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Spatial-temporal analysis of flood patterns in semiarid river catchments of SE Iberian Peninsula since CE 1850

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ABSTRACT

Study region: The province of Almería, southeastern Iberian Peninsula.
Study focus: The main objective of this study was to analyse the evolution of the spatial distribution and the frequency of floods in the four main basins of the Province of Almería since 1850. A database of the main historical floods reported in written historical documents in the Almanzora, Andarax, Antas and Aguas river basins was compiled, and information on the damage caused by the floods was retrieved from 15 historical archives, allowing an understanding of how floods have behaved over the past 170 years and how they are likely to behave in the near future.
New hydrological insights for the region: The river basins of the province of Almería are drained by ephemeral flows mostly related to episodes of heavy rainfall or to long-lasting rainfall attributed to low pressure systems that can persist for several days. The region's climatic, topographical, and lithological characteristics make this region prone to floods that lead to economic damage in the floodplains. In total, more than 106 flood events were recorded between 1850 and 2020 throughout the study area. Since 1850, the frequency of floods has increased and they have been heterogeneously spatially distributed. Three flood-rich periods have occurred, from 1870 to 1900 (43 floods), from 1966 to 1982 (18 floods), and from 2000 to 2020 (19 floods), each with different characteristics in terms of the distribution of flood events. Specifically, the period 1870–1900 shows a higher frequency of ordinary, extraordinary, and catastrophic floods compared to the other flood-rich periods, with a very high trend of events observed across all the studied basins. Three factors explain the changes in the frequency and the spatial distribution of the flood events: a) an increase in the frequency of ordinary flood events; b) new construction in highly vulnerable areas and in coastal areas close to river mouths; and c) changes in land use. Therefore, studies on low-frequency floods should be taken into account in regional planning, and the organization of flood-prone basins should be rethought as they are developed. This reorganization is needed particularly in regions sensitive to the consequences of climate change, such as the Mediterranean and arid and semi-arid areas.

1. Introduction

Floods are one of the most dangerous natural hazards affecting the population around the world (UNISDR, 2015; Schulte et al., 2019a). A higher impact of less severe floods has been observed in recent years in urban areas along the Mediterranean coastal regions

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of the Iberian Peninsula (Barriendos et al., 2019; Sánchez-García and Francos, 2024). Nonetheless, flood events have been reported since 1850 CE by the local and regional administrations, allowing them to claim funds to cover damage caused by the floods (Pérez-Morales et al., 2018). Studies on historical floods within the context of climate change are essential, as they can shed light on potential underestimations of return periods calculated to date (Viglione et al., 2023; Sánchez-García and Schulte, 2023). Including non-parameterized floods may reveal previously unknown flood thresholds and help mitigate and prevent certain catastrophic events (Balasch et al., 2018).

The study of textual and factual documentary sources allows us to compile series of historical floods beyond the current instrumental records (Wetter et al., 2011). Historical floods have been studied in detail in Europe (Glaser and Stangl, 2004; Brázdil et al., 2012; Schulte et al., 2015; Paprotny et al., 2018; Blöschl et al., 2020), with studies based on historical documentation dating back up to a millennium. On the other hand, in the Iberian Peninsula, despite the large number of works addressing historical floods, it is only from the early 2000s that the first references were published, and especially from 2015 to the present (Balasch et al., 2018; Barriendos et al., 2019). However, the compilation of historical floods from small to medium sized semiarid catchments (Machado et al., 2017: Sánchez-García, 2019; Schulte et al., 2019b; Benito et al., 2020; Sánchez-García and Schulte, 2023) without gauge stations is rare, therefore, there is a lack of studies addressing this topic, whose importance is evident in relation to the hydrological dynamics of this type of river, balancing anthropogenic activity and natural factors.The lack of synchronicity between breaks and the simultaneous increases and decreases in fluvial activity (flood-poor and -rich periods) is manifest as shown by the flood chronologies compiled and discussed by Schulte et al. (2019a) in the review editorial article of a Special Issue on paleofloods (18 papers in Global and Planetary Change, 2019 and 2022), in which different catchments were compared.

Our study focused on four catchments, namely the Andarax, Almanzora, Antas and Aguas, located in the most arid region of continental Europe (Tanoue et al., 2016). Historical floods on the Spanish Mediterranean Coast have been studied elsewhere (e.g. Sánchez-García et al., 2019; Barriendos et al., 2019; Sánchez-García and Schulte, 2023), but a spatiotemporal analysis (Schulte et al., 2019b) of these floods within specific time frames and locations to examine spatial characteristics across different periods has not been thoroughly conducted in the study area.

The objective of the current study was to analyse the frequency of extreme flood events since 1850 as well as to explain the flood trends during the last 170 years. The four river catchments have been greatly affected by both large flood events and severe drought periods. In this study, we focused on floods documented between 1850 and 2020. The archived and published flood reports from this

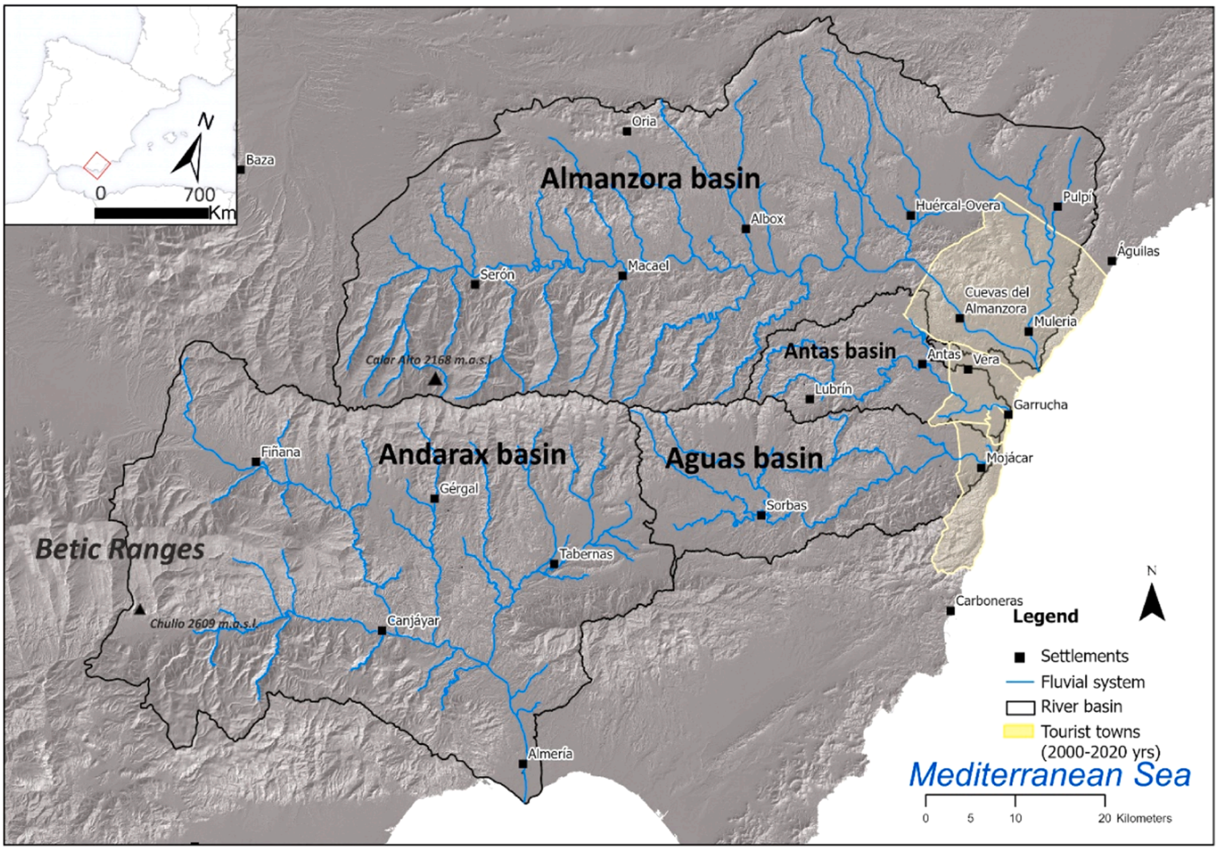

Fig. 1. Almanzora, Aguas, Antas and Andarax basins in the southeastern Iberian Peninsula. Yellowish area represents the municipalities with a significant increase in tourism during the last three decades.

period are considered reliable as the local historical archives are complete and regional newspapers were published regularly. The usual lack of information about low-magnitude floods before the second half of the 19th century in municipal archives was overcome by obtaining information from regional newspapers. Many historical flood series of ungauged and remote mountain catchments of the last 500 years found that only the largest flood episodes (e.g. magnitude 2 at a scale of 4) were reliably handed down (Schulte et al., 2015; Sánchez-García et al., 2019), and that information about smaller flood events during early modern times was never written down or has been lost over the centuries (destruction or damage of municipal archives by floods, fires, conflicts, etc.).

Here, the reconstruction of flood series is presented from four complete datasets and the spatial distribution of flood impacts in the river basins of the semi-desert of southeast Spain from 1850 to 2020.

2. Regional settings

The orography of the four studied river basins, Andarax, Almanzora, Antas and Aguas (Fig. 1), shows a marked contrast between the high mountains of the Betic Ranges, with elevations of up to 2600 m, and tectonic depressions filled with Neogene – Quaternary marine and continental deposits with an elevation ranging between 0 and 400 m above sea level. Since the Late Pliocene, fluvial processes, particularly floods, have shaped a unique complex fluvial landscape of pediments, fluvial terraces, alluvial fans, incised channels, gorges and meanders (Schulte, 2002a; Schulte et al., 2008). According to geomorphological and sedimentological studies conducted by Schulte (2002b), Holocene terrace deposition occurred in the lower Antas and Aguas rivers during the Atlantic period, early Middle Ages, Little Ice Age (LIA) and the 20th century. The aggradation of the lower terraces and the floodplain was mostly climate induced although human impact on the landscape (e.g. mining boom of the 19th century) may have played an important role in river dynamics (Schulte et al., 2008).

The streams of the region, also called *ramblas,* show ephemeral flow characteristics, whereas the region's large rivers such as the Almanzora River, flow continuously during the winter months in the upper and middle reaches, but not in the lower stretch (Costigan et al., 2017). The rivers within the study area range in length from 105 km (Almanzora River) to 40 km (Antas River), with basin areas covering over 2000 km^2 for the Almanzora and Andarax rivers, and 500 km^2 and 260 km^2 for the Aguas and Antas rivers, respectively. The average discharge is close to zero in most cases, with only the Almanzora River maintaining a continuous minimal flow throughout the year (data from the Andalusian Mediterranean Basin Confederation, 2023 report). Additionally, due to precipitation characteristics, flows increase very rapidly, with the highest recorded flow occurring in the Almanzora River during the 2012 flood at 3600 m^3/s. Flood events are typically associated with convective precipitation due to available potential energy (Capel Molina, 2008; Sánchez-García et al., 2019; Sánchez-García and Schulte, 2023).

During such episodes, surface runoff and discharge can be exceptionally high and cause damage to roads, hydraulic infrastructures, settlements and agriculture (Benito et al., 2012; Gil Meseguer et al., 2012).

3. Materials and methods

3.1. Data collection

The flood series were reconstructed from written descriptions obtained from: (1) municipal historical books and legal documents, collected from 15 different historical archives; (2) historical newspapers such as *El Minero del Almagrera (1870–1930)* and *La Crónica Meridional (1866–1924)*; (3) TV documentaries (particularly the 1973 and 2012 floods); and (4) scientific manuscripts (Benito et al., 2012; Sánchez-García, 2019; Sánchez-García et al., 2019; Sánchez-García and Schulte, 2023). During three archive campaigns (2016–2018), documents from 15 historical archives of the province of Almería were explored. Besides the books and legal documents from the 15 towns, the diocesan historical archive of the Cathedral of Almería and the Provincial Historical Archive were consulted. Furthermore, secondary sources such as articles from the historical written press since 1866 and non-historical written press (mass media, TV, photos, etc.) were compiled. To collect information on the maximum number of floods, firstly all events recorded in secondary sources, such as the *Catálogo de Inundaciones Históricas de Protección Civil* (Dirección General de Protección Civil y Emergencias, 2011), were used to crosscheck the information obtained from the historical archives, municipal books and legal documents, which are the primary sources.

3.2. Data validation

Verification was done firstly by looking for the dates mentioned in the secondary sources in the primary sources and then checking if the dates coincided, and deleting those that did not coincide. The decision to exclude reports of floods that did not align was based on the duplication of some information and confirmation of exact dates using secondary sources. Only two events were excluded in this way, as secondary sources specifically placed them in certain years (1897 and 1987) rather than the correct ones (1879 and 1887). Secondly, extraordinary proceedings and technical reports were analysed to check for information on non-common events that had occurred in the area. Some floods were found in these types of document for which, apart from flood events, other issues such as droughts or water mill construction were also found and gave a social context to our study. One example of this is the 1887 flood event that occurred in the Almanzora river basin, which was found in an extraordinary proceeding and not in an ordinary proceeding. Finally, it was necessary to check the reliability of the documents, avoiding errors in their interpretation or transcription. For example, information about flood damage was considered to be reliable if the original document was written by a contemporary witness (Barriendos et al., 2003).

3.3. Flood classification

According to the descriptions, floods were classified into four qualitative magnitude classes based on the severity of the damage. Table 1 shows the flood magnitude classes and damage criteria used to classify the events. The methodology used to classify flood events was adapted from Barriendos et al. (2003) and Schulte et al. (2015), adding new indicators to take into account the physiographic and sociocultural characteristics of the region. For the frequency analysis, the present work focused on flood occurrence, and therefore it was plotted against time for each river, ranging from 0 to 1, with 0 meaning no event and 1 meaning 1 event. Blöschl et al. (2020) terminology has been adopted, such that periods with more events, when the slope in the Poisson test increased (more than 1 flood event per 3 years), were considered flood-rich periods and, when the slope in the Poisson test decreased (less than 1 flood event per 3 years) these periods were considered flood-poor periods; the breakpoints mark the changes between clusters.

The method used to count and classify floods was the same for all catchments. The classification method was based on the description of the damage in written sources (Sánchez-García et al., 2019; Sánchez-García, 2019). Through the categorization of damage, a classification involving three magnitude classes was established: 1, ordinary; 2, extraordinary; and 3, catastrophic. Additionally, when an event had caused substantial spatial damage, meaning it had affected more than one basin in the case of the Antas and Aguas river basins, or more than one sub-basin in the case of the Andarax or Almanzora river basins, an extra point was added (Table 1).

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. To differentiate the primary indicators of ordinary and extraordinary floods, a geomorphological analysis of every point of damage was carried out. If any damage was documented near the river, within 10 m or less, and there was a low gradient slope, the flood was classed as ordinary. On the other hand, if any damage was documented far from the river or on higher terrain, the flood was considered extraordinary or catastrophic, depending on other indicators. Whenever a flood had affected houses, the events were classified as extraordinary or catastrophic floods (magnitudes 2 and 3), because in most cases these houses were located far from the riverbed or in elevated areas. Finally, the most catastrophic events (magnitude 4) were 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.

3.4. Frequency analysis

Lang et al. (1999) provided some guidelines for choosing an appropriate threshold to better interpret the different flood periods. These included a stationary test based on the computation of the tolerance interval of the number of floods (m_t) within an interval [0; t], that means that any data above or below this interval is statistically non valid, in the case of both datasets, they are statistically corrects. The null hypothesis H_0 is to assume that the flood event can be described by a homogeneous Poisson process. Poisson test has been used based on the validity of this method, as it has been applied in many studies on the frequency of extreme events and is well-documented in the scientific literature on this topic (e.g., Barriendos et al., 2003; Naulet et al., 2005; Machado et al., 2015; Sánchez-García and Schulte, 2023). The 95 % tolerance interval of the cumulative number of floods above a threshold, or censored level, is computed (Fig. 2). Stationary flood series are those remaining within the 95 % tolerance interval (Naulet et al., 2005). It is assumed that, in each period, all reported floods above the perception threshold (S) were recorded in historical documents, i.e. no flood event larger than S was missing, in this case the perception threshold is the lower level of flood magnitude for each dataset. The hypothesis of a fit to a Poisson distribution can be accepted for the whole period, based on one dataset with all magnitudes, according to Table 1 (S = All magnitudes, M1 – M4), and a second dataset excluding M1 (S = M2 – M4) (Fig. 2). The first dataset is characterized by a smaller number of floods in the first few decades of the series and a higher number of events during the 2000–2020 period because of a higher frequency of pluvial floods (Viglione et al., 2023), during which more M1 flood events occur.

3.5. Spatial analysis

For the spatial analysis, all events were mapped at the point where the damage was described using the ArcGIS PRO software. This

Table 1
Criteria for flood magnitude classification.

Flood magnitude	*Classification*	*Primary indicators*	*Secondary indicators*
1	Ordinary floods	Flooding, erosion, damage to crops next to the riverbank	Short event duration
2	Extraordinary floods	Affected agricultural plots far from the riverbank. Damage to buildings and hydraulic infrastructures	Severe damage to fields close to the river, loss of animals
3	Catastrophic floods	Fatalities Partial or complete destruction of settlements	Flood event is recognized with a name (common in very important floods); population migration; high economic impact
4	+ 1 Added when the event was recorded in more than one river reach.		

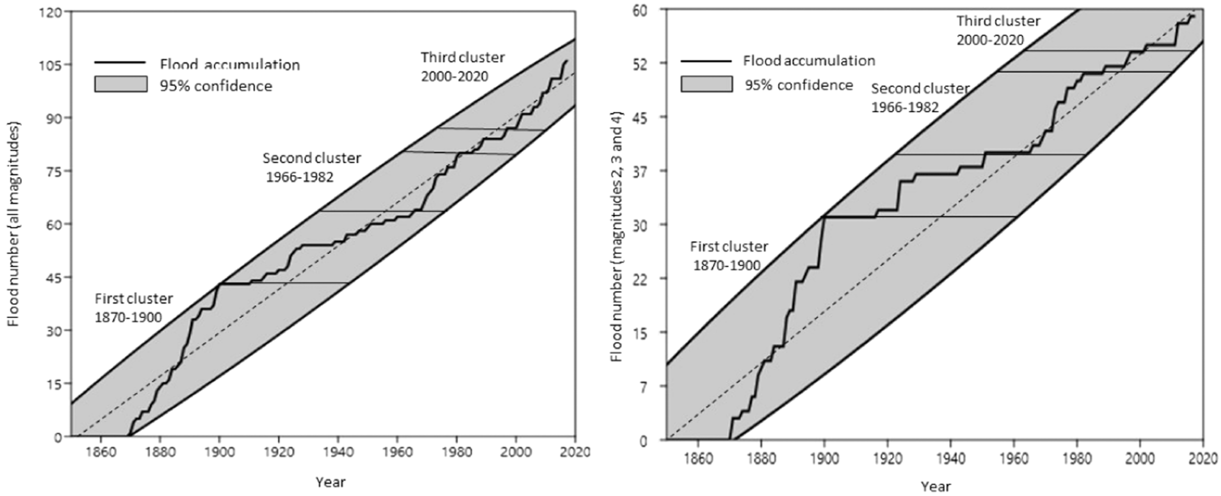

Fig. 2. Poisson test of the flood time series in the Almanzora, Andarax, Aguas and Antas river basins. Left: All magnitudes counted. Right: magnitudes 2, 3 and 4 counted.

procedure was divided into two parts: first, all points were mapped without distinguishing between time period; and second, the points were classified according to the flood-rich time period in which they occurred, in order to identify possible spatial behaviors depending on the timing of the damage. Four maps corresponding to the four flood-rich periods were created, along with one map for events that occurred during flood-poor periods. The spatiotemporal comparison enabled an interpretation of the synergies in flood behavior.

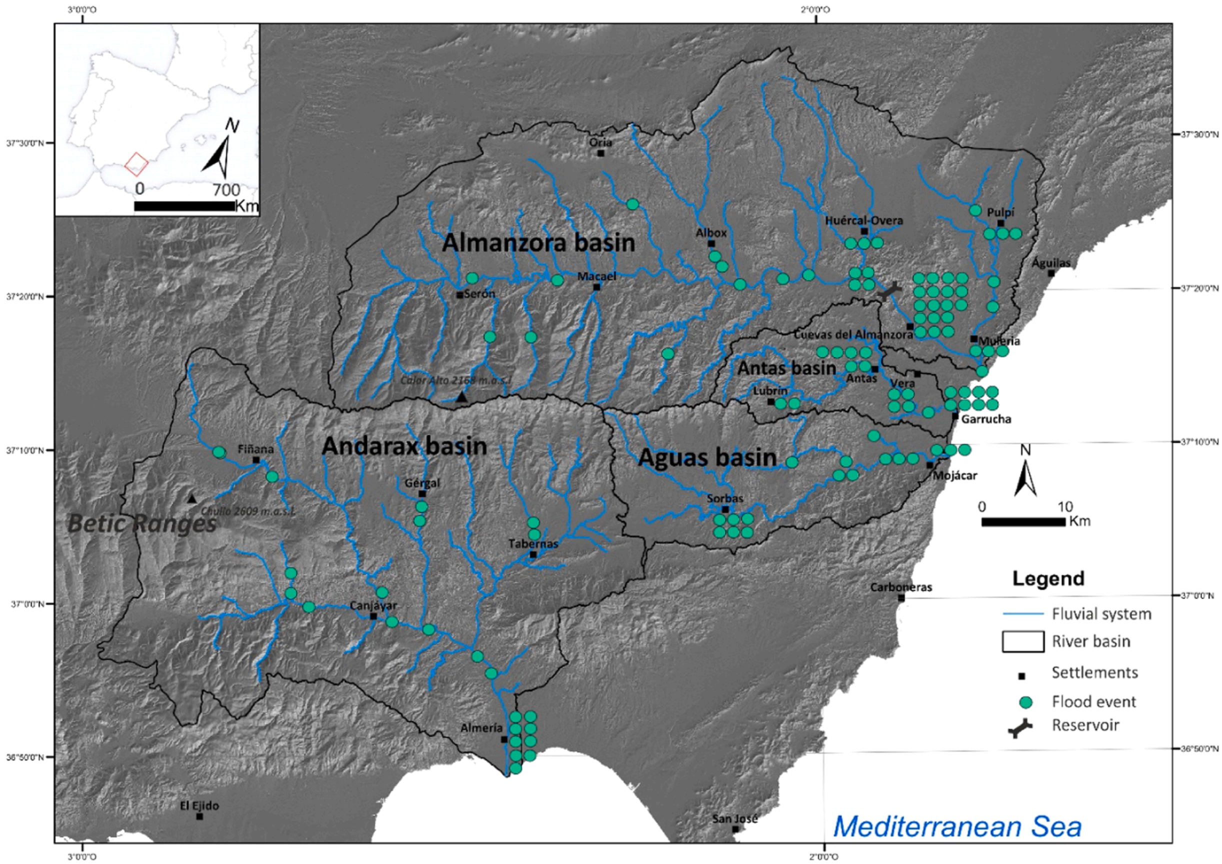

Fig. 3. Spatial distribution of the flood events during 1850–2020.

3.6. Demographic correlation

Finally, demographic data was obtained from INE (Instituto Nacional de Estadística, National Institute of Statistics, 2020). A statistical analysis was carried out using Pearson correlation to show the relationship between the increment in the population of the study catchments and the accumulation of documented flood events (Fig. 5).

4. Results and discussion

The evidence of 106 flood events occurring in the study area from 1850 to 2020 has been found. The Almanzora river basin has reported 44 flood events (two of M4, in 1879 and 1973), the Andarax river basin 24 (one of M4, in 1891), the Antas river basin 21 (three of M4, in 1884, 1973 and 2012) and the Aguas river basin 17 (two of M4, in 1899 and 2012). Based on the trend analysis carried out using the Poisson test, three distinct periods were identified for the Almanzora, Andarax, Aguas and Antas basins (Fig. 2).

The flood frequency time series show changes over time (1870–1900, 1966–1982 and 2000–2020) that may correspond to natural, low-frequency variations in the climate, hydrological system or non-stationary dynamics related to anthropogenic changes, mainly in key parameters such as land use (Barriendos et al., 2003; Machado et al., 2015). Climate variability could also be non-stationary, especially during the current period of Global Warming. Various geographic and geomorphological changes also need to be considered such as changes linked to new irrigation systems that have destroyed the natural landscape by flattening the terrain, or those linked to the construction of mitigation infrastructure like the reservoir in Cuevas de Almanzora (1993) and the channelization of the final stretch of the Almanzora River (1975); all of these were taken into account in the final analysis.

4.1. Flood spatial-temporal analysis

Fig. 3 shows the spatial distribution of all classified floods. The map highlights areas where the impact has been more frequent than in others. For example, municipalities located near floodplains have been more affected in terms of overall damage (Cuevas del Almanzora, Antas, or Almería). Meanwhile, other municipalities have been more affected by M3 and M4 floods, with a lower total number of floods (Albox, Vera, and Mojácar).

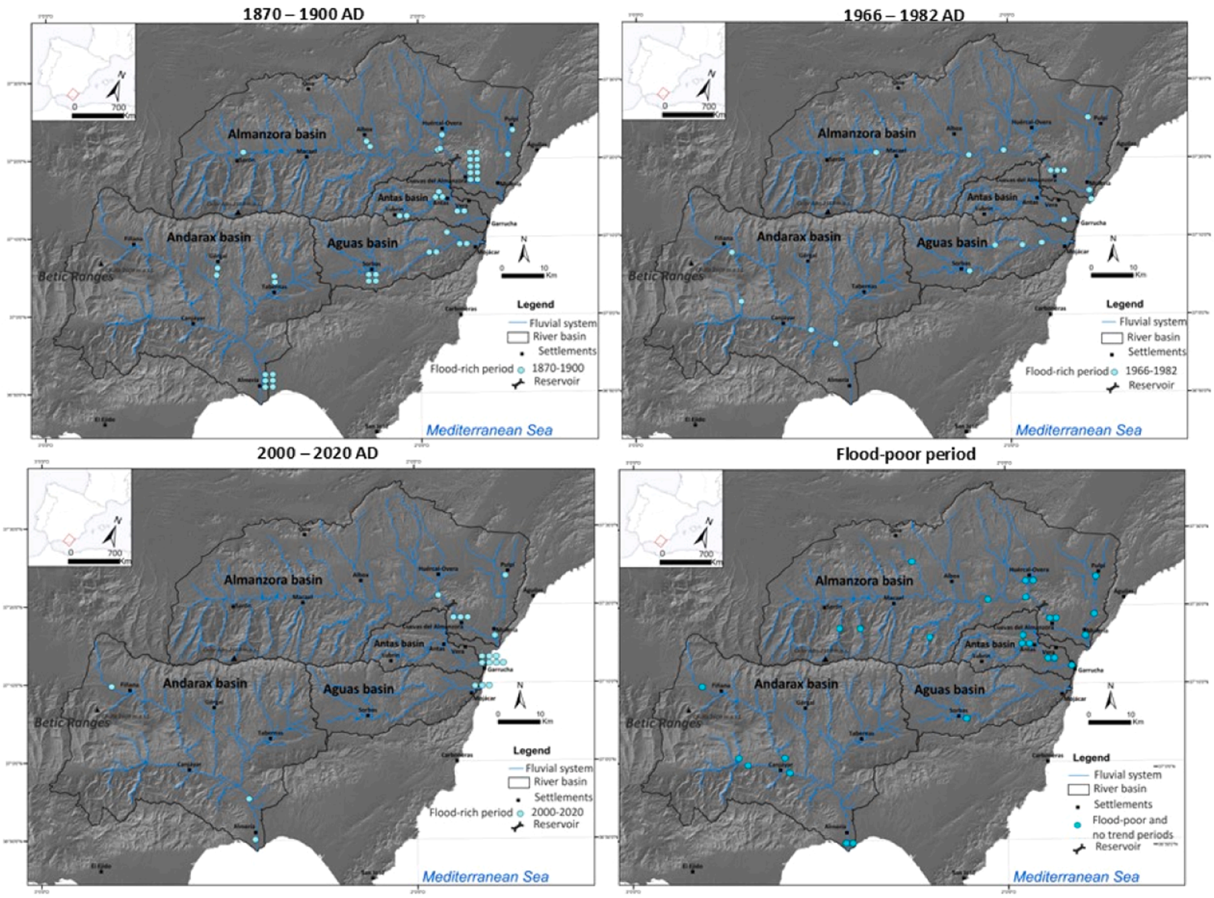

Fig. 4. Spatial distribution of the events in flood-rich periods (1870–1900, 1966–1982 and 2000–2020) and the flood-poor period.

Whereas in the smaller basins (Antas and Aguas), the locations of flood impact are distributed more evenly, and have affected multiple municipalities (e.g., Mojácar, Turre, Garrucha), the larger basins (Almanzora and Andarax) show a more heterogeneous spatial distribution. In headwaters and middle reaches of the rivers in the inner tectonic basins several municipalities have experienced only one or two events during the entire period (Canjáyar in the Andarax basin or Serón in the Almanzora basin), whereas the cities of Almería and Cuevas del Almanzora located on the floodplains of the lower courses of the Andarax and Almanzora rivers have recorded a high number of flood damage episodes.

The spatial distribution of reconstructed floods during the three flood-rich periods and flood-poor period is shown in Fig. 4. The frequency of floods is presented as a series of maps and as a binary record since 1850 (Figs. 3 and 4), the magnitude in this case is not the focus, just if the presence or the absence of floods in a given year. The three flood-rich periods (Fig. 5) with increased flood frequency across the four basins are highlighted in Fig. 4a–c: (1) 1870–1900, (2) 1966–1982 and (3) 2000–2020. To show the relation between flood frequency and the increase in population in the area, demographic data for the towns in the studied river basins is also plotted in Fig. 5.

In the Almanzora and Andarax river basins flood damage was recorded during all three flood-rich periods (1870–1900, 1966–1982 and 2000–2020) in several locations throughout the basin, more flood damage was recorded in the cities of Almería and Cuevas del Almanzora, constructed on the floodplains next to the river deltas (Fig. 4a–c).

This spatial pattern of lower impact in the upper catchment areas of the Andarax and Almanzora catchments during flood-rich and flood-poor periods (Figs. 3 and 4) might be related to the following factors: i) the spatial distribution of local torrential rainstorms often affect different sub-catchments and therefore the flood frequency per village is lower; ii) riverbeds in the headwaters are deeply incised, thus only the highest flood magnitude reach the villages (except in the case of Albox and Zurgena); iii) exposure of the population and their properties to floods in these remote rural areas is low; and iv) limited economic and demographic development has not forced people to construct their homes in flood-prone areas. The pattern of flood impact on the larger cities on the coastal floodplains is the reverse, given their location on the riverbanks of unincised rivers with large catchments recording higher flood frequencies, population growth since the second half of the 19th century (e.g. mining) and unplanned development that has promoted the expansion of the cities towards the floodplains and low gradient slopes.

In the Antas and Aguas river basins the old towns are traditionally located on Pleistocene fluvial terraces, glacis and slopes, more than 20 m above the floodplain (i.e. in the Aguas basin: Mojácar and Sorbas, and in the Antas basin: Lubrín and Vera). The distribution and spatial variability of the relatively few sites and events of flood damage during the 1870–1900 and 1966–1982 flood-rich periods mirror this settlement pattern. However, during the most recent flood-rich period (2000–2020) extreme events affected new urban areas in the Antas and Aguas river basins. This phenomenon is frequent in semiarid catchments of SE Spain that have seen a change in

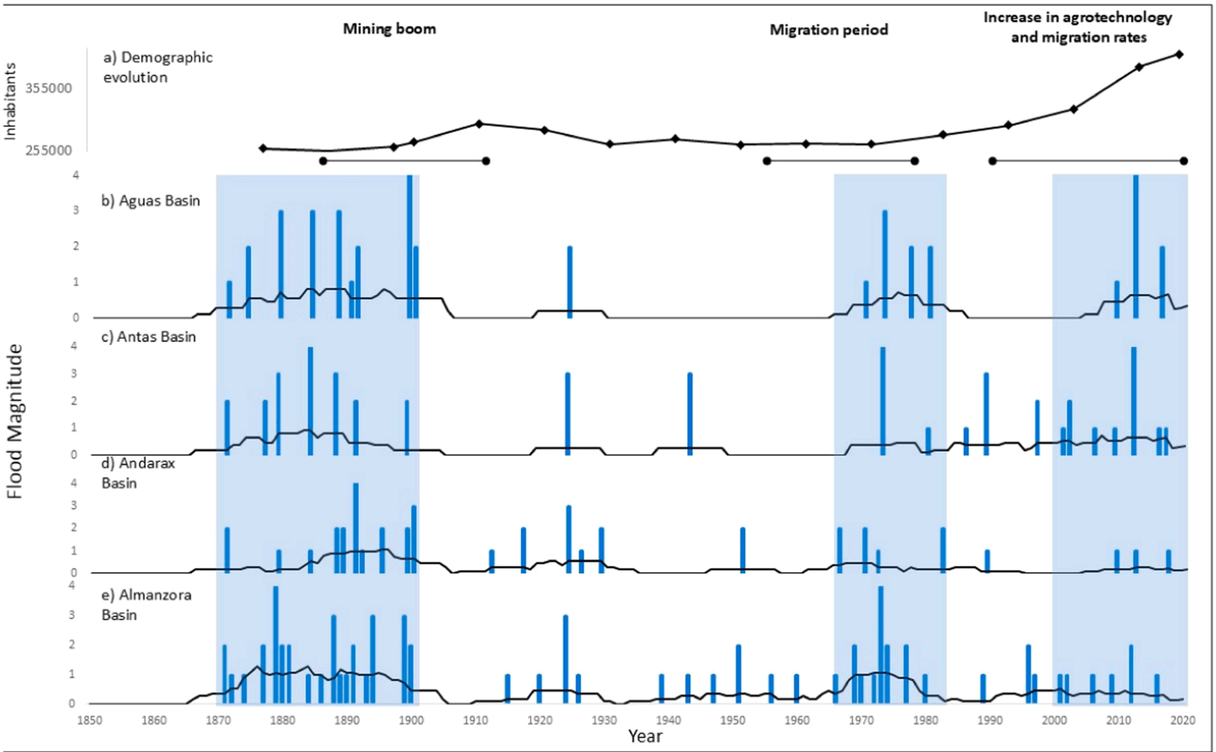

Fig. 5. Series of floods reported in the studied catchments and demographic evolution of the study area. a) Temporal evolution of the number of inhabitants in the study area (INE: Instituto Nacional de Estadística, 2020) since 1877. b-e) Occurrence of flood events as reported in documentary records. Blue shading shows flood-rich periods, according to the Poisson test.

the urban model, from small towns far away from the river channels towards touristic settings in the coastal areas and river floodplains (Pulido-Bosch et al., 2018).

To summarise, the three flood-rich periods show the following patterns:

1. *From 1870 to 1900*: clustered distribution with higher frequency in the towns of Cuevas del Almanzora, Almería, Sorbas and Antas. The reason for this spatial distribution of impact is likely connected to the increase in population in growing cities without adequate mitigation measures. This trend has also been observed in other rivers of southeastern Spain such as Segura and Guadalentín (Machado et al., 2015), and in the northern parts of the Mediterranean coast (Barriendos et al., 2019).
2. *From 1966 to 1982:* random distribution along the main rivers except for a cluster at Cuevas del Almanzora. In this case, the distribution is linked to the abandonment of the land during the 1950s and 1960s. Land use and the hydrological dynamics changed in the ephemeral rivers of the study area during this period (Sánchez-García and Schulte, 2023).
3. *From 2000 to 2020:* Clustered distribution with a higher frequency in Cuevas del Almanzora and coastal towns such as Mojácar, Vera (coastal area) and Garrucha. The evolution of the distribution of the damage indicates a shift in flood damage to the coastal areas. The touristic buildings together with the sealing of some river channels in the eastern part of the study area have triggered an increase in ordinary floods caused mainly by pluvial/urban floods.

In addition to flood-rich periods, there have been intervening periods with less frequent flooding. These flood-poor periods occurred in 1850–1870, 1900–1920, 1926–1940 and 1950–1965 (Figs. 2 and 3). For instance, during the period between 1926 and 1940 just seven floods of all magnitudes and two floods excluding M1 were recorded in the four basins (Fig. 5). This is consistent with the studies of Machado et al. (2011) and Barriendos et al. (2014) in the Segura River and with studies of river catchments located along the Catalan coast. An explanation may be the drier conditions prevailing during this period in the southeast Iberian Peninsula (Rodrigo et al., 2000). However other studies (Barriendos et al., 2019) have reported a high number of flood events during this dry period in northeastern Spain, and therefore the relevance of the climatic driver in the southeast of the Iberian Peninsula is very likely. Another possible explanation for the few reported floods is the lack of data in the historical archives because of the damage that occurred in the municipal archives during and after the Spanish Civil War (1936–1939) (Sánchez-García and Schulte, 2023). However, this explanation can be ruled out given the lack of flooding observed in neighbouring basins such as those of the Segura and Guadalentín rivers (Machado et al., 2011; Barriendos et al., 2014), and in some river courses in Granada and Málaga (Barriendos and Rodrigo, 2006; Barriendos et al., 2019), all of them in the southern Iberian Peninsula. In the historical archives of major cities such as Granada, Murcia, Málaga, or Almería, the records are preserved, and no major floods are documented during that period.

4.2. Flood frequency: flood-rich and -poor periods

Four flood series from 1850 to 2020 were compiled from all documentary flood descriptions. Flood periods were defined according to the Poisson test and flood series were compared with the population of the province of Almería. Although the basins of the Antas and Aguas rivers are smaller than those of the Almanzora and Andarax rivers, M4 events have frequently been observed. Specifically, three have been recorded in the Antas river basin (Fig. 5), partly due to the river's hydrological response regime, with a higher average slope in the longitudinal profile of the main channel (> 2 % compared to lower values in the other three rivers) and the proximity of several towns to the floodplain (Antas, Vera, and more recently, Garrucha) (Benito et al., 2012; Sánchez-García et al., 2019; Sánchez-García and Schulte, 2023).

The first flood-rich period occurred from 1870 to 1900, with up to 43 events, showing a remarkable flood cluster in the Almanzora basin (17 events), with almost every year reporting an event, as well as in the Andarax (10 events), Aguas (9 events) and Antas (7 events) basins (Fig. 5). This flood-rich period represents a significant cluster for this type of study. It is observed that the frequency of events during these 30 years is higher than in the rest of the series and higher than in the other two flood-rich periods. Thus, it is established as one of the periods with the highest frequency of floods in the Mediterranean basins of the Iberian Peninsula (Sánchez-García and Francos, 2022). The difference between the Almanzora basin and the other three catchments can be attributed to differences in availability of information (in Almanzora more than 200 documents mention floods whereas in the other three catchments, there are only 150 documented reports in total), or the fact that, until the last few decades of the 19th century, towns were generally located further away from the floodplains and river channels (Sánchez-García and Schulte, 2023).

The second flood-rich period (1966–1982) is characterized by a large number of floods (18) and includes the large 1973 flood event that affected the Almanzora, Antas and Aguas rivers but not the Andarax river. In this case, the Almanzora basin had the highest number of events (8) followed by the Aguas and Andarax basins (4 events each), whereas the Antas basin only had 2 events. During this period, the 1973 flood had a remarkable effect on subsequent flood risk reduction management because after this event the administration channelized the lower part of the Almanzora River to reduce the size of the flood risk zones. The channelization flood mitigation plan has been effective at reducing flood vulnerability to large magnitude floods since 1974 in the town of Cuevas del Almanzora. These mitigation measures along the Almanzora river led to the lower occurrence of events during the period 1966–1982 and during the most recent flood-rich period (2000–2020) in the lower basin of the river (Figs. 4b and 4c). However, the spatial distribution upstream of the mitigation measures shows a very similar pattern across the first two flood-rich periods and the flood-poor period (Figs. 4a, 4b, and 4d).

The most recent flood-rich period covers the years 2000–2020 and is characterized by a high number of floods (19). In this case, the Antas river basin (7) and Almanzora river basin (6) have recorded the highest number of floods, whereas the Aguas river basin and Andarax river basin have recorded fewer events (3 each). New touristic areas in the lower basins of all rivers and a substantial increase in the population in rural coastal areas due to the explosion of capital-intensive agriculture (trickle irrigation and greenhouses) since the 1990s has clearly led to increased exposure and vulnerability to floods in all basins (Fig. 4c). The increase in number of ordinary events (M1, Table 1) in the eastern basins is also related to more complete information and better techniques for flood tracking. For example, new sources of information (e.g. social media) have been a way of finding records of ordinary floods that were not available in previous periods (Fig. 4), additionally to the graphic documentation available, such as videos or photos, which allow for a more reliable categorization of the floods.

When these results are compared with those of other studies, it can be seen that the first and second flood-rich periods coincide with the flood-rich periods in the Segura River (Machado et al., 2011). The third period was not fully covered by Machado et al. (2011). In the case of the Almanzora, Antas and Aguas basins, their geomorphological (glacis, low gradient slopes and fluvial terraces), climatological (low annual precipitation, less than 400 mm per year) and hydrological (ephemeral rivers) characteristics are very similar to those of the Segura and Guadalentín basins (Schulte, 2002a; Capel Molina, 2008; Sánchez-García et al., 2019; Sánchez-García and Schulte, 2023). However, the flood frequency shown in Fig. 4 not only coincides with the behaviour of the Segura River (Machado et al., 2015), but also with that of other basins along the eastern coast of the Iberian Peninsula (Ruiz-Bellet et al., 2017). The Ebro and Segre Rivers also experienced a higher frequency of extreme floods at the end of the 19th century (Balasch et al., 2018). In addition, the Llobregat River recorded a greater number of events in the second half of the 20th century (Llasat et al., 2005).

Figs. 1 and 3c illustrate the increase in population in the study area, partially related to touristic and agricultural development. During the last few decades of the 19th century, mining activity led to a doubling of the population in the study area. For instance, in the Almanzora basin the population increased to its maximum in 1910. During the 20th century the population began to decline throughout the area, apart from in the capital city, Almería, until the end of the century. During this time, investment in new agrotechnology expanded in the eastern area of the province (Antas, Aguas and Almanzora) and near Almería. Moreover, the construction of touristic infrastructure in flood-prone areas in parallel with the destruction of old agricultural areas (previously dedicated to extensive areas of crops) may have led to a higher runoff index (Gil Meseguer et al., 2012).

From 1966 until present, the incidence of flooding has remained very high, with two flood-rich periods (Fig. 5). During the last flood-rich period (2000–2020) there was an increase in the number of floods documented; this increase is characteristic of many areas in the eastern Iberian Peninsula due to the sensitivity to and attention given by both local administration and insurance companies to flooding (Balasch et al., 2018; Sánchez-García, 2019; Barriendos et al., 2019).

In addition, pluviometric time series have shown an increase in extreme rainfall events (i.e. 2012, 2016, 2017 and the recent torrential events of 2024) that have caused extreme floods in many towns (such as Barcelona, Lleida, and Valencia) on the Mediterranean coast of Spain (Llasat et al., 2005). Instrumental data from ERA5 (Hersbach et al., 2020; Gomis-Cebolla et al., 2023; Tejedor et al., 2024) support this observation of increased precipitation, and the IPCC (2023) has stated that torrential events would increase during the next 50 and 100 years along the Spanish Mediterranean coast.

However, natural climate forcing from the preindustrial period should also be considered. Sánchez-García and Schulte (2023) conducted an analysis of all Iberian Peninsula flood series from 1500 to 2020 and identified two flood gaps and two flood-poor periods. These gaps – and particularly the flood gaps in southeastern Spain – are aligned with negative phases of total solar irradiance and negative phases of the North Atlantic Oscillation index (-NAOi) promoting southern trajectory of low-pressure systems. Nine of twelve flood pulses in the southeast of Spain correlate with positive TSI. Sánchez-García et al. (2019) performed a meteorological characterization of four high magnitude events (1550, 1729, 1879 and 1973) using CESM-LME simulation and reconstruction from the 20th Century V2 Reanalysis Project (20CRP). According to their results these episodes were triggered by low-pressure systems that contributed to the advection of warm, wet air into the low levels of the troposphere, approaching from the Mediterranean Sea into the coastal basins of the Betic ranges in Almería Province.

Recent climate trends together with land use changes have had a direct consequence on the number of floods in the study area, represented by M1 floods in recent decades, which have become more frequent. These events impact the lower parts of the Antas and Aguas river basins (see the points in Fig. 3) because of the sealing of the soil in flood-prone areas. For instance, both the 1989 and 2012 flood events damaged the new tourist suburbs of Vera, Garrucha and Mojácar, where before 1980 no flood damage was reported (Benito et al., 2012; Sánchez-García et al., 2019). Since 2005, when the population peaked at more than 350,000 inhabitants, there have been 15 floods, 11 of which are considered M1. Therefore, the trend for increased flooding remains homogeneous until the present. Finally, more than 50 % of the increment in the population has been concentrated in coastal areas, especially in the Antas and Aguas river basins (INE: Instituto Nacional de Estadística, 2020), increasing the exposure to floods in areas that are frequently affected.

Risk reduction will likely involve redistributing urban spaces to areas with a lower flood risk and adopting mitigation measures, such as nature-based solutions, to actively prevent damage from future extreme events. In the Mediterranean geographical context, as in other arid and semi-arid areas, global change is expected to increase these types of catastrophic events, making it essential to incorporate these considerations into territorial and urban planning.

5. Conclusions

The paper presents an analysis of the frequency of floods in four basins in the southeast of the Iberian Peninsula from 1850 CE to 2020 CE. Documented flood data shows an increase in the number of reported floods over time. Three flood-rich periods were identified, namely 1870–1900, 1966–1982 and from 2000 to the present. The latest period is related to changes in land use, such as changes in agriculture (from extensive to intensive) that have been taking place since the end of the 20th century and, in particular, to the construction of touristic settlements in flood-prone areas. According to the spatial analysis, in the Antas and Aguas basins the damage has been concentrated in the lower part of the catchment, even more so in the last flood-rich period (2000–2020), near the river delta. On the other hand, the areas affected in the Andarax and Almanzora basins were randomly located in the catchment during the first two flood-rich periods, but during the third, flood damage shifted towards the coast in the Almanzora basin. In addition, the Antas and Aguas river flood-series show a higher number of floods in the last 30 years than in the previous decades and a higher magnitude during the first and second periods than in the third. During the last 170 years extraordinary and catastrophic floods have decreased in southeastern Spain, perhaps because of mitigation measures adopted during the last 50 years along the riverbanks. Moreover, the frequency of ordinary floods has increased, the event data shows that the period from 1870 to 1900 concentrates a higher frequency of both ordinary and extraordinary or catastrophic floods compared to the other two flood-rich periods (1966–1982 and 2000–2020) across all the studied basins. Therefore, those 30 years represent one of the periods with the highest frequency of recorded historical floods studied so far. However, ordinary floods have increased, particularly in urban areas near the coast. Finally, the relationship between the increment in the population and the number of harmful reported floods, such as in 2012, 2016 and 2017, points to the need for adequate science-based urban planning in potential flood-risk areas. It is probably necessary to reconsider flood mitigation measures in the study area to adapt to potential extreme events that may occur in the future.

CRediT authorship contribution statement

Lothar Schulte: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Carlos Sánchez-García:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Data availability

Data will be made available on request.

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