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Changes in flood hazards: Insights from palaeoflood studies

Cambios en los peligros de inundación: aportaciones de los estudios de paleocrecidas

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ABSTRACT

Climate models predict an increase in extreme hydrological events (droughts and floods) as global temperatures respond to anthropogenic increases in greenhouse gases. This change in the pattern of extreme events due to global climate change raises uncertainties in assessing the risk of future droughts and floods. Conventionally, this problem has been addressed from a “top-down” approach based on downscaling of climate models. The development of this approach generates a high uncertainty that, in practice, does not allow determining in a reasonable and operational manner the magnitude of the change. Recently, it has been proposed to move towards a “bottom-up” approach of progressive adaptation to change based on the experience of recent events. It is assumed that future climate change will not create entirely new types of extreme weather events that have never before occurred on the planet. In this work, we review the main paleo-records (geological and botanical), which allow us to characterize and quantify hydrological extremes and their relation to climate variability at multi-decadal and secular time scales. This information is relevant to advance in the adaptation to extreme events in the context of climate change, particularly in the design of infrastructures, urbanism and territorial planning.

Keywords: Palaeofloods; Flood hazards; Paleoclimatology; Flood frequency analysis; Climate change adaptation.

RESUMEN

Los modelos climáticos predicen un aumento de los fenómenos hidrológicos extremos (sequías e inundaciones) a medida que las temperaturas globales aumentan debido a las emisiones de gases de efecto invernadero.

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Este cambio en el patrón de los fenómenos extremos debido al cambio climático constituye un motivo de gran preocupación y plantea incertidumbres a la hora de evaluar el riesgo de futuras sequías e inundaciones. Convencionalmente, este problema se ha abordado desde un enfoque «descendente» basado en la reducción de escala de los modelos climáticos. El desarrollo de este enfoque genera una gran incertidumbre que, en la práctica, no permite determinar de manera razonable y operativa la magnitud del cambio. Recientemente, se ha propuesto avanzar hacia un enfoque «ascendente» de adaptación progresiva al cambio basado en la experiencia de eventos extremos recientes. Se asume que el cambio climático futuro no creará fenómenos meteorológicos extremos cuya situación sinóptica no haya ocurrido en el pasado. En este trabajo, revisaremos los principales registros naturales (geológicos y botánicos), que nos permiten caracterizar y cuantificar los extremos hidrológicos pasados y su relación con el clima a escalas temporales multidecadas y seculares. Esta información es relevante para avanzar en la adaptación a los fenómenos extremos en el contexto del cambio climático, particularmente en el diseño de infraestructuras, urbanismo y planificación territorial.

Palabras clave: Paleoinundaciones; Riesgos de inundación; Paleoclimatología; Análisis de frecuencia de inundaciones; Adaptación al cambio climático.

Introduction

Global warming is leading to widespread changes in the water cycle, although the chain linking greenhouse gases to their effects is long and complex (Jiménez Cisneros et al., 2014). A more variable climate, and therefore a more variable hydrological cycle, is likely to affect the pattern of rainfall-producing floods (Döll et al., 2014). So far, there are not widespread observations supporting widespread changes in flood magnitude or frequency due to anthropogenic climate change (Jiménez Cisneros et al., 2014). Therefore, the public perception of an increase of flood activity is mainly related to an increasing number of reported floods with catastrophic consequences worldwide (Delforge et al., 2025). Three possible factors explain this perceived increase in flood risk: greater population exposure, increased vulnerability, and higher magnitude or frequency of hazards (Kundzewicz et al., 2014). However, the relative contribution of these factors to the current increase in flood risk remains a subject of ongoing debate. Most studies have attributed the upward trend in reported losses since 1980 to an increase in the population and assets exposed to flooding (Handmer et al., 2012). Only a few cases have reported links between increased flood losses and observed changes in weather patterns or rainfall characteristics (Barthel & Neumayer, 2012; Chang et al., 2009). This lack of significant statistical association between climate change and changes in flood hazards during the 20th century is explained by the high inter-annual variability of extreme events and short stream gauge data series (Kundzewicz et al., 2014). Moreover, land use changes and river regulation by dams have obscured the detection of climate-driven changes on floods (Blöschl et al., 2015).

Several reviews on the impacts of extreme events associated with anthropogenic climate change has recognised the importance of palaeohydrology and palaeoflood hydrology for understanding the incidence of climate on flood hazards (Hall et al., 2014; Kundzewicz et al., 2014). A long-term flood-climate perspective is urgently needed to improve our understanding of modern flood hazards and regional changes under a warming climate (Baker et al., 2022; Benito et al., 2022a). Over the last decades, geological and biological indicators have been used to quantify flood discharge and frequency over centennial to millennial time scales, with applications to engineering design and risk assessment (Baker, 2008). These palaeoarchives provide physical evidence of the natural persistence of floods, their range of magnitude, and their response to atmospheric circulation (Ely et al., 1993; Wilhelm et al., 2019).

This paper describes recent advances in the use of historical and palaeoflood data to improve our understanding of flooding and flood hazards under climate variability. The following sections outline on some of the key research questions related to flood hazards in a changing climate, and how palaeohydrology contributes to understanding, predicting and improving flood risk assessment. The specific topics are: (1) analysis of spatial and temporal patterns of flood frequency to assess relationships with climate, land use and geomorphic response; (2) assessment of recent flood magnitudes in the context of past events based on several case studies and regions; and (3) recent contributions of palaeoflood hydrology to improve frequency analysis under stationary and climate-driven non-stationary assumptions.

Data sources and methods for palaeoflood reconstruction

Palaeoflood indicators include various types of geologic evidence (sedimentary and erosional features) and physical effects on vegetation (tree scars and tilting). The methodological approach in the study of palaeofloods is dictated by the river channel type (bedrock vs. alluvial rivers), channel slope, and by the characteristics of the sedimentary archives and palaeostage indicators. Resistant channels (cut on bedrock or cemented alluvium) provide the most suitable conditions for filtering records of large and rare floods, and to derivate palaeostage indicators from which calculate flood discharges. Typical sedimentary environments on bedrock rivers include slackwater flood sediments (Baker, 2008; Benito et al., 2022b; Greenbaum et al., 2006) and mountain torrent deposits —debris flows and boulder berms— (Bodoque et al., 2015). Slackwater and boulder berm deposits provide records of individual flood events sometimes with annual to decadal resolution (Benito et al., 2010; Maas & Macklin, 2002). In mountain streams the high flow energy characteristics and coarse sediment size (e.g. boulder berms) limit the temporal scales and spatial distribution of vegetation-based flood evidences (Ballesteros-Cánovas et al., 2015).

Alluvial rivers contain rich stratigraphic archives from which we may reconstruct a flood history but discharge estimations in erodible channels lose accuracy. There are four main types of sedimentary environments on alluvial rivers: (i) overbank floodplain deposits (Jones et al., 2015), (ii) abandoned channels and palaeomeanders (Toonen et al., 2015); (iii) flood basin environments or wetland environments at the distal side of the floodplain (Schulte et al., 2015); (iv) river channel gravels preserved by lateral migration or avulsion processes (Uribelarrea & Benito, 2008). Sedimentation in overbank floodplain environments is controlled by water-sediment load relationships over long-time periods (decades to centuries). Abandoned channels and flood-basin environments are usually weltlands and lake environments filled with organic material periodically punctuated by fine-grained sediment layers from major floods. In floodplain depressions (e.g. palaeomeanders), the estimation of flood magnitude based on stage indicators has been difficult due to large floodplain widths which suppress the elevation differences between normal and rare floods. Alternatively, magnitude proxy indicators were used in the Lower Rhine to reconstruct historical flood discharges over the last 450 years (Toonen et al., 2015). Here, the ages of the sedimentary record from palaeomeander infills were calibrated to known historical events and their normalized grain-size were used as magnitude proxy, where the coarse tail of the grain-size distribution was used to estimate peak-flood discharges (Toonen et al., 2015).

Palaeoflood archives from lake records have shown a great potential to complete regional records of extreme events to understand flood-climate relationships (Corella et al., 2014). Detailed studies of detrital layers embedded in annually laminated —varved— lake records have been used to assess the variability of extreme events on a seasonal scale over the last centuries or even millennia (Corella et al., 2016; Swierczynski et al., 2012). Unfortunately, these records are very scarce and recent anthropogenic activities in lake catchments often hamper the calibration of detrital layers against instrumental precipitation and/or water discharge observations of the last century (Wirth et al., 2013).

Cave environments hold a great potential to serve as precise records of past flood events as they form continuous records over centuries to millennia which are well-suited for radiometric dating by ^{238}U-^{230}Th disequilibrium analysis (Bartolomé et al., 2021; Denniston & Luetscher, 2017; Gázquez et al., 2014). During a cave flood, sands and silts are transported through the cave system and a coating of this detritus is deposited on speleothem surfaces (Bartolomé et al., 2024; González-Lemos et al., 2015). As the water recedes, speleothem deposition is re-initiated and detrital coatings are trapped within the speleothem layers. This process is repeated for centuries or millennia along the growth axis, providing a unique and continuous record of palaeofloods in a given region (Fig. 1). Speleothems formed near streams inside the cave can therefore record ordinary floods, whereas speleothems formed in areas far from the stream or in the upper levels will record only extraordinary floods (Fig. 1). Determining the magnitude of a flood in a cave is a complex task influenced by various factors, including changes in land use, sediment supply, and pre-existing water levels (Denniston & Luetscher, 2017). Understanding the origin of the cave river's water, monitoring flow rates and water levels, and developing hydraulic models that accurately represent the cave's three-dimensional conduit system are fundamental for assessing the magnitude of cave floods (Jeannin, 2001). Observing and monitoring extreme rainfall events in caves is particularly challenging (e.g. Bartolomé et al., 2021; Giménez et al., 2024), and due to their rarity, such events may not even be witnessed within a human lifetime. In the absence of direct observations, hydrological modelling serves as a valuable alternative for simulating these occurrences. By integrating hydrological observations with cave-specific hydrological modelling (infiltration + 3D gallery models), it becomes possible to estimate the magnitude of past floods recorded in speleothems (Bartolomé et al., 2024).

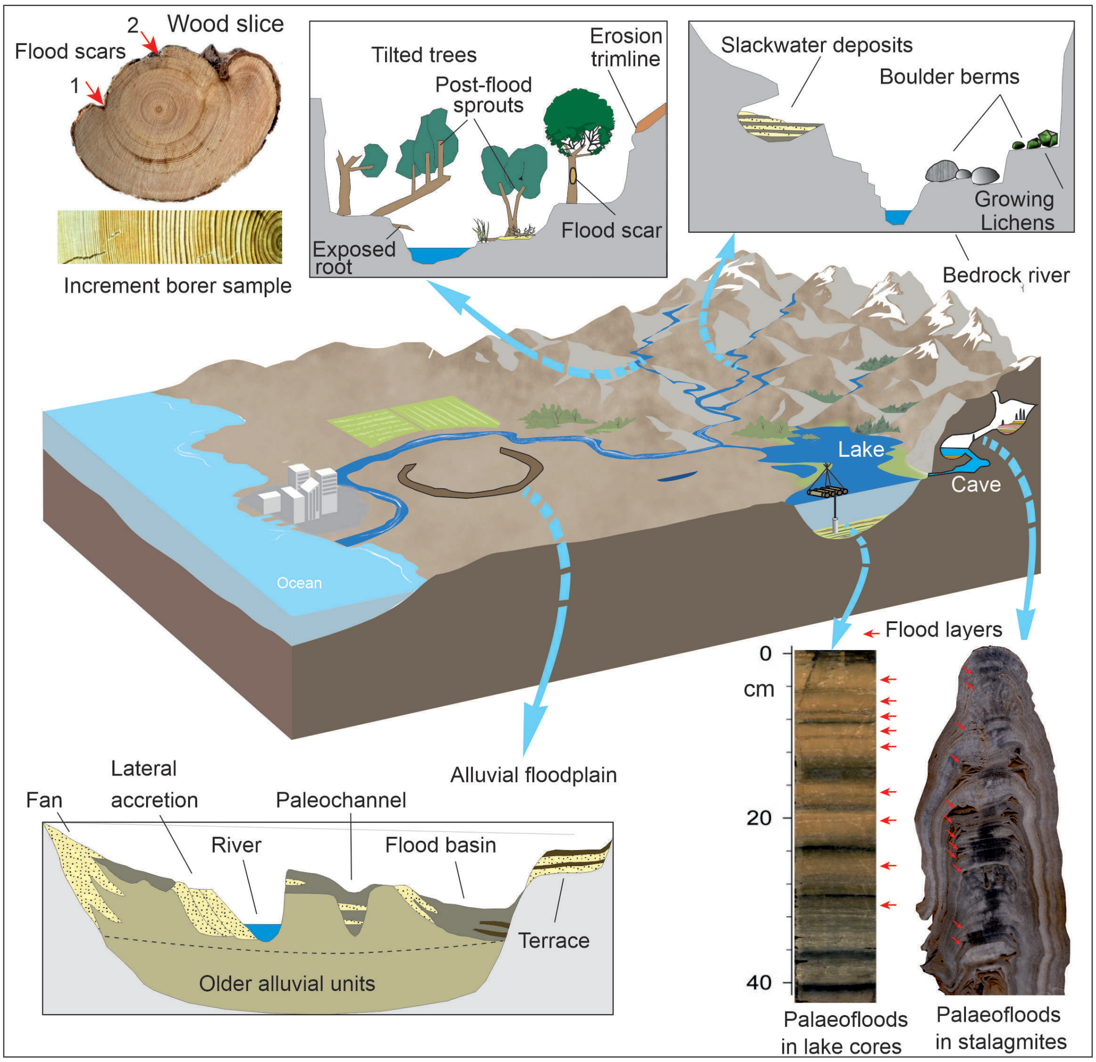

Figure 1.— Block diagram illustrating the location of sedimentary and botanical environments related to flood deposition. Upper: On bedrock canyons, slackwater flood deposits typically comprise multiple flood layers deposited at high elevations, whereas several episodes of boulder berms deposition (dated by lichenometric techniques) are placed at lower locations. Botanical flood evidence includes flood scars, exposed roots and damaged trees. Bottom: In cave systems, flood transport sands and silts that deposited coating the speleothem surfaces. This detrital coating is trapped inside the speleothems layering, providing a continuous record of palaeofloods in a particular region (red arrows indicate flood layers). In lake systems, the flood suspended sediments are accumulated on the lake bottom with distinctive coarse sand material which can be differentiated from seasonal deposition layers. In alluvial flood plains (Macklin & Lewin, 2008), flood deposition mainly accumulate on depressions such as paleochannels or flood basin areas.

Flood reconstructions using biological flood evidence (dendrochronology and lichenometry) has gained a great development worldwide, particularly suited for mountain regions (Ballesteros-Cánovas et al., 2017; Macklin & Rumsby, 2007). Botanical-based flood records are described as external disturbance on trees (such scar or tilted stems) or changes in vegetation patterns caused by flood impacts and dated using tree-rings procedures. The elevation of the botanical disturbance can be used as a palaeostage evidence to estimate the flood discharges using hydraulic modelling (Ballesteros-Cánovas et al., 2011).

Lichens growing on boulders in river channels can serve as indicators for dating the last mobilisation of these boulders (Gob et al., 2003), estimating flood competence (Gob et al., 2010), and assessing flood frequency (Macklin & Rumsby, 2007; Macklin et al., 2010) and magnitude using palaeo-competence equations (Johnson & Warburton, 2002). By analysing size-frequency plots and regional lichenometric growth curves —calibrated with dated reference points such as gravestones and historical monuments— it is possible to determine the past flood event responsible for the last movement of each lichen-covered boulder (Gob et al., 2010). In addition, lichens on canyon walls and terraces can help to date incision or abrasion phases associated with floods, allowing researchers to establish the timing and boundaries of floods, which in turn provides insight into flood magnitudes (Gregory, 1976). In some paleoflood studies, cosmogenic radionuclide dating of flood boulders and flood-eroded bedrock surfaces has been used to reconstruct glacial outburst floods (e.g. in the Himalayas and Siberia; Margold et al., 2018), dating of megaflood deposits (e.g., Missoula floods; Balbas et al., 2017), and occasionally used alongside slackwater deposits and other sedimentological records to cross-validate flood chronologies (Thorndycraft et al., 2019).

Long-term flood frequency response to climate and environmental drivers

Climate variability affects low-frequency atmospheric circulation and weather patterns that lead to floods (Redmond et al., 2002). Analysis of past flood records has shown that flood magnitude and frequency are very sensitive to subtle changes in atmospheric circulation, with greater sensitivity for the largest “rare” floods (50-year flood and higher) than for smaller frequent floods (2-year flood) (Knox, 1993). A typical flood response of floods to natural variability on atmospheric circulation is the alternation of “rich-flood” and “poor-flood” periods, which affect both the flood frequency and magnitude of floods. These cyclic changes, or flood clusters, have been described in instrumental (Robson et al., 1998), historical (Brázdil et al., 2006) and palaeoflood records (Benito et al., 2023). These studies show that large floods occur with a higher frequency at distinct time intervals, questioning the assumption of stationarity used in conventional flood hazard assessment.

Episodes of flood clusters have been reported both at site-based palaeoflood records (Benito et al., 2003) and at regional compiled palaeoflood data (Ely et al., 1993; Macklin et al., 2006). The understanding on the causes of natural variability of flooding and their link to weather patterns and climate is essential for the assessment of the future changes of extreme events. For example, Ely et al. (1993) observed in south-western U.S. an increase frequency of high-magnitude palaeofloods coinciding with periods of cool, wet climate, whereas warm intervals, such as the Medieval Climatic Anomaly, corresponded with dramatic decreases in the number of large floods. In this region, a positive relationship between the palaeofloods and long-term variations in the frequency of El Niño events is evident at least over the last 3000 years (Ely et al., 1996; Kale et al., 2003).

Recent fluvial research has focused on trying to extend flood series primarily as a means for identifying changing atmospheric circulation patterns modulated by climate variability (Benito et al., 2023). However, Holocene flood records from alluvial archives are seldom complete and homogeneous, and even in exceptional outcrops it is unlikely to date all the exposed flood units. Several models and methodologies have been recently proposed to complete flood histories from radiometrically dated fluvial units for specific sites or rivers (e.g. Bayesian models), or at regional scale analysing meta-data of dated flood units from multiple sites within a hydroclimatic region (Benito et al., 2015; Ely et al., 1993; Macklin & Lewin, 2003).

At local scale, Bayesian modelling incorporates information about the stratigraphic sequence (number of individual flood units) and depth data, as well as dating information in the form of probability distribution functions that indicate the likelihood that an undated unit has a particular age (Thorndycraft et al., 2011). This age modelling is frequently used on sedimentary environments with continuous deposition, such as lakes (Corella et al., 2021) and speleothems (Scholz & Hoffmann, 2011), but it is seldom used in discontinuous alluvial deposition environments (Jones et al., 2012; Toonen et al., 2012). As river flood deposition is episodic and the sedimentation events are punctuated by unknown periods with no sedimentation, each individual flood unit identified in the stratigraphy is separated by using a boundary function. This means that, for each undated flood unit, a modelled age is produced dependent on the sequence of events within the control provided by the radiocarbon dated units. An erroneous age from the depositional sequence may lead to mistakes in interpretation of the flood frequency. This highlights the need for multiple dating of the same flood units (Chiverrell et al., 2011) as well as increasing the numbers of dated units (Thorndycraft et al., 2011). In practice, these two conditions may be problematic due to the lack of availability of organic materials for radiocarbon dating and the high economic costs. On the positive side, the age modelling of undated flood units may be used to improve the flood magnitude-frequency plots, assuming that preservation of depositional units is completed at the section (Thorndycraft et al., 2011).

A major recent achievement related to the interpretation of alluvial records has been the development of new combined analysis of large radiometrically dated fluvial databases (Macklin & Lewin, 2003) which allow fluvial activity periods to be more precisely defined and characterized in terms of forcing hydroclimatic conditions (Macklin et al., 2006). Using this analytical approach, records of fluvial activity in different countries and regions can be compared with different climate proxies and other environmental drivers (e.g. land-use change). Inter-regional comparison provides insight into predicting river response to future environmental/climate change.

An example of inter-regional comparison is the analysis of a meta-database of 62 Mediterranean rivers, containing 515 published and unpublished 14C dates and 53 OSL dates from sediments associated with fluvial activity (Benito et al., 2015). The study covered flood events in (1) the western and eastern Iberian Peninsula, (2) southern France, (3) southern Italy, (4) northeastern Morocco, (5) Tunisia, and (4) the eastern Mediterranean. Only dates from sediments indicating major floods or abrupt changes in sedimentation rate or type (referred to as “change” dates) were used. Each regional dataset was processed using the OXCAL calibration programme (Ramsey, 2009) to generate cumulative probability density functions (Jones et al., 2015). Flood episodes were identified when the relative probability exceeded the mean and at least three dated samples fell within two centuries (Fig. 2).

The geographical and temporal distribution of flood clusters is influenced by changes in atmospheric circulation. In the western Iberian region, more frequent floods coincide with transitions to cooler, wetter conditions and a southward shift of the westerlies, leading to a negative North Atlantic Oscillation (NAO) mode. Historical records also associate a negative NAO index with catastrophic floods (Benito et al., 2008; Machado et al., 2015) and eventually enhanced by occurrence of warmer sea temperature (Ballesteros-Cánovas et al., 2019). In North Africa, increased flood frequency corresponds to drier periods and low pedogenesis rates in floodplain sediments (Zielhofer & Faust, 2008). In the eastern Mediterranean, extreme flood events were more frequent during wetter periods. The analysis reveals an opposite pattern of flood episodes between the western Iberian and eastern Mediterranean regions. The opposite centennial-to-multi-centennial flood pattern indicates that bipolar hydroclimatic conditions existed in the Mediterranean during the Holocene.

The composite analysis revealed that eleven flood periods, most of which occurred in the Late Holocene (<4800 cal BP), with only one event (7400–7100 cal BP) from the Early Holocene (Fig. 2). This temporal bias probably reflects better preservation of younger deposits, although hydroclimatic and environmental factors also played a significant role. Several studies suggest that the mean atmospheric state of the early Holocene resembled the positive phase of the Artic/North Atlantic Oscillation (NAO+) (Bendle & Rosell-Melé, 2007; Rimbu et al., 2003). In particular, the composite measure of major dust deposited soluble elements in the ice-core time series GISP2 (Greenland Ice Sheet Project Two) show a significant correlation of high input of non-sea-salt calcium (n.s.s. Ca^{++}) with stronger westerlies (O’Brien et al., 1995; Yan et al., 2005); Fig. 2). Periods of higher flood frequency coincide with low values of n.s.s. Ca^{++} when high-latitude westerlies are weakened (e.g. 7500-7100 and 2400-2100 cal BP), and conversely peaks of n.s.s. Ca^{++} are associated with reduced flood activity (e.g. 5000-6000 cal. BP; c. 8200-8500 cal. BP).

The increase in flood episodes during the Late Holocene is consistent with increased winter insolation due to orbital changes after 5000 cal BP in the Northern Hemisphere, resulting in weaker westerlies and wetter, milder winters (Benito et al., 2015). Greater heat exchange between latitudes is

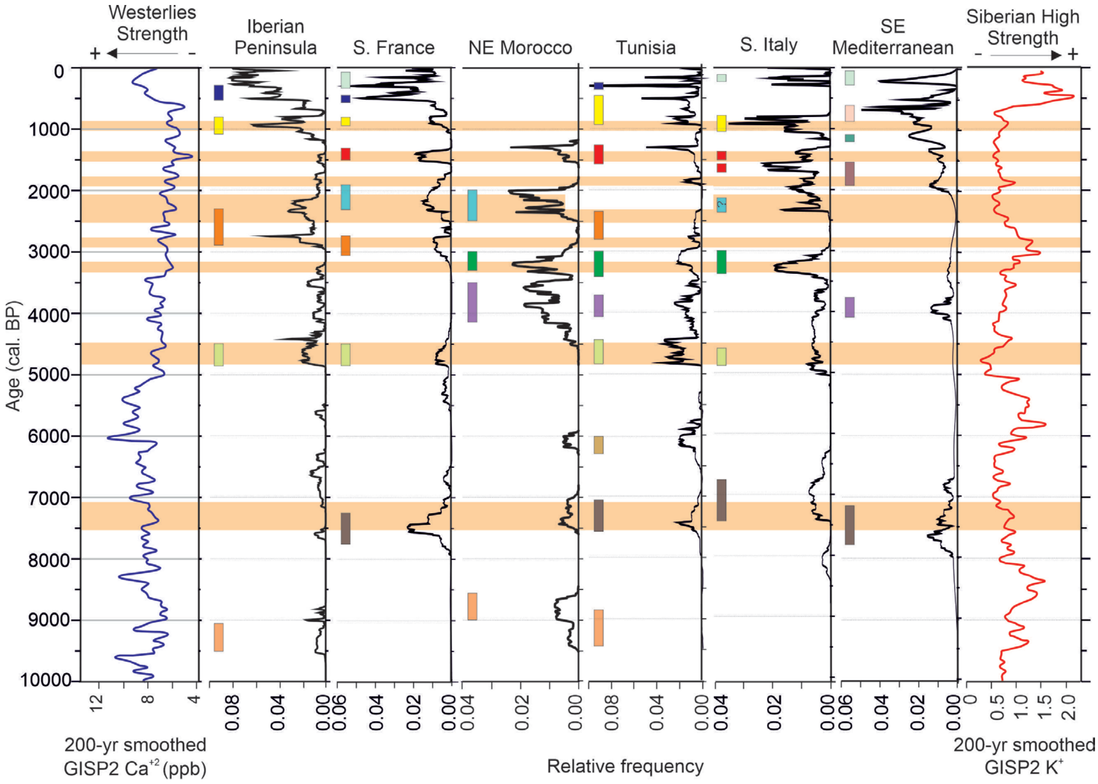

Figure 2.— Meta-analysis database analysis of hydrological event frequency during the Holocene of regions of the conterminous Mediterranean (Iberian Peninunsula, Southern France, north-eastern Italy, southern Italy, southeastern Mediterranean, Tunisia and north-east Morocco; modified from Benito et al. (2015). In each region, black lines correspond to relative CPD plots of radiocarbon dates from floods and extreme fluvial event units. Proxy paleoclimate data during the Holocene is obtained from the composite measure of major dust deposited soluble elements in the ice-core time series GISP2 (Greenland Ice Sheet Project Two). The most left vertical plot is a proxy of the Westerlies strength which show a positive significant correlation with high input of non-sea-salt calcium (n.s.s. Ca++). In the last vertical plot, the Siberian High strength is reproduced from the GISP2 K+ proxy (Mayewski et al., 1997; Meeker & Mayewski, 2002).

likely to have intensified spring and autumn cyclogenesis in the Mediterranean (Zhong et al., 2024). Over the past 2000 years, flood episodes in this region have coincided with strong positive anomalies of the Siberian High (SH), as reconstructed from the GISP2 K^+ proxy (Mayewski et al., 1997; Meeker & Mayewski, 2002) (Fig. 2). Cyclogenesis in the eastern Mediterranean intensifies when cold air from the SH extension mixes with warm Mediterranean air, generating excess potential energy (Makorgiannis et al., 1981). Human activities, such as increased runoff associated with early Neolithic settlement (Jalut et al., 2009) may have influenced flood patterns, although regional environmental influences were not synchronous across the Mediterranean.

Current flood magnitude in the context of the palaeoflood discharges

In a world dominated by visual media, natural disasters are widely broadcast, contributing to the widespread perception that climate change has increased the flood hazards. While flood losses have indeed risen over recent decades, understanding the causes behind these figures requires careful regional analysis. A significant part of the increase in flood losses is due to increased societal susceptibility—specifically, increased exposure and vulnerability. However, regional changes in flood hazards, including shifts in their magnitude and frequency, cannot be overlooked. Long-term flood records reveal three distinct regional flood responses to climate change: (i) rivers where recent floods fall within the upper extremes of palaeoflood magnitudes; (ii) rivers experiencing changes in flood frequency or magnitude that affect only certain types of floods (seasonal or frequency class); and (iii) regions with a general decrease in flood frequency but affected by occasional, isolated extreme floods with catastrophic consequences.

The first group includes many tropical storm regions, which show an increase in high-magnitude floods over the last 70 years suggesting a widespread climatic cause (Kale & Baker, 2006). In the monsoon-dominated Narmada River region (India subcontinent), a palaeoflood study by Ely et al. (1996) found that several modern floods, including the 1961 event (55,323 m^3/s), are the largest in at least 3,000 years —likely due to 20th-century climate change. A period of fewer large floods from the 14th to 19th centuries roughly coincides with the Little Ice Age (LIA; 1300–1850), which was characterised by cooler, drier conditions and a weaker Indian summer monsoon (Kale & Baker, 2006). This decline in monsoon rainfall in India during the LIA is also recorded in a high-resolution composite δ18O record of speleothems (Sinha et al., 2011). Palaeoflood records show clusters of extreme floods during the Medieval Climate Anomaly (around the 13th or 14th century CE), supporting the link between a warmer climate and a stronger monsoon in India (Ely et al., 1996; Kale et al., 2003).

On the second category of regional response includes floods related to glacier and snow-melt processes, such as glacial lake outburst floods (GLOFs) and rain on snow episodes. In high mountain regions, as glacier retreat due to climate warming, new lakes appear in the moraine's terminus. Flood caused by the sudden failures of these moraines can cause major disasters down valley. Over the last centuries, historical records have demonstrated a common-like signal on GLOF activity worldwide (Fig. 3), likely related to the impact of the climate condition during the late phases of the LIA (Harrison et al., 2018). Palaeoflood records confirm similar signal in the northern Tien Shan (Zaginaev et al., 2016), but also underline the potential geomorphological control of the glacier-moraine complexes on GLOF activity (Zaginaev et al., 2019). In a longer temporal context, palaeofloods records have suggested major catastrophic floods in Andes (Benito & Thorndycraft, 2020), affected by the Holocene deglaciation of the former Patagonian ice sheet. Thus, the historical and palaeoflood analyses of past GLOF events are highly informative, and suppose the basis to understand how these events will evolve in the near future (Zheng, Allen, et al., 2021). For instance, in the Indus-Kush-Himalaya region, the risk related to GLOF events could significantly increase in the near future due global warming (Zhang et al., 2024; Zheng, Bao, et al., 2021). It is expected that GLOF will occur more frequently, although their magnitude may be reduced due to the creation of smaller glacier lakes in a warming climate (Veh et al., 2025). On the other hand, an increase of torrential floods in mountains is being detected due to changes in seasonality and an enhance of rain-on-snow processes (López-Moreno et al., 2021). Based on historical, a positive trend in the occurrence of torrential floods have been found in several mountain ranges over the last decades (Ballesteros-Cánovas et al., 2017; Llasat et al., 2024; Schmocker-Fackel & Naef, 2010), but in a longer temporal context, palaeoflood records suggest an increase of flooding during cooler periods (Glur et al., 2013).

A third type of flood response involves occasional extreme floods that can occur even in regions experiencing a general decline in flood frequency. These isolated extreme events are usually considered outliers, and it is complex to determine whether they are part of long-term climate variability or influenced by anthropogenic warming conditions (Greenbaum et al., 2006). In the western Mediterranean region, most studies suggest that pre-instrumental flood magnitudes were larger than those recorded by modern gauges, although notable exceptions exist (Benito et al., 2010). Specifically, the Spanish Mediterranean region has experienced recent extreme floods whose magnitudes surpass previously observed events (Fig. 4). One such example is the October 1973 flood in southeastern Spain, which recorded a historic maximum rainfall of 600 mm in just five hours (Capel Molina, 1974), leading to catastrophic consequences across rivers in Granada, Almería, and Murcia (Fig. 4). In Puerto Lumbreras (Murcia; Fig. 4, 5A), the Rambla de Nogalte (139 km^2) the 1973-flood reached an estimated peak discharge of 1,974 m^3/s, with 40% consisting of sediment (López-Bermúdez, 1987; López-Bermúdez & Gutiérrez Escudero, 1983). This event caused 86 casualties and extensive damage to houses near the river channel. Similarly, in Rambla de Albuñol (115 km^2; Granada Province; Fig. 4), the 1973-flood recorded a discharge of 1,100 m^3/s, with damages exacerbated by the collapse of a clogged bridge, resulting in over 40 deaths and the destruction of 74 houses (Fig. 5B, 5C). Other rivers in the region, such as the Almazora River (2,611 km^2), reported a discharge of 3,500 m^3/s, along with significant flooding of the Guadalentín River (Almería-Murcia provinces).

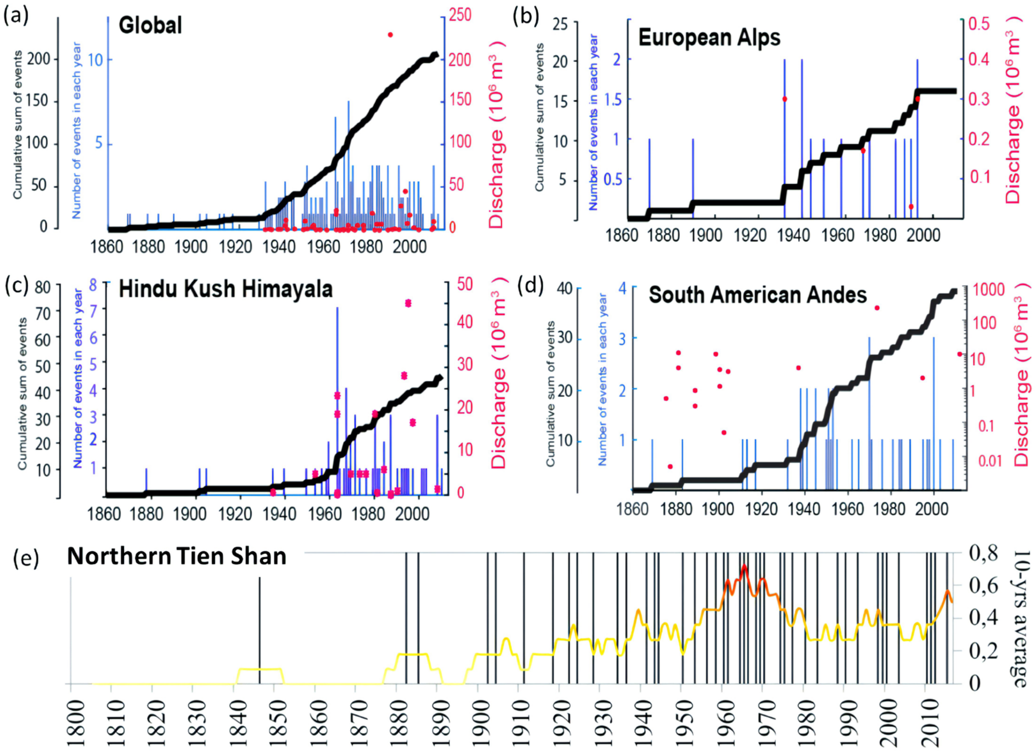

Figure 3.— a-d: Selected informative panels from historical records on the frequency and magnitude of GLOFs (from Harrison et al., 2018) at Global scale (a), European Alps (b), Hindu Kush Himalaya region (c) and south Andes (d). Blue columns indicate number of recorder events, while black lines represents the accumulative number of events. Red points provide information on the discharge magnitude. e: regional composite palaeoGLOF records for the Northern Tien Shan (Zaginaev et al., 2019), showing an enhance of activity during 60's and 70's, which is coherent with the global perspective (a).

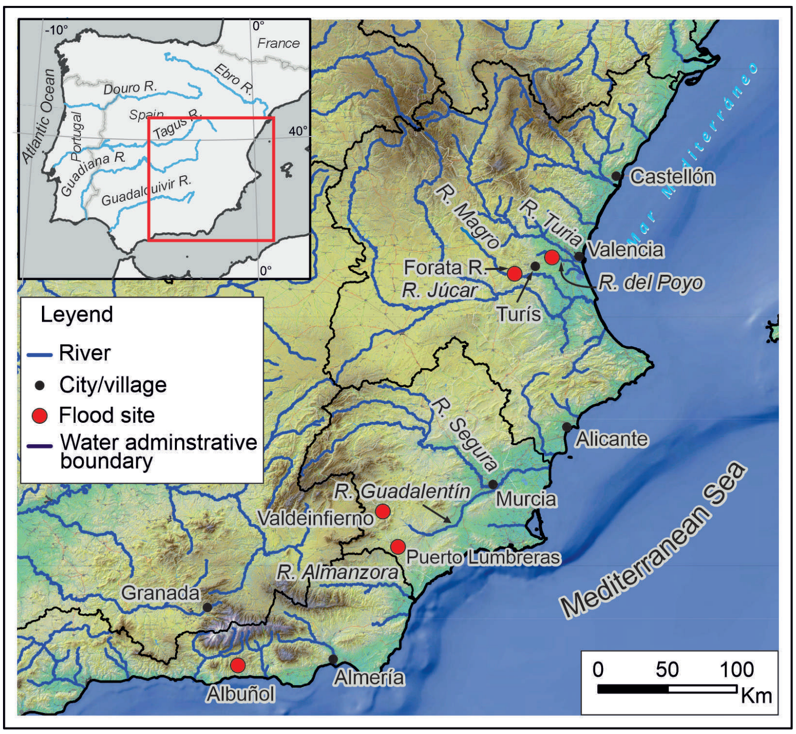

Figure 4.— The central-south-eastern Mediterranean region of the Iberian Peninsula (red square in the upper left inset) and the location of selected flood sites (red circle) described in the paper.

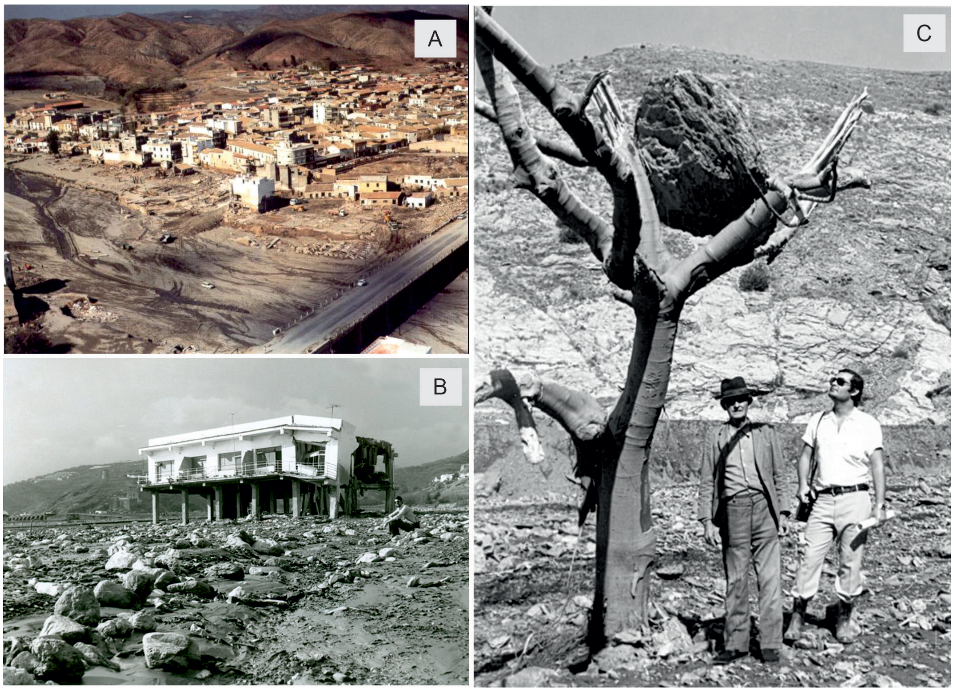

Figure 5.— Photos illustrating the morphological changes and impacts of the 1973 flood in SE Spain. A: View of the Rambla de Nogalte en Puerto Lumbreras (Murcia) after the 1973 flood (Photo: Ayuntamiento de Puerto Lumbreras). B. Boulder field and mud deposited by the 1973 flood at the final reach of Rambla de Albuñol (La Rábita). According to witnesses, during the flood a clogged bridge collapsed releasing a torrent of water, mud and solid waste more than 4 m high that swept away everthing in its path (Source: Andrés Aguilera París). C: A large boulder transported by the flood wave was stacked on the top of a tree in Rambla de Albuñol (Source: Andrés Aguilera París; Adra).

A palaeoflood study conducted in the upper Guadalentín Basin (311 km²), at Valdeinfierno area, found the 1973 flood to be the largest on record, surpassing other major historical floods from 1941 and 1891 (Fig. 6A, 6B). The primary stratigraphic exposure —a 7-meter-thick flood bench— shows evidence of at least 24 significant floods deposited over the last 1,000 years (Benito et al., 2010). Radiocarbon and OSL dating of the eight highest flood units matched well with documented major floods occurring between AD 1831 and 1973 (Medialdea et al., 2014), with minimum discharges estimated between 730 m³/s and 1,616 m³/s. A more recent event, the September 2012 flood —also known as the “San Wenceslao” flood— was triggered by 235 mm of rainfall over 12 hours and was initially reported as the largest on record by the Segura Basin Water Authorities. However, a field survey revealed that the elevation of woody debris and sediments left by the 2012 flood was lower at the aforementioned palaeoflood site compared to previous events (Fig. 6B). The flow stage of this debris corresponds to an estimated discharge of 980 m³/s, contrasting with the 4,500 m³/s reported by the water authority, which was based on 30 minutes of water level monitoring at the Valdeinfierno Reservoir. The palaeoflood deposits indicate that the 1973 flood likely remains the largest event recorded in the upper Guadalentín Basin over the past 500 years.

One of the most recent catastrophic flood in eastern Spain (Fig. 4) was caused by a high-altitude isolated depression (DANA, according to the Spanish acronym). In Turís (Valencia), rainfall reached an intensity of 185 mm in one hour, with a daily accumulation of 771 l/m². This flood ranks among the deadliest natural disasters in Spain, resulting in 229 deaths and economic losses exceeding 17 billion euros. The Júcar River water authorities reported a discharge of 2,282 m³/s at Rambla del Poyo (384 km²) before the level sensor was lost. During the same event, the Magro River, at the entrance to the Forata Reservoir (with a catchment area of 1,014 km²), recorded a discharge of 2,017 m³/s —surpassing the dam’s design flood capacity of 1,334 m³/s. These figures are still preliminary, but it is evident that such flood magnitudes approach the upper limit of regional discharge capacity for the catchment area. Ongoing post-flood fieldwork has allowed the identification of slackwater flood deposits in the Rambla del Poyo and Magro rivers. In the Magro River there is evidence of several paleofloods larger than the 2024 flood. In the Rambla del Poyo, flood sediments are located at an elevation similar to that of the 2024 flood, most likely deposited by some documented historical floods (e.g. Nov 1776 and Nov 1897). Further discharge calculations need to take into account the channel incision that has been observed especially in Rambla del Poyo since the 1970s. At this stage, the potential contribution of anthropogenic warming to the 2024 flood cannot be excluded.

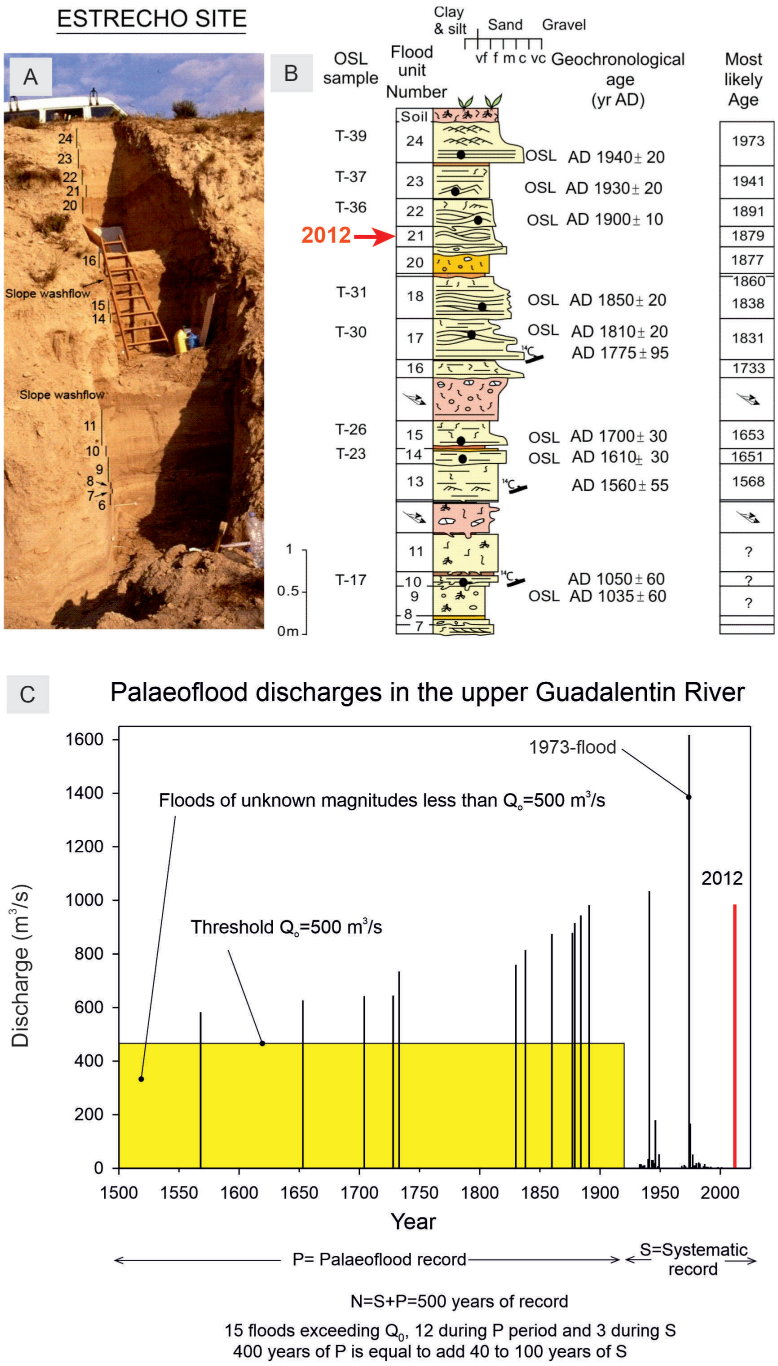

Figure 6.— Palaeoflood record of the Guadalentín River, upstream of the Valdeinfierno reservoir (Benito et al., 2010; Medialdea et al., 2014). A: View of the slackwater flood deposits at the Estrecho profile. B: Stratigraphic description of the Estrecho profile showing at least 24 flood units deposited over the las millennium. The flood stage during the 2012 flood is shown (red arrow) which was recorded from float woody debris observations a week after the event. with indication of the maximum water stage. C: Discharges estimated using the flood layers as minimum stage with the HEC-RAS hydraulic model. In red, the maximum discharge for the 2012 flood event.

Palaeoflood contributions to flood hazard assessment

An important topic in hydrology is to define the hazards of large floods. The statistical approach consists on the collection of a sample of observed floods (usually annual maximum discharge) and applies efficient and robust numerical techniques to provide the best estimate of flood hazards. The standard statistical analysis used to predict the probability of occurrence of large and rare floods involve several problems. The first concern is the data quantity issue, if the available flood record is sufficient long and representative to include the largest and rarest floods (Baker, 1994). Conventional flood frequency analysis (FFA) is usually restricted to few dozens of observations which are used to estimate the properties of floods that exceed a chance of at least one in a hundred years. The value of palaeoflood records is the potential to incorporate discharge data of large floods and to reduce the uncertainty on the recurrence time of the most extreme events (Cloete et al., 2022; Greenbaum et al., 2014; Zituni et al., 2021).

The basic hypothesis in FFA incorporating palaeoflood information (non-systematic) is that a certain threshold of water level exists and all the exceedances of this level over a specific time interval have been recorded (Fig. 6C). The threshold level (censured level) is usually related with geomorphological elements (river banks or flood benches) above which overflow produces a new deposition (Frances et al., 1994; Stedinger & Cohn, 1986). The discharge associated with threshold levels is estimated using hydraulic formulae applied to cross-section geometry (Benito & O'Connor, 2013). The palaeoflood data is incorporated into the FFA as the number of observations exceeding the discharge threshold (Stedinger & Cohn, 1986). The statistical parameters (mean, median, mode, variance) of different established flood distribution functions (e.g. Gumbel, LogPearson 3) can calculated using different methods, such as the Maximum Likelihood estimators (Stedinger & Cohn, 1986), the expected moment algorithm (Cohn et al., 1997), and a fully Bayesian approach (O'Connell et al., 2002). These methods have provided a practical framework for incorporating imprecise and categorical data as an alternative to the weighted moment method (England Jr. et al., 2019). In practice, the recorded number of floods exceeding the perception threshold is more important than the uncertainty in the discharge value (Viglione et al., 2013).

An important issue in the estimation of flood quantiles are the consequences of possible climate-related non-stationarities which can lead to misjudgement and misuse of flood-frequency analyses (Dunne & Leopold, 1978). The stationarity assumption has persisted in conventional flood hazard studies because of short stream flow records and the lack of other prescribed framework for dealing with a non-stationary process and the associated annual risks. The use of non-stationarity poses in a serious challenge to risk concepts, since the probability density function will change with time (Sivapalan & Samuel, 2009). In this debate, palaeoflood hydrology can contribute providing data and scientific understanding about timing and persistence of flood clusters and identifying the flood relationships with low-frequency atmospheric circulation or other environmental drivers.

In a cyclical non-stationary variability forced by climate, short gauge records may only represent a portion of the flood variability, therefore misrepresenting the flood frequency of subsequent periods. Palaeoflood data provides centennial to millennia flood evidence with a wide range of flood magnitudes imprinted by climate variability. The use of palaeofloods in flood frequency analysis brings up the issue of the relevance of past floods as predictor of future flood hazards (Benito et al., 2022a). A similar problem applies to conventional flood frequency analysis, requiring an analysis of the stationarity of the data. In censored palaeoflood samples, stationarity is obtained when the average number of flood exceedances above the threshold level remains consistent over time. Lang et al. (1999) proposed a test based on the computation of the tolerance interval of the number of floods during a certain interval of time. The null hypothesis is to assume that the flood process can be described by a homogeneous Poisson process. The test can be applied to palaeoflood data series (Benito et al., 2022b) using different thresholds related to a palaeostage or discharge value. A rejection of the test is characterised by the output of cumulative number of floods outside the 90% tolerance interval, which implies the refusal of the Poisson process hypothesis (i.e. non-independent and non-homogeneous values).

Recent advances in flood frequency analysis have focused on modelling time series under non-stationary conditions, considering the effects of natural climate variability or environmental changes such as land use, deforestation, dam construction (Ouarda & El-Adlouni, 2011). Studies of FFA under non-stationary framework have mostly applied to monotonic changes of statistical parameters using time as covariate (Villarini et al., 2009). Most realistic non-stationary models relate temporal flood changes with their climatic and environmental drivers affecting flood magnitudes on the short-and long-term (Ouarda & El-Adlouni, 2011). Several attempts have been made to incorporate hydro-climatic covariates into FFA, particularly identifying a climatic index indicative of an atmospheric circulation mode or weather pattern leading to flooding (e.g. Pacific Decadal Oscillation – PDO, North Atlantic Oscillation – NAO, Arctic Oscillation – AO) (López & Francés, 2013). The use of climatic indices as external covariates describing non-stationary flood series is suitable for the incorporation of past flood data together with reconstructed climatic indexes from proxy or documentary-based data (Fig. 7). Machado et al. (2015) proposed a method for non-stationary flood frequency modelling of a 300-year flood record reconstructed from documentary data using climatic and environmental indexes as external covariates. The incorporation of external covariates used the Generalized Additive Models for Location, Scale and Shape (GAMLSS) to obtain the changes on statistical parameters as proposed by Rigby and Stasinopoulos (2005), and later applied to instrumental flood records by Villarini et al. (2010) and López and Francés (2013).The temporal variation of the statistical parameters associated to the selected distribution function (e.g. Lognormal, Gumbel) was obtained using the winter NAO index, reconstructed by Luterbacher et al. (2001) and a reservoir index (RI) as external covariates (López & Francés, 2013). The results demonstrate the existence of a high decadal variability on flood percentiles in response to the effect of the atmospheric circulation in the flood occurrence (Fig. 7). The non-stationary GAMLSS modelling applied over a period of 300 years shows that a "hundred-year" flood (0.01 annual exceedance probability) may vary between 4180 m^3s^{-1} and 560 m^3s^{-1} whereas in the stationary model (log-normal distribution) it is ~1450 m m^3s^{-1} (Machado et al., 2015).

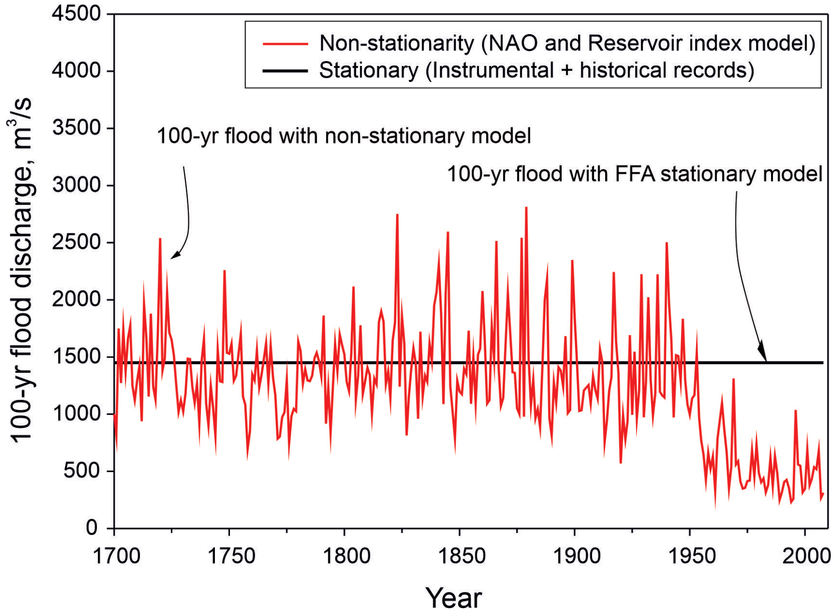

Figure 7.— Quantile estimates of the annual maximum floods with 0.01 annual exceedance probability (100-yr flood) for the Tagus River in Aranjuez based on stationary and nonstationary models using non-systematic data. The non-stationary modelling of flood frequency included the NAO winter and reservoir index (RI) as external covariates of the statistical parameters of the parametric distribution (after Machado et al., 2015).

The October 2024 flood in the Valencia record opened the public debate about the impact of climate change on extreme events. The few attribution studies done so far are mainly focuses on the rainfall analysis. Attribution studies suggest a 12% increase in the likelihood of such extremes due to human influence (Faranda et al., 2024). However, these estimates are based on large-scale models with limited resolution for regional and historical contexts, introducing significant uncertainties (Harrison et al., 2025). The calculation of hydrological frequency of such extremes in ephemeral Mediterranean rivers is challenging due to the scarcity of such extreme events in the observational record. For instance, the Rambla del Poyo gauge station has been in operation since 1989 (25 year of record), whereas the documentary and palaeoflood records show evidence of multiple large floods, some depositing sediments at similar stage of the 2024 flood. The understanding geomorphic systems and their forming discharges obtained from palaeoflood archives are critical tools for flood prevention and adaptation to modified environmental conditions, induced or not by climate warming.

Concluding remarks and perspectives

Current perception of increasing flood risks is partly consequence of failure of the mitigation measures that brings into debate the efficiency of traditional statistical methods under changing risk conditions (Baker et al., 2022). Geomorphological data can provide new insight into hydrological design and risk mitigation actions based on better understanding of flood patterns, improved quantification of extreme flood magnitudes and data, and mapping of areas subjected to inundation during extreme floods. In particular, palaeoflood hydrology extracts the experience of past floods beyond instrumental records and provides methods to evaluate flood hazards even on ungauge basins (Zituni et al., 2021). Palaeoflood methods are consistent and reliable to seek practical solutions for engineering design and mitigation policies in relation to flood hazards.

Palaeoflood research can contribute to analyse the spatial and temporal characteristics of floods (response and persistence) in three specific topics: (a) understanding flood patterns and process in relation with climate and environmental changes, (b) quantification of the peak discharge and flood timing and over centennial time-scales, and (c) developing analytical methods (deterministic and stochastic) for integrating different source of information with applications for flood hazard and engineering design. Obviously, the integration of flood histories embracing palaeofloods, documentary information and instrumental records face a number of problems reflecting different quality of data related to sedimentary preservation, dating accuracy, reliability, temporal and spatial resolution and coverage (Benito et al., 2022b). Despite these problems, long records of floods allow a wider perspective of recent and future extreme floods in relation to anthropogenic climate change (Benito et al., 2022a; Knox, 2000).

A major issue of concern within the hydrologic community is to improve the knowledge of flood variability due to climate and environmental change. The studies palaeoflood records show cyclic or clusters of flood occurrences which are interpreted as a result of changing atmospheric patterns modulated by climate variability at decadal and centennial time-scales. Recent studies show a differential regional flood response to climate variability with overlapping timing on flood clusters within regions of similar hydroclimatic conditions, and opposite decadal-to-centennial timing of flood clusters on other regions. The combined data from modern and palaeoflood records allows the interpretation of flood clusters with persistent mode of large-scale atmospheric circulation. For instance, western Mediterranean large floods are associated with negative phase of North Atlantic Oscillation index (NAO). The integrated regional flood records across the Mediterranean provide bases for identification of temporal persistence of these atmospheric features. These flood-climate relationships can be used to recognize external covariates driving temporal changes on flood hazards.

A second topic of concern is how past flood information is representative of the future in the face of changing environment. The word "past" for the hydrological community refers to gauged records or modelled flood discharges from rainfall stations where the most extreme events may be misrepresented. Long-term palaeoflood data provide a wide sample of extreme floods with a great value in the understanding of the determinitic and stocastic behaviour (long term – short stationarity) of hydrological systems. In general, palaeoflood discharges tend to be larger than modern floods, primarily because extending the recorded period provides additional data on the upper tail of large and rare flood events (Enzel et al., 1993). While past flood magnitudes may not always be indicative of future ones in all regions, it remains crucial to consider a broad spectrum of potential maximum floods. For instance, weather conditions that triggered severe flooding in the late 19th and early 17th centuries in the Mediterranean could recur in the future. In fact, several recent floods —such as those in 1973, 2012 and 2024 in Spain— fall within a similar order of magnitude to the 19th-century floods. This suggests that comparable floods can be expected in the future, although their frequency may change (either increasing or decreasing) in response to a warming climate.

It can be argued that land cover conditions in the late 18th and 19th centuries were very different from those observed today. Towards the end of the Little Ice Age (LIA), numerous studies have documented significant environmental changes in these catchments, including widespread deforestation, overgrazing and intensification of agricultural practices (Segura Beltran, 2004; Machado et al., 2017). These activities have left catchments with exposed soils and reduced infiltration capacity (Rodriguez-Lloveras et al., 2015, 2017). Such degraded conditions may partly explain the high magnitude of floods recorded during this period. Nevertheless, during extreme rainfall events, rainfall intensity often exceeds the infiltration capacity of the soil, leading to Hortonian overland flow, i.e. surface runoff that occurs even when soils are not fully saturated. Under these extreme conditions, the role of land cover in attenuating runoff is limited. An example is the Rambla de la Viuda, where the long-term behaviour of high magnitude floods (>1000 m^3/s) has been stationary over the last 500 years, despite the potential influence of historical land use changes on soil hydrology (Machado et al., 2017).

In palaeoflood studies, channel geometry is the most important factor in the calculation of discharge for a given stage, so evaluating this assumption is important for the overall uncertainty analysis. It is known that rivers in the early 20th century were oversupplied with sediment and channels were wider and shallower than today (e.g. Liébault and Piégay, 2002; Segura-Beltran and Sanchis, 2013). The selection of bedrock-bounded or semi-alluvial channels for quantitative palaeoflood studies is then crucial to reduce uncertainties in discharge estimates. In the case of bedrock-bounded channels with alluvial bottoms, where incision, widening or deposition may have occurred since the palaeoflood evidence was deposited, special consideration should be given to determining the plausible ranges of channel geometry at the time of the flood (e.g. Larsen and Lamb, 2016). In this regard, some adjustments to the pre-incision channel bed topography may be applied to reconstruct previous conditions based on field evidence (e.g. former alluvial channel surfaces, lichen marks on bedrock surfaces; Machado et al., 2017), old topographic maps and incision marks on old bridge piers.

In general, palaeoflood discharges have exceeded those of the observation record demonstrating the added value of past flood records to assess the upper tail of the high magnitude extremes. Several statistical methods have been applied to estimate parametric distribution functions adjusted with palaeoflood data sets (Stedinger & Cohn, 1986). Since most palaeofloods discharges plot on the upper limit of the regional envelop curves (Enzel et al., 1993), palaeoflood data is ideally suited for design sensible structures (e.g. dams) and hazard analysis of nuclear power plants. The method has been used extensively by the U.S. Bureau of Reclamation (England Jr., 2003) in applying palaeohydrological analysis toward dam-safety assessment, and by U.S. Water Resources Council in flood hazard studies (England Jr. et al., 2019).

A key premise in flood frequency analysis is stationarity of statistical parameters, therefore predictions of likely occurrence of floods can be made from past observations and data. Alternative methodological options are deterministic approaches -resulting from climate models- and statistical or stochastic models under a non-stationarity assumption, both quite difficult to implement in the practical realm (Montanari & Koutsoyiannis, 2014). Several authors claimed that uncertainty introduced by these approaches is higher than those relying on the hypothesis of stationarity (Lins & Cohn, 2011). As this debate continues on among hydrologists, two ways to go forward can be proposed. First, under the assumption of stationarity, extending flood records into the past can improve our understanding of flood hazards over time. This does not necessarily alter the statistical parameters of the model but enhances our knowledge of the flood-generating processes. Second, the use of climatic indices to explain past flood occurrences has been successfully applied within non-stationary modeling frameworks (Machado et al., 2015), and this approach represents a promising avenue for future research.

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DECLARATION OF COMPETING INTEREST

The authors of this article declare that they have no financial, professional or personal conflicts of interest that could have inappropriately influenced this work.

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