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The Paleo-Serchio River: history of floods between Lucca and Pisa during the Roman period

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ABSTRACT: The reconstruction of flood frequency beyond the Instrumental Era is challenging and mostly based on historical sources, but it rarely covers more than the last 1000 years when abundant documentation is preserved. To investigate the long-term trends in flooding and obtain insight into current climatic changes it is necessary to extend these data to a larger number of rivers beyond the Instrumental Era and available period of historical documentation. In this paper we reconstruct the paleoflood record for the Roman Period of the Serchio River (*Auser* in antiquity, located in Northern Tuscany, Central Italy) using geoarcheological data. The complex hydrological evolution of the river and the development of the important cities of Lucca and Pisa on the river bank allowed an important collection of data, showing a prominent peak in flood activity during the 1st century CE, which seems to correspond to an increase in regional rainfall interpreted from speleothem proxies. A secondary peak is present in the 6th century CE, which corresponds locally with an increase in precipitation recorded by speleothems. The phases of increased flooding, when compared with present-day synoptical meteorological conditions, probably developed during a period of negative North Atlantic Oscillation (NAO) Index, and it is partially supported by comparison with paleoproxies for NAO. These findings confirm that an extensive collection of geoarcheological data, supported by geological and geomorphological investigation, represents a powerful tool to be integrated with historical data for the reconstruction of floods. The concomitance of local paleohydrological proxies can help in disentangling the origin of the signal from other causes. © 2024 The Author(s). *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: Arno river; Auser; central Italy; geoarcheology

Introduction

There are concerns that current climate change is altering the frequency and magnitude of river floods in an unprecedented way (Paprotny et al., 2019; Blöschl et al., 2019, 2020). However, the lack of long-term observational time series of flood events makes verification challenging (e.g. Diodato et al., 2019; Blöschl et al., 2019, 2020). In Southern Europe and in the Mediterranean region, where the impact of human activities on the landscape has been particularly profound, the flood frequency and magnitude have been affected by climatic and non-climatic-human induced factors such as catchment deforestation (e.g. Aldrete, 2007) and/or urbanization (e.g. Brock et al., 2021). Historical studies have identified flood-rich periods in the past millennia in various regions of Europe and Mediterranean using different approaches, notably analyses of historical sources, archeological and geological data (e.g. Bini et al., 2020, Benito et al., 2015; Blöschl et al., 2020; Rossato et al., 2015). For the most recent period, direct measurement and historical documentary evidence are the most important data sources, but their availability and reliability decrease exponentially reaching back further in time. One way of overcoming this issue is to extend flood series beyond the observational and historical data using sedimentary archives (e.g. Benito et al., 2015) or archeological excavations (e.g. Bini et al., 2020). However, a concern for past reconstructions remains the development of an accurate flood recurrence reconstruction within the context of both climatological and environmental conditions. Over the Common Era (the past 2000 years) climate history is often illustrated by specific climatic epochs, such as the Middle Age Climate Anomaly, the Little Ice Age and others, but the climatic conditions are not spatially coherent and represented by unique conditions (e.g. Roberts et al., 2012; Trouet et al., 2009; Neukom et al., 2019). For greater accuracy, analyses should be conducted in a restricted area using a multi-historical-proxy approach, comparing flood reconstruction with local proxy data of the climate/hydrological conditions. These data should then be inserted in the regional frame of information to get more general conclusions, and for discriminating the climate from non-climate signature of flood activity.

Ancient civilizations often developed on riverbanks and unpredictable flood conditions have contributed to societal development (Aldrete, 2007; Bini et al., 2018a; Brock et al., 2021; Maganzani, 2023). In North Tuscany (Central Italy, Fig. 1) the

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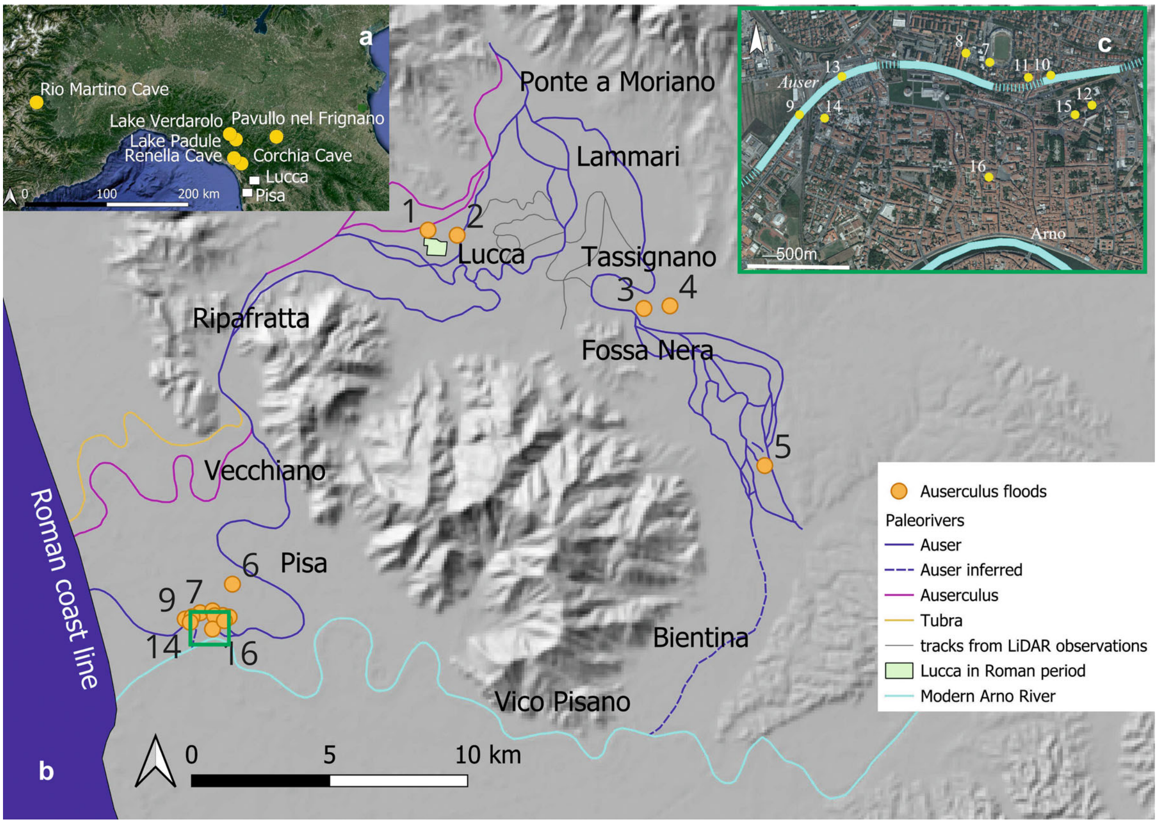

Figure 1. Study area: (a) location of paleoclimatic proxies cited in the text; (b) reconstruction of the main Serchio river branches during Roman times; (c) hypothetical reconstruction of the paleohydrography of Pisa in Roman times and localization of the sites within the city and its immediate suburbs (green box in b; for numbers see Table 1).

Serchio river (former *Auser* in Roman times) represents a particularly suitable case study (Fig. 1). Along the *Auser* river banks important cities such as Lucca and Pisa flourished. This gives the unique opportunity to explore the possibility of reconstructing flood events from the beginning of Roman time to Late Antiquity, using a multidisciplinary approach. This paper represents an improvement compared to previous work on a similar topic from Bini et al. (2020), and it is specifically focused on the reconstruction of flood events only ascribable to the *Auser* River using mostly geoarcheological information, and moreover the chronological period investigated is extended to Late Antiquity (Fig. 1). The reconstructed record of flooding phases is then compared with regional paleohydrological proxies obtained from speleothems from caves located in Northern Tuscany (e.g. Regattieri et al., 2014; Isola, Zanchetta, et al., 2019; Zanchetta et al., 2021) to get possible insight between evidence of flooding variability and paleoclimatic changes.

Materials and methods

Due to the almost complete absence of historical information on floods during most of the Roman and Late Antiquity periods for the area, we followed the approach described in Bini et al. (2020) using archeological data to identify paleoflood evidence.

The stratigraphy of published archeological sites was reviewed to identify evidence of historical floods. Evidence of alluvial deposits in archeological successions is often characterized by the presence of sandy and/or silty deposits without archeological remains or with diachronic and floated archeological remains. These are sometimes associated with the destruction of archeological structures along the banks. Moreover, we also considered the reclamation interventions near the riverbanks, due to their structuring coinciding with flood events.

Archeological sites were selected in areas where evidence of flooding phases can be unambiguously related to the *Auser* River. To correctly attribute flooding phases, geological and geomorphological data were used to identify old stream positions in relation to the archeological site. In addition to archeological excavation, stratigraphic information was further obtained from published cores (Bini et al., 2015, 2018b). For the Pisa plain old branches of the Serchio river are from stratigraphic and geomorphological work mostly based on Della Rocca et al. (1987), Gattiglia (2011), Bini et al. (2015) and Sarti et al. (2010). For the Lucca plains a new survey was performed by first reviewing previous references (Cosci, 2005; Basile, 2021; Basile and Carrer, 2022) and adding new remote sensing analysis based on airborne images available on the Regione Toscana website (www.geoscopio.it) (Fiorentini, 2020). The published archeological stratigraphy and the setting of the Roman sites further helped in constraining the chronology of the river branches identified by remote sensing (e.g. Ciampoltrini and Andreotti, 2002).

Identification of flooding in archeological excavation can be challenging. First, the identification is related to the level of detail provided during the excavation, but it can be further problematic to obtain correct information only by reviewing published archeological stratigraphy. In addition, it is not always possible to separate single flood events from longer phases of alluvial aggradation, waterlogging and/or human intervention related to flood occurrence and successive restoration. Therefore, any conclusion needs to be considered carefully.

The chronology of the alluvial phases in this study was based on published archeological evidence (for details of the chronology for each site see the references in Table 1), which

Table 1. Archeological site and/or historical data used for the flood reconstruction.

No.	Site	River	Event	Chronology	Reference(s)
1	Lucca S. Fredianus miracle	Serchio	Several floods	550–575 CE	Gregorius Magnus, Dialogues, III, 1 (de Vogüé 1978–1980)
2	Lucca, Orti di San Francesco	Serchio	Alluvial phase	10–20 CE	Ciampoltrini (2007)
3	Frizzone, Casa del Lupo	Serchio	Land reclamation intervention	1–100 CE	Ciampoltrini Giannoni (2009)
4	Casa del Lupo	Serchio	Alluvial phase	27 BCE – 14 CE	Ciampoltrini (2004)
5	Botronchio, Orentano	Serchio	Alluvial phase	50–100 CE	Ciampoltrini Andreotti (1993)
		Serchio	Alluvial phase/waterlogging	401–500 CE	Ciampoltrini Andreotti (1993)
6	Via di Gello	Serchio	Single flood	90–110 CE	Donati et al. (2020)
		Serchio	Single flood	301–400 CE	Donati et al. (2020)
7	Arena Garibaldi	Serchio	Land reclamation intervention	75–100 CE	Genovesi and Bueno (2020)
8	Via Galluppi	Serchio	Alluvial phase	110–10 BCE	Anichini et al. (2009); Menchelli et al. (2020)
		Serchio	Alluvial phase	1–50 CE	Anichini et al. (2009); Menchelli et al. (2020)
9	S. Rossore	Serchio	Single flood (Hellenistic shipwreck)	200–170 BCE	Benvenuti et al. (2006); Lippi et al. (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli et al. (2006)
		Serchio	Single flood (shipwreck M)	50–1 BCE	Benvenuti et al. (2006); Lippi et al. (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli et al. (2006)
		Serchio	Single flood (shipwrecks E, G, B, C)	1–15 CE	Benvenuti et al. (2006); Lippi et al. (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli et al. (2006)
		Serchio	Single flood (shipwrecks H, F, N)	117–138 CE	Benvenuti et al. (2006); Lippi et al. (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli et al. (2006)
		Serchio	Single flood (shipwreck A)/ alluvial phase	250–280 CE	Benvenuti et al. (2006); Lippi et al. (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli et al. (2006)
		Serchio	Alluvial phase (shipwrecks I, Q, L)	390–410 CE	Benvenuti et al. (2006); Lippi et al. (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli et al. (2006)
		Serchio	Single flood (shipwreck O)	401–600 CE	Benvenuti et al. (2006); Lippi et al. (2007); Camilli (2005, 2012); Camilli and Setari (2005); Camilli et al. (2006)
10	Via Marche	Serchio	Single flood	450 BCE	Minozzi et al. (2023)
		Serchio	Alluvial phase	50 BCE – 14 CE	Fabiani and Rizzitelli (2022)
		Serchio	Alluvial phase	190–210 CE	Fabiani and Rizzitelli (2022)
11	Via S. Ansano	Serchio	Land reclamation intervention	27 BCE – 100 CE	Fabiani and Rizzitelli (2022)
12	Via San Zeno	Serchio	Land reclamation intervention	27 BCE – 100 CE	Fabiani and Rizzitelli (2022)
13	Piazza Andrea del Sarto	Serchio	Alluvial phase	190–210 CE	F. Fabiani (unpubl. data)
14	Via Giunta Pisano	Serchio	Alluvial phase	600–300 BCE	SABAP-PILI Archive, prot.o no. 6277- 29/04/2021
		Serchio	Alluvial phase/waterlogging	200–100 BCE	SABAP-PILI Archive, prot.o no. 6277- 29/04/2021
15	San Zeno Core C-6	Serchio	Alluvial phase	27 BCE – 14 CE	Fabiani and Rizzitelli (2022)
16	San Sisto Garden (Pisa)	Serchio	Single flood/alluvial phase	500–600 CE	Cantini and Tumbiolo (2023)
		Serchio	Single flood/alluvial phase	500–600 CE	Cantini and Tumbiolo (2023)

usually relate to pottery chronological successions or, more occasionally, to radiocarbon dating of organic remains. The chronology has been defined by dating the lower and upper archeological layers bracketing the alluvial phase or directly on the material collected (even if presumably partially reworked) in the alluvial sediments. Therefore, it is often difficult to define with accuracy the chronology of flood events/phases recorded in archeological stratigraphy. In some instances, chronological attribution may appear too accurate, but this is related to the use of the standard numerical definition of the initial and final chronology of Roman periods to which archeological remains are referred (e.g. Late Roman Republic in the study area 89 BCE to 28 BCE, Anichini and Gattiglia, 2012).

With these limitations in mind, sites with insufficient stratigraphic and chronological information or not connected to the *Auser* River were discarded. In a specific case (S. Sisto site no. 16, Table 1), where the attribution of *Auser* and/or Arno was problematic, and the excavation is still open, sediments were collected and geochemically characterized. It has been demonstrated that *Auser* and Arno have a subtle, but recognizably different geochemical fingerprinting (Amorosi et al., 2013). Sediments were collected from a fresh surface, dried and sieved at 2 mm and powdered. The powder was analyzed at Bologna University laboratories using X-ray fluorescence (XRF) spectrometry (Philips PW1480 spectrometry with Rh tube). The concentration of major elements was calculated using the method of Franzini et al. (1975), while the coefficients of Franzini et al. (1972), Leoni and Saitta (1976) and Leoni et al. (1982) were used for trace elements. The estimated precision and accuracy for trace element determinations are better than 5%, except for those elements at 10 ppm and lower (10–15%). Loss on ignition (LOI) was evaluated after overnight heating at 950 °C. The data are reported in Supporting Information Table S1.

Results

Paleohydrography during the Roman Period

The integration of historical, archeological, geomorphological and remote sensing data shows that the *Auser* was characterized by a complex hydrographic network, with several ramifications, experiencing frequent lateral migrations, avulsions and abandoned channels. The *Auser* provided an important connection between the two well-known cities of Lucca and Pisa from the early Roman period to Late Antiquity. Pisa gradually takes shape as an urban form between the 7th and 6th centuries BCE at the confluence of the Arno and *Auser* (Strabo V,2,5 C222; Bruni, 1998; Guerini, 2021) while Lucca was founded in 180 BCE in proximity to a branch of the *Auser* (Ciampoltrini, 2009, 2016), over an area where previous Villanovian (Iron Age) and Etruscan settlements pre-existed (e.g. Ciampoltrini and Giannoni, 2021). Historical sources document that the *Auser* was the most important river for the two cities during Roman time and it was used mainly for trading purposes between the two cities and among these cities and the sea (Basile and Carrer, 2022; Fabiani and Rizzitelli, 2022; Fabiani and Genovesi, 2023; Bini et al., 2015). Furthermore, there is no doubt that it provided these cities with the water resources used for manufacturing, agriculture, fishing and livestock purposes (Basile and Carrer, 2022; Fabiani and Rizzitelli, 2022; Fabiani and Genovesi, 2023; Bini et al., 2015), but at the same time, it influenced their development with frequent flood events testified by historical sources and archeological data (Bini et al., 2015, 2020; Zanchetta et al., 2021). Indeed, both cities developed in the context of a dense and unstable fluvial network, in which the *Auser* played the crucial role.

Despite the contribution of several studies to the knowledge of the paleo-hydrographic network, identifying several paleotraces of the *Auser* river in the area using different techniques (Pasquinucci, 1988; Ceccarelli Lemut, 1994; Cosci, 2005; Salvini et al., 2006; Ciampoltrini and Andreotti, 2008; Baldassarri and Gattiglia, 2009; Sarti et al., 2010, 2015; Bini et al., 2015, 2018b; Gattiglia, 2011; Basile and Carrer, 2022), the picture of the hydrographic network in Roman time still has elements of uncertainty (Fig. 1). It is currently possible to identify only the main directions of the watercourse, and several concerns still remain about the precise course location during Roman times, but more precise data are available regarding the passage of the *Auser* in the urban center of Pisa (Fig. 1c). In detail, it is possible reconstruct that the *Auser* reached the Lucca alluvial plain at Ponte a Moriano (a few kilometers north of Lucca) and split into two branches (Fig. 1b): a smaller one, called *Auserculus*, which turned westwards entering the Pisa plain through the Ripafratta gorge, and a bigger one which continued flowing towards the south with the name of *Auser*. The latter was further divided into two branches near today's village of Lammari. The eastern branch descended towards the south reaching the village of Tassignano with a large bend, then, continuing further towards the south, it reached two Late Republican farms, known as Fossa Nera A and B (Cosci, 2005; Ciampoltrini, 2009), here continuing towards the south with a complex network where it finally reached the Arno River near the villages of Bientina and Vico Pisano, even if the real position during the Roman Period is unknown. The western *Auser* branch from Lammari meandered westward reaching the city of Lucca to the south. According to Ciampoltrini (2008) and Sommella and Giuliani (1974) the western branch of the *Auser* flowed very close to the city of Lucca, as the northern and western wall might suggest. After Lucca the river continued towards the west merging with the *Auserculus* on the way to Ripafratta and Pisa. Crossing the Ripafratta gorges the river reaches the Pisa alluvial plain. South of Ripafratta gorge the river split again into three branches: the *Tubra*, *Auser* and *Auserculus*. Limited information is available about the course of the *Tubra* branch that flowed to the north of Pisa near the village of Vecchiano. The *Auserculus* course was similar to that of the current Serchio River and reached the sea to the north of Pisa (Fig. 1).

The most important branch was the *Auser* which flowed north to south, in the first stretch near the Pisani mountains from where it diverges to reach the northern part of Pisa city (Bini et al., 2015) where in Roman times it assumed the function of dividing the urban area from the northern suburb (Fig. 1c; Fabiani and Rizzitelli, 2022). Then a branch of the *Auser* flowing towards south-west merged with the course of the paleo-Arno near Pisa city centre (Strabo V,2, 5,c,222; Bini et al., 2015; Fabiani and Rizzitelli, 2022; Fabiani, 2024).

Paleoflood reconstruction

Despite the presence of two important Roman towns, Pisa and Lucca, historical data on floods for the *Auser* are scarce. Various episodes of flooding of the *Auser* north of Lucca are reported by Gregory the Great for the second half of the 6th century (Dialogi, Liber Tertius, IX, de Vogüé 1978-1980, table 1), as a prelude and necessity to justify San Frediano's miracle (Squatriti, 2010; Zanchetta et al., 2021), the artificial diversion of a branch of the *Auser* to avoid the continuous floods of the city of Lucca.

Archeological and stratigraphic data allow us to recognize 29 floods/flooding phases from ca. 600 BCE to the end of 600 CE (Table 1).

Although *Auser* and Arno sediments show strong geochemical affinity, the San Sisto alluvial deposits, dated archeologically to the 6th century CE (Cantini and Tumbiolo, 2023, Table 1), can probably be attributed to the *Auser* River based on their geochemical signature (Fig. 2; Amorosi et al., 2013; Cortecci et al., 2008). The element ratios shown in Fig. 2 are not the same selected by Amorosi et al. (2013) for their discrimination, which was defined from a collection of present-day samples and from samples obtained from cores. In particular, Amorosi et al. (2013) used CaO as one of the oxides useful for discriminating sediment from the two rivers. However, in archeological context, sediment may have been contaminated by human material such as rubble or bricks, which can be difficult to separate before the analyses and contain a certain amount of CaO. Therefore, the proposed biplot can be more suitable for discrimination of the Arno/Serchio deposits in archeological context.

Figure 3 shows the chronological range of alluvial phases identified in the archeological and historical records.

The cumulative histogram of Fig. 4 shows the highest frequency of floods during the period between the 1st century BCE and the 1st century CE (Late Republic to Early Empire), with a peak during the first century CE. There is a decrease and a recovery with a secondary peak in the 6th century. Because the histogram is constructed attributing the same probability of occurrence of an event for the interval occurring in different centuries, this can introduce some bias in the frequency of the events, but has low impact in defining the highest frequency of the events during the Late Republican Period and Early Empire period (1st BCE to 1st CE).

The histogram of Fig. 4 has been constructed with the same approach as Bini et al. (2020). To use a different approach to reduce potential biases we produced the graphic shown in Fig. 5 attributing a flood for any year of the flooding interval identified by the archeological data, assuming the same probability of occurrence in the interval, and then applying a moving average. The red lines indicate moving averages with a window of 100 (solid line) and 200 (dashed line) years. Also in

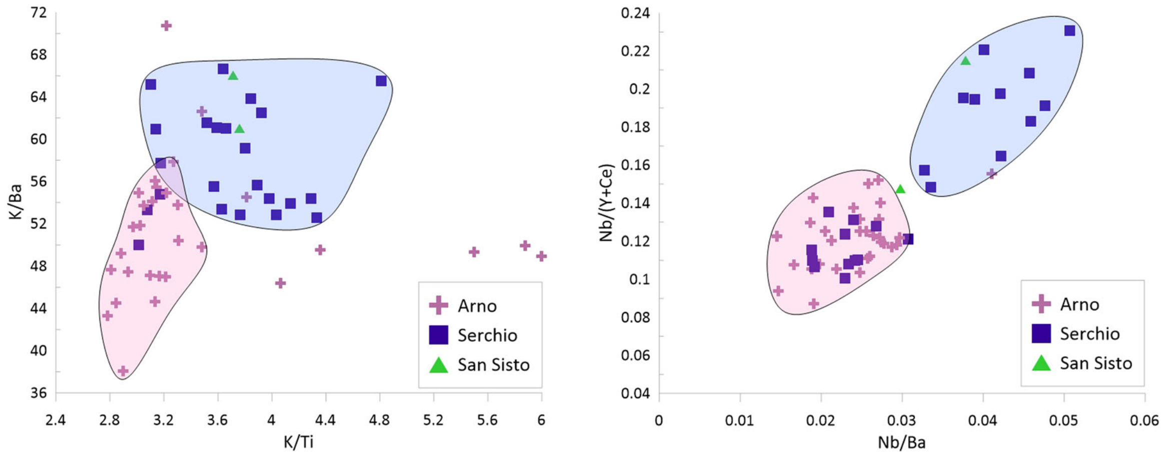

Figure 2. Discrimination between Arno and Serchio (*Auser*) sediment from selected cores of the Pisa coastal plain, and current river bed sediments. San Sisto alluvial deposits are shown as green triangles. From the cores, only the samples taken from levels whose facies have been attributed to floodplain, river channel or crevasse splay were considered. Geochemical data of Serchio and Arno are from Cortecci et al. (2008) and Amorosi et al. (2012, 2013).

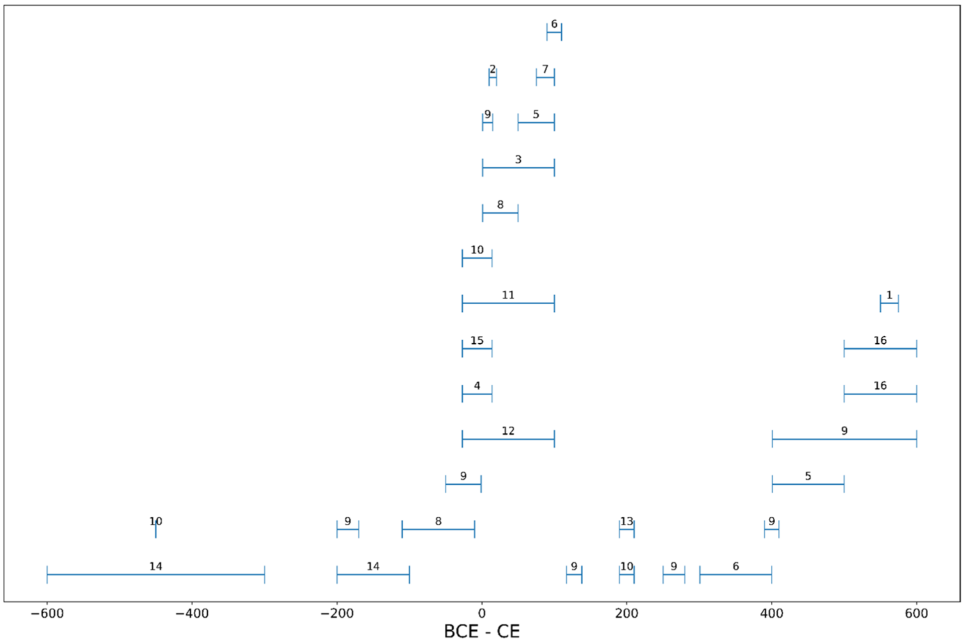

Figure 3. Chronological range of alluvial phases identified in the archeological sites and historical records (for site numbers see Table 1 and for site locations see Fig. 1).

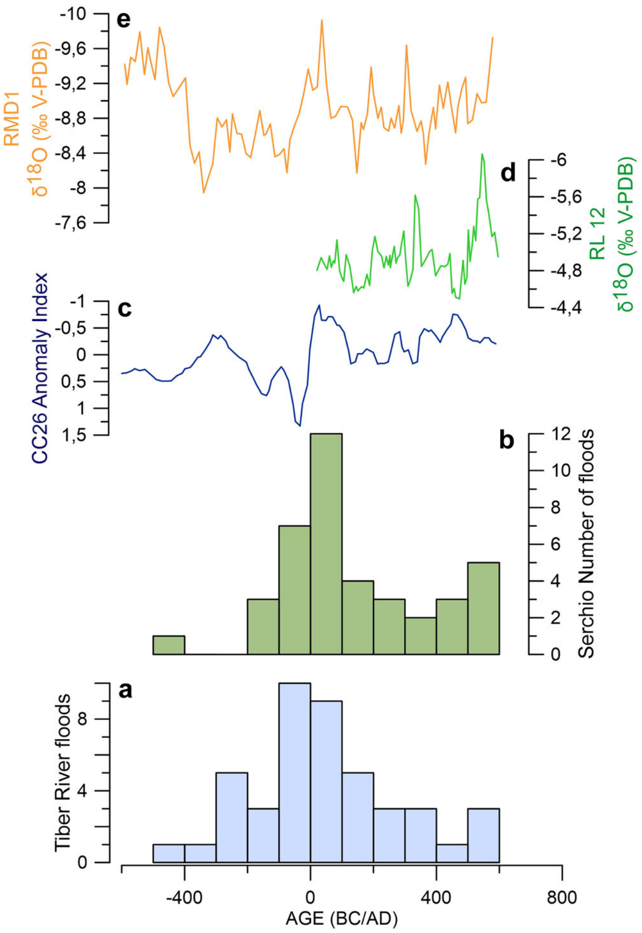

Figure 4. Comparison of the paleoflood record from the *Auser* River (b), with the paleoflood record from the Tiber River (a), Aldrete 2007 CC26 anomaly index (Regattieri et al., 2014) (c), RL12 $\delta^{18}O$ record (Zanchetta et al., 2021) (d) and RDM1 $\delta^{18}O$ record (Regattieri et al., 2019) (e).

this case, we observe an increase of flood events in the 1st century BCE and the 1st century CE and a progressive increase in flooding since the 4th century CE.

This distribution confirms the finding of Bini et al. (2020), which was based on a lower number of data, but also included sites not influenced by the *Auser*, but by the flooding of different local rivers mainly located in the coastal area. Interestingly, flood data for the Tiber River (which is the best record based on historical accounts, for the Roman Period, e.g. Aldrete 2007) show a similar trend since the 4th century BCE, culminating with the highest frequency of events in the 1st BCE to 1st CE. However, the trend diverges significantly after the 2th century CE with the Tiber showing a progressive decrease in the number of floods (Fig. 4).

Discussion

The climatic significance of the observed flood trends is not necessarily obvious. Many floods and/or flooding phases would not have been recognized and/or historical data are necessarily incomplete. Moreover, a flood is an extreme event, so it can occur due to a very specific number of causes, including anthropogenic impact on the catchment (e.g. deforestation, Aldrete, 2007), but floods can also be more frequent in a specific synoptic climatic regime.

Instrumental measurements show that meteoric precipitation in Tuscany is anticorrelated with the North Atlantic Oscillation (NAO) where the negative phase of the North Atlantic Oscillation index (NAO-I) is characterized by higher precipitation due to the major advection of vapor masses from the Atlantic to Mediterranean in the winter (e.g. Luppichini et al., 2021).

For instance, for the Arno, this is confirmed by the analyses performed by Luppichini et al. (2024), which found a Spearman coefficient of −0.74 between the NAO-I and Arno River discharge ($p < 0.001$). To confirm if these paleoflood trends have some climatic significance it is necessary to compare them with paleohydrological proxies. The $\delta^{18}O$ of speleothems from the Central Mediterranean is usually interpreted as mainly related to the amount of precipitation during the recharge season of the cave (e.g. Drysdale et al., 2006; Zanchetta et al., 2007, 2014, 2021; Regattieri et al., 2019), and in some cases interpreted as indirect evidence of NAO-I variability (Zanchetta et al., 2021). For comparison with the paleoflood records, we use two records from speleothems obtained from the Corchia (CC26) and Renella (RL12) caves in the Apuan Alps (Fig. 1), in northern Tuscany. Both records have a decadal resolution but the chronological constraints are better for RL12 from Renella Cave, which does not cover the whole chronological interval (Zanchetta et al., 2021). By contrast, CC26 from Corchia Cave covers the whole interval (Zanchetta et al., 2007; Bajo et al., 2017; Fig. 4), but the original age model has a lower resolution. For CC26, we use the 'mean anomaly index'. This index was obtained by combining detrended, smoothed and normalized Mg/Ca, $\delta^{18}O$ and $\delta^{13}C$ time series, assuming that all three respond sensitively to hydrological variations and in particular to changes in cave recharge (Regattieri et al., 2014). This statistical treatment better highlights significant hydrological changes and is considered a more robust paleohydrological indicator compared to a single proxy (Regattieri et al., 2014; Isola, Zanchetta, et al., 2019). The peak in flooding during the 1st century corresponds to an increase in rainfall precipitation recorded in the CC26 record (Fig. 6), as already noted by Bini et al. (2020), and to the interval of increased precipitation recorded at Rio Martino Cave in NW Italy. However, the previous period of drying during the 2nd to 1st BCE, visible in the CC26 and Rio Martino records, is not particularly evident in the reconstructed flooding trend.

The secondary peak in the 6th century is further supported by archeological evidence for the Arno river in the city of Florence where archeological excavations in Via dei Castellani have discovered two flooding phases archeologically dated to the first and second half of the 6th century (Arnoldus-Huyzendveld, 2007).

The RL12 $\delta^{18}O$ record shows a prominent peak of low $\delta^{18}O$ values indicating increasing precipitation in the 6th century (Zanchetta et al., 2021). During this period, historical and archeological data reveal an increase in flood events in some parts of Central and Northern Italy (Cremaschi and Gasperi 1989; Rossato et al., 2015; Bini et al., 2020; Zanchetta et al., 2021). However, there is no clear increase in the Tiber River flood record (Aldrete, 2007). In this regard, it is suggested that there was continuity in the maintenance of the river for navigation purposes, as evidenced by Theoderic entrusting the prefect of the praetorium with the task of removing any obstacles to Tiber navigation in the mid-6th century AD (Dio., *Var.*, 5, 17).

About two century-long cooling events have been identified during the 6–7th century CE, the so-called Late Antiquity Little Ice Age (LALIA), well expressed by dendroclimatological data from Central Europe and Urali (e.g. Büntgen et al., 2016). Reconstructed Central European summer aridity using tree-ring stable carbon and oxygen ($\delta^{13}C$ and $\delta^{18}O$) data instead

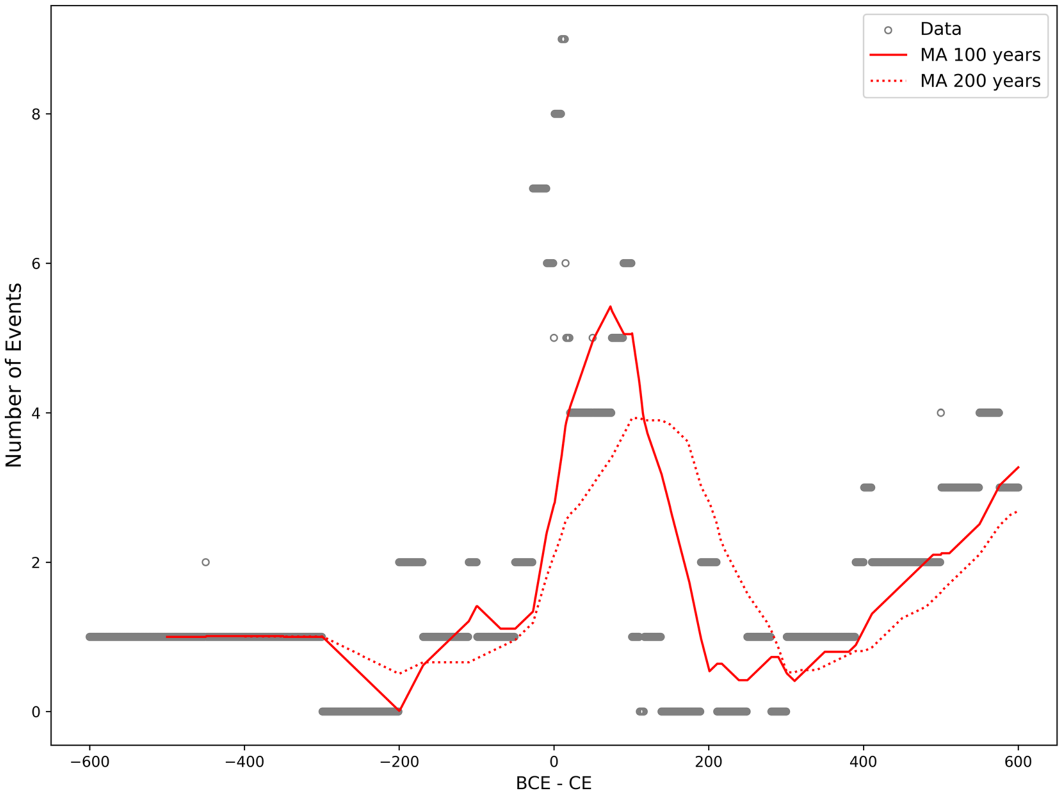

Figure 5. Flood distribution calculated assuming the same probability of occurrence in the interval; the red line represents a moving average of 100 years, and the dotted line represents a moving average of 200 years.

suggests drier conditions between ca. 400 and 600 CE (Büntgen et al., 2021: fig. 6). In the central Mediterranean this situation seems reversed as expected for negative NAO-I (e.g. López-Moreno et al., 2011). Pollen and lacustrine δ^{18}O records from Lake Pergusa in Sicily indicate a wetter period between ca. 450 and 750 CE (Sadori et al., 2016; Zanchetta et al., 2022), as well as the δ^{18}O speleothem RL12 from Renella (Fig. 6; Zanchetta et al., 2021). Paleoproxies for NAO-I are controversial, there is no clear evidence for an NAO-I negative phase during the 1st century, but some evidence seems to support a negative NAO phase during the 6–7th century (Olsen et al., 2012).

The comparison with regional to extra-regional proxies is not always convincing, and clear antiphases are evident, so we need to consider possible bias related to age control of some records (more limited for dentroclimatological data). However, the comparison with Tiber data appears particularly instructive. Synoptical climatic conditions are consistent for central Italy (e.g. López-Moreno et al., 2011) and the general trend of flooding events recognized from the 4th BCE to the 1st CE from our record and Tiber data is particularly convincing. Also, the flooding decrease after the 1st century is consistent in the two records. It is important to remember that Tiber data are from historical accounts, whereas our record is related to geoarcheological data. The different nature of the proxy can exclude the causality even if we cannot rule out that a bias is due to the number of data available (historical accounts and archeological excavations). The flooding peak during the 1st century CE corresponding to the local increase of rainfall as recorded by the CC26 record can indicate that this signal may be a genuine climatic signal.

Selected archeological contexts for Pisa and Lucca, in addition to ancient sources and particularly Roman legislation regarding flood management seem to support this interpretation. The *ius alluvionis* attributed to the jurist *Trebatius*, active as early as the mid-1st century BCE and still active between the late 1st century BCE and the early 1st century CE (Maganzani, 2023), indicates that flood management and limitation were highly regarded by the emperors. This is also evidenced by the establishment, by Augustus or Tiberius, of the *curatores alvei Tiberis et riparum*, tasked with cleaning the banks of the Tiber and its bed, reflecting the need to find an effective and lasting solution to the recurrent danger of flood events. After the devastating flooding of Rome in 15 CE, these *curatores* were called upon to consider a possible solution to the Tiber's flow (Tac., Ann., 1, 79). The solution would have involved diverting the Clanis, an ancient course of the Chiana River, into the Arno and halting the inflow of other Umbrian tributaries. The protests from Florence and other cities involved in the project may have led the *curatores* to not proceed with the plan. While we cannot be certain of the presence of *curatores* in every city of the Empire, it is certain that each of them sought to limit flood events as much as possible through the maintenance of natural embankments or the creation of artificial works and the reclamation of unstable areas. Between the 1st century BCE and the 1st century CE, Lucca responded to the floods recorded in the city (Orti di San Francesco, site no. 2: Ciampoltrini, 2007) and its territory (Botronchio, site no. 5: Ciampoltrini and Andreotti, 1993; Case del Lupo, site no. 4: Ciampoltrini, 2004), with land reclamation interventions, as indicated by the amphora structure at the Frizzone site, Casa del Lupo (no. 3: Ciampoltrini and Giannoni, 2009). Pisa, on the other hand, implemented multiple public interventions beyond amphora reclamations, such as those at Arena Garibaldi (site no. 7, Genovesi and Bueno 2020), Via S. Ansano (site no. 11, Fabiani and Rizzitelli 2022) and Via San Zeno (site no. 12, Fabiani and Rizzitelli 2022). The riverbanks were constantly maintained, as evidenced by the case of Via Marche (site no. 10, Fabiani and Rizzitelli 2022), where a flood is dated to between the second half of the 1st century BCE and the first half of the 1st century CE, as indicated by the *post quem* and *ante quem* dates provided by the ceramics found in

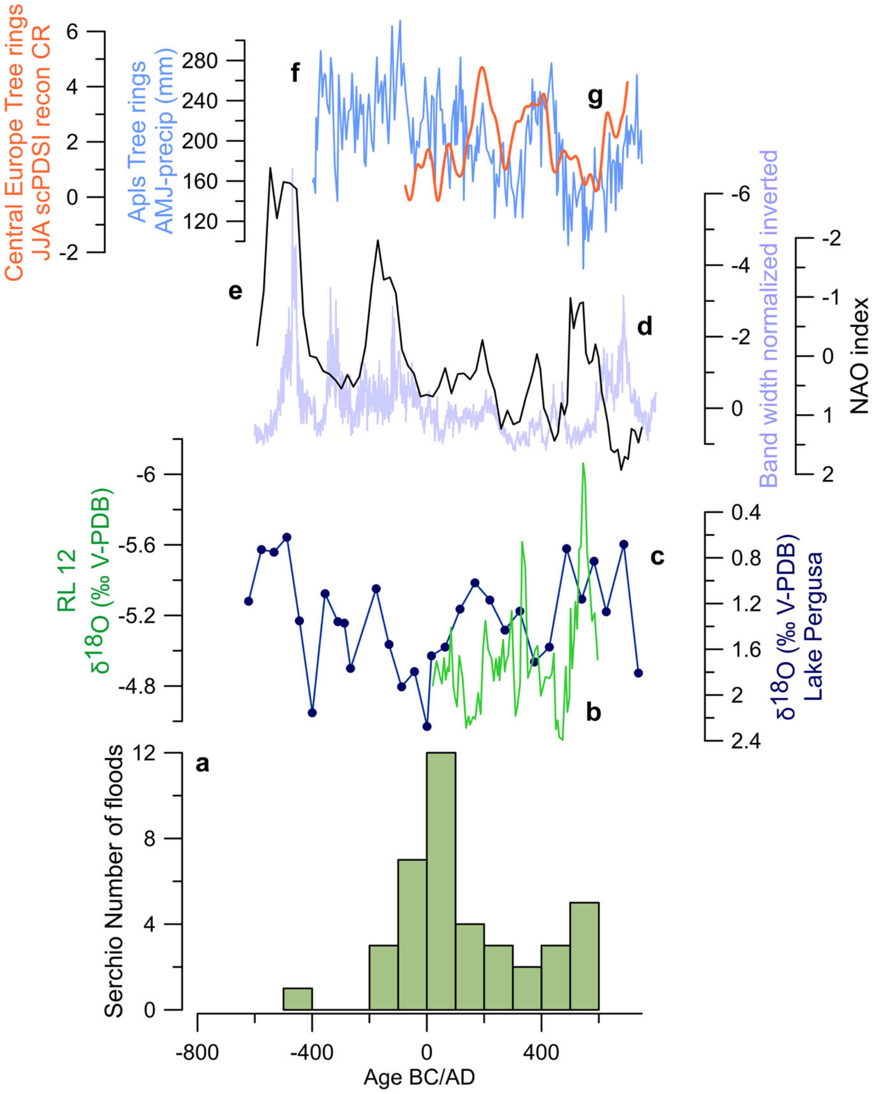

Figure 6. Comparison of climate characteristics from proxy data. (a) Floods of the Serchio and Arno Rivers; (b) δ^{18}O of RL12 speleothem, from Renella Cave (Apuan Alps, Zanchetta et al., 2021); (c) δ^{18}O from Pergusa Lake (Sicily, Zanchetta et al., 2022); (d) speleothem band width as a proxy of NAO-I (Baker et al., 2015); (e) NAO-I (Olsen et al., 2012); (f) tree ring-based reconstructions of central European April-to-June precipitation (Büntgen et al., 2021); and (g) tree ring-based reconstructions of central European Summer Drought Severity Index (Büntgen et al., 2021).

the stratigraphic sequence that destroyed the late Republican-era quay; the embankment was immediately rebuilt with a massive concrete wall. While it is true that from the early 2nd century CE to the 6th century CE there is no such intense series of floods, it is noteworthy that a phase of instability concentrated between the late 2nd century CE and the early 3rd century CE led to a redefinition of the floodplain area in the urban section of the *Auser* River. The single flood recorded in Via Marche (site no. 10, Fabiani and Rizzitelli, 2022) corresponds precisely to that of Piazza Andrea del Sarto (F. Fabiani, unpubl. data). At both sites, thick layers of *Auser* sand have been archeologically investigated, upon which two necropolises are established, indicating a redefinition of the river course (F. Fabiani, unpubl. data). Finally, the peak flood of the 6th century CE, based on the RL12 record, also seems to have a genuine regional climatic signal, as evidenced both in Pisa with the shipwreck of the vessel O near S. Rossore (site no. 9; Camilli and Setari 2005) and in Lucca at Botronchio (site no. 5: Ciampoltrini and Andreotti, 1993). The dangers posed by the *Auser* River probably compelled the community to divert the course of the river during the same century, as would also be suggested by the so-called 'miracle of San Frediano'. According to Gregorius Magnus (Dialogues, III, 1), Frediano, bishop of Lucca, redirected the course of the dangerous river away from the city.

However, flooding activity can be affected by human impact such as deforestation in the catchment and/or impact the river course linked to specific activity such as damming or narrowing of the riverbed in urban areas. There is insufficient enough archeological evidence to suggest that flood frequency was influenced by the progressive expansion of Pisa and Lucca urban areas. Instead, the impact of deforestation can be explored by palynological evidence from the river catchment area. Palynology is widely used to detect changes in vegetation cover and land use due to human activities and natural ecological processes (e.g. Mensing et al., 2016). The palynological data are sparse for the area and chronology is not always optimal. However, available pollen records were downloaded from the Neotoma Paleoecology Database (Williams et al., 2018) by adopting the following criteria: (i) location nearby the catchment area of the Serchio river; (ii) at least one chronological control point (e.g. accelerator mass spectrometry ^{14}C dating) in the last 2000 years; and (iii) mean resolution below 500 years in the period 800 BC to 800 AD. Based on these criteria, the Pavullo nel Frignano (Vescovi et al., 2010), Lago Verdarolo (Morales-Molino et al., 2020) and Lago Padule

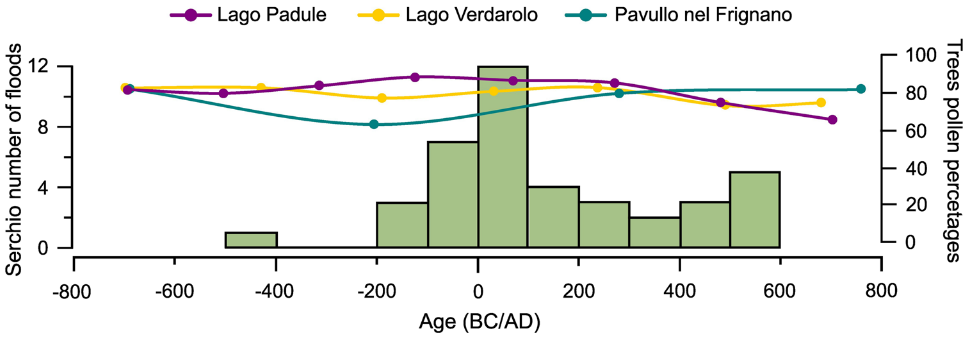

Figure 7. Comparison of historical floods of the Serchio river with pollen percentages of trees near the catchment area. Tree pollen percentages include only wild trees, and thus exclude cultivated trees such as olive (*Olea*), chestnut (*Castanea*) and walnut (*Juglans*). Data for Lago Padule from Watson (1996), Lago Verdarolo from Morales-Molino et al. (2020) and Pavullo nel Frignano from Vescovi et al. (2010).

(Watson, 1996) pollen records were selected (Fig. 1) to understand possible human impact on flood frequency.

Palynological evidence indicates no outstanding drops in pollen percentages of wild trees near the catchment area (Fig. 7), suggesting that forest areas were not subjected to intense deforestation between 800 BC and 800 AD. This is in agreement with, for instance, palynological data in the Rieti basin (central Apennines), where there is limited evidence for environmental degradation (deforestation and erosion) during Roman times (Mensing et al., 2015).

Conclusion

The reconstruction of flood frequency beyond the period of instrumental measurement is challenging and mostly based on historical sources, but it rarely covers more than the last 1000 years when abundant documentation is preserved (e.g. Brown, 2023). A notable exception is the case of Tiber floods, for which historical data are available for more than 2000 years (Aldrete, 2007). However, to investigate the long-term trends in flooding to obtain insight on current climatic changes it is necessary that the data are extended to a larger number of rivers for a period beyond the Instrumental Era and historical accounts. The case of the *Auser* is particularly instructive, for which, thanks to detailed re-analysis of archeological excavations, a reconstruction of paleoflood history was obtained for the period from ca. 600 BCE to 600 CE. The analyses of the data show a prominent peak in flood activity during the 1st century CE, which seems to correspond to an increase in regional rainfall as shown by speleothems proxies. This period is almost coincident with a flood frequency peak in the Tiber River, suggesting a common driver. A secondary peak is present in the 6th century CE, which corresponds locally to an important increase in precipitation reconstructed from speleothem proxies. Regional historical data seem to confirm the increase in flood frequency (Zanchetta et al., 2021). Pollen data from higher altitude close to the Serchio catchment indicate that there is no evidence of significant deforestation during Roman times, and suggests that human impact has a minor effect in the reconstructed flood history.

The phases of increasing floods, considering also the present-day synoptical meteorological conditions, are more favorable in a context of negative NAO-I, and are partially supported by comparison with paleoproxies for NAO (Fig. 6, Olsen et al., 2012). The particularly rich collection of paleoflood data and convincing consistent correlation with local climate paleoproxies is certainly related to the specific role exerted by the *Auser* for the development of the important cities of Lucca and Pisa during the Roman Period and the valuable collection of archeological data in the last few decades.

Moreover, it confirms that extensive collection of geoarcheological data, supported by geological and geomorphological investigation, represents a powerful tool to be integrated with historical data for the reconstruction of flooding activity. This can also be particularly useful in hypothesizing possible future trends in a flood-prone area.

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Data availability statement

Data supporting this study are included within the article and supporting materials. Additional information can be obtained from the corresponding author.

Supporting information

Additional supporting information can be found in the online version of this article.

Abbreviations. NAO, North Atlantic Oscillation; NAO-I, North Atlantic Oscillation index.

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