 2021; Balasch et al., 2019; Machado et al., 2011; Benito et al., 2021) (Fig. 9). The Guadalentín river basin was affected only by the severe 1973 flood according to Machado et al. (2011), while only the 1965 flood was recorded in the Ebro and Segre river basins (Balasch et al., 2019). With respect to the basins of the Atlantic slope, the flood series for the Duero and Tajo river basins stop at the beginning of the 20th century for the same reason, namely, the construction of dams and reservoirs along their courses. In contrast, frequent floods occurred along the Besòs and Llobregat rivers throughout the 20th century (Barrera-Escoda and Llasat, 2015).

5.3. Spatial distribution of floods in the province of Almería

Fig. 11 shows the geographical distribution of M3 and M4 floods according to the five flood-rich periods in the study basins. The map of historical flood incidence points to only a few locations during the flood periods I, II and III. By contrast, the explosion of sites with flood impacts in period IV is associated with the mining boom, a dramatic increase in population, and the expansion of agriculture. The urban growth of cities and towns is an additional factor.

The spatial distribution of flood evidence depends not only on the hydrological pattern of floods and flood frequencies, but also on the length of the flood data series. The historical flood archives for the Almanzora and Andarax basins date back to 1500 CE, whereas they start in 1750 and 1850 CE for the Antas and Aguas basins. In addition, the history, size and location of towns are critical factors. In the case of the Andarax river basin, the capital of the province is located practically at

the mouth of the river. In addition, several ramblas (e.g. Rambla Belén) have flowed through the town and caused severe damage in the past (i.e. the floods of 1580 and 1891). The settings of the Almanzora River are similar: the historic centers of Albox and Cuevas del Almanzora are located very close to the riverbeds and have been affected by floods for centuries, whereas in the Aguas and Antas the old towns of Mojácar, Lubrín, Turre, Antas and Vera are located on higher fluvial terraces or on mountain slopes. These local settings of the main settlements define the exposure and vulnerability of communities and influence the geographical distribution of regional flood impact. According to Fig. 11, all the major floods in the Andarax basin have occurred in the city of Almería. In the case of the Almanzora, incidences are recorded in Albox, Cuevas del Almanzora and Rambla de Canalejas (the village of Mulería). In the Aguas and Antas basins, most of the flood damage has occurred on the coastal plains except for the 1884 flood, which affected the towns of Sorbas (Aguas River) and Antas (Antas River). In fact, the most affected areas are the floodplains of the Cuevas del Almanzora region, Almería city and the delta plain of the Antas River.

The distribution of catastrophic floods has recently undergone major changes as a result of changes in land use. Historically, floodplains and river valleys have been dedicated to agriculture (Martín García, 2010; Gil-Meseguer et al., 2012). Since 1990, however, the coastline and the mouths of the Antas and Aguas rivers have been transforming. The changes involve dry and/or irrigation farming, an urban boom related to the tourism industry, and increasing exposure to the risk of flooding (Schulte, 2002b). The historical shift of flood incidence towards the coastal areas is shown in Fig. 11. However, in the basins of the Andarax and Almanzora rivers, intensive agriculture has increased since the

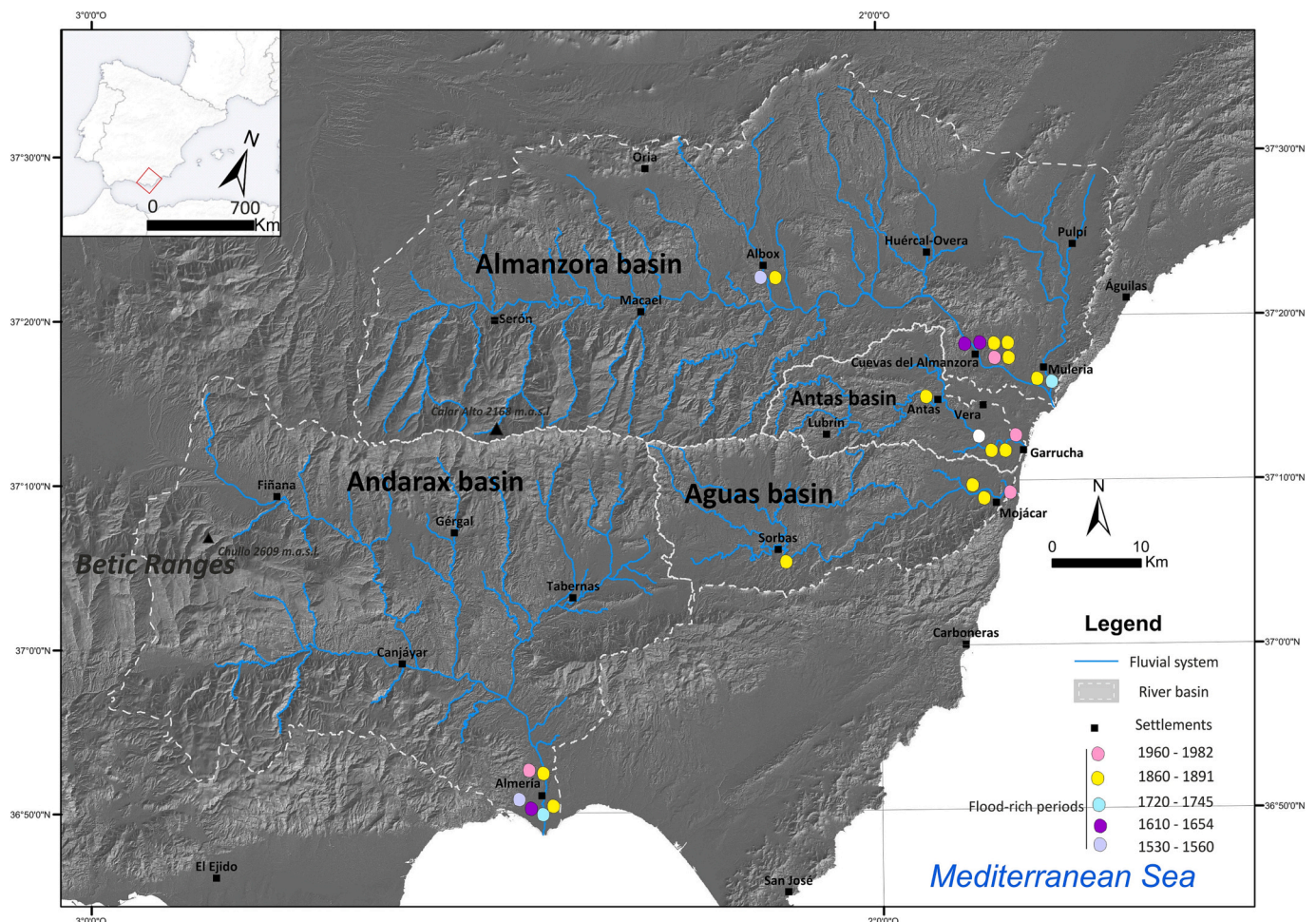


Fig. 11. Map of study area with dots to indicate flood events (colour-coded to indicate the flood-rich period to which they belong).

nineties so that the irrigation water supply has changed both the exposure to floods and the levels of run-off.

Despite the existence of a climatic boundary between the Andarax basin (influenced by westerlies from the Atlantic façade) and the Almanzora, Antas and Aguas basins (influenced by Mediterranean low pressures) (Benito et al., 1996), there is no significant difference between the location of extraordinary and catastrophic events as they affect both the Andarax and Almanzora basins, except for individual floods such as the 2012 flood recorded in the Almanzora, Antas and Aguas river basins and not in the Andarax basin.

Low pressure systems over the western Mediterranean produce a humid air flow from the coast causing torrential rainfall in the coastal mountains of eastern Almería (Capel Molina, 1987). An example of this are the floods of 1973 and 2012, when flash floods occurred in the Antas and Aguas rivers and in the Almanzora river tributary stream, specifically the Rambla de Canalejas (Benito et al., 2012; Sánchez-García et al., 2019), but not in the Andarax river basin, which is located in the rain shadow. On the other hand, the 1982 flood affected the Andarax river basin owing to the humid Atlantic flow, but it did not affect the Aguas, Antas and Almanzora river basins.

5.4. Flood, gaps and climate proxies

To understand the intensity of flood damage, the historical flood series were compared with total solar irradiance (TSI; Steinhilber et al., 2009) and the North Atlantic oscillation index (NAOI; Luterbacher et al., 2001).

Flood pulses were recorded during positive and negative TSI anomalies (Fig. 11b), and the highest number of floods occurred during positive phases of TSI. The basins in the province of Almería show the maximum flood periods after the Dalton minimum and during the last 20 years in the series.

At the regional level, the southeastern Iberian Peninsula shows a similar correlation; however, the historical series for the Segura river basin (light grey bars in Fig. 12d and g) must be highlighted, since the record is continuous (Machado et al., 2015) and it is not affected by TSI. This fact is due to the characteristics of the historical archives and the geographical factor of the city of Murcia (Machado et al., 2011). At a supraregional level, the basins of the northeastern and west-central Iberian Peninsula follow the same dynamics as the basins in the province of Almería. That is, they present a higher number of floods during positive TSI anomalies (Fig. 12e and f) and reach a maximum at the end of 19th century.

In the period 1500–1730 CE, floods occurred mostly during negative NAOi phases (Fig. 12a), while from 1730 CE onwards they occurred during positive and negative NAOi. In the province of Almería, the greatest number of floods occurred during a period of negative NAOi phase at the end of the 19th century – a fact that is repeated at the regional level (in the southeastern basins) and at the supraregional level (including all basins, Fig. 12g).

Considering only extraordinary and catastrophic floods and M3 and M4 floods in the Andarax, Aguas, Antas and Almanzora basins, two flood gaps (G-I and G-II) and two flood-poor periods (G-III and G-IV) have been identified: 1500–1540, 1660–1720, 1790–1845 and 1955–1970. The G-I and G-II flood gaps and the G-III flood-poor period are associated with negative NAOi phases and negative TSI anomalies.

Flood gaps G-I and G-II coincide with negative TSI during the Spörer and Maunder minimum (Shindell et al., 2001; Steinhilber et al., 2009), while the Dalton minimum falls in the center of the flood-poor period G-III (1790–1845). The short flood-poor period G-IV is associated with the pattern of negative NAOi phase (1955–1970) but coincides with a TSI maximum (Fig. 12b). Despite the fact that the dry phases coincide with positive NAOi in most parts of the Iberian Peninsula, floods and intensive rainfall events have occurred frequently during or at the end of drought periods (Benito et al., 2021).

The province of Almería shows that the flood gaps are perfectly

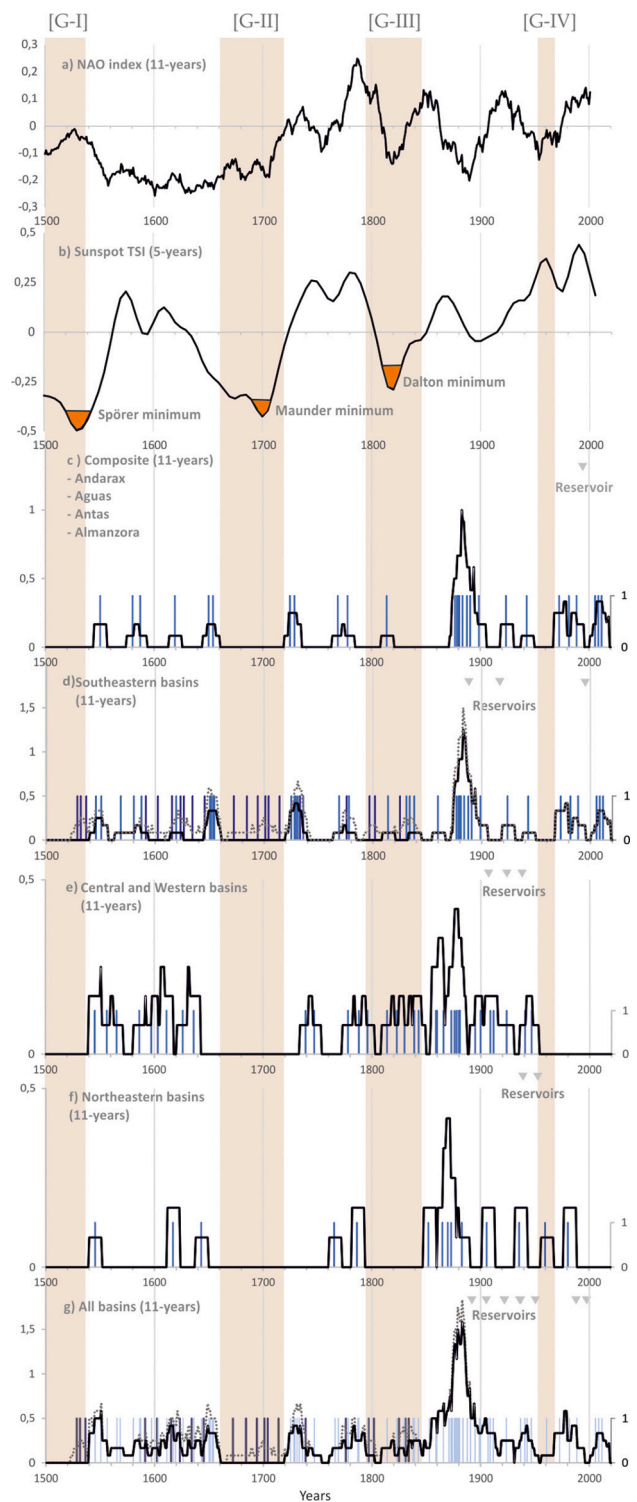


Fig. 12. a) NAO index series (Luterbacher et al., 2001); b) solar activity converted into sunspot data (Steinhilber et al., 2009); sum of 11-year average of floods (lines) and years with flood events (bars) for c) our study area river basins; d) all southeastern basins (black line with Segura River series excluded; grey line with Segura River included, bars in purple Segura series); e) west-central basins; f) northeastern basins, and; g) all basins (black bars with Segura River series excluded; grey bars with Segura River included, bars in purple Segura series). Vertical shading represents flood gaps (GI and GII) and flood-poor periods (GIII and GIV) across all basins. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reflected during the TSI minimums, except for G-IV. When we add the Guadalentín and Segura river basins, a similar dynamics is observed at the regional level, but once again the dissonant factor is the series of Segura floods that do not correlate with the TSI. Additionally, the historical series of the northeastern and west-central basins of the Iberian Peninsula corroborate the flood gaps and the flood-poor periods, although the west-central basins have a certain number of floods during the period G-III, undoubtedly owing to the management of the basins and the importance of the cities where the historical archives are located (Benito et al., 2021; Machado et al., 2015; Bravo-Paredes et al., 2021).

Moreover, the flood gaps coincide with negative NAOi phases in all cases, supporting the climatic variability argument with respect to the frequency of floods over the last 500 years. As previously mentioned, floods have a more erratic behavior in correlation with the negative and positive phases of the NAOi, but the phases with a low number of floods are characterized as negative, except for the negative phase at the end of the 19th century, which coincides with a maximum number of extraordinary events.

At supraregional scale, the NAOi has an influence on the rainfall regime from 1500 to 1850 CE in the basins of the west-central Iberian Peninsula in spring (Bravo-Paredes et al., 2020; Castro et al., 2010; Hernández et al., 2020; Peña et al., 2022), acting as a trigger for floods in the subsequent winter and spring. According to Castro et al. (2010), however, there is no statistical evidence of a correlation between the NAOi and ordinary floods in the Mediterranean catchments. For the northeastern basins, by contrast, Barriendos and Llasat (2003) do show a correlation between a negative winter NAOi and droughts (e.g. Maldà anomaly; Vicente-Serrano and Cuadrat, 2007; Cuadrat et al., 2022). The Ebro and Segre rivers are more sensitive to the Western Mediterranean Oscillation index (WeMOi) in negative phase (Martín-Vide and López-Bustins, 2006). In the case of the southeastern basins, by contrast, floods correlate only with very negative WeMOi phases (e.g. the floods of 1879 or 1973 in the Almanzora basin) (Sánchez-García et al., 2019).

All Europe is under the effect of the NAOi, which has different impacts depending on the region (Pfister, 1999; Luterbacher et al., 2001; Schulte et al., 2008b; Brázdil et al., 2012; Schulte et al., 2015). While the interaction between the NAOi and extreme flood events in the Iberian Peninsula and Southern Alps (Wirth et al., 2013) coincide with negative phases, destructive summer floods in the Northern Alps are related mostly to the positive phase of the Summer North Atlantic oscillation (SNAOI) (Peña and Schulte, 2020; Schulte et al., 2015, 2019a).

6. Conclusions

The reconstruction of the historical flood series for the main rivers of the Almanzora, Andarax, Aguas and Antas basins in the province of Almería over the last 500 years provides a wealth of evidence to analyze the occurrence and magnitude of flood events and to determine flooding periods, trends and spatial incidence. From a comparison of the Almería flood series in the context of the Iberian Peninsula, we are able to draw five main conclusions:

- The comparison between the historical flood series for the province of Almería and the flood series for the west-central, northeastern and southeastern basins of the Iberian Peninsula shows a coincidence of five flood periods and a correlation of 15 flood episodes.
- The last two centuries are marked by anthropogenic factors, mainly a mining boom and an increase in population. Furthermore, since 1850 CE, the appearance of local newspapers has provided a wealth of flood information that contributes to the increase in the index. The last three decades of the 19th century constitute a flood-rich period with the highest number of events across all basins over the last 500 years.
- From an analysis of all the Iberian Peninsula flood series, two flood gaps and two flood-poor periods have been identified. The flood gaps are in line with negative phases of TSI and NAOi. At global scale, the

flood gaps correlate well with the Spörer and Maunder solar minimum. This event highlighted the flood-gap periods recorded in Iberian Peninsula except the Segura basin. The Dalton minimums do correlate with flood-poor periods in the west-central, southeastern and northeastern basins of the Iberian Peninsula.

- In the last 500 years five flood-rich periods have been identified in the Iberian Peninsula. The flood-rich periods represent more severe hydrological activity in the Iberian Peninsula giving rise to flood events during both, negative and positive phases of NAOi and TSI.
- The anthropogenic influence is noticeable in the 20th and 21st centuries. The construction of reservoirs and embankments in most of the basins changes the hydrological dynamics and leads to a decrease in flood frequencies and magnitudes of the Vera basin.
- The increase of low flood events in coastal areas, mostly concentrated in tourism areas such as the mouths of the Antas and Aguas, is another example of the consequences of the tourism boom and uncontrolled construction in the coastal areas of the province of Almería.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Lothar Schulte reports financial support was provided by Ministerio de Economía y Competitividad de España.

Data availability

Data will be made available on request.

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