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Recent advances in paleoflood hydrology: From new archives to data compilation and analysis

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ABSTRACT

Assessments of present and future flood hazard are often limited by the scarcity and short time span of the instrumental time series. In pursuit of documenting the occurrence and magnitude of pre-instrumental flood events, the field of paleoflood hydrology emerged during the second half of the 20th century. Historically, this field has mainly been developed on the identification and dating of flood evidence in fluvial sedimentary archives. In the last two decades, paleoflood hydrology approaches have also been deployed to investigate past floods contained in other natural archives. This article reviews major methodological and technological advancements in the study of lake sediments with the aim to showcase new, robust and continuous paleoflood series. Methodological advancements of flood archives such as tree rings and speleothems are also addressed. The recent developments in these fields have resulted in a growing paleoflood community that opens for cross-disciplinary analysis and synthesis of large data sets to meet the pressing scientific challenges in understanding changes in flood frequency and magnitude.

1. Introduction

Extreme flooding is a growing societal challenge with an expected increase in flood hazards due to the ongoing climate change [1] and the increasing exposure of people and assets in flood-prone areas [2]. Accurate flood hazard assessments are thus required to assess present and future risks and to prepare societies for future flood events. However, still considerable uncertainties remain; e.g. on the evolution of flood magnitudes and the frequency of future events to occur [3]. A main source for uncertainty in flood risk assessments is the short time span and the limited spatial coverage of the available instrumental time series. This particularly limits our knowledge of rare low-frequency, high-magnitude events. In the second half of the 20th century, researchers developed a field-based approach to reconstruct past river floods and discharges for pre-instrumental periods; i.e. prior to systematically monitored records or descriptions in historical archives [4]. From that time onwards, methodologies have evolved, spread beyond the fluvial domain to other settings, and the number of dedicated field studies has increased. All these factors have contributed to improve our understanding of current flood risk, and helps to assess potential future changes. In this paper we discuss recent methodological advances in the field of paleoflood hydrology, with a focus on studies that targeted lake environments and newly-explored paleoflood archives from speleothems and tree-ring records. Our main aim is to inform a broad audience, ranging from flood risk managers and environmental planners to scientists, about the potential use and quality of paleoflood data with reference to recent technological and methodological advances.

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2. The historical development of paleoflood hydrology in the fluvial domain

The most common natural archive for paleoflood studies is the fluvial sedimentary archive, formed during floods when sediments are conveyed to slackwater zones outside the channel, where a stacked natural record of events can be preserved.

Fundamental methodological advances took place during the 1980s [4–6]. Pioneer studies targeted bedrock canyons, which allowed a rather direct comparison between past and present discharges, because the morphology of the channel and valley remained relatively stable. The level of slackwater deposits was used as a paleoflood stage indicator (PSI), and used as input for discharge calculations [4,7], generally using the slope-area method [8]. In more complex canyon morphologies, this method proved to be imprecise. Hence, later studies started to combine multiple valley cross-sections in advanced modelling tools (e.g. HEC-RAS; [9,10]).

The methodologies deployed in canyons have a limited applicability to upland and lowland regions with dynamic river channels and rather unconfined valleys. Paleoflood records in upland regions were explored in the 1990s [11]. Field measurement of the clast-sizes of boulder berm deposits were used as an indicator of paleoflood magnitude [11]. Lowland regions have only been studied recently, with investigation of sequences of overbank deposition preserved in abandoned channels and flood basins [12,13]. There, flood unit coarseness was measured with cm-scale laser diffraction grain-size measurements [14] or mm-scale non-destructive geochemical measurements as a proxy for relative grain-size [12], following similar progress in lake sediment studies (Section 2). Recent studies found a direct correlation between gaged peak discharges and flood unit coarseness [14,15], and used this to estimate the discharge of events that predated gaged records.

In order to place the identified flood deposits in a temporal context, developments in dating techniques have been important for paleoflood reconstructions. Because of the scarcity in organic material in flood units, traditional radiocarbon dating could not be deployed in some settings. In addition, extreme floods often cause riverbank erosion and can thus transport reworked (older) organic material from upstream. Advanced dating techniques, first ^{210}Pb and ^{137}Cs radiometric and later Optically Stimulated Luminescence (OSL) dating [16,17], were recently adopted in paleoflood studies. OSL dating, with a precision of roughly ± 10% of the total age, allows the last moment of exposure of sand grains to sunlight to be dated. In the last decade, the dating of individual single sand grains has become possible [18]. These are generally found in flood units, and therefore this technique is highly suitable for deployment in paleoflood studies (e.g. [15,19]). Importantly, the ability to date clastic units or intervals also provides additional calibration points in age-depth models for sedimentary sequences. For upland boulder berms the dating through lichenometry, precision of c. ± 10 years, provides solid age control for the last centuries [20]. Lichen growth rates, established from surfaces of known age (e.g. tombstones), were compared to the size of lichens on boulders to indirectly date the event that caused deposition. The required dating control on flood events and data series depends on its intended use. For example, for the design of hydraulic structures the precise date of an extreme paleoflood event is of lesser importance than its maximum peak discharge. In contrast, maximum dating control is required when matching event occurrence with synoptic paleoclimate conditions or important drivers of the global climate system, such as the North Atlantic Oscillation (NAO) or the El Niño-Southern Oscillation (ENSO).

3. Lake sediments, a sedimentary archive on the rise

Lake sediments have been increasingly studied during the last two decades as recorders of past floods. Establishing paleoflood records from lake sediments relies on the observation that floods erode and transport large amounts of material from the lake catchment. These sediment-laden flows enter the lake waters and deposit the mostly-detrital material at the lake bottom forming « flood layers » [21,22]. Such layers are preserved in deep and undisturbed areas of the lake and stacked in sediment sequences, providing a great potential to reconstruct long and continuous flood series. Although flood sedimentary processes have been investigated in lakes since the late 19th century [23], the reconstruction of paleoflood series started much later; at the turn of the 21st century (e.g. [24–26]). Flood layers are enriched in detrital material, composed of (organo-)clastic catchment material, compared to the organic-rich background sediments resulting from lake bioproductivity. This encouraged paleoflood hydrologists to develop methods for detecting flood layers based on their geochemical and mineralogical composition as well as textural (grain-size) and physical (density) properties [27,28]. The refinement of methodological and analytical techniques has recently permitted to substantially i) improve the detection of flood layers in sedimentary sequences, ii) reduce dating uncertainties of flood layers and iii) quantify the completeness of flood layer record through calibrations. Here, we review these three major advances in the field that strongly support paleoflood hydrologists to quantitatively reconstruct long-term flood variability.

Initially, methods to detect flood layers though geochemistry and density measurements often required a destructive sediment core sampling and minimum sediment sample sizes, strongly limiting both the sampling resolution and the number of measured samples. These limitations have largely been overcome through the developments of core scanning techniques that permitted non-destructive, high-resolution measurements. First, multi-sensor core loggers enabling millimeter scale (down to 2 mm) measurements of density and magnetic susceptibility, and later the emergence of micro-X-ray fluorescence (µXRF) core scanners [29] providing micrometer-scale (40–200 µm) estimations of elemental composition have progressively made detection of thinner and more subtle flood layers possible (e.g. [30,31], Figs. 1A and 2A). X-ray imagery is a complementary non-destructive technique employed since the 1970s to detect environmental changes in lake sediment cores. The recent development of X-ray 3D computed tomography (CT) has further improved the detection of high-density flood layers in organic-rich background sediments on sub-millimetre scale using medical CT scanners, (e.g., [32]) or micrometer scale using industrial type CT scanners (Fig. 1B). X-ray imagery are particularly useful whenever there are large density differences between the flood deposit of interest and the surrounding sediments, and 3D CT scans may as well provide a unique qualitative data on e.g. erosional boundaries or determining presence of macrofossils present within event layers (e.g. [33]). CT and µXRF scanning techniques have even been combined with high precision quantitative geochemical analyses such as Inductive Coupled Plasma (ICP) and sophisticated environmental magnetism analyses [34], as well as analysis of mineralogy using X-ray diffraction (XRD) [30,35] to identify the provenance of the transported material. These developments have enabled characterization of different types of event layers according to i) the triggering event, e.g. gravity-driven mass movements versus flood events [36–38], ii) the sediment load, e.g. high-density local debris flows and regional flood events [39] or iii) hydrometeorological characteristics, e.g. snowmelt, intense rainstorms, or a combination of both [34].

Selecting among the range of methods developed to detect flood layers in a lake sedimentary sequence [27,28], the most suitable method for a specific study site will always be site-dependent. For instance, in high-altitude and high-latitude environments or in small catchments highly sensitive to erosion, the detrital fraction dominates in both flood layers and background sediments. This results in a lower contrast of density or geochemistry between these deposits, making analyses described previously less sensitive. Grain-size analyses by laser diffraction may in these cases be a more suitable approach, identifying increases of grain size related to increases of discharge during flooding [40]. However, this method is time-consuming, destructive and limited to a c. 5-mm sampling resolution. To overcome these limitations, µXRF

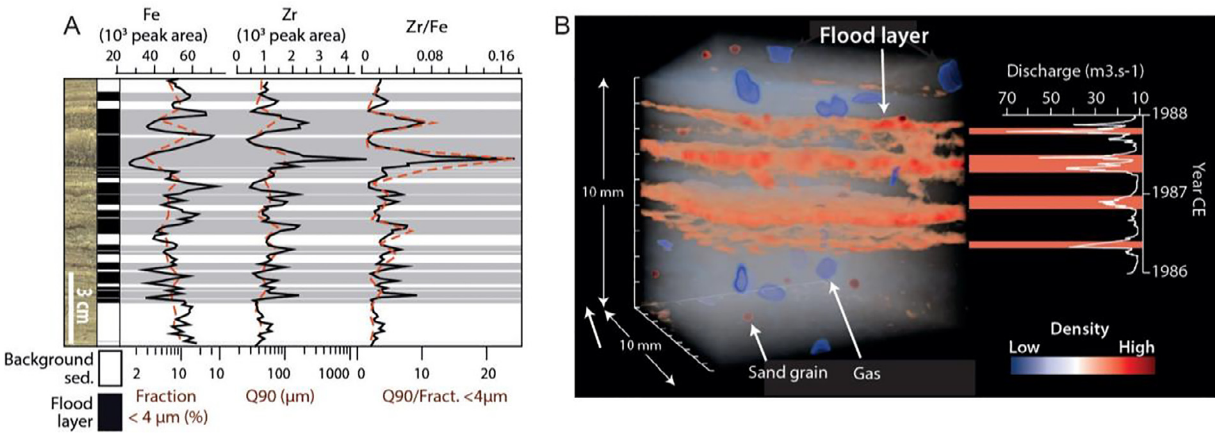

Fig. 1. Technological advances substantially help detecting progressively thinner and more subtle flood layers in lake sedimentary sequences as exemplified with (A) µXRF core scanning that allows non-destructive, micrometer-scale geochemical measurements used here as a high-resolution grain-size proxy (modified from [31]) and (B) computed tomography (CT) that allows 3D micrometer-scale density measurements to visualize sub-millimetre thick high-density flood deposits (red) in an organic-rich background sediment (white-blue). This examples show a sediment 10 by 10 mm core section from Flyginnsjøen, Southern Norway, and also illustrates how the sedimentary deposits (210Pb-dated) correspond to spring and fall floods in CE 1986 and 1987 recorded at the nearby gauge station at Magnor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

core-scanner measurements have been explored to identify high-resolution (up to 200 µm) grain-size proxies, assuming a different geochemistry between the finest and the coarsest sediment fractions [41]. This is illustrated in Fig. 1 with the couple Zr/Fe [31]. Zirconium (Zr) can be found in heavy minerals called zircons, thereby assumed to be associated to the coarse sediment fraction. Iron (Fe) is often associated to clay minerals, thereby assumed to be associated to the finest fraction. However, the appropriateness of the adopted geochemical ratio depends on the site characteristics and lithology, and generally requires preliminary testing of detection limits for geochemical elements. Other studies also deployed Al, K, Rb, Si and Ti to set up grain-size ratios (e.g. [12]). For instance, potassium (K) should be prefered to Fe when redox processes occur in the lake waters [42]. Although such a “proxy-to-proxy“ calibration may introduce uncertainties and reduce precision, this cost and labour effective approach have been successfully deployed in many environmental settings to increase sampling resolution and thus also the threshold of flood layer detection in detrital lake sedimentary sequences (e.g. [31,42–44]), and also in fluvial sequences [12].

Dating of abundant flood layers in lake sediments has been greatly improved, in particular through the detection of flood layers intercalated in annually laminated (varved) sediments. Varved sediments result from anoxic lake bottom conditions that impede lamination disruption by bioturbation and allow the preservation of seasonal layers [45]. The identification and counting of flood layers in varved lake sediments thus provide seasonally to annually-resolved flood chronologies (Fig. 2A). Despite excellent dating control, dating uncertainties may result from counting errors or poor varve preservation. Recent

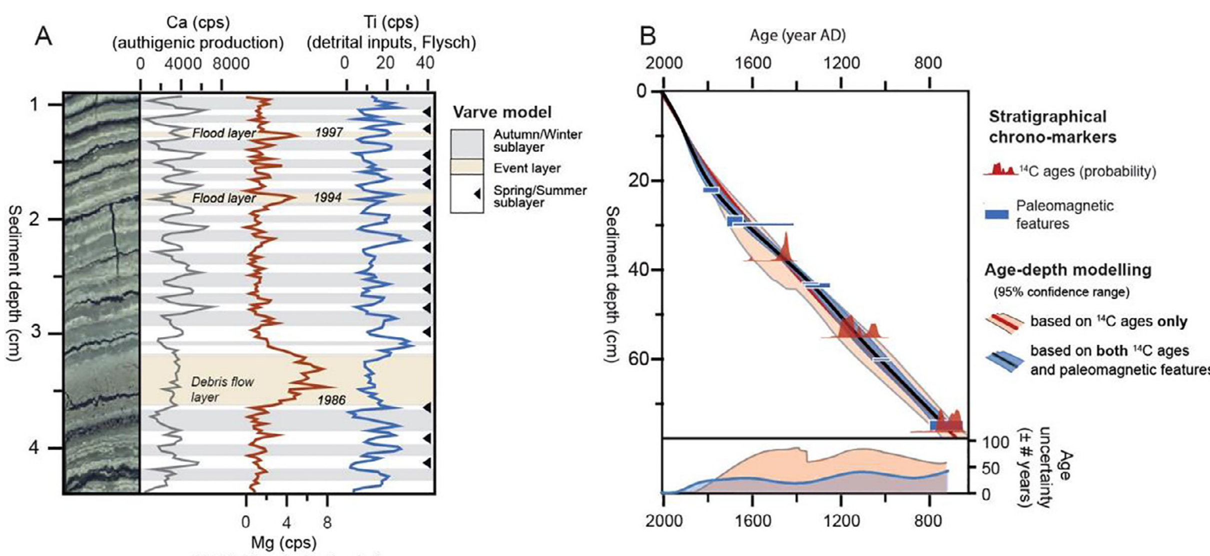

Fig. 2. Recent advances on dating paleoflood occurrence mostly rely on (A) the development of paleoflood reconstruction from seasonally laminated (varve) sequences (modified from [51]) and (B) developments of methods such as paleomagnetism to constrain radiocarbon uncertainties (modified from [43]). High-resolution geochemical measurements (cps – counts per seconds, µXRF) highlight the spring/summer layer enriched in authigenic products as characterized by high content of calcium (Ca) and the autumn/winter layer enriched in detrital material as shown by increased content of magnesium (Mg) and titanium (Ti). In combination, microfacies analysis and geochemical measurements allow to distinguish between different event types and sediment provenance. Thick event layers are triggered by local debris flows from the dolomitic catchment as indicated by high Mg content, whereas thin event layers are triggered by regional floods transporting both, siliciclastic (Ti-rich) and dolomitic (Mg-rich) material into the lake.

developments of i) efficient computer-based image analysis based on automated or semi-automated varve counting from digitized varve sequence photographs [46]; ii) automated methods for varve interpolation in areas of poor varve preservation avoiding subjectivity derived from manual interpolation approaches [47] and/or iii); dual combination of µXRF core scanning and X-radiography for varve counting [48] have significantly contributed to minimize varve counting errors. Thus, dating uncertainties of recent varve-based flood records do not exceed 1 to 3% (e.g. [49–53]). Using a complementary sedimentary facies analysis on thin sections helps refining the relative microstratigraphical position of the flood layers within the varve succession. This provides valuable information about the flood seasonality (e.g. [49–52]). However, sediment sequences of most lakes are not seasonally laminated and alternative dating methods, similar to those applied to date fluvial sediments, should be used to construct the age-depth models [27]. Radiocarbon (^{14}C) dating of vegetal macro-remains is the most common tool to date sequences covering millennial time scales (Fig. 2B). Significant progress of this method permitted to reduce minimum sample weights and measurement uncertainties, using e.g. gas ion source measurements of samples containing only 5–100 µg carbon [33]. However, ^{14}C ages still encompass large uncertainties (often ± 100 years). Recently, the secular variations of the geomagnetic field have been explored as a complementary dating approach (e.g. [54]) and applied to better constrain paleoflood ages. This approach assumes that magnetic particles are oriented in the sediments according to the magnetic field state of the deposition time. Then, the magnetic variations, measured along the core, are assumed to reflect past geomagnetic variations, which are compared to reference series provided by global models of the geomagnetic field (e.g. [54]). Similar features identified in both series allowed additional chrono-markers to be proposed. First applications already allowed paleoflood age uncertainties to be reduced from 30 to 50% (< ± 50 years; [44,55], Fig. 2B).

Improvements in flood layer detection and dating allowed reconstructing detailed paleoflood chronicles. Over the last years, the completeness of such records have been evaluated by comparing ages of individual flood layers with observations such as runoff and precipitation data sets [39,49,56–62], historical flood records ([36,38,39,43,55,61], Fig. 3A) or monitoring of flood-related sediment deposition in the water column ([62,63], Fig. 3B). Such calibration studies showed that individual floods result into detrital flood layer deposition in most of the cases. Flood layer records are principally a minimum estimate of flood occurrences. Reasons for missing flood layers are factors limiting sediment transport from the catchment and within the lake that can have random and systematic effects. For instance, flood layer formation in some lakes show a seasonal pattern with favoured deposition in summer that is explained with favoured lake-internal sediment transport along the thermocline in summer [63]. Sediment delivery can be reduced in winter due to snow cover and frozen ground of the catchment [49]. Sediment transport into the lake can also be hampered during large-scale flooding when sediments preferably deposit in the catchment rather than transported into the lake [28]. In a few 'random' cases, sediment availability in the catchment might be limited due to generally reduced sediment mobility in the catchment, e.g. in a year with multiple floods that reduces the availability of sediments [28]. Systematic seasonal effects on flood layer completeness imply that such flood records are significant only for specific seasons [49,58]. Randomly missing floods can be included into paleoflood reconstructions for estimating uncertainties of flood frequency calculations.

Beside the record completeness, calibration studies have also revealed site-specific discharge thresholds record by flood layers [49,56–58,60,62]. For instance, flood layer deposition occurs in Lake Bourget when the Rhône River discharge exceeds 1500 $m^3.s^{-1}$ ([61], Fig. 3B), and in Lake Mondsee when the Griesler Ache River discharge exceeds 40 $m^3.s^{-1}$ ([63], Fig. 3C).

For reconstructing flood magnitudes directly from the sedimentary deposit two distinct approaches have been developed. The first assumes that the higher the flood magnitude, the larger the amount of sediments deposited. A high-magnitude flood is then expected to trigger the deposition of a thick flood layer and/or a large volume of sediments. Similarly to approaches developed with fluvial sediments, the second assumes that the higher the flood magnitude, the higher is the flood layer coarseness. The few recent calibration studies elucidated relations between flood magnitudes and layer thickness ([55,57,58], Fig. 3C), sediment volume ([56,61], Fig. 3B) and grain size patterns [31,43,59]. Nevertheless, a systematic methodology to reconstruct flood magnitude using a specific proxy has not yet been established since the relation between flood magnitude and sediment proxies is non constant but varies between different coring sites within one lake [61] and between different lake settings [57,58]. Reasonable might be to further consider site-specific factors controlling sediment responses to floods of different magnitude such as the effect of lake stratification in some temperate lakes [63], occasional massive sediment release from the river channel [64] or small-scale soil disturbances [65]. Although such observations are still scarce and do not yet reflect the broad range of lake sediment-based flood reconstructions they show that hydro-sedimentary process knowledge provides crucial steps for quantified flood reconstruction, for instance, through herping to select the most suitable lake sites and coring locations.

Calibrations of both flood record completeness and flood magnitude support the quantitative paleoflood reconstructions on the recent past. However, major changes in catchments, largely due to human actions, may limit the accuracy of paleoflood reconstruction and flood measurements on longer timescales, whether produced from fluvial or lake

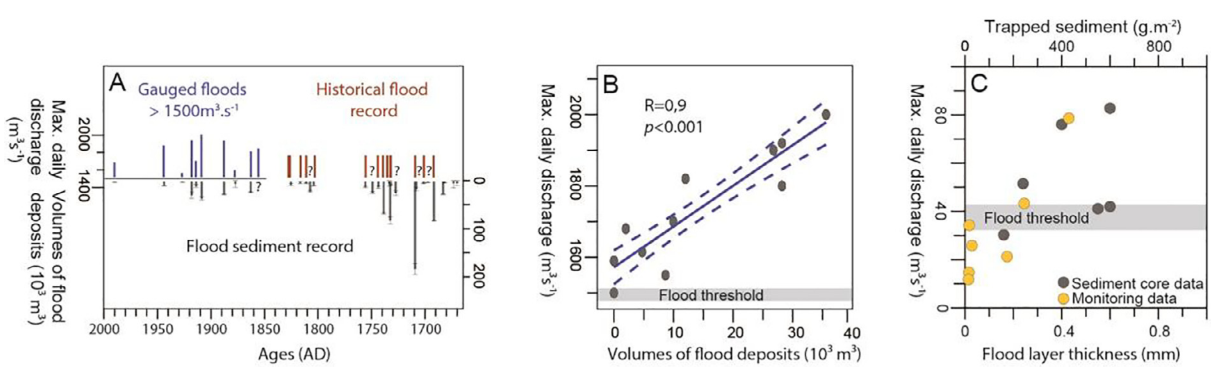

Fig. 3. Recent calibration studies strongly support reconstruction of both flood occurrence and magnitude as exemplified with the calibration of (A) the reconstructed flood occurrences of the Rhône River using both gauge data and historical flood dates (modified from [61]), (B) volumes of flood deposits as a proxy of the Rhône River flood magnitude with gauge data (modified from [61]) and (B) flood layer thickness and amounts of trapped sediment versus Griesler Aache flood magnitude using gauge data (modified from [63].

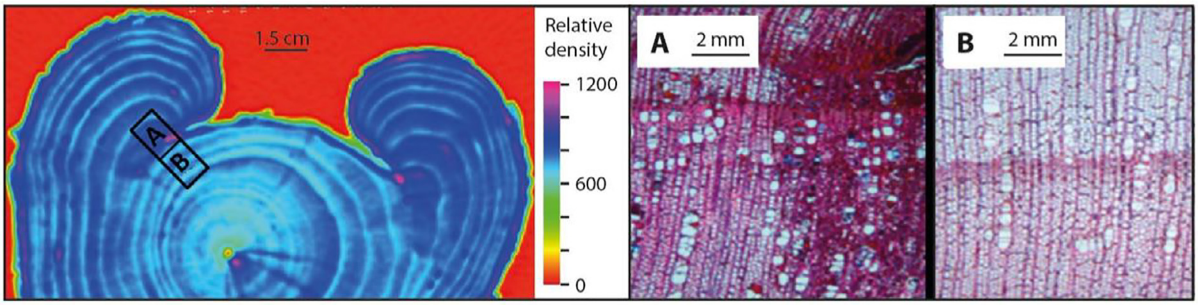

Fig. 4. Examples of observed wood anatomical changes in CT images of riparian trees wounded by floods. A cross-sectional view of a wounded tree after filter processing to highlight changes in wood density as a function of the X-ray attenuation coefficient as result of the injury border. Micro-cuts related to the affected (A) and non-affected (B) zones to show differences in the wood anatomy related to wound anatomical features (adapted from [78]).

sediments. Human impact possibly alter the sediment dynamics, modifying the relation between water discharge and sediment supply and, thereby, biasing reconstructed signals of flood frequency and magnitude [52,66,67]. Therefore, changes in anthropogenic activities within the catchment and related impacts on erosion processes should be systematically and adequately addressed when reconstructing paleoflood records. This classically undertaken by studying pollens of plants linked to anthropogenic activities (e.g. cereals, ruderal and nitrophilous herbs) that are trapped in the sediment sequences. However, pollen records may represent the evolution of vegetation at a much larger scale than the one of the catchment of interest because pollens can travel over considerable distance before its deposition. Alternative methods based on spores of coprophilous fungi and ancient DNA coming both from the catchment mostly by the rivers are being developed to tackle this issue (e.g. [44,66,68]). Another problematic issue is how to test the potential effect of the anthropogenic activities on the reconstructed flood frequency or magnitude. In most studies, the two records are compared and links are established if both increased simultaneously. However, this does not prove the causal link between the two variables. This only makes a climatic interpretation of the paleoflood record uncertain during those periods of increased anthropogenic activities. Hence, further research efforts are still required to better disentangle these possible and complex climate-human interplays on sedimentary processes [69].

4. Current developments of other paleoflood archives

4.1. Speleothem, the newly developed sedimentary archives

Cave deposits such as speleothems are the most recent sedimentary archive studied to document paleofloods [70]. During floods, cave sediments can be mobilized and deposited on speleothems, where they form detrital layers. These layers are then rapidly cemented by the formation of calcite during the speleothem growth. The recognition of flood layers trapped in the speleothems is mainly based on high-resolution imaging and geochemical analyses such as e.g. Raman spectroscopy, laser ablation-ICP-MS, synchrotron-XRF and electron microprobe. U/Th techniques permit then layers to be dated with relatively low uncertainties (ca. 1–3%) even in the distant past (i.e. up to hundreds of thousands years, [71]. Denniston and Luetscher [70] reviewed first developments and results in the field, suggesting speleothems are a promising tool to date past moderate-to-large flood events and reconstruct their flood magnitude. Based on this review, the authors have also proposed a methodological framework with pragmatic recommendations toward accurate paleoflood reconstructions from speleothems.

4.2. Tree rings, the contribution of botanical archives

Tree-ring reconstructions of paleofloods are based on the interaction between flood waters and trees. They use imprints in the form of damage on tree stems, branches or roots, resulting in tree growth anomalies, which can be detected and dated in tree-ring records. The use of botanical evidence in paleoflood hydrology started in the 1960s to improve flood-frequency analyses [72,73]. However, first tree-ring reconstructions of paleoflood series appeared much later at the beginning of the 21th century. During those 40 years, researchers have contributed to develop tree-ring methods to date past floods events thanks to the ubiquitous presence of trees along streams in many mountain ranges across the globe (see [74]). Methodological advances have been focused on i) understanding flood signal detection in different trees species and ii) investigating the reliability of botanical indicators for flood magnitude estimations.

Recent improvements in the detection of flood signals in tree-ring series permit to maximize the quantity of acquired information and optimize their interpretation. For instance, significant specific cell changes have been observed as a result of flooding in both experimental and natural conditions on various tree species (see review in [74]). Persistent floods that occur during the growing period of trees and shrubs will favor anoxic conditions which in turn cause disrupt growth hormone activity in trees, and consequently impact cell anatomy [75,76]. In addition, trees can also be injured through the mechanical impact of ice, wood or sediments on tree stems during floods, which then often results in the formation of scars. Scar-induced anatomical changes, such as tangential rows of traumatic resin ducts, callus tissues or cell-size reduction are formed within days after wounding and can thus be used as precise indicators for the dating of past floods [77]. The extension of such anatomical changes has been explored in detail and by employing 3D computed tomography ([78], Fig. 4). This information is valuable as it helps the definition of growth response zones in trees and thus allows methodological improvements of increment core sampling on stems and flood-signal detection in tree-ring records. In addition to these advances in paleoflood signal detection, oxygen-isotope compositions in tree rings after specific flood events have recently been analyzed in four different conifer and broadleaves tree species. This approach in development aims to track the origin of flood rainfalls, which could be of utility to identify hydrometeorological mechanisms and improve flood-frequency analysis [79].

The reliability of peak discharge estimations based on botanical PSI has been investigated recently by relating the variability in peak discharges estimated from scar heights with the geomorphic position of trees [80]. Scar heights in mountain streams can vary between 20 and 40% depending on the location of the tree selected for analysis and its position with respect to the stream [80]. The range of variability may, however, vary in other fluvial system. This information will permits providing sampling recommendations to reduce uncertainties in future reconstructions of paleoflood discharge. Similarly, geomorphic positions where intermediate energy prevails have been shown to be the locations in which the most affected trees can be found [81]. Therefore, sampling trees from these geomorphic positions would yield the most reliable estimates of peak discharge. Finally, study of tree tilting through a mechanical deformation model recently suggested that tilting may be a promising, complementary indicator of flood magnitude, especially in fluvial systems where tree scars are sparse [82].

5. Perspectives in paleoflood hydrology

The research field of paleoflood hydrology has advanced considerably since its beginning in the 1970s, substantially increasing the number and quality of paleoflood data, especially those documenting low-frequency, high-magnitude flood events. Advances are associated with methodological and technical progresses but also to the diversification of studied paleoflood archives. This goes along with the involvement of different archive-specific communities contributing to a new and fast-growing paleoflood community, including also historians who provide wealth information on past flood occurrence, magnitude and impacts.

While paleoflood data sets are continuously growing and wealthier, they are most of the time analysed in the frame of case studies. Combining data from multiple archives with state-of-the-art statistical and/or modelling tools would then lead to an integrated product with better coverage and precision in time, space and intensity level than any single archive type could deliver alone. Such products could serve to feed regional to global syntheses of the natural flood variability or as inputs for regional or global climate and hydrological model studies. This promising avenue first challenge other communities (e.g. statisticians, hydrologists, and modellers) to collaborate on this exciting but complex topic that also requires technical developments to take into account peculiarities of paleoflood data such as e.g. their variable dating uncertainties, the intrinsic uncertainties of the reconstructions or the various archive sensitivity to record floods.

Information about paleofloods can also be used by other sectors (i.e. with other academic communities, stakeholders or engineers) for different purposes. Paleoflood data provide information about discharges, submerged areas and impacts associated with low-frequency, high-magnitude flooding that can provide substantial socio-economic benefits. For instance, those improved paleoflood series already helped to better estimate such events, thereby improving flood frequency analyses [83,84] and disaster risk reduction strategies [85]. Such data changed the previously anticipated risk to hydraulic structures, and placed recent, sometimes incorrectly deemed 'unprecedented', events in a long-term perspective of natural flood occurrence (e.g. [6,86]).

Recognizing, collecting, storing and sharing the wealthy data sets of existing paleoflood series is a requirement for their promotion and use but also for further, integrated analyses or regional syntheses. A call-for-contribution and a careful review permits a first identification of c. 400 published historical and paleoflood series (http://pastglobalchanges.org/ini/wg/floods/wp1/data). However, this large and highly valuable data set is dispersed across different data repositories, databases and personal computers. Creating a single paleoflood database gathering all these data then becomes an obvious but challenging target for the whole community. This challenge would require an additional effort from the paleoflood community to format and share their data but this also requires dealing with technical issues such as the need to standardize the different types of archives and to assess their degrees of accuracy, while maintaining a fundamental data structure common to all archives types.

The fast developments of both paleoflood community and data set thus appear timely to address these changes by providing a long-term perspective on flood frequency and magnitude. Hence, scientific challenges for the coming years include:

(i) Getting a comprehensive and universal understanding (e.g. strengths, weaknesses, uncertainties, meaning) of paleoflood data sets provided by the different archive communities (e.g. historians, geologists, geographers),
(ii) Improving the recognition and access to the growing paleoflood data sets,
(iii) Moving towards deeper, integrated analyses of these data sets through collaborations with other communities (e.g. statisticians, hydrologists, climatologists, modellers).

These challenges have been identified during the 'Cross-community workshop on past flood variability' and further developed in the frame of the PAGES Floods Working Group. Detailed information on these challenges and suggested perspectives to take them up can be found in the White Paper [87].

Acknowledgments

The 'Cross-community workshop on past flood variability' was the first meeting of the PAGES Floods Working Group (Grenoble, France, June 27-30, 2016) and it has been generously supported by PAGES, Labex OSUG@2020 (Investissements d'avenir – ANR10 LABX56), European Geosciences Union, Grenoble-INP and Université Grenoble Alpes. PAGES is supported by the US National Science Foundation and the Swiss Academy of Sciences. The open Floods Working Group aims to provide an ideal platform to bring together researchers from the growing community reconstructing past floods (e.g. historians, geographers, geologists) and to promote collaborations with those studying current and future floods (e.g. hydrologists, modelers, statisticians, etc.). The overall goals of the working group are to coordinate, synthesize and promote data and results on the natural variability of floods. Structure, actions and deliverable of the Floods Working Group are detailed in a open-access White Paper (PAGES Floods Working Group, 2017). Juan Pablo Corella currently holds a Juan de la Cierva – Incorporación postdoctoral contract funded by the Spanish Ministry of Economy and Competitiveness (ref IJCI-2015-23839). The CT-scan imagery presented in Fig. 1 was created using a ProCon CT-Alpha Core at EARTHLAB (NRC 226171), University of Bergen. The authors are very grateful to the Editor Bruno Merz for the invitation to prepare and submit this manuscript and to Daniel Schillereff and the anonymous reviewer for their constructive comments.

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