Pluridisciplinary analysis and multi-archive reconstruction of paleofloods: societal demand, challenges and progress

Lothar Schulte[1], Daniel Schillereff[2], Juan Ignacio Santisteban[3]

[1] FluvAlps Research Group, Department of Geography, University of Barcelona, Spain, schulte@ub.edu

[2] Department of Geography, King's College London, United Kingdom, daniel.schillereff@kcl.ac.uk

[3] Department of Geodynamics, Stratigraphy and Paleontology, Fac. of Geological Sciences, Complutense University of Madrid, Spain, j.i.santisteban@geo.ucm.es

Corresponding author: *Lothar Schulte, schulte@ub.edu*

Abstract.

Floods are one of the gravest natural hazards for societies, worsened by population growth, unchecked development, and climate change. From a Global Change perspective, past extreme events merit particular interest because they can be linked to wider climate and environmental changes, introduce perturbations. During the last decade, knowledge of long-term flood frequency and magnitude has been improved by extracting data from different types of archive. But, despite advances in dating methods, proxies and statistical techniques and efforts to identify atmospheric drivers, some fundamental questions remain unresolved. The Special Issue entitled "Pluridisciplinary analysis and multi-archive reconstruction of paleofloods" in the journal Global and Planetary Change addresses these uncertainties and complexities by assembling a selection of studies, which were first presented at the Past Climate Changes (PAGES) Open Scientific Meeting held at Zaragoza in 2017. In this introductory paper, the guest editors outline the 17 research contributions and meta-data from the 17 paleoflood studies were systematically analyzed in terms of i) geographical distribution; ii) methodologies applied; iii) types of archives; iii) numbers of flood series compiled and iv) spatial and temporal resolution of paleoflood data. The data indicate that paleoflood studies focused on fluvial depositional environments show a higher rate of integration with other types of paleoflood archive (mean of 4.5 types of archive) than studies focused on documentary sources (mean of 3.5) and lake sediments (mean of 2.4). We suggest that this strategy of archive integration has been adapted to effectively compensate for the higher uncertainties of fluvial deposition in floodplains. Statistical processing of the meta-data shows quantitative associations between specific types of flood archive and offers a solid platform for designing the optimal approach for multi-archive paleoflood research. A qualitative review and visual comparison of the 17 paleoflood series shows some consistent trends and breaks but also notable differences within and between regions. While a trend of increased flooding since 4-5 ka BP is evident, the lack of synchronicity between breaks and the coeval increases and decreases in fluvial activity is manifest. The majority of studies in the Special Issue do denote the 19th century - including the youngest cool climate pulses during the Little Ice Age - as a particularly flood-rich period. It is more difficult to assess the 20th century because of social changes, population growth and extensive river modification. Despite the mentioned uncertainties, 10 of 14 papers do not record the 20th century as an exceptional flood period. Assessing the effects of human impact on paleoflood calendars and disentangling anthropogenic from natural drivers are major challenges in integrated paleoflood analysis.

It is concluded that the interpretation of flood series is complex as landscapes and flood drivers are heterogeneous and systems show different sensitivities to flood control and drivers. Thus, the study of past floods, from historical and natural archives, is challenging but also offers unparalleled opportunities to document low-frequency, large-magnitude flood events, which occurred under a broad range of climate and/or environmental scenarios, and, probably, the only way to reconstruct robust paleoflood series.

Keywords: Paleoflood hydrology; flood hazard; natural archives; documentary sources; multi-archive reconstruction; integration model.

1. The motivation of this Special Issue

The integration of multi-archive flood proxies to reconstruct flooding hundreds or thousands of years ago is like putting together a puzzle. In the beginning, the numerous pieces appear chaotic and confusing. But after struggling for some years or even decades, structure and eventually a diffuse picture becomes recognizable. This differs from an ordinary puzzle, however, because the number of pieces is not finite and the puzzle will never be finished. Although this might produce at a first glance a certain frustration, there are many other aspects which fully satisfy the expectations of scientists.

The first aspect is that the development of multi-archive flood records is a relatively modern approach. Over the last two decades, a growing number of studies have reconstructed flood records spanning centuries and millennia from fluvial sediments, lake deposits, speleothems or tree-rings (Baker, 1987; Benito et al., 2004; Schulte et al., 2008, 2009b; Wilhelm et al., 2012; 2019; Díez-Herrero et al., 2013; Wirth et al., 2013, Schillereff et al., 2014; Ballesteros-Cánovas et al., 2014; Santisteban et al., 2017; Denniston and Lütscher, 2017). These data series were largely confined to comparisons of paleoflood series with historical sources and instrumental measurement of discharge and precipitation. More recently, efforts were made to depict flood patterns across larger regions based on instrumental data covering half a century (Blöschel et al., 2017). At the same time, historians and geographers produced regional compilations also from historical sources (e.g. Röthlisberger, 1991; Glaser, 2001; Brázdil et al., 2005a, 2005b; Wetter, 2011; Macdonald and Sangster, 2017; Paprotny et al., 2018). Historical records and long instrumental records are mostly restricted to larger river towns (Pfister, 1999; Barriendos et al., 2014; Elleder et al., 2015; Wetter, 2017) whereas catchments in more remote regions, particularly mountain basins, are often ungauged and historical sources may be scarce (Schulte et al., 2009a, 2015). Since flood archives are embedded in different geographical and environmental settings, and their "perfect" study sites do not coincide geographically, paleoflood information is often fragmented.

Multi-proxy approaches have become standard in paleoenvironmental and paleoflood research (Santisteban et al., 2017; Wilhelm et al., 2019), whereas multi-archive studies *in sensu strictu* which integrate more than three different types of flood archives are extremely rare (Schulte et al., 2015). This presents opportunities for creative researchers to open doors to a fascinating world where they can explore, combine, disentangle and test several combinations of flood archives.

A second motivation is the attraction of multi-disciplinary research. It is exciting to meet researchers from other fields at conferences, workshops, field excursions, or on interdisciplinary field work and listen to them describe their approaches to researching floods. It is remarkable that they all look at the same physical process but use other archives, proxies, markers, thresholds and so on. For example, who could imagine that bioindicators such as algae and lichens in cm-small alveoli in canyon rock walls could provide information about floods? Therefore, it is vital for the paleoflood community to test reconstructed past floods through different techniques, methods, and scientific views.

A third aspect is the spatial dimension of the flood phenomenon. Different archives allow flood information to be obtained that better reflects the diversity of landscapes that experience flooding compared to studies that focus on only one type of archive. For example, in mountain regions, flood information can be obtained from high-altitude lakes, tree-rings and lichen colonization of river banks, gorge rock surfaces, and alluvial fan deposits at mid-altitudes, and from low-altitude floodplains and deltas (alluvial sediments, historical and archaeological evidence, pollen, etc.). In some basins, flood data can be obtained from multiple sites that differ in elevation by 1500 m or more within only a few kilometers (Schulte et al., this issue; Zaginaev et al., this issue). Another promising approach is the reconstruction of single flood events in terms of total flooded area, the propagation of the flood wave and the path of the precipitation field (Kiss, 2009; Elleder et al., this issue). Furthermore, where a high density of paleohydrological data is available, the production of paleoflood maps can improve our spatial understanding of flood dynamics (Röthlisberger, 1991; Schmocker-Fackel and Naef, 2010; Barriendos et al., this issue; Schulte et al., this issue). In this context, a further methodological innovation is the reconstruction, reanalysis and modelling of synoptic sea level pressure maps of extreme flood episodes, which improve our knowledge about atmospheric variability as a flood driver (Ortega et al., this issue; Peña and Schulte, this issue; Sánchez-García et al., this issue, Schulte et al., this issue).

2. Foci of the PAGES Floods Working Group

The exposed range of opportunities is one of the reasons why multidisciplinary analysis and multi-archive reconstruction of paleofloods define one of the three core activities of the Past Climate Changes (PAGES) Floods Working Group since its founding in 2015. According to the White Paper (PAGES - Floods Working Group, 2017), the Working Group "aims to bring together all the scientific communities reconstructing past floods (historians, geologists, geographers, etc.) and those studying current and future floods (hydrologists, modelers, statisticians, etc.) to coordinate, synthesize and promote data and results on the natural variability of floods". Also in 2017, the Floods Working Group launched three work packages (WP): WP1 focuses on collecting, storing and sharing of global paleoflood data, WP2 on integrating and analyzing paleoflood data and WP3 on communicating and disseminating paleoflood science and data at different levels, including stakeholders. Conference sessions of the WP2 topic were organized in 2016 during the first Floods Working Group Workshop in Grenoble and in 2017 on the PAGES Open Scientific Meeting held at Zaragoza. Also in 2016 several members of WP2 launched a pilot project of paleoflood data integration in the Swiss Alps. The results of the first phase of this research of geographers, historians, geologists, and geochemists are presented in the paper of Schulte et al. entitled "Integration of multi-archive datasets towards the development of a four-dimensional paleoflood model in alpine catchments" in this

Special Issue. These research activities will continue during the second phase (2019-2021) of the FWG Program.

3. Societal demand for multi-archive reconstruction of paleofloods

Floods are one of the gravest natural hazards for societies, worsened by population growth, unchecked development and climate change (UNISDR, 2015). So, the transfer of long flood series to public agencies is crucial for producing reliable evaluations of floods and societal risk. However, although policies have been developed (e.g. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks; Real Decreto 903/2010, of July 9th, Assessment and management of floods), the integration of paleoflood studies into spatial planning and flood risk assessment is not sufficiently applied. From a Global Change perspective (Baker, 2006), past extreme events are of interest as they can be linked to climate and environmental changes, introduce perturbations in natural systems and can be traced in paleoenvironmental archives. Hence, paleoflood research is a rapidly developing approach through which insight from multiple disciplines (hydrology, geomorphology, climatology, paleolimnology) has implications for human life as its goal is to understand and quantify flood risk over extended periods of time.

During the last decade, knowledge of flood frequency and magnitude has improved through data coming from different types of archives (Baker, 1987; Benito et al., 2004; Schulte et al., 2015; Schillereff et al., 2016; Wilhelm et al., 2019). But, despite advances in dating methods, proxies and statistical techniques and efforts to identify atmospheric drivers, some fundamental questions remain unresolved. The interpretation of flood series is complex as landscapes and flood drivers are heterogeneous and systems show different sensitivities to hydrometeorological forcings. Thus, the study of past floods using historical and natural archives is challenging but also a rare opportunity to document low-frequency, large-magnitude flood events. Long-term studies also allow trends in flooding that occurred under a broad range of climate and/or environmental scenarios to be explored, which is probably the only way to reconstruct robust paleoflood series. This issue addresses these uncertainties and complexities by assembling a selection of studies with a global geographical distribution (high to low latitude, from mountains to lowlands) and provide an insight about present state on multi-source data (lakes, floodplains, geomorphology, tree-rings, historical and archaeological sources, soils, marine sediments, etc.), controls/drivers and time-scales integration (from Pleistocene to present time) plus methodological and societal issues in paleoflood research.

4. Contents of contributions to multi-archive paleoflood reconstruction

The compilation of this Special Issue, which includes 17 research papers, is the outcome of the PAGES OSM Conference session entitled “Multidisciplinary reconstruction of paleofloods”. Sixteen oral contributions and 18 posters from most continents were presented and lively discussed. The papers showcase substantial progress in the analysis and interpretation of flood archives, important methodological advancements, including innovative approaches to integrate and model diverse archives and flood series, and a focus on remote regions with difficult access.

The research papers of Santisteban et al. (this issue) and Fuller et al. (this issue) are case studies from Central Spain and New Zealand that demonstrate how high-resolution, continuous geochemical flood proxies can be inferred from alluvial sediments that span most of the Holocene. Santisteban et al. (this issue) use several geochemical ratios as proxies for water competence, water level, and sediment discharge to reconstruct flood pulses. Similarly, Fuller et al. (this issue) estimated the flood recurrence interval using normalized Zr/Rb measurements and a tight age-depth model in a volcanically-reset catchment.

The studies of Agatova et al. (this issue) and Lombardo et al. (this issue) focus on large-scale flood areas in Asia and South America which are difficult to access. In south-western Amazonia, Lombardo et al. (this issue) combined proxies such as phytoliths and stable carbon isotopes from sedimentary flood archives and soils to provide a solid reconstruction of past Holocene land cover change and periods of low or modest flooding. Agatova et al. (this issue) used geomorphological, geological and geoarchaeological data to reconstruct the presence of Late Pleistocene ice-dammed lakes and cataclysmic outburst floods in the Mongolian Inland Drainage Basin. A multi-century dataset of regional glacial outburst floods (GLOF) is presented by Zaginaev et al. for the Tien Shan (Central Asia). These high discharge flash-floods were reconstructed by tree-ring analyses from six different torrential fans providing insights on regional process activity.

A different approach is adopted by the following four papers: extracting evidence from documentary archives to produce regional centennial flood series. Barriendos et al. (this issue) provide 18 extensive flood event chronologies for the Spanish Mediterranean coast from 14th to 20th centuries. They discuss the profound influence of social factors on historical flood data series and evaluate methods of integrating multi-source information such as population and flood protection measures. This human component also affects the 450-year reconstruction of historical discharges performed by Sánchez-García et al. (this issue) from semi-arid South-eastern Spain. Furthermore, the synoptic atmospheric configurations of four catastrophic flood events were investigated. In the River Jing catchment, southern Chinese Loess Plateau, Yu et al. (this issue) identified decadal solar activities as an important driver for floods and droughts. Multiple documentary sources and a precipitation-runoff model were used by Elleder et al. (this issue) to explore the spatial imprint of the 1872 flash-flood in central Bohemia and model the river's runoff response.

Another five papers deal with paleoflood reconstruction and flood frequency analysis using lake records. Evin et al. (this issue) propose a novel statistical approach that combines a classic series of paleoflood observations for the Rhône River reconstructed from lake sediments (Lake Bourget, Northwestern Alps, France) and disseminates uncertainties related to the reconstruction method during the estimation of extreme quantiles. Albrecher et al. (this issue) applied a change-point analysis to sedimentary flood frequency data from six large alpine lakes. This enabled a comparison to be made with other flood records and possible links to be drawn between event frequencies and climatic conditions. Corella et al. (this issue) present a new method for estimating seasonally-resolved flood erosion rates using millennium-long varved lake sediments. Their use of high-precision, multi-proxy data also sheds light on the main environmental drivers (climatic or anthropogenic) controlling sediment yield in a mountainous Mediterranean watershed. The respective roles of human and climate forcings on

Holocene flood frequency were also investigated by Rapuc et al. (this issue) in Lake Iseo (Southern Alps). Similarly, Schillereff et al. (this issue) showed that detailed sub-sampling and proxy analysis based on particle size data, coupled with careful evaluation against independent hydrological data and accounting for variations in external sediment supply potentially driven by anthropogenic landscape modification, is an appropriate methodology to extract paleoflood records from temperate lakes.

To explore climatic forcing of floods Peña and Schulte (this issue) performed a paleoclimate modeling experiment of the atmospheric variability related to large summer floods in the Hasli-Aare (Swiss Alps) from the AD 1300 to 2010. They propose the name of paleo-SNAO to define this decadal atmospheric variability related to summer floods in the alpine catchment.

Schulte et al. (this issue) designed an innovative methodology that integrates multi-archive datasets towards the development of a spatial-temporal (four-dimensional) paleoflood model in alpine catchments. The most continuous and accurate series from natural and anthropogenic flood archives were integrated over the period from AD 1400 to 2005 into a synthetic flood master curve for the Bernese Alps.

Ortega et al. (this issue) analyzed extreme ENSO-driven torrential rainfalls at the southern edge of the Atacama Desert during the Late Holocene and their projection into the 21st century. The integration of marine paleoclimate proxies, historical data, and the future projection helps to understand oceanic and climatic factors conditioning the variability of extreme rainfall events.

5. Geographical location and meta-data of paleoflood records

The 17 papers of the Special Issue present a diverse body of work in terms of i) geographical distribution (four continents, northern and southern hemisphere; Figure 1); ii) types of paleoflood archives; iii) numbers of flood series compiled; iv) spatial and temporal resolution and v) methodologies applied for the integration of flood data (Table 1).

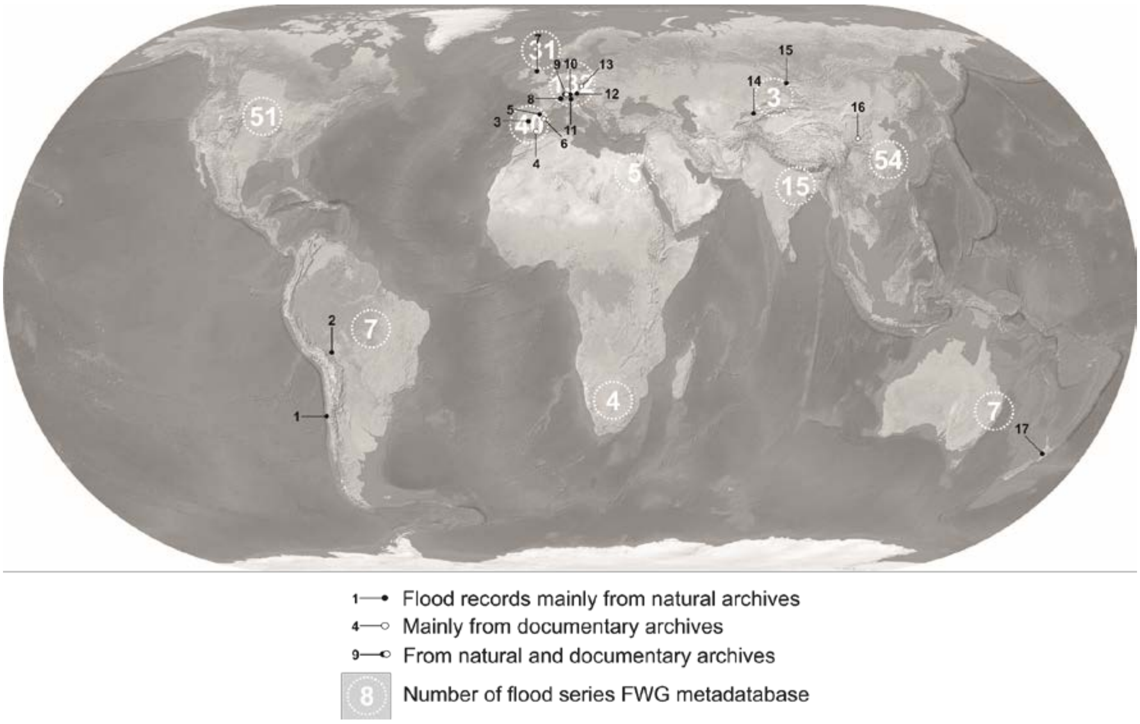

Figure 1. Location of the case studies (black numbers) presented in the research papers of this Special Issue. The ID of each paper is listed in Table 1. White numbers encircled presents the number of studies recorded in the paleoflood metadatabase of the PAGES Floods Working Group for each region (PAGES-FWG, http://www.pages-igbp.org/ini/wg/floods/wp1/data, date of access January 10th, 2019).

Figure 1 reflects two types of data: the papers presented in this Special Issue (black numbers) and the regional distribution of studies recorded in the paleoflood metadatabase of the PAGES Floods Working Group (FWG; http://www.pages-igbp.org/ini/wg/floods/wp1/data, white circled numbers). More than half of the studies archived in the FWG databank are located in Europe. More than 50 studies were carried out in North America as well as in China, 15 in India, whereas low numbers are recorded in Australia/New Zealand, Central Asia, Africa, and South America. 36% of these records were obtained from historical documents, 33% from riverine sediments, 29% from studies of lake sediments and tree rings and, finally 2% from speleothems (PAGES Floods Working Group, 2019). These numbers and consequent distribution do not include all worldwide published works but may reflect some general trends. The high numbers obtained in Europe reflect the intense research activities in the field of paleoflood reconstruction across the continent, but, on the other hand, these numbers are also influenced by the location of organized workshops and annual meetings, the hosting of the PAGES office and members of the FWG steering committee and the lower level of cooperation with researchers from other continents. For example, in recent years several European researchers (many active in the FWG network) attended paleoflood conferences organized by US researchers (e.g. Rapid City 2016) and vice versa, but no joint conference has yet been organized by both communities. The paleoflood community is in a similar situation with regard to links with Asia.

In addition to the innovative topics and methodological progress of the presented research papers, the metadata of these case studies presented in Table 1 provides interesting insight into the structure of multi-archive paleoflood approaches. According to Table 1 and Figure 3, the papers presented in this special issue can be subdivided into different groups. The first group includes papers which present flood series from alluvial and fluvial depositional environments and landscapes; the second group reconstructs flood calendars from historical sources, and the third investigates past floods from lake deposits.

Finally, there are contributions that focus on flood records from tree-rings and marine sediments or integrate numerous types of flood archives.

		Multi	Botanical	Marine	Alluvial sediments and soils				Documentary sources				Lake sediments					Model
Basic meta data	**Research papers of Special Issue**	**Schulte et al.**	**Zaginaev et al.**	**Ortega et al.**	**Santisteban et al.**	**Agatova et al.**	**Lombardo et al.**	**Fuller et al.**	**Elleder et al.**	**Sánchez-G. et al.**	**Barriendos et al.**	**Yu et al.**	**Evin et al.**	**Corella et al.**	**Rapuc et al.**	**Schillereff et al**	**Albrecher et al.**	**Peña & Schulte**
	Reference in Figure 1	9	14	1	3	15	2	17	13	4	6	16	8	5	11	7	12	10
	Location of study area	46°41'N 6°04'E	74°33′E-74°48′E 42°25′N-42°42′N	32°S-26 °S 71°43′W-69°28′W	39°5′N 3°45′W	50º15´N-49º45´N 89º45´E-90º10´E	14°30′S 65°00′W	39°43′S 175°09′E	49°57'N 14°04'E	37º12′N 1º46′W	35°50'N-43°34'N 5°58'W-4°30'E	34°48'N-36°12'N 107°14E-108°40'E	45° 43′N 5° 52′E	42º19´N 0º59´E	45°44′N 10°4′E	54°30'N 2°55'W	47°48'N 13°23'E	46°41'N 6°04'E
	Total catchment area (km2)	2117	145	no data	26232	no data	78000	7380	8286	2611	156930	16057	4000	1.39	45	13,01	241	596
Types of archives analyzed for regional flood series	Sediments (Stratigraphy, geochemistry)	4	6		3 (12)	2 (15 sect.)	4	1 (3)										1
	Landforms: flood plains, terraces, alluvial fans	3				2 (basins)	4											
	Soil sequences	4				2 (15 sect.)	4 (37)											
	Mapping, aerial photographs, GIS	3	6				4											
	10Be erosion rate data							1										
	Lichenometry	4																
	Dendrochronology/Dendromorphology	[1]	6															
	Palynology	[1]												1				
	Documentary sources (flood series)	6	6	1	2			1	2	1 (4)	18	1 (10)				1	[1]	1
	Documentary sources (drought series)				1							1 (10)						
	Flood series from flood marks	[1]							10									
	Archeological sites	1			1	2									[1]			
	Precipitation records (meteorological stations)	[4]		1	[11]				12	2	18			1				
	Instrumental records (gauging stations)	7			4			1	9	3	18		1			3	[1]	
	Lake sediments	4											1 (32)	1	1	1	1 [5]	
	Marine sediments			1														
	Geophysical sections				1									1	1			
	Variability of glaciers	[2]	6															
	Climate reanalysis / modeling (CESM at NCAR)	1		1						1								1
	Hydraulic / Hydrological modeling	[1]							1									
	Total of sytematically analysed archive	10	5	4	6	4	4	4	5	4	3	2	2	4	2	3	1	3
Time	Max. range of flood series (cal yr AD)	1400	1874	1301					1872	1550	1301	1646	1650			450		1300
	Max. range of flood series (cal yr BP)	3600			9500	>11600	10000	1770						2775	12000		7096	
Resolution of flood series	exact day	1	1						1	1	1	1						1
	seasonal	1	1						1	1	1	1		1				1
	annual	1	1						1		1	1	1	1		1	1	1
	intradecadal	1		1	1								1	1	1	1	1	1
	decadal	1			1			1					1	1	1	1	1	1
	multidecadal				1			1										
	centennial						1											
	multicentennial						1											
	millennial					1	1											

Table 1: Metadata of Paleoflood case studies published in the Special Issue. A) Numbers of different types of archive analyzed to compile regional flood series. Legend: 2 = number of analyzed flood series (one series per type of archive and catchment, region or area). If data is available: (2) = number of records; [1] = punctual data record or data not explicitly discussed in paper

The number of systematically analyzed types of flood archives listed in Table 1 varies significantly between papers. Seven studies - primarily investigating historical sources and lake sediments - draw on one to three types of archives; nine papers incorporate four to six types of archive and one paper utilizes up to ten. The meta-data indicates that paleoflood studies focused on fluvial depositional environments show a higher rate of integration of different types of paleoflood archives (mean of 4.5 types of archives) than studies focused on documentary sources (mean of 3.5) and lake sediments (mean of 2.4).

Papers in this Special Issue present paleoflood reconstructions over variable time periods, ranging from one and a half centuries (tree rings; Zaginaev et al., this issue) to the Early Holocene (lake and alluvial flood records; Rapuc et al., this issue; Santisteban et al., this issue) while the reconstruction of catastrophic floods from the Mongolian Great Lakes Basin reaches back to the Late Pleistocene (Agatova et al., this issue). The highest temporal resolution (exact dates, seasonal and annual flood information) were obtained by studies using documentary sources or papers that combine natural flood archives (e.g. tree rings and varved lake sediments) with documentary and instrumental data. It is striking that most approaches exploiting natural archives (except soils and fluvial landforms) achieve a temporal accuracy of decadal or better.

With regard to the spatial scale, large differences in the size of study areas and catchments are noticeable in Table 1. Catchments smaller than 100 km^2 are associated with lake reconstructions, whereas larger areas of more than 50,000 km^2 were studied by papers focused on landscape, landform and soil development. Barriendos et al. (this issue) submitted the paper with a total area of 156,930 km^2, which presents documentary flood records from 18 catchments spanning the Mediterranean slope of the Iberian Peninsula.

6. How are paleoflood archives combined and integrated?

A possibility to develop a conceptual framework for multiple-archive paleoflood integration is the performance of a qualitative approach (PAGES - Floods Working Group, 2017). However, statistical processing of the meta-data from paleoflood studies published in this Special Issue could provide valuable insight. This testing shows associations between different types of flood archive, achieving a solid background for the design of an integrated multi-archive paleoflood approach.

The variables (number of flood archive types analyzed for generating paleoflood series) presented in Table 1 were transformed into a binary system and introduced into a matrix. Factor analysis (FA) was performed to explore the variability of flood archives across the 17 studies. Figure 2 shows the 2-dimensional plot of the first two factors explaining 34% (F1) and 19% (F2) of the variability. The following groups are identified: (i) fluvial and terrestrial archives (red circle); (ii) botanical archives (green circle); hydrological archives (light blue circle) and (iv) precipitation, discharge measurements and documentary sources (blue circle). The variables climate modeling, lake sediments, and marine sediments show a more scattered distribution.

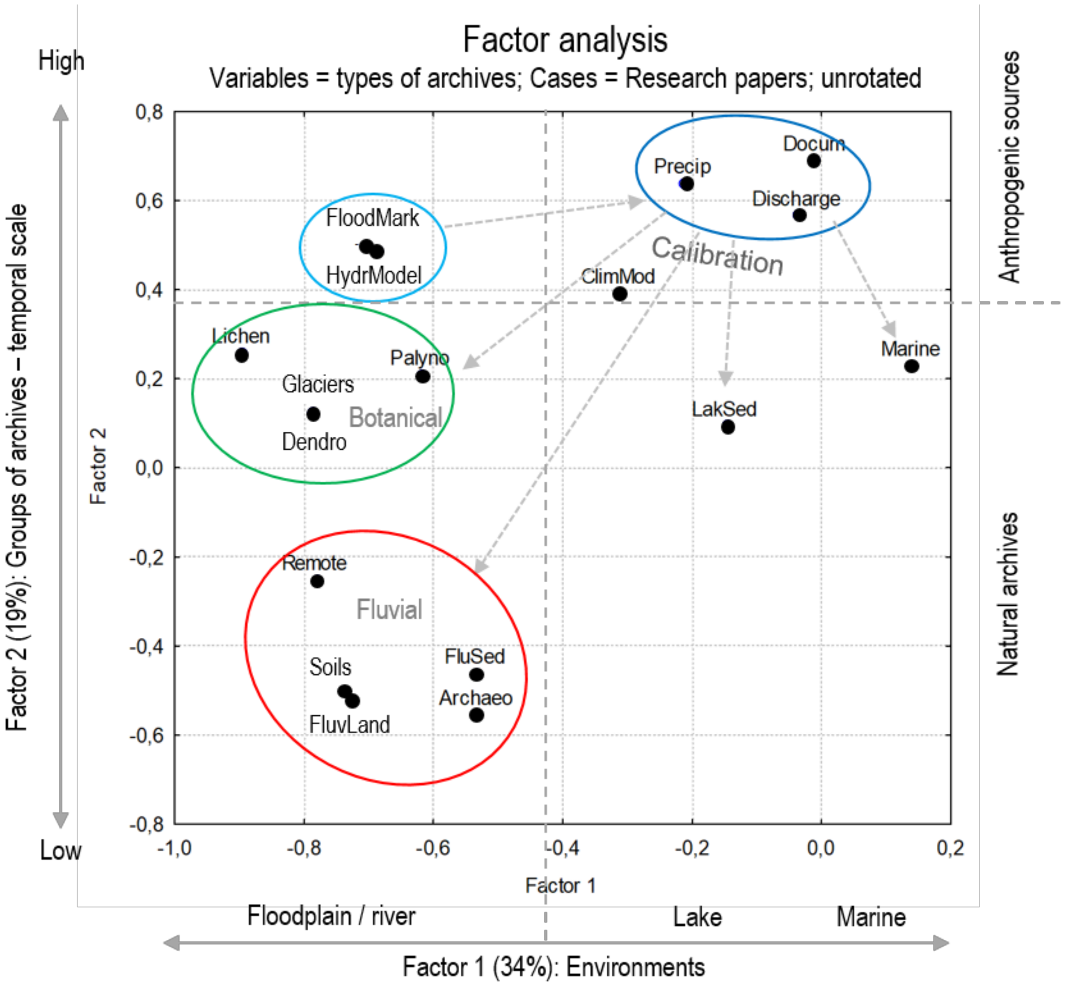

Figure 2: 2-D plot of the first two factors explaining the variability of types of archives analyzed by the research papers in this Special Issue.

The factor F1 is interpreted as the range of environments of natural flood archives: floodplain and river environments show negative loadings, whereas subaquatic (lakes and marine) archives show positive loadings. The second factor reflects the temporal resolution of archives from low (millennial-scale resolution of fluvial landforms and soils) to high (exact hour and/or day of river discharge, documentary sources, flood marks and precipitation records). This distribution is similar to the 2-D plot (not shown) where temporal resolution (Table 1) is included in the FA matrix as an additional binary variable. Another interesting outcome is the clear division (0.3 F2 loading) between natural archives and anthropogenic sources (Figure 2).

Our explanation for this variability is that high-resolution lake records are mostly calibrated against instrumental records of discharge and precipitation as well as documentary sources at annual and, in the best cases, seasonal resolution (Corella et al., this issue; Evin et al., this issue). Accurate calibration can also be applied in the studies of tree-rings and lichens. However, the botanical archives show a closer relationship with the group of fluvial archives, landforms, and soils because they are also used when dating flood deposits, flood levels, and impacts (Schulte et al., this issue; Zaginaev et al., this issue).

Terrestrial archives such as fluvial landforms, deposits, soils, and archeological sites provide flood information at lower temporal resolution than e.g. lakes but they can explain the spatial scale of flooding more accurately (Agatova et al., this issue; Lombardo et al., this issue). With regard to the fluvial sediments in floodplains, the studies of Fuller et al. (this issue), Santisteban et al. (this issue) and Schulte et al. (this issue) demonstrate that fluvial deposition mirrors sensitively severe and medium-magnitude floods.

7. Perspectives of the integration of paleoflood archives

To understand the epistemic concepts of paleoflood research, the thematic relationships relationship between the 17 research papers of the Special Issue were explored. Factor analysis (FA) was performed from the binary matrix (chapter 3), where research papers are variables and flood archives analyzed by each study are considered as cases. The 2-dimensional plot of the first two factors shows the distribution of the research papers. Below the citations (values), the types of flood series, generated by each study, are listed additionally.

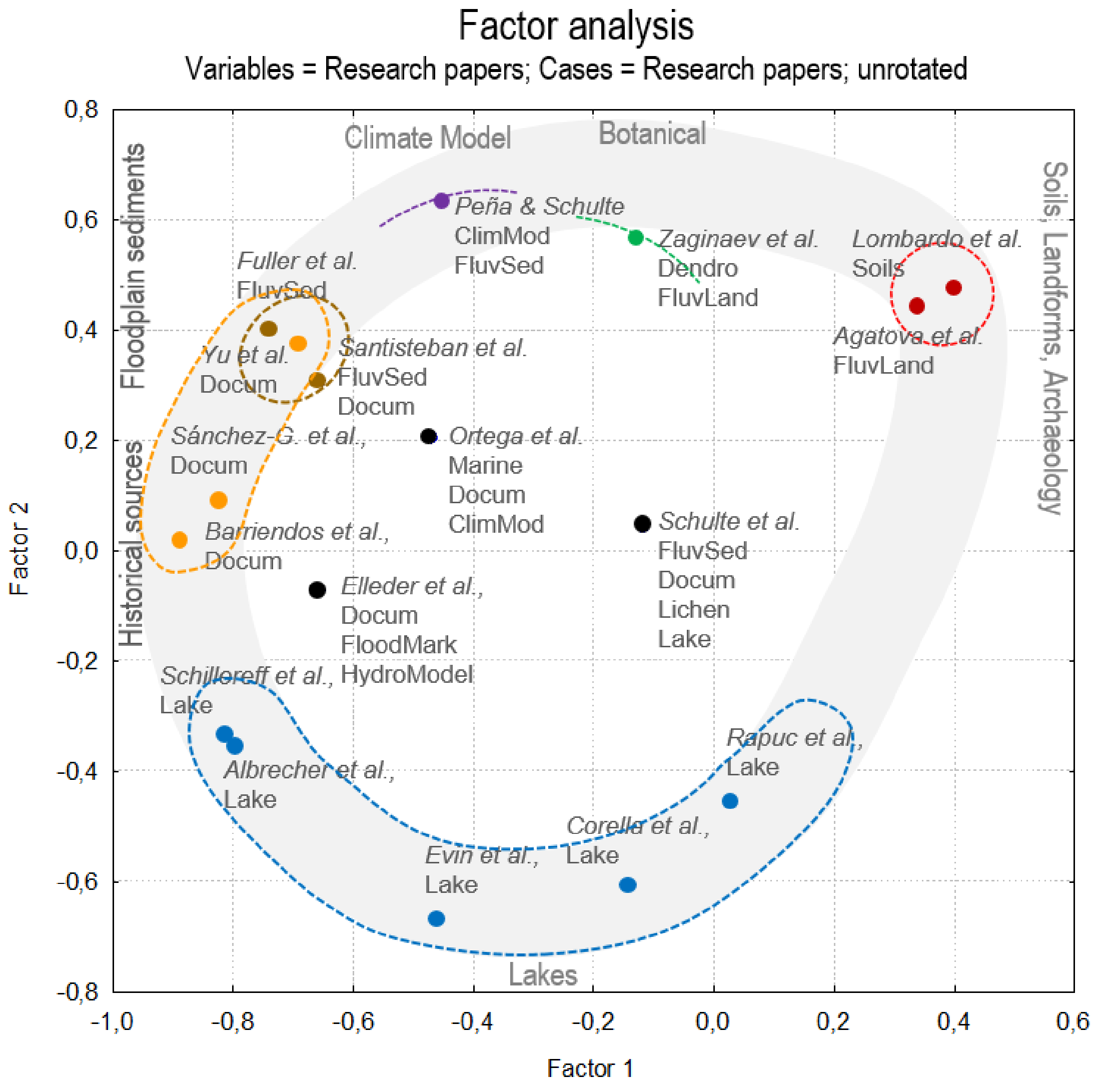

Figure 3: 2-D plot of the first two factors explaining the variations and associations of the 17 paleoflood approaches presented in the Special Issue. The matrix is defined by binary data of analyzed types of archives. Below the references, the types of flood series generated by each study are listed. Note that the number of generated flood series is lower than the total of flood archives used for the compilation of flood series.

The 2D-plot in figure 3 presents a very clear structure. Papers that used data from 2 to 4 different types of flood archive are located around the periphery, essentially defining a circle (grey shading). Those papers which focus mainly on lake records are located at the bottom (negative loadings of F2). The different factor F1 loadings of these studies result from the fact that Schillereff et al. (this issue) and Albrecher et al. (this issue) compare their records with historical sources and instrumental discharges (also Evin et al., this issue), whereas Corella et al. (this issue) consider palynological data and Rapuc et al. (this issue) provide a calibration using precipitation records.

Papers that primarily explore historical sources of flood information (Barriendos et al., this issue; Sánchez-García et al., this issue; Yu et al., this issue) are situated on the left (strong negative loadings of F1) and show a close relationship to the studies of floodplain sediments (Fuller et al., this issue; Santisteban et al., this issue). This association arises from the fact that both types of archives - documentary evidence of damage and flooding of settlements and infrastructure on one hand, and aggradation of overbank deposits, on the other - are sourced from similar areas of a catchment, e.g. in the floodplains of river valleys and deltas (Schulte et al., this issue).

The loadings and associations of the only paper exclusively dedicated to paleoclimate modeling (Peña and Schulte, this issue; strong positive loading of F2) result from the fact that the flood periods of this model were inferred from geochemical floodplain proxies. The dendromorphological paper presented by Zaginaev et al. (this issue) is positioned a relatively short distance from the two papers dedicated to landforms, soils and archaeology (Lombardo et al., this issue; Agatova et al., this issue; positive loadings of F1 and F2), since trees were sampled on alluvial cones for the reconstruction of flash-floods and debris flow dynamics. The works of Agatova et al. (this issue) and Lombardo et al. (this issue) take slightly eccentric positions because these approaches are not strictly related to the analysis of flood records but rather on fluvial landscape and soil development.

Those papers that show the strongest degree of multi-disciplinary research and the highest number of integrated flood series are located in the center of the circle (Figure 3). Furthermore, they performed climatological or hydrological modeling. In the case of the study of Elleder et al. (this issue), the authors analyzed one single flood episode reconstructing the propagation of the 1872 flooding by different documentary and instrumental archives. The study of Ortega et al. (this issue) focuses on marine, documentary and instrumental archives. Finally, the widest range of methodologies and archives are presented by the research cluster of the Bernese Alps (Schulte et al., this issue), where fluvial, lake, documentary and lichenometric flood series are integrated (Table 1).

Despite the rather modest number of cases (defined by the papers published in this special issue), this factor analysis helps elucidate the different yet complementary approaches of palaeoflood research.

Thus, the distribution of papers and type of flood series (variables in Figure 3) were integrated into the conceptual model presented in Figure 4.

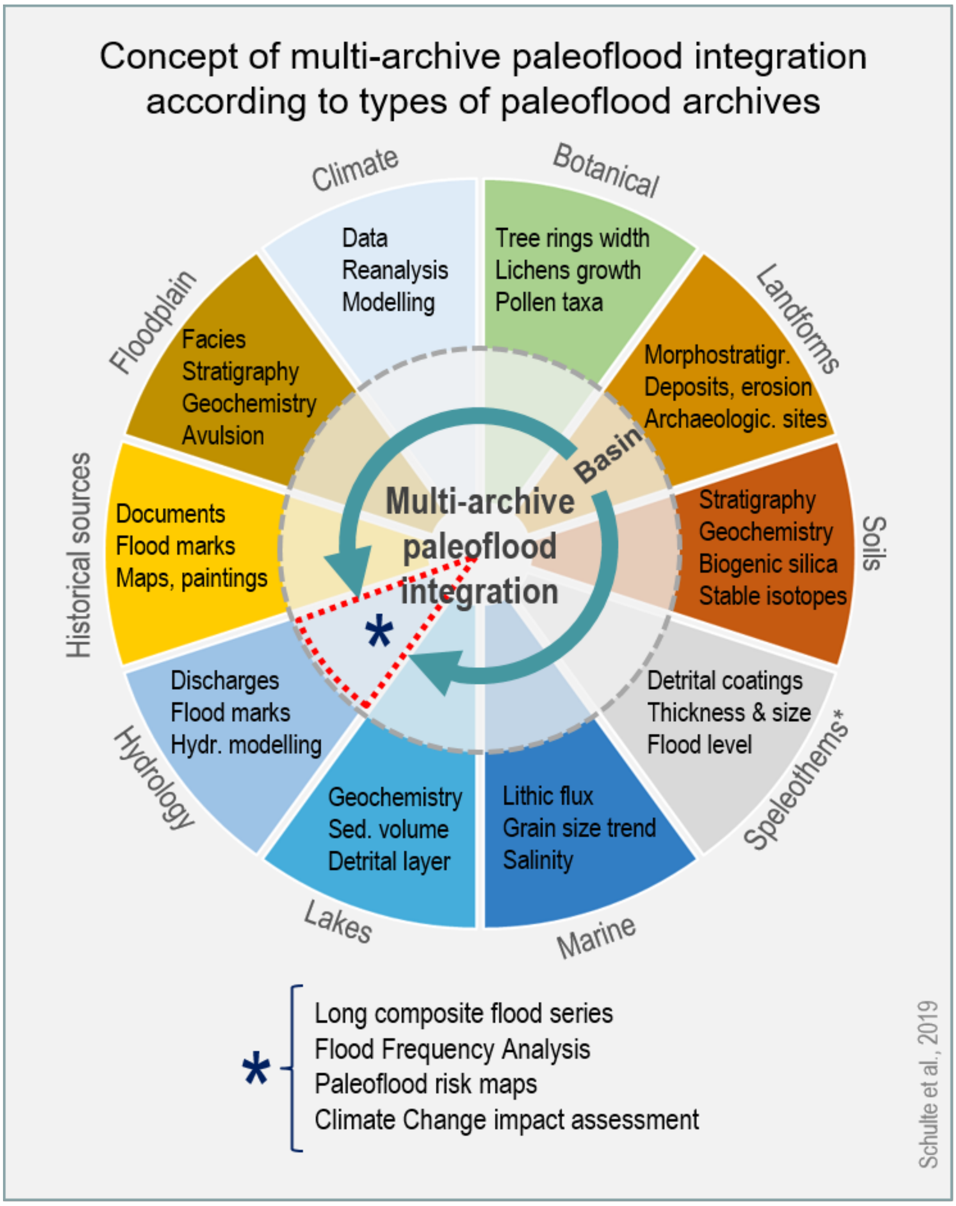

Figure 4: Concept of multi-archive paleoflood integration according to the type of flood archive. The assembly of the type of flood series mirrors the distribution of papers and constructed flood series shown by the 2D-plot of the Factor Analysis of figure 3. Thus, the concept is not only based on a qualitative background but also on an empirical background inferred from the metadata of Table 1. Paleoflood records from speleothems* were not presented by any case study of the Special Issue, but they were included to complete the concept.

The conceptual model is structured in the form of a pie chart, in which each slice represents a type of paleoflood archive. Their arrangement is guided by their nature and statistical association (Figure 3). Furthermore, each slice assembles the most commonly used paleoflood proxies or techniques applied to that type of archive. These archive types (external boundary of the chart) largely correspond to scientific disciplines focused on analyzing past floods. The (sub-) horizontal slices in the middle (vertical order) represent terrestrial archives (geosphere), including floodplains, soils, and landforms as well as historical sources. On top of the geosphere are located botanical archives (biosphere) and climatological data series (atmosphere). Slices at the bottom of the conceptual model are associated with the hydrosphere and subaquatic archives: hydrological and hydraulic data from rivers, sedimentary and environmental archives from lakes and oceans and speleothem proxies from subsurface flooding.

All these flood archives can be integrated by means of statistical processing (inner circle) to compose synthetic regional flood records that reflect flooding up to basin-scale. At these points, it has to be stressed again that the combination of proxies (and archives) and their statistical processing are presented in Table 1 and Figures 2 and 3.

Finally, robust multi-archive flood records can provide accurate information for fundamental concerns of society (bottom of Figure 4):

i) Centennial and millennia-long flood calendars allow clusters of extreme events to be detected as well as changes in trends of flood frequency and magnitude during periods of changing cold/warm and dry/wet climate pulses and periods (Schulte et al., 2008, 2009a, 2015; Wilhelm et al., 2012);

ii) Flood Frequency Analyses (FFA) based on long time series of field evidence (“real flood evidence”) of extreme floods can account for changes in the pattern of flooding during different climate conditions and cycles (i.e., non-stationarity; Knox, 2000; Mudelsee et al., 2003);

iii) Compiling spatial information of paleofloods in thematic maps contributes fundamental information on local hazard and risk, thus improving river and flood management and ensuring appropriate spatial planning (Röthlisberger, 1992; Schulte et al., 2009b, this issue; Geoportal des Kanton Bern, 2018);

iv) The holistic knowledge of flood dynamics during past climate periods (e.g. RWP, DA, MCA, LIA) is critical for the assessment of the impacts of flooding in the context of Climate Change (Global Warming).

To conclude, the strong arguments in favor of integrated paleoflood approaches are the possibility of cross-calibrating independent proxies of past floods from different archives and bringing to light the flood phenomena from different perspectives. This diversity of foci on past floods and internal validation should reduce uncertainties and help to identify unusual data in flood series.

8. Major trends and drivers of paleoflood series

Despite the heterogeneity of the presented records in terms of sources, settings and timescales, a qualitative comparison between the flood series reveals some consistent patterns. The most evident structural elements in Figures 5 and 6 are: i) similar trends in frequencies and magnitudes of flooding; ii) periods of noticeable higher activity (“event periods”); and iii) “breaks” at which an abrupt fall in values occurs where thresholds in fluvial and erosional systems have been exceeded.

Relatively few records of multi-millennial timescale (Fig. 5) are presented, and they are all based on sedimentary reconstructions. Most long records show an overall trend of increasing flood frequency/magnitude from ca. 4 to 5 ka BP, with some earlier episodes of high fluvial activity in Amazonia (before 8 ka BP; Lombardo et al., this issue) and central Spain (from 8.5 to 7 ka BP; Santisteban et al., this issue). Patterns of flooding around the world during the last five millennia show more complexity, which could relate to: i) the higher temporal resolution of available archives; ii) the higher number of shorter flood records; iii) the use of documentary sources and a wider range of natural archives spanning the last millennium; and iv) the progressive intensification of human impact on the landscape and river systems (Fig. 6). Flood regimes during the last few millennia are typically characterized by longer (many decades to centuries) periods of increased flood activity punctuated by short or abrupt drops in flood occurrence (e.g. 2.2 ka BP at site 3, 1.5 ka BP at site 5, 1.8 ka BP at site 11 and 12 in figure 5). However, it is important to note that these gaps do not occur synchronously (Fig. 5).

Whereas flood activity increases through the mid-Holocene in most records, (i.e. Albrecher et al., this issue; Rapuc et al., this issue; Santisteban et al., this issue), the picture of flood trends for the last 2500 years is much more diverse. Rapuc et al. (this issue) show an overall decrease in flooding activity while Albrecher et al. (this issue), Ortega et al., (this issue) and Santisteban et al. (this issue) show an increase until the last centuries.

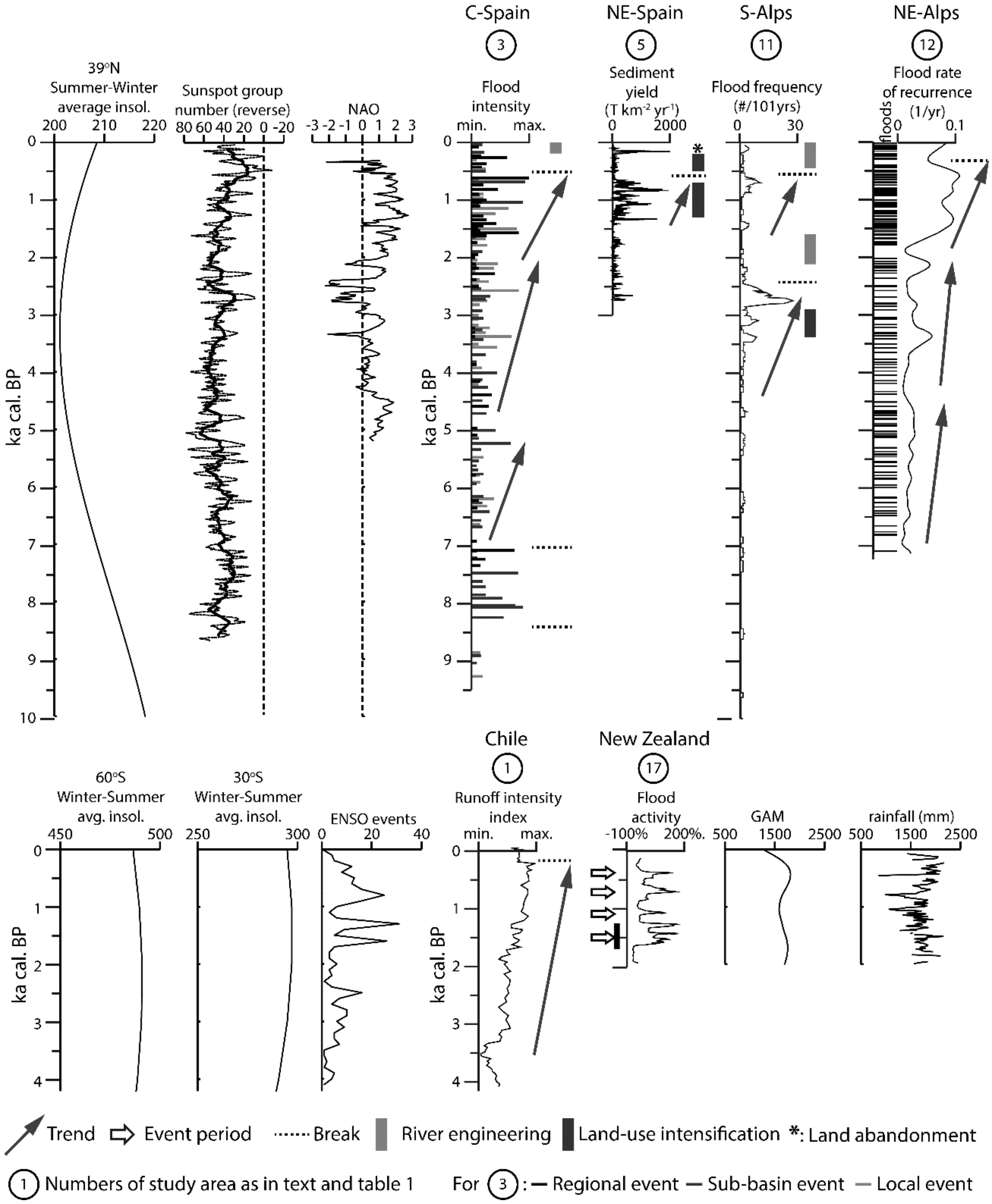

Figure 5.- Millennial-scale flooding episodes according to research papers in the Special Issue and their relation to solar activity (sunspot group number and 21-points [210 years] moving average: Wu et al., 2018; 39ºN summer-winter difference calculated using the R package 'palinsol', Crucifix, 2016, using the calculations of Berger and Loutre, 1991) and NAO index (Olsen et al., 2012) for European records and insolation at 60ºS and 30ºS (Berger and Loutre, 1991), ENSO events (Moy et al., 2002) and ENSO-related GAM and rainfall episodes in subtropical Australia (Barr et al., 2019) for the Pacific records. References of paleoflood studies: site 3 =

Santisteban et al. (this issue); site 5 = Corella et al. (this issue); site 11 = Rapuc et al. (this issue); site 12 = Albrecher et al. (this issue); site 1 = Ortega et al. (this issue); site 17 = Fuller et al. (this issue).

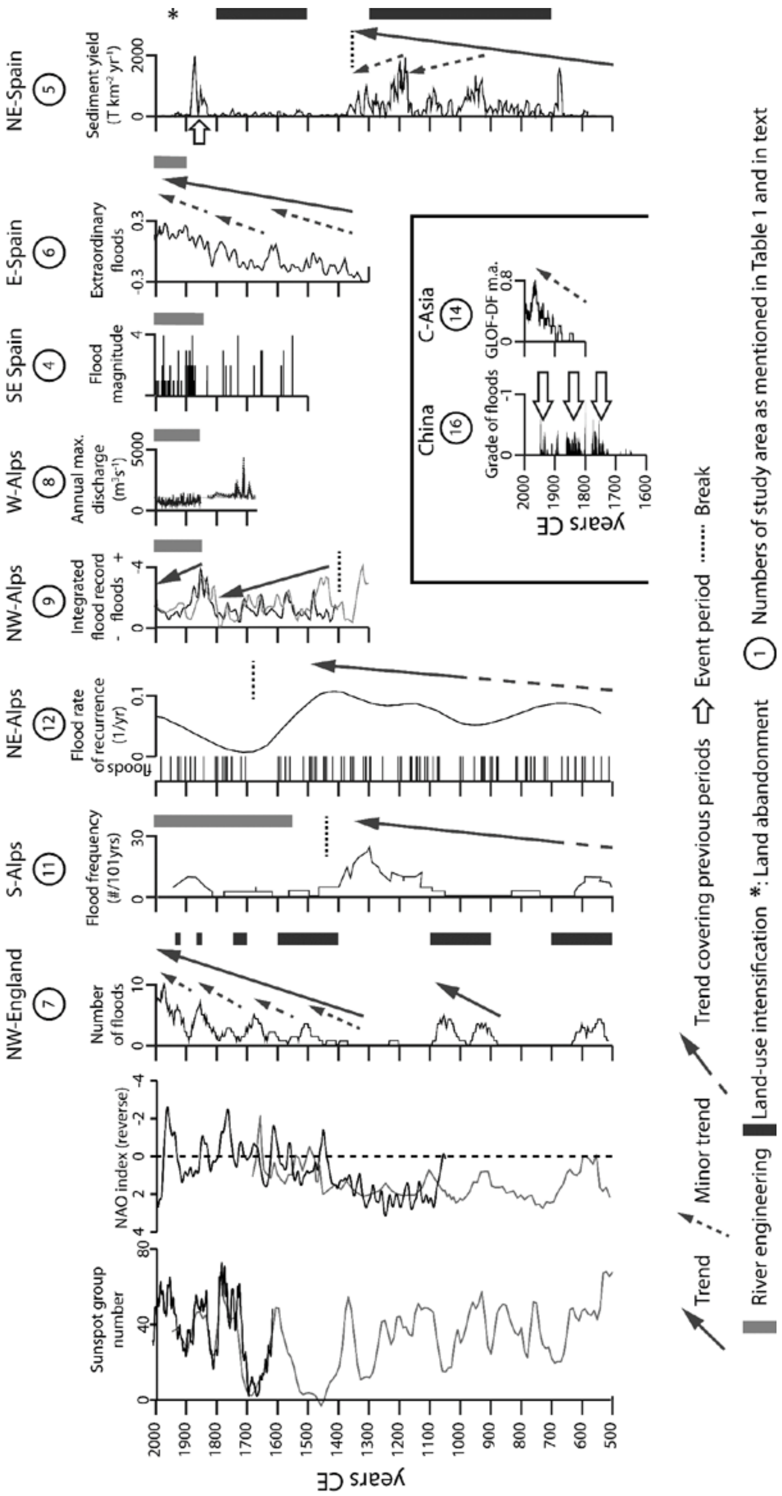

Figure 6.- European flood records spanning the last 2000 years, NAO (in reverse scale) (grey: Olsen et al., 2012; black: Trouet et al., 2009) and sunspot reconstructions (grey: Usoskin et al., 2014; black: WDC-SILSO, Royal Observatory of Belgium, Brussels http://sidc.be/silso/home). Similarities emerge in trends and periods of sunspot, NAO and flooding activity. There is a stronger link between NAO and flooding than at the millennial time-scale. References of paleoflood studies: site 7 = Schillereff et al. (this issue); site 11 = Rapuc et al. (this issue); site 12 = Albrecher et al. (this issue); site 9 = Schulte et al. (this issue); site 8 = Evin et al. (this issue); site 4 = Sánchez-Garcia et al. (this issue); site 6 = Barriendos et al. (this issue); site 5 = Corella et al. (this issue); site 16 = Yu et al. (this issue); site 14 = Zaginaev et al. (this issue).

Figure 6 presents ten data-rich paleoflood records that span the last 1.5 ka and show similar variability (Fig. 6). Whilst most records show an increasing trend over this period, there are exceptions.

This heterogeneous pattern continues towards the present, when human action has become an increasingly important driver. Records showing sudden decreases (i.e. Corella et al., this issue; Ortega et al., this issue; Schulte et al., this issue) coincide at times with periods of increasing activity elsewhere (i.e. Barriendos et al., this issue; Schillereff et al., this issue; Zaginaev et al., this issue). These changes have been attributed by the authors to different natural forcings, depending on the period and timescale. For the millennial timescale, Rapuc et al. (this issue) and Santisteban et al. (this issue) relate the long-term trend to changes in insolation that could have affected seasonality and the persistence of atmospheric patterns (Fig. 5). Over shorter intervals, a number of regional ocean-atmosphere processes have been invoked as important natural forcings. Most presented studies for Europe relate flooding activity to negative NAO phases (e.g. Rapuc et al., this issue; Santisteban et al., this issue; Schillereff et al., this issue), (positive and negative) phases of summer NAO (Peña and Schulte, this issue; Schulte et al., this issue), changes in solar activity (Peña and Schulte, this issue; Schillereff et al., this issue) or cold phases linked to Atlantic multidecadal variations (Barriendos et al., this issue). For the Pacific domain, floods have been correlated to displacement of the westerlies/monsoon systems (Pacific Decadal Oscillation, PDO; Southern Annular Mode, SAM) and ENSO (Fuller et al., this issue; Ortega et al., this issue; Yu et al., this issue).

However, the frequency and intensity of flood events are the result of diverse and interacting factors operating at the local, regional and global scales. This produces complex records that are challenging to interpret. For example, Corella et al. (this issue) show a lake sediment record that responds to the seasonal distribution of storms and longer-term changes in soil properties (resulting from climate and land-use change).

The comparisons presented in Figures 5 and 6 (and in the papers mentioned) highlight that temporal correlations between regional forcings and flood reconstructions can rarely be drawn precisely. However, numerous studies in the Special Issue emphasis that the 19th century - including the most recent cool climate pulses during the Little Ice Age - is a particularly flood-rich period (Barriendos et al., this issue; Rapuc et al., this issue; Schillereff et al., this issue; Sánchez-García et al., this issue; Yu et al., this issue) and the period with highest flood intensity in some regions (Corella et al., this issue; Schulte et al., this issue). This could be a consequence of synergetic effects between climate forcing and human factors (land-use, river management). With regard to the 20th century, it is difficult to assess the influence of global warming because of intensifying social factors, the effect of hydraulic infrastructure and management, and demographic and urban growth (Barriendos et al., this issue; Sánchez-García et al., this issue). Research drawing on historical sources might also be affected by the increased availability of flood information about smaller and moderate floods since the second half of the 19th century. In addition, some flood types such as GLOFs and debris flows can be favored by particular physiographic settings like the formation of new glacier lakes in the Tien Shan mountains (Zaginaev et al., this issue). It is, however, noteworthy that 10 of the 14 papers displayed in Figures 5 and 6 do not record the 20th century as the exceptional flood period.

Based on this synthesis of current research, palaeoflood data are optimally explored at decennial to centennial time scales (trends or periods). Finer-resolution data are highly desirable but we must be conscious of multiple limiting factors. For example, the mixing depth of sedimentary records may limit data resolution. In addition, the timing of flooding in adjacent catchments can differ considerably, as shown by Schulte et al. (this issue) in the Bernese Alps, Santisteban et al. (this issue) in Central Spain and Barriendos et al. (this issue) in eighteen catchments of eastern Spain. This is unsurprising because hydrometeorological processes, sensitivity to climate variability or land-use change and thresholds may be site-specific. Palaeoflood research must account for this diversity. There are many potential pathways towards improvement: new chronological tools that circumvent technical limitations, such as ^{14}C plateaus/anomalies coupled to higher-resolution, multi-proxy studies, basin-scale studies, these need to be coupled with improved reconstructions of local factors, especially human activity, and climate forcing. For example, evaluating NAO or ENSO as a long-term flood driver is limited by the temporal resolution of NAO reconstructions. These requirements should guide future research and will be best achieved by expanding collaborative efforts.

9. Human impact and disentangle anthropogenic from natural drivers

Anthropogenic modifications to the landscape can dramatically alter flood regimes. Land-use change, in particular, the removal of mature vegetation covers and intensification of agriculture, destabilizes hillslopes and increases surface runoff and soil erosion potential (Dotterweich, 2008; Hoffmann et al., 2010). Structural interventions in rivers also affect the flood hazard (Schulte et al., 2015; Wetter et al. 2017; Munoz et al., 2018). Disentangling climatic and anthropogenic forcings in palaeoenvironmental data is a persistent challenge, however (Mills et al., 2017). Palaeoflood researchers are cognizant of these difficulties (Brisset et al., 2017; Wilhelm et al., 2019) and this set of papers presents an opportunity to explore current approaches and limitations when evaluating the human influence on long-term flood risk.

Some common approaches are evident, in general, but also in this Paleoflood Special Issue. There is common agreement that regional consistency across multiple proxies from independent archives denotes a climate signal whereas localized shifts probably point towards human disturbance (e.g. Barriendos et al., this issue; Fuller et al., this issue; Rapuc et al., this issue; Sánchez-García et al., this issue; Schulte et al., this issue). There is also evidence that interactive effects characterize the climate-human-flood nexus. For example, flood occurrence in northern Britain correlates with solar activity and NAO dynamics but concurrent woodland clearance for pastoralism appears to amplify flood frequency and magnitude (Schillereff et al., this issue). Similarly, Rapuc et al. (this issue) show a striking increase in flood frequency at Lake Iseo (Italy) around 3000 yr BP that coincides with forest clearance indicators but lags the onset of climate-driven catchment erosion. Subsequent channel diversion, however, reduced sedimentation and discontinued the depositional flood record in some areas of lake basins (Rapuc et al., this issue) and floodplains (Carvalho and Schulte, 2013). Researchers must be aware that channelization can equally produce areas of aggradation and delta progradation (Schulte et al., 2009a; Wirth et al., 2011; Santisteban et al., this issue). Crucially, the effects of human pressure on flood regimes are often irregular through time. Corella et al. (this issue) infer from high-resolution, multi-proxy palaeoecological data that burning, grazing and cultivation triggered a prolonged period of frequent flooding around 700-1300 AD in northeast Spain. Equivalent activity during later centuries produced a more muted flood response, suggesting the system rebalanced to accommodate disturbance.

Hydraulic infrastructure also induces complex effects. Flood risk declined on Spanish rivers after expansive 20th-century dam building (Barriendos et al., this issue). Similarly, in several catchments of the Alps the combination of river correction and diversion into large alpine lakes lower peak downstream discharges because these lakes regulate flood waters like large retention areas (Wetter et al., 2011, Schulte et al., this issue). Conversely, channelization amplified flood magnitudes on the Mississippi (Munoz et al., 2018) while Elleder et al. (this issue) show the Mladotice dam collapse (Czech Republic) was a key factor behind the destructiveness of the 1872 flood. Sánchez-García et al. (this issue) note more recent dam construction, such as on the Almanzora River, Spain

(Sánchez-García et al., this issue), has shifted the hydrometeorological baseline. This hinders efforts to evaluate flood risk under 21st-century climatic warming.

This compilation of evidence stresses that the role of human activity as a flood driver and proxy evidence used to characterize an anthropogenic signature must be established on a site-by-site basis. This presents a number of challenges: first, while the multi-proxy approach of Corella et al. (this issue) that distinguishes the impacts of grazing, burning and cultivation is a powerful tool and Schulte et al. (this issue) sift their synthesis of the European Alps for sites least affected by human presence, such bountiful paleoflood data is rare. Second, we must keep in mind that vegetation and fire dynamics can respond independently to climate so evidence of human-induced changes is crucial (Corella et al., this issue). Third, inter-site comparisons will widen chronological uncertainty. For example, most periods of frequent flooding in northern Britain (Schillereff et al., this issue) align with geomorphic evidence of hillslope destabilization across the region but both datasets depend on radiocarbon dates with multi-decadal uncertainties. Communicating the temporal uncertainty for comparator datasets should, therefore, be encouraged. Similarly, the approach of Rapuc et al. (this issue) to re-examine local archaeological evidence in a flooding context builds confidence in the time-transgressive role of human activity. Lastly, we must be wary of circular reasoning: catchment destabilization usually alters the rainfall-runoff relationship and soil erodibility. In this scenario, an anomalous lamination need not reflect a major flood because of modest rainfall on recently exposed, fragile soils could produce a similar signature. Mechanistic interpretations that consider transport capacity, for example, become crucial (Evin et al., this issue; Schillereff et al., this issue). Similarly, Corella et al. (this issue) convincingly attribute a shift in flood seasonality to human influence because known advancements in tilling practice would create the observed response. Site selection is also important. For example, Schulte et al. (this issue) show a divergent flood response on either flank of the Bernese Alps.

Isolating the anthropogenic component can be a formidable challenge. This collection of papers showcase how a coupled multi-archive, multi-proxy approach is imperative. In sedimentary systems, for example, do different geochemical proxies reflect rates of erosion and the carrying capacity of the system (grain size). Determining the nature of human modifications must also occur on a specific basis. Channel diversion and hillslope vegetation clearance may exert quite different effects on the flood regime. This could draw on archaeological evidence, for example (Rapuc et al., this issue). As human and climatic modifiers may coincide, less equivocal proxy evidence of human presence is needed. Indicator pollen (Corella et al., this issue) or pastoral DNA (Giguet-Covex et al., 2014) show real promise but may require deeper collaboration amongst international research groups in the future. Integrating sedimentary data with an independent archive, such as historical documents or tree rings would also be wise.

10. Outlook: scoop and limitations of multi-archive paleoflood integration

Taking a long-term perspective on flooding is fundamental for adequate hazard and risk assessment (e.g. flood-frequency analysis). The research papers in this Special Issue demonstrate that integrating field-data on “real” past floods derived from multiple historical and natural archives provides excellent flood data series. These datasets are uniquely positioned to document low-frequency, large-magnitude flood events that vary under different climate regimes (cooler, warmer and transitional climate periods) and/or environmental conditions (changes in land cover, land use, and river management).

However, reliable and accurate integration of paleoflood data relies on accounting for several critical issues:

i) Although this paper does not focus on the dating of flood records, we would like to stress first that considering dating uncertainties within the time series is vital prior to perform statistical analysis. The temporal resolution of records can vary significantly, however. Before flood data series from different natural and anthropogenic archives can be integrated into a regional model, a critical assessment of chronological models and homogenization of flood data is needed.

ii) The comparability of flood series from heterogeneous catchments and landscapes is often complex because the controlling factors and system sensitivity (e.g. of erosion or aggradation) to climatological conditions and hydrological extremes varies greatly across diverse hydrological and environmental settings.

iii) Indirect flood proxies recording climatic-environmental signals (e.g. sediments that are deposited by surface runoff in a small sub-catchment) are different from records that are directly involved in the process of river flooding. Thus a precise understanding and a careful interpretation and/or calibration of physical processes are mandatory.

iv) Due to the heterogeneous natural response of different subsystems to flood drivers, not all flood series from a basin or a region can be integrated into a regional synthetic paleoflood master curve. The criteria for selection or rejection of individual flood series must not only follow statistical protocols but also consider process-based arguments. To identify “false alarms” and “missed” floods, data series should be tested against known regional hydrological extreme events that are documented by several records.

v) Human modification to many river systems has had major effects on the flood regime. These non-stationary conditions impose challenges when performing flood frequency analysis and evaluating flood risk under future climate change projections. Effort should be invested to isolate the anthropogenic component, ideally through a coupled multi-archive, multi-proxy approach.

vi) There is good evidence that some regional/global factors can systematically affect the dynamics of flooding over long timescales. There is now a need to achieve wider spatial and temporal coverage, leading to better understand the factors affecting intra-basin variability, especially interactions between natural and anthropogenic forcings.

When critical points i) – vi) are carefully taken into consideration, it seems clear that using a variety of paleoflood data from multiple archives and methodologies from different scientific fields is the best approach. Such multi-dimensional investigations can better account for limitations in individual records and more effectively analyze the spatial distribution (horizontal and vertical) of flood records in order to capture the physiographic and environmental diversity of a catchment. Schulte et al. (this issue) conclude from their integrated paleoflood pilot project in the Alps that such a multi-archive methodology can be applied in many regions. They do recommend, however, that this approach will be most effective in catchments where a high number of paleoflood records already exist and a profound understanding of the different flood proxies and flood generating mechanisms has been built up.

The meta-data of the case studies presented in this Special Issue in Table 1 suggest that paleoflood studies focused on fluvial depositional environments show a higher rate of integration with other types of paleoflood archive (mean of 4.5 types of archive) than studies focused on documentary sources (mean of 3.5) and lake sediments (mean of 2.4). We suggest that this adopted strategy of cross-correlation is an effective method to compensate for the higher uncertainties of fluvial deposition in floodplains due to lower temporal sample resolution and possible effects of unconformities (possible gaps of flood information). The apparently more precisely dated lake and documentary flood records focus predominantly on instrumental calibration instead of multi-archive integration. However, several studies showed that neither of these series always record continuous flood information and they should be completed by other archives. In addition, spatial accuracy of flooding processes is a weak point of studies where flood information is obtained from single locations such as lakes, flood marks or settlements instead of larger flood-prone areas. In this latter case, terrestrial natural flood archives contribute highly valuable information.

Based on the gathered experience from the Special Issue, the activities of the work package WP2 and the FWG pilot multi-archive project, we suggest that over the next few years the agenda of regional paleoflood research might include the following trends:

i) Design of methodological approaches integrating paleoflood datasets through numerous regional pilot studies in different environments,

ii) Improvements in flood frequency analysis and spatial flood risk assessment using multi-archive analysis,

iii) The progress of methodological and statistical approaches to analyze paleoclimate models in relation to the flood variability,

iv) Assessment of the changes of flood pattern due to the effect of land-use changes in basins,

v) Examination of changes in external forcing and atmospheric variability of the flood periods by paleoclimate modeling. Furthermore, these comparisons help to predict future climate change related to flooding.

vi) Detailed consideration of the role of anthropogenic landscape modification in controlling flood dynamics and develop and apply multi-proxy approaches to disentangle the effects of human activity from climatic drivers of flooding. This will be most effectively achieved through wide collaborations.

We, the invited editors of the present Special Issue and authors of this introductory article, hope that the collection of papers presented in the Paleoflood Special Issue and at the PAGES Open Scientific Meeting in 2017 contribute to the progress of paleoflood research and inspire interested readers to promote the research on multidisciplinary analysis and multi-archive reconstruction of paleofloods. Finally, we would like to express our gratitude to the more than 101 authors and co-authors who shared enthusiastically their knowledge at the PAGES OSM conference session at Zaragoza and contributed with their studies and research projects to this Special Issue on Paleofloods.

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