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A review of flood records from tree rings

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Abstract

Palaeohydrology is now recognized as a valuable approach to characterize the hazards posed by flooding. Tree rings have emerged as an important source of evidence for paleohydrological studies, and, since the 1960s, have been used to document the occurrence of past floods. In this progress report we outline the major contributions of tree-ring records to flood research. By reviewing the key advances in this field, documenting different research trajectories, and highlighting recent developments, we make an argument in favor of more extensive use of tree rings in flood analyses. We show how tree-ring data have been applied to risk assessment and outline how the widespread distribution of flood-affected trees can be used to improve the understanding of flood processes. In addition, we outline new approaches and future perspectives for the inclusion of woody vegetation in hazard assessments, and end with new thematic perspectives.

Keywords

Paleohydrology, paleofloods, tree rings, dendrogeomorphology, floods, flash floods

I Introduction

Floods are natural processes that provide essential ecosystem services. They shape the earth surface, provide rich soil, replenish subsurface water reservoirs, and play an integral role in the ecology of riparian ecosystems. However, extreme flood events can lead to large economic and personal losses in societies (Baker, 2008), and are responsible for several of the costliest natural hazards worldwide.

According to the Intergovernmental Panel on Climate Change (IPCC), the frequency or intensity of heavy precipitation events has likely increased in North America and Europe since 1950, and this increase is very likely to continue through the 21st century as a result of the greater water-holding capacity of a warmer atmosphere (IPCC, 2012). Because intense precipitation

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events are important causes of floods, similar trends in extreme flooding may be expected, especially in small upland catchments where floods arise from intense, convective and/or orographically enhanced rainfall. Other areas may experience increased extreme flooding because of circulation changes that result in prolonged or recurring precipitation episodes that saturate catchments, or an increase in rain-on-snow or snowmelt flooding in response to earlier and warmer springs. Floods, by their very nature, are rare events and result from a complex interplay between weather, climate, and catchment-specific runoff characteristics. Because of this, sufficiently long records are required to evaluate trends or decipher a link to climate change. Long records also provide a more complete history of extreme events for flood hazard assessment purposes. Therefore, a strong need exists to augment systematic, instrumental flood records with information from both historical archives and indirect evidence in the paleorecord (Baker, 2008).

Paleoflood hydrology deals with the reconstruction of magnitudes and frequencies of recent, past, or ancient ungauged floods and combines indirect evidence and hydraulic methods as well as statistical techniques (Baker, 2008 and references therein; Benito et al., 2003; House et al., 2002). The focus of paleoflood research is to augment information about the flooding behavior of a catchment (Baker et al., 2002; Sigafoos, 1964) and its relation to hydroclimatology (Hirschboeck, 1988) by including evidence of past floods derived from geomorphic, botanical (Baker 1998), and/or lichenometric indicators (Foulds et al., 2014).

An important source of indirect evidence of floods is contained in the vegetation growing on floodplains. The interaction between floodwaters and trees can leave datable evidence of past flood activity on tree stems and branches and, consequently, in the growth-ring record of disturbed trees. Floodplain vegetation can therefore be used as a natural archive of past floods, which can in turn be deciphered using dendrogeomorphic techniques (Alestalo, 1971; Stoffel and Corona, 2014; Stoffel et al., 2010). Perhaps surprisingly, after the pioneering work of Sigafoos (1961, 1964), botanical evidence has not been used as often as other subsequently recognized types of paleoflood evidence, e.g. slackwater deposits (Kochel and Baker, 1982; see a complete review in Baker, 2008). Yet there is enormous potential for extracting information about past flood events in tree-ring records, not least because of the ubiquitous presence of trees with discrete annual rings in temperate and boreal locations (St George, 2014). A clear need thus exists to review the current status of flood-related studies in dendrogeomorphology and to direct the attention of the paleohydrologic community to this useful indicator of past flood activity.

This progress report (i) provides an extensive review of recent trends and developments of dendrogeomorphic research focusing on past floods, (ii) describes methodologies used, and (iii) outlines new approaches for flood chronology and magnitude reconstructions of unrecorded recent and more ancient floods. This contribution also (iv) outlines the potential of trees to assist in flood hazard assessment and (v) concludes with proposals for future research directions.

II Review of flood studies using tree rings

The potential of the tree-ring record for hydrological studies (i.e. annual streamflow reconstruction) was recognized in the early decades of the 20th century by Hardman and Reil (1936). However, it was not until the 1960s, only a few years after the first formal description of paleohydrology (Leopold and Miller, 1954), when the links between riparian vegetation and flood frequency were initially described by Sigafoos (1961) along the Potomac River (Washington, USA). Three years later, Sigafoos (1964) extended his observations and provided the first description of botanical evidence of floods. Through tree-ring dating of new sprouts growing from tilted and buried trees, as well as through the study of injured trees (predominantly cambial scars), Sigafoos reconstructed time series of flood events and concluded that botanical evidence had a significant applied value to hydrology. Subsequently, Helley and LaMarche (1968, 1973) combined geomorphic evidence and tree-ring information to analyze floods over a period of 400 years in different watersheds located in northern California. Stewart and LaMarche (1967) compared pre- and post-event changes in forests to investigate flood characteristics. Harrison and Reid (1967) used scarred trees to analyze flood frequency, concluding that large numbers of scarred trees meant substantial amounts of debris had been transported during flood events and therefore could be interpreted in terms of flow magnitude. Everitt (1968) observed that cottonwood forest dynamics were closely related to river discharge and geomorphic changes in the floodplain. The impact of ice jamming on tree scarring and its role in the hydrology and hydraulics of flood events was analyzed by Henoch (1973), Egginton and Day (1977), Smith and Reynolds (1983), and Tardif and Bergeron (1997). Contemporaneously, several studies addressed interactions between fluvial geomorphology and riparian vegetation (Bedinger, 1971; Bell and Johnson, 1974; Friedman et al., 2005; Hupp, 1982; Hupp and Osterkamp, 1985, 1996; Malik, 2006; Scott et al., 1996).

Examining the anatomical responses of trees to flood events, as well as information about the flood tolerance of woody species (e.g. Gill, 1970) has led to further methodological improvements in tree-ring interpretation and allowed dating of past flood events with seasonal precision. Yanosky (1983, 1984) used vessel-size anatomical changes in *Fraxinus* sp. samples to identify and reconstruct summer floods in the Potomac River. He related these anatomical changes to a disruption in growth hormone transport along the stem caused by anoxia associated with floodwater. Further work along these lines focused on anatomical responses to flood processes in other environments and tree species (Arbellay et al., 2012ab; Astrade and Begin, 1997; Ballesteros-Cánovas et al., 2010a, 2010b, 2015a; Kozlowski, 1997; St George and Nielsen, 2003; St George et al., 2002; Stoffel et al., 2012; Wertz et al., 2013; Yamamoto, 1992). Collectively, these studies contributed to an improved identification of past floods events in continuous tree-ring records.

Flood chronologies also have been derived from tree-ring analysis in ungauged mountain areas. Zielonka et al. (2008) used scars on trees to determine flash-flood activity in an ungauged mountain catchment in the Tatra Mountains (Poland). Ruiz-Villanueva et al. (2010) combined the use of signal intensity with the geomorphic position of trees to obtain information on past flash floods in a mountain stream in Spain. Recently, Ballesteros-Cánovas et al. (2015b) integrated forest management data, historical archives, and long records of daily precipitation to evaluate flash-flood activity and its hydrometeorological triggers over the last century. Therrell and Bialecki (2014) reconstructed spring flooding on the Lower Mississippi River based on anatomical tree-ring signatures of floods. Similar tree-ring analyses have reconstructed regional flash-flood activity in Central Spain (Ruiz-Villanueva et al., 2013), the Tatra Mountains (Ballesteros-Cánovas et al., 2015d), and in the flysch Carpathians (Czech Republic; Šilhán, 2015).

Beyond dating procedures, tree rings have been successfully used for flood-magnitude estimation in combination with paleohydraulic techniques (Corriell, 2002; Gottesfeld, 1996; McCord, 1990, 1996). Ballesteros-Cánovas et al. (2011a, 2011b) combined two-dimensional hydraulic models and scar heights of specific (tree-ring dated) flood events to understand scar genesis and its relation to flood peak discharge in two fluvial environments. It was demonstrated that this information clearly affects the estimated return periods of flood frequency based on systematic records alone (Ballesteros-Cánovas et al., 2011b) and that these data can be used to assess epistemic uncertainty in flood-risk assessments (Ballesteros-Cánovas et al., 2013). The notion to extend the flow series with new non-systematic source data coming from trees led the researchers to test the hypothesis that the inclination of tilted trees is correlated with flood magnitude in different rivers and tree species (Ballesteros-Cánovas et al., 2015a). As such, tree-ring data have improved knowledge about floods over large areas of Central Spain, for which data have been very scarce prior to analyses (Ballesteros-Cánovas et al., 2012). Stoffel and Wilford (2012) and Díez-Herrero et al. (2013) provide summaries of these recent studies. In this report, Table 1 provides an extensive list of previous experience in paleoflood dating based on tree rings and Figure 1 indicates where paleoflood studies have been undertaken.

III Synthesis of methodologies

1 Botanical evidence of past flood events

Dendrogeomorphic studies of floods are usually based on the "process–event–response" concept as defined by Shroder (1978). Under this scheme, the "process" can be any kind of geomorphic agent (in this case, a flood), the "event" is represented by an externally visible defect in the tree that occurred during a specific flood-related incident, and the "response" refers to the anatomical imprint left by the flood event in the tree-ring record. Paleoflood evidence recorded by trees includes impact or abrasion scars, abnormal stem morphologies, eroded roots, titled stems, standing dead trees, and anatomical abnormalities caused by prolonged inundation (Figure 2).

The distribution of riparian vegetation and the determination of its age can provide insights into flow dynamics and/or competence (Hupp and Osterkamp, 1985, 1996; Stoffel and Wilford, 2012). The intensity and timing of extreme flows can be inferred when trees growing in riparian areas receive external wounds on their stems (flood scars) as a result of the impact of rapidly moving flood debris. The partial removal of bark and cambium tissues by such wounds produces callus pads next to the open wound and, depending on the species, may result in several growth disturbances. In conifer trees, the main indicators are decreased ring widths along with a significant reduction in earlywood tracheid size (Arbellay et al., 2012a, 2012b; Ballesteros-Cánovas et al., 2010a). In *Abies*, *Larix*, *Picea*, or *Pseudotsuga* (Stoffel, 2008), tangential rows of traumatic resin ducts (TRD) may be formed after a mechanical disturbance. Specifically, TRDs created around the wound (Bollschweiler et al., 2008; Schneuwly et al., 2009a, 2009b) are an excellent indicator of a "hidden" scar and can be used as a dating tool with seasonal precision (Stoffel and Beniston, 2006). The responses of broadleaf trees to flood disturbance varies between species, but by far the most common response is a major decrease in mean vessel area within rings formed during flood conditions (Arbellay et al., 2012b; Astrade and Bégin, 1997; Ballesteros-Cánovas et al., 2010b; St George and Nielsen, 2003; St. George et al., 2002; Wertz et al., 2013). In some respects, scars are the most useful botanical indicators of paleoflood information. They can provide seasonal resolution for the occurrence of a flood event as well as be used as paleostage indicators (PSIs) in flow discharge estimations (Ballesteros-Cánovas et al., 2011a, 2011b). Floods can also tilt trees when the unilateral hydrodynamic pressure induced on the stem partially exceeds stem elasticity and root-plate system anchorage. As a consequence, both the stem and the root-plate system can be deformed by the flood. Trees will attempt to

Table 1. Summary of research that has exploited tree rings to study past flood events. Location: 56% of studies were carried out in North America, 36% in Europe, 5% in South America, and < 2% in Oceania. The average number of sampled trees per study was 104 $\pm$ 122 trees, of which 60% were broadleaved trees and 40% conifer trees.

Author	Location	River	Aims	Dated events	Species
Sigafoos, 1961	USA (Washington)	Potomac River	Relationship between plants and flood	1961	*Fraxinus* sp.
Sigafoos, 1964	USA (Washington)	Potomac River	Dating flood events	1929, 1936, 1942, 1947, 1952, 1956, 1958	*Fraxinus* sp. (43 trees)
Harrison and Reid, 1967			Dating flood events		
Stewart and LaMarche, 1967	USA (Washington)	Coffee Creek	Dating flow erosion	1964	Spruce-pine-fir
Everitt, 1968	USA (North Dakota)	Little Missouri River	Paleocompetence and forest dynamic	Geomorphic changes during last 150 yrs	Cottonwood
Phipps, 1970	USA (Eastern North)	–	Methodological		
Helley and LaMarche, 1973	USA (North California)	Smith, Klamath, Trinity Mad, Van duzen, and Eel rivers	Dating flood events	1964, 1955, 1861, 1750, 1600	Douglas-fir tree; Redwood; White fir
Honoch 1973			Dating flood ice jams		
Egginton and Day, 1977	Canada (Mackenzie)	Hodgson Creek	Dating flood events (ice scars)	Since 210 yrs. BP	
Smith and Reynolds, 1983	Canada (Alberta)	Red Deer River	Comparison between ice-scars stage and flow gauge data	Period: 1935–1975	Cottonwood (70 samples)
Osterkamp and Hupp, 1984	USA (Oregon-California)	Whitney Creek	Dating alluvial landform	1670–1840	*Pinus jeffreyi* (-)
Hupp and Osterkamp, 1985	USA (Virginia)	Passage Creek	Paleocompetence and forest dynamic	–	Several riparian species

(continued)

Table 1. (continued)

Author	Location	River	Aims	Dated events	Species
Yanosky, 1983, 1984	USA (Washington)	Potomac River	Anatomical analysis (dating flood events)	Nine floods exceeded 1270 m3 s during the study period, 1930–1979	*Fraxinus americanum* L. and *F. pennsylvanica* Marsh. (91)
Gottesfeld and Gottesfeld, 1990	Canada (British Columbia)	Morice River	Dating flood events and fluvial dynamic	1885–1990 (31 flood event)	–
Martens, 1992	Australia	Hawkesbury River	Dating fluvial landform	–	Riparian trees (39 trees)
Gottesfeld, 1996	Canada (British Columbia)	Skeena River	Peak discharge estimation	May 29 to June 6, 1990	Different conifer and broadleaves trees (27)
Hupp and Osterkamp, 1996	USA (southwestern)	Four streams	Paleocompetence and forest dynamic	–	Several riparian species
Scott et al., 1996	USA (Montana)	Missouri River	Fluvial landform dating	1927, 1964, 1968, 1970, 1978, 1981	Cottonwoods (-)
McCord, 1990, 1996	USA (Arizona, Utah, New Mexico, and Colorado)	Several streams	Dating flood events and peak discharge estimation	17 flood events during the period 1866–1990	Seven species of conifers and 10 deciduous species (113 trees)
Tardif and Bergeron, 1997	Canada (Western Quebec)	Duparquet River	Dating flood events (ice-scar)	Period: 1655–1996	Mostly White Cedar and Beech (81 trees)
Astrade and Begin, 1997	France	Saône River	Anatomical analysis (dating flood events)	1983, 1986, and 1989	*Populus tremula* L. and *Quercus robur* L.
Royall, 2000	USA (Virginia)	Crooked stream	Dating flood events and peak discharge estimation	1983, 1989, 1991	Different broadleaves trees (-)
St George and Nielsen, 2003	Canada (Manitoba)	Red River	Anatomical analysis (dating flood events)	1826, 1852	*Quercus macrocarpa* (194 trees)
Correill, 2002	USA (Vermont)	Middlebury River	Peak discharge estimation	–	–
St George and Nielsen, 2003	Canada (Manitoba)	Red River	Anatomical analysis (dating flood events)	1997, 1979, 1950, 1852, 1826, 1762, and 1747	*Quercus macrocarpa* (348 trees)

(continued)

Table 1. (continued)

Author	Location	River	Aims	Dated events	Species
Friedman et al., 2005	USA (New Mexico)	Rio Puerco	Fluvial landform dating	Period: 1966–1999	*Tamarix ramosissim* and Salix *Exigua* (6 trees)
Malik 2006	Poland	Mała Panew River	Fluvial landform dating		
Zielonka et al., 2008	Poland	Potok Waksmundzki stream	Dating flood events	17 flood events between 1928 and 2005	*Picea abies* (58 trees)
Ballesteros-Cánovas et al., 2010a	Spain (Center)	Venero Claro stream	Anatomical analysis (dating flood events)	Floods in 2004, 1997, 1989	*Pinus pinaster* Ait. (14)
Ballesteros-Cánovas et al., 2010b	Spain (Center)	Venero Claro stream	Anatomical analysis (dating flood events)	Floods in 1981, 1997, 2000, 2004	*Fraxinus angustifolia*, *Alnus glutinosa*, *Quercus pirenaica* (70 trees)
Ruiz-Villanueva et al., 2010	Spain (Center)	San Pedro stream	Dating flood events	22 flood events between 1943 and 2010	*Pinus pinaster* (98 trees)
Ballesteros-Cánovas et al., 2011a	Spain (Center)	Venero Claro stream	Peak discharge estimation	1997	*Alnus glutinosa* (23 trees)
Ballesteros-Cánovas et al., 2011b	Spain (Center)	Alberche River	Peak discharge estimation	1970, 1989, 1993, 1996, 2000, 2002, 2003, 2005	*Alnus glutinosa* (44 trees)
Stoffel et al., 2012	Argentina (Patagonian Andes)	Los Cipreses torrent	Fluvial landform dating	21 erosive events since 1870	*Austrocedrus chilensi*, *Nothofagus dombeyi* and *Pseudotsuga menziesii* (31 trees)
Arbellay et al., 2012a	Switzerland	St-Barthélemy torrent	Anatomical analysis (dating flood events)	Spring 2007	*Fraxinus excelsior* (18)
Stoffel and Wilford, 2012			Methodology		
Ballesteros-Cánovas et al., 2013	Spain (Center)	Alberche River	Risk assessment	1970	*Alnus glutinosa* (44 trees)
Díez-Herrero et al., 2013	Spain (Center)		Methodological review		

(continued)

Table 1. (continued)

Author	Location	River	Aims	Dated events	Species
Ruiz-Villanueva et al., 2013	Spain (Center)	2-moutain streams	Regional reconstruction	41 flood events between 1936 and 2010	*Pinus pinaster* and *Alnus glutinosa* (198 trees)
Wertz et al., 2013	USA (North Dakota)	Red River	Anatomical analysis (dating flood events)		*Quercus macrocarpa* Michx.
Ballesteros-Cánovas et al., 2015b	Spain (Center)	Arroyo de los Puentes	Dating flood events	25 flash-flood events since AD 1802	*Pinus sylvestris* (178 trees)
Ballesteros-Cánovas et al., 2015a	Spain (Center)	3-moutain streams	Peak discharge estimation	18 flood events since 1900's	*Pinus sylvestris*, *Alnus glutinosa* and *Fraxinus angustifolia* (35 trees)
Ballesteros-Cánovas et al., 2015c	Spain (Center)	Alberche River	Methodological		*Salix atrocinerea*, *Fraxinus angustifolia* and *Alnus glutinosa*
Ballesteros-Cánovas et al., 2015d	Poland	4-moutain streams	Regional reconstruction	47 past flash floods between 1866 to 2012	*Picea abies* and *Abies alba* (218 trees)
Casteller et al., 2015	Patagonian Andes	Los Cipreses torrent	Dating flood events	21 flash floods AD 1890–2009	*Astrocedus chilensis*; *Picea menziesii*; *Nothofagus dombeyi* (43 trees)
Šilhán, 2015	Flysch Carpathians	10-moutain streams	Regional reconstruction	64 floods AD 1883–2012	*Fagus sylvatica*, *picea abies*, *Acer pseudoplatanus* (542 trees)
Therrell and Bialecki, 2015	USA (Missouri)	Mississippi River	Dating flood events	42 spring flood events 1779–2008	*Quercus lyrata* and *Quercus macrocarpa* (33 trees)

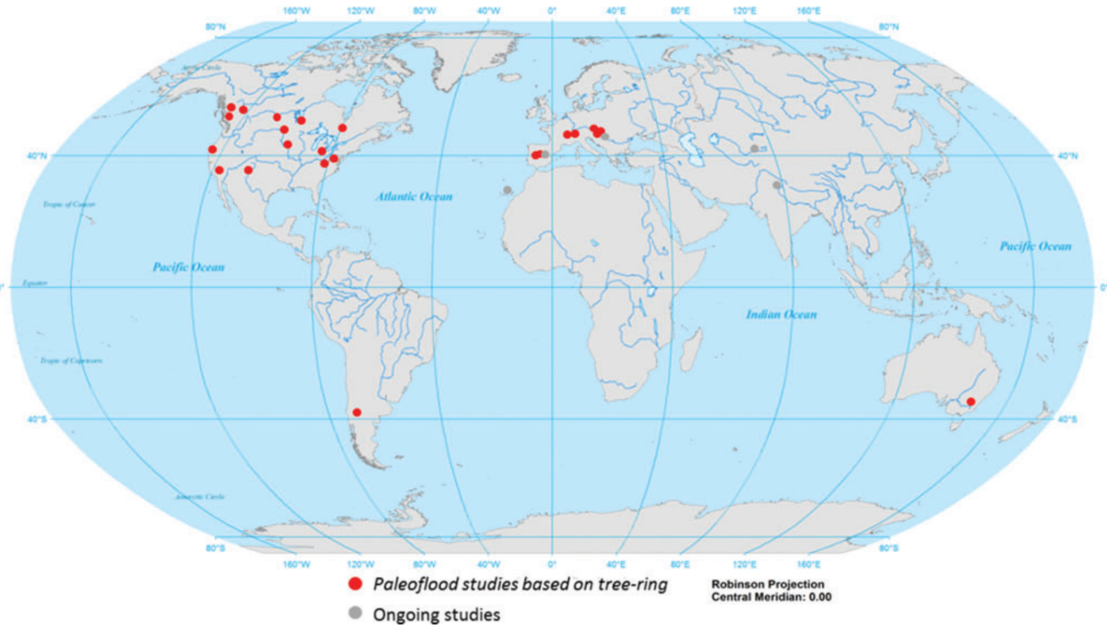

Figure 1. Map illustrating the locations of paleoflood studies based on tree-ring evidence.

compensate for the tilting through the formation of reaction wood (Timell, 1986) and eccentric growth will become apparent in the tree-ring series. The annual ring showing the initiation of this response can be used to date the time of occurrence of the flood event. In conifers, reaction wood is formed on the tilted side of the stem (so-called compression wood), whereas broad-leaved trees form tension wood on the side facing the flow. Early work on tilted trees focused on the growth of new sprouts as a result of re-differentiation of meristem cells guided by positive phototropism. The age of such sprouts can be determined and thus a minimum age of flood events can be estimated (Sigafoos, 1964).

The impact of floating debris can lead to crown breakage in shorter trees, which in turn may lead to a significant decrease in phototropism rates and abrupt growth reductions in tree-ring series (Sigafoos, 1964). In addition, tree stems can be partly buried by sediments, thereby limiting water uptake and nutrient supply, and result in an abrupt decrease in ring widths (Friedman et al., 2005; Hupp 1988; Kogelnig et al., 2013).

Root exposure occurs when stream banks are eroded as a result of (bankfull) floods (Malik, 2006; Stoffel and Wilford, 2012). The exposure of roots will lead to significant changes in wood anatomy, mainly in the form of decreased early-wood tracheid sizes and increased presence of latewood cells (Stoffel et al., 2012, 2013).

Trees growing in endorheic areas linked to fluvial systems may also document the existence of past floods, even in the absence of externally inflicted evidence of such events. It has been observed that prolonged anoxic conditions of the root system can influence the production and basipetale transport of growth hormones (such as auxin) and induce changes in wood anatomy (Wertz et al., 2013). In addition, tree species not physiologically adapted to such conditions could die as a result of an excess of the prolonged anoxic environment produced by changes in the channel pattern in response to a flood.

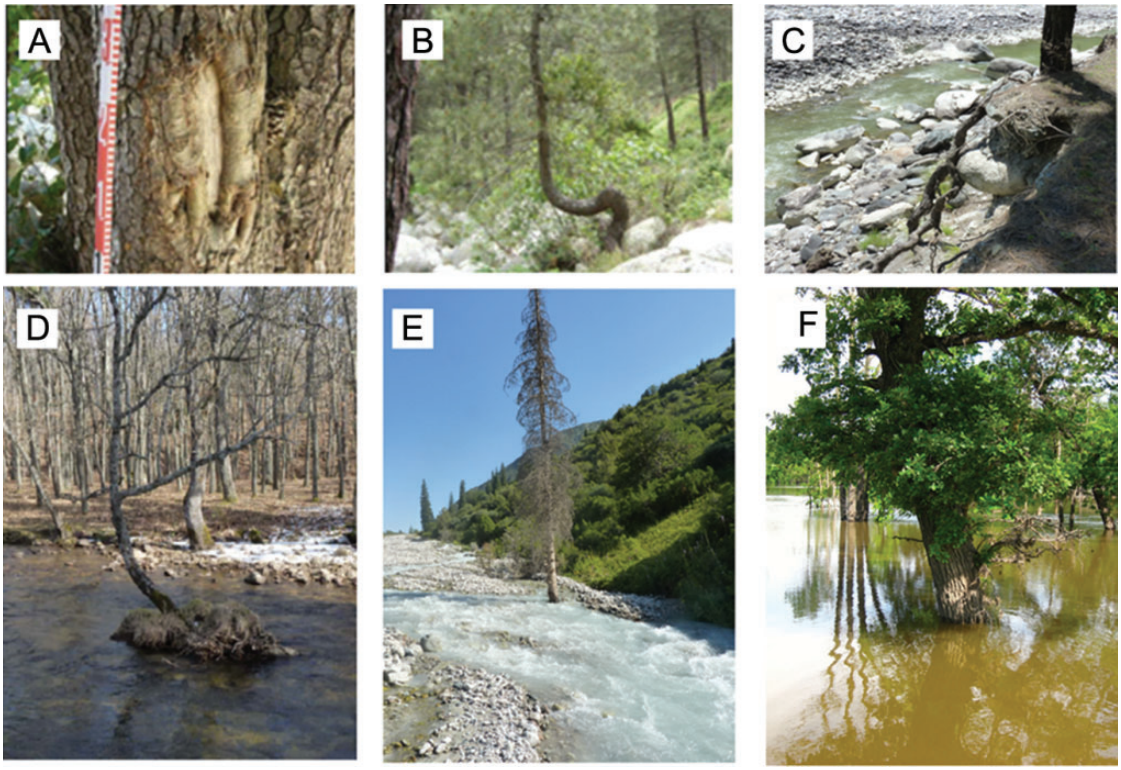

Figure 2. Types of botanical evidence used to identify paleofloods using tree rings. (A) Trees can be injured by the impact or abrasion of boulders or course woody debris transported by flood waters. (B) Flood debris may break the main stem, causing trees do adopt unusual stem morphologies after regrowth. (C) Bank erosion caused by flooding can cause tree roots to become sub-aerially exposed. (D) The hydraulic pressure of floodwaters can tilt tree stems. (E) Changes in channel position or pattern can kill trees growing within the riparian zone. (F) Flooding during the early growing season can cause inundated oak trees to form abnormal anatomical structures within the newly formed wood.

2 Field survey and sampling strategies

The first step required to evaluate the potential for flood records from tree rings at a site is to identify any flood-impacted trees that exhibit common flood responses. Before compiling a botanical record of flood damage, an understanding of flow dynamics and geomorphology is needed to avoid including trees that may have been damaged by processes unrelated to floods. For instance, trees presenting elongated scars might be caused by neighboring trees that fell during a wind storm or by broken branches.

Field studies have shown that the position of disturbed trees within a river cross-section can play an important role in determining the reliability of disturbance features for use in flood dating and magnitude reconstruction. As a general rule, disturbed trees located in exposed positions on the banks of straight channel reaches, or on the internal side of meander bends, are preferred (Ballesteros-Cánovas et al., 2011a, 2015c; Ballesteros-Cánovas, Stoffel, Czajka, et al., in review; Figure 3). A critical inspection of the river's reach based on the researcher's experience and the systematic analysis of sequences of past aerial photos can help to evaluate the reliability of the site for the extraction of flood information from tree-ring

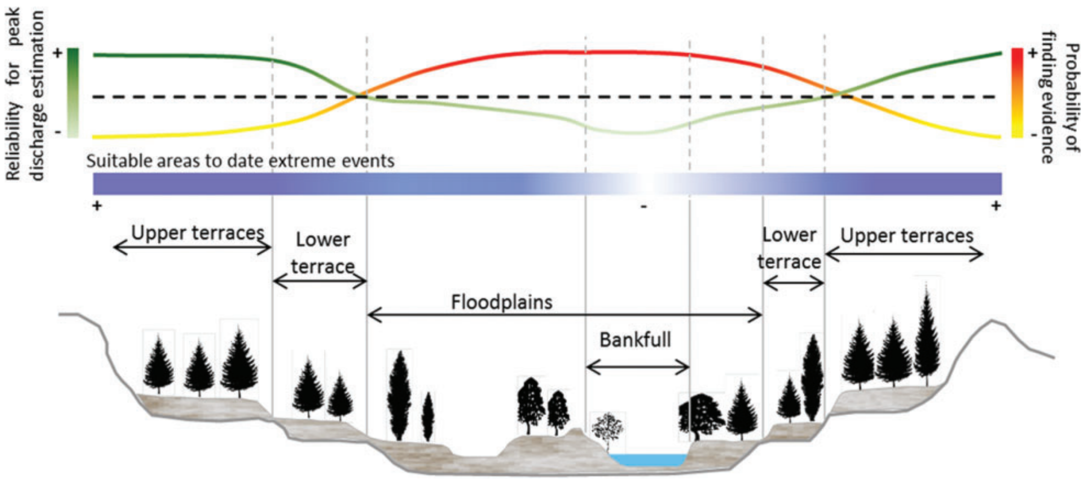

Figure 3. Distribution along a river cross-section of: (i) the expected probability of finding flood-related botanical evidence (red = highest, yellow = lowest), (ii) the areas most suitable for obtaining information on extreme past events (blue), and (iii) the relative reliability of botanical evidence for use in peak discharge reconstructions (green).

analysis. Once either all—or a representative subset—of spatially distributed flood-affected trees are identified, the sampling procedure can proceed either through core sampling with an increment borer (Grissino-Mayer, 2003) or the destructive sampling of dead trees, branches, or exposed roots for the preparation of cross-sections. The locus of coring on the tree should be determined by the nature of the disturbance being sampled. For injured trees, complete tree-ring series should be obtained as close as possible to the injury (preferably in the upper portion of the damaged area; see Schneuwly et al., 2009a, 2009b). For tilted trees, core sampling should be done in the maximum curvature of the tilt. For trees with broken crowns or stem morphology anomalies, core sampling should be done below the damaged area. The position of each tree should be recorded with a GPS device, measurements taken of the tree and the disturbed feature (e.g. height of scar, tree height, and diameter), and photographs made of each tree. This information will be later compiled to assist the researcher in tree-ring record interpretation.

3 Flood chronologies using tree rings

One of the main goals of tree-ring flood studies has been to extend chronologies of flood events in ungauged or sparsely gauged catchments. Early studies were usually based on a limited set of growth anomalies in trees (e.g. Sigafoos, 1964), although over time the use of other typologies of growth anomalies has expanded (e.g. Gottesfeld and Gottesfeld, 1990). In studies of low-gradient fluvial rivers, flood chronology reconstructions have focused on the occurrence of anomalies in anatomical structures (described as "flood rings"; St George and Nielsen, 2002; St George et al., 2003; Wertz et al., 2013), whereas in high-gradient streams, scars on tree stems have been used predominantly (e.g. Ballesteros-Cánovas et al., 2010a, 2010b, 2011a; Yanosky and Jarrett, 2002; Zielonka et al., 2008). Flood chronologies have also been developed with other types of botanical evidence. Malik (2006) and Stoffel et al. (2012, 2013) used the timing of root exposure to describe flood dynamics, while Casteller et al. (2015) used growth anomalies in stems and roots to reconstruct past floods and to distinguish between erosional and depositional processes in a high-gradient stream of the Patagonian Andes. What these studies all have in common is that expert criteria, based on the replication of disturbance in several trees, were used to identify past floods (for details, see Stoffel et al., 2010).

While the occurrence of various anomalies related to floods certainly facilitates the identification of past events, it also calls for a weighting of different parameters and intensities, along with reliable thresholds for objective event definition. For example, Ruiz-Villanueva et al. (2010) used different types of damage evidence, the percentage of damaged trees (with respect to all trees living at the time of sampling), and the spatial distribution of these damaged trees for event definition. Kogelnig-Mayer et al. (2011) developed a weighted index (Wit), based on different intensities of tree reactions as well as the percentage of damaged trees during an event. Later, Schneuwly-Bollschweiler et al. (2013) determined reliable thresholds for event definition using both the Wit index and geostatistical analysis to address spatial connectivity between the reacting trees. Based on this approach, Corona et al. (2012) were able to provide guidelines for the sample size of trees needed to separate the effects of tree-damaging geomorphic processes from noise at different confidence levels. This approach has been recently used to reconstruct the longest annual resolved paleoflood chronologies based on tree-ring analyses in the Spanish Central System and Tatra Mountains (Ballesteros-Cánovas et al., 2015b, 2015c; Figure 4; Figure 5).

4 Peak discharge estimations from botanical paleostage indicators

Paleoflood discharge estimations require the resolution of a hydraulic equation with two degrees of freedom. In this regard, the height and location of a scar on a tree stem can be assumed to represent a PSI of a past flood event, and consequently can be used for paleoflood discharge estimations (Jarrett, 1990; Jarrett and England, 2002). In hydraulic equations, PSIs can be used to reduce the number of unknown parameters. According to Webb and Jarrett (2002), different hydraulic procedures exist to transform heights determined from PSIs to peak discharge. The step-backwater approach is used most extensively and is based on the conservation of energy between two cross-sections having PSIs along a river reach. This method estimates the hydraulic parameterization and boundary conditions of past floods through an iterative procedure. Water height is obtained with general hydraulic equations (available in conventional 1D or 2D hydraulic modeling software), and peak discharge is then derived through a trial-and-error approximation between the heights defined by the PSI and modeled water table profiles (Yanosky and Jarrett, 2002). The critical-depth method has frequently been used (for an explanation see Webb and Jarrett, 2002), although it requires the existence of PSIs in a cross-section where the flow reaches the minimum energy (from a geomorphological point of view: upper section of waterfall or narrow constrictions). Uncertainties related to flood-related topographic changes can be minimized if analyses are performed in stable sections of the river (e.g. a bedrock channel) where channel stability is guaranteed, at least in the shorter to medium term (Ballesteros-Cánovas et al., 2011a).

The reliability of peak discharge estimation is linked to the relationship between maximum flow or high water marks (HWM) and scar height. In low-gradient streams, Smith and Reynolds (1983) found the average difference between ice-flood scar height along the Red Deer River and the stage recorded by flow gauge records for the same event was almost 1.37 m $\pm$ 0.94 m. Gottesfeld (1996) observed uncertainty around 0.19 $\pm$ 0.03 m based on single event study. Later, Ballesteros-Cánovas

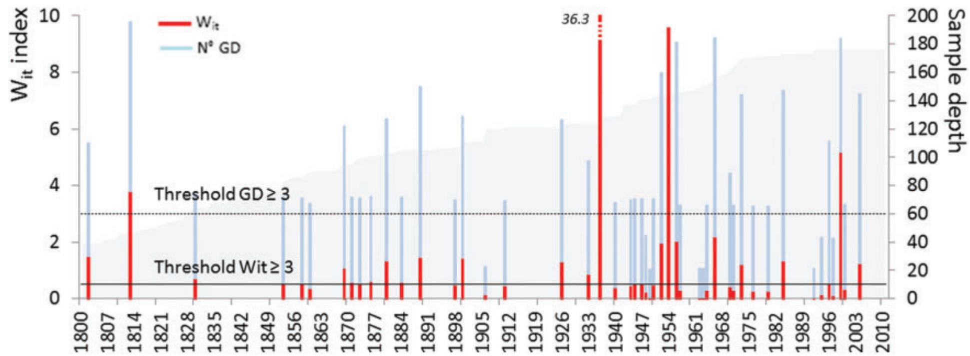

Figure 4. Example of a flood-chronology derived from flood-affected trees based on the Wit-index and the number of growth disturbances (GD) (see Ballesteros-Cánovas et al., 2015b).

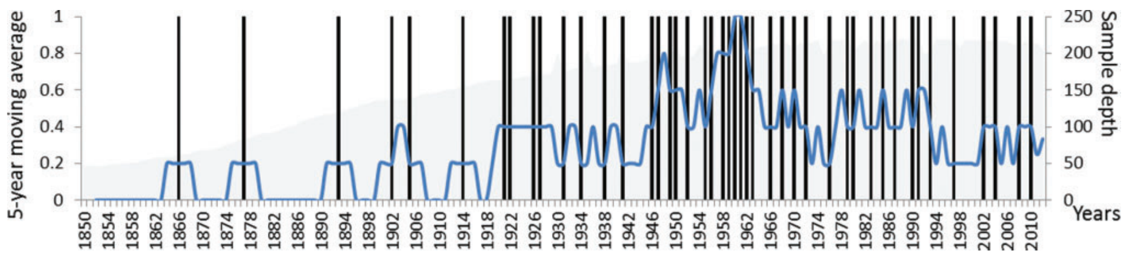

Figure 5. Reconstructed flooded years in Tatra Mountains (see Ballesteros-Cánovas et al., 2015c).

et al. (2011b) demonstrated that the uncertainty related to scars inflicted by floating woody debris will increase with flood magnitude. In high-gradient streams, Yanosky and Jarrett (2002) suggested there are different levels of uncertainty in high-gradient vs. low-gradient streams, with deviations in high-gradient streams ranging from as low as –0.6 m to as high as 1.5 m. This range of uncertainties has been recently confirmed by Ballesteros et al. (2011a) who observed deviations above and below the observed flow of between –0.8 to 1.3 m (Figure 6) depending on whether the stage estimate was determined from large or small scars.

New peak discharge reconstruction approaches based on tree-deformation energy have been employed. Inspired by structural analysis, Ballesteros-Cánovas et al. (2015a) studied the relationship between tree tilting and flood magnitude using 35 trees growing next to gauging stations (Figure 7). The authors demonstrated that fairly moderate to high correlations (up to $r = 0.65$) exist between the degree of tilting and minimum peak discharge, and concluded that tilted trees may be used to provide additional information about minimum peak discharges during specific flood events.

IV The role of tree-ring studies in flood hazard and risk assessment

The systematic incorporation of paleoflood data into traditional flood-frequency analyses for risk assessment is still challenging. One reason is that paleoflood evidence is not well-preserved in all catchments and where it is preserved data collection involves expert field-based inferences to determine stage and other hydraulic attributes of a flood. Another reason is that, when extreme paleoflood-based discharges appear as outliers in

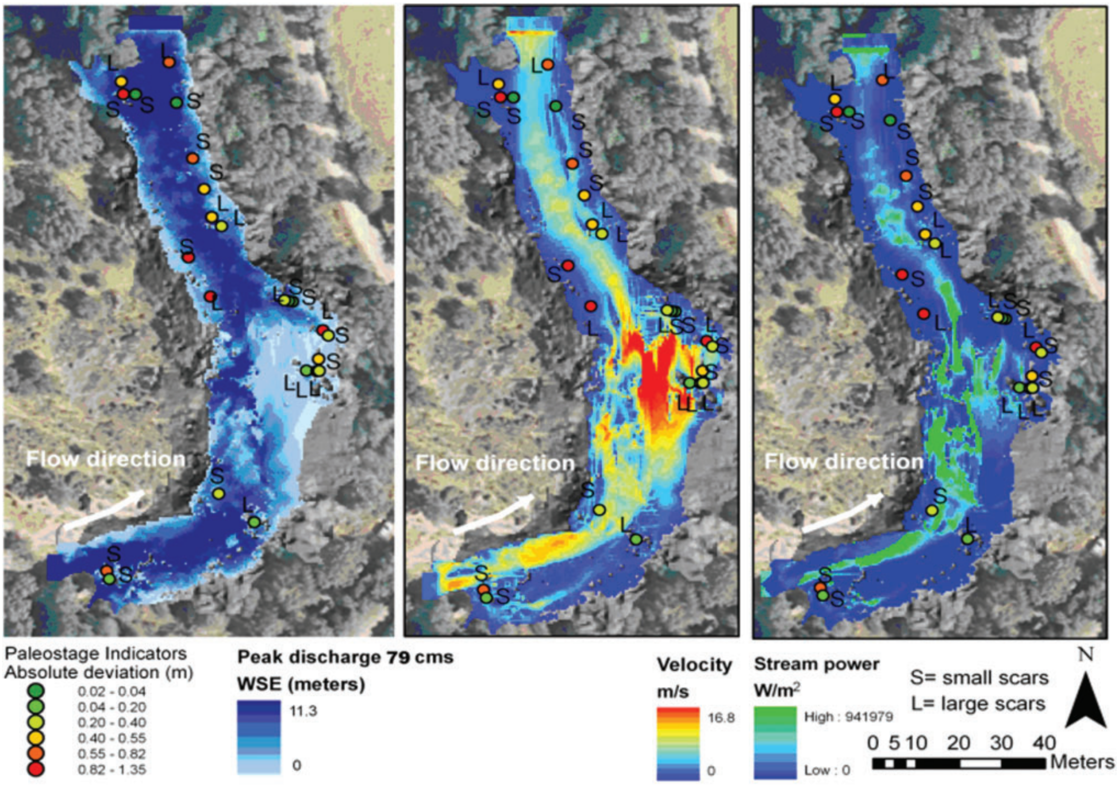

Figure 6. Peak discharge reconstruction based on 2D hydraulic models and tree scar height for an intense flow event that took place in Venero Claro, Spain (see Ballesteros-Cánovas et al., 2011a).

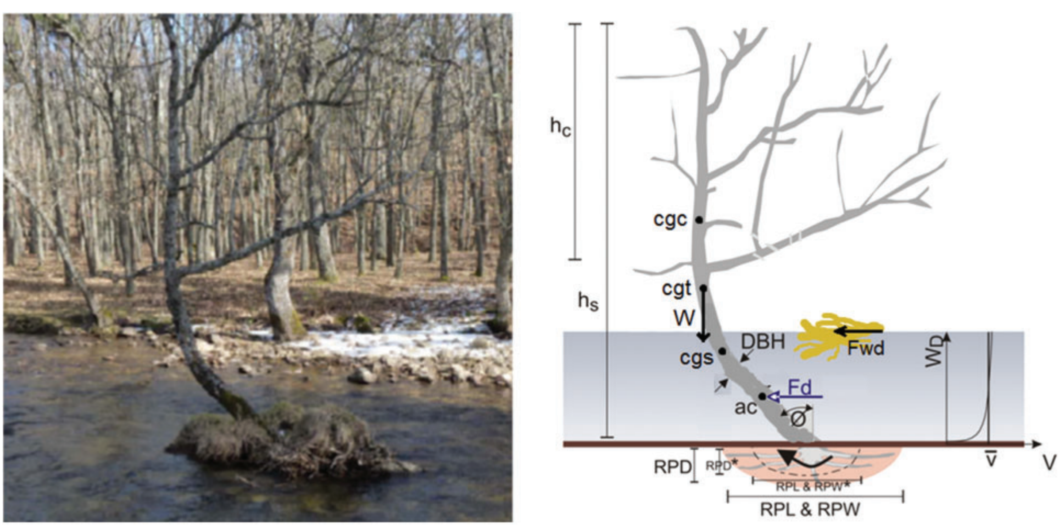

Figure 7. Schematic diagram of forces owing to hydrodynamic loads acting on a tree to tilt it during a flood event (a detailed description can be found in Ballesteros-Cánovas et al., 2015a).

an augmented flood time series, the issue of stationarity arises (see Baker 2008; Benito et al., 2004; Klemes, 1986; Milly et al., 2008). Proponents of integrating paleoflood information into risk assessment argue that the landscape evidence of the most extreme floods that have occurred in the past is precisely what flood hazard managers need to know. Yet a criticism often raised is that under a changing climate, the record of past floods will not be representative of future flooding, hence emphasis should be placed on the most recent portion of a flood record. In response to this critique, studies of both historical records (Macdonald and Black, 2010) and paleoflood records (Greenbaum et al., 2014) have shown that multi-century to millennia-length augmented flood records may have an advantage over shorter, more recent instrumental records because longer records incorporate a much larger range of naturally occurring high and low flood events and therefore result in more robust flood-frequency estimates.

An illustration of this can be seen in paleoflood studies based on tree-ring analyses of the Red River of the North, which frequently affects communities in the American states of North Dakota and Minnesota and the Canadian province of Manitoba, that used "flood rings" to extend the record of high-magnitude floods back to the mid-17th century (St George and Nielsen, 2003). These data constituted the first physical evidence of the Red River flood of 1826, which destroyed the nascent Red River Settlement and was previously known only through eye-witness accounts (St George and Rannie, 2003). Because the extended paleoflood record did not support fragmentary accounts of an exceptionally large Red River flood in 1776, this event has been omitted from contemporary assessments of regional flood hazards (Brooks and St George, 2015). The paleoflood record for the Red River of the North has also been cited by the United States Army Corps of Engineers to argue that the hydrology of this watershed is highly non-stationary, and is prone to extended, multi-decadal periods of higher or lower flood hazards because of climate and land-use change.

Important advances have also been made in incorporating non-systematic data into flood-frequency analysis for hazard assessment (Benito et al., 2004; Kjeldsen et al., 2014; Martins and Stedinger, 2001). Tree-ring-based flood records may have advantages over sediment-based paleoflood studies when using these approaches because they can provide annually resolved flood event dates within a time frame that can be more easily referenced to the systematic record. With a few exceptions, tree-ring-based flood reconstructions generally focus on the last few centuries (see Table 1); Ballesteros-Cánovas et al. (2011b) demonstrated that adding recent ungauged extreme flood events dated by tree rings to the observed flood record can lead to important impacts on flood-percentiles (Figure 8) and proposed that these changes in the flood frequency may be incorporated stochastically into a formal flood-risk assessment (Ballesteros-Cánovas et al., 2013). Similar impacts of the flood-percentiles have also been recently reported for the Tatra Mountains, where peak discharges based on the height of dated scars and 2D-hydraulic models have been used to extend the short and highly fragmented flow records during the last century (Ballesteros-Cánovas et al., in review).

V Future directions

Compared to other sources of paleoflood information, tree rings are distinguished by their high temporal (annual or sub-annual) and spatial resolution. Because of this detail, regional paleoflood chronologies have the potential for being able to identify the full range of natural flooding variability in an area, potentially linking the floods to both climatic drivers and relevant catchment variables. To date, only two comprehensive, regional reconstructions based on paleofloods have been carried out

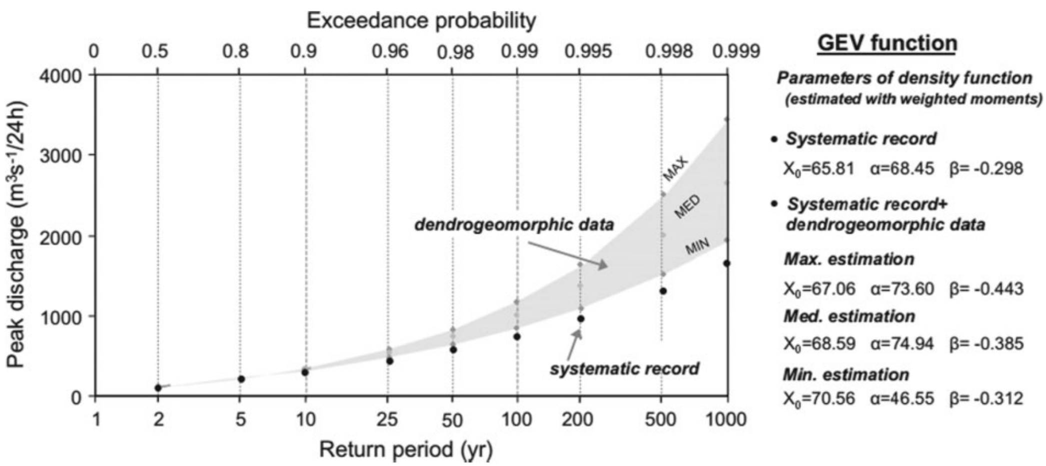

Figure 8. Example of how exceedance probabilities, based on a censored flood series that include dendrogeomorphic data, compare to peak discharge percentiles obtained from the gauged record alone at Navaluenga, Spanish Central System (Ballesteros-Cánovas et al., 2011b). In this example, the inclusion of nonsystematic data resulted in an increase in flood magnitude estimates. Depending on the situation, however, the inclusion of tree-ring data could either lead to an increase or a decrease in percentile estimations.

(Ballesteros-Cánovas et al., 2015d; Šilhán, 2015); therefore, there is a great need for similar efforts in other regions.

There is also great potential for broader application of wood anatomy in paleoflood research. Distorted wood anatomy caused by prolonged inundation (lasting several weeks) of the root and lower stem provides clear, unambiguous evidence of flooding that may be preserved for several centuries in live and dead trees. Most paleoflood studies based on wood anatomy have been conducted in the midlatitudes and have primarily focused on broadleaf deciduous trees (most commonly *Quercus* spp.). Although this approach has not been widely tested in the tropics, López et al. (2014) showed that floodplain trees in the Darien Gap, Colombia, produce more vessels when water levels rise, indicating that tree rings may retain useful information about past hydrology in these settings. Moreover, more detailed wood analyses based on both stable isotopes and chemistry elements are needed to corroborate hypotheses about the quality and characteristics of water flow condition during past flood regimens (Ferrio et al., 2015; Pop et al., in press).

As mentioned, one of the sources of uncertainty in the estimation of the magnitude of the event lies in the lack of information on the exact difference between HWM and flood scars or other evidences. More post-event field recognition (e.g. Smith and Reynolds, 1983; Yanosky and Jarrett, 2002 could contribute to defining a range for these uncertainties in different geomorphologic environments. For instance, the confirmation of the hypothesis linking scar height and the top of levees in mountain streams (Figure 9) will improve the efficiency of sampling procedures and reduce methodological uncertainty in the flow estimation using PSI from trees.

Detailed knowledge about the interaction of trees and geomorphic processes is still scarce and there is a clear need for more fundamental work as well as efforts that will promote synergies between process modeling and the mechanistic study of trees and their root systems (e.g. Lundström et al., 2008; Stokes et al., 2005,

Figure 9. Left: detail of scar on a *Pinus sylvestris* L. stem from the Arroyo de los Puntes (Valsain, Spain). Scar height matches with the maximum height of the levee. Right: longitudinal levee limiting the spatial distribution of the existing vegetation containing evidence of the recent flash-flood event (Adygine stream, Kyrgyzstan).

among others). For example, process-based studies on the utility of tilted trees and broken stems for peak discharge estimation of paleofloods have yet to be fully explored. Analogous to structural analysis, it may be possible to use evidence of tree deflection and broken stem-branches to provide estimates of the minimum energy of the external load needed to produce such impacts. It is expected that collaboration between multidisciplinary researchers can address questions like these and numerous other aspects of the interaction between trees and floods so that this information can be used to increase knowledge about flooding and its impacts in more areas and over longer periods of time to improve flood-risk assessment.

The suitability of tree-ring based paleoflood chronologies for practical purposes should be more explicitly highlighted in future studies. A clear need exists for a broader dissemination of the value and potential of paleoflood studies for the hydrological community. Paleoflood studies can test the validity of uncertainty ranges in flood estimations, and consequently improve the reliability of risk assessments. Moreover, tree-ring based flood information may also contribute to a better understanding of floods through comparative hydrology across processes, places, and time scales (see Blöschl, 2006), especially in mountain environments, where models based on physical-catchment parameters alone may not explain the observed variability in flood processes (Ballesteros-Cánovas et al., 2015c).

Although not focused specifically on floods, another area in which tree-ring information is used extensively in paleohydrology is to reconstruct mean annual (or seasonal) streamflow chronologies. Multi-century dendrochronological streamflow reconstructions are invaluable for evaluating long-term paleohydrologic variability and are now being used for water management purposes, especially with respect to evaluating the risk of extreme dry years and extended droughts (see Meko and Woodhouse, 2011). Individual wet or dry years and multi-year episodes of high and low flow can be resolved well in streamflow reconstructions, but short-duration individual flood peaks are imperceptible. Because of this, linking paleoflood evidence to annual streamflow reconstructions in the same watershed is challenging. Redmond at al. (2002) explored the link between tree-ring reconstructions and paleofloods in western United States with mixed results. In Arizona, when viewed on centennial-length time scales, an increase in paleoflood occurrence tended to coincide with a high frequency of the most extreme reconstructed annual streamflows, but such a correspondence was not evident in the short term on an interannual basis. Hirschboeck (2013) used a "mechanistic" weather-based approach to explore the degree to which flood events were detectable in time series of observed and reconstructed mean annual streamflow and found that floods produced by synoptic-scale winter storms could be detected, but convective storm floods and tropical storm floods could not. Future work along these lines may find other ways to combine chronologies of tree-ring-based flood information for use in risk assessment and climate change studies.

Finally, more work is needed on the physical causes of paleofloods. Klemes (1986) argued that understanding the physical basis for the occurrence of extreme floods of the past is necessary for a meaningful interpretation of derived flood probabilities (e.g. 100-year flood). Standard flood-frequency analysis assumes the flood record is a stationary time series consisting of independent, identically distributed random variables, which, according to Klemes (1986), "strips all hydrologic context" from real-world flood records, leaving them devoid of any causal or physical meaning. An understanding of the causes of past extreme floods also addresses the relevance of paleoflood information for risk assessment in a changing climate. Studies that combine a thorough understanding of the hydrometeorological causes of observed floods in paleoflood-augmented systematic records (Hirschboeck et al. 2000) with careful analysis of the thermodynamic ocean-atmosphere drivers of recent extreme floods (Trenberth et al., 2015) may be the most advantageous way to prepare realistic and robust flood-risk assessments for an uncertain future.

VI Conclusions

Palaeohydrology is a scientific discipline that is contributing important new data and approaches to the study of hydrologic variability. In this progress report we have provided an overview of the many ways tree rings have been used in identifying and analyzing palaeoflood events. We have also outlined recent developments and future challenges for extending the methodology. Although the use of tree-ring records in palaeohydrology is typically limited to the past several centuries, the temporal and spatial resolution these records provide is of crucial importance for understanding the distribution, timing, and controls of recent and past events. In many mountain areas, moreover, tree-ring records are a unique source of information for understanding the frequency and magnitude of past flood processes. Consequently, this information can be integrated into hazard and risk assessment using innovative methods that extend our understanding of flood behavior and its variability in ungauged regions and over periods much longer than available in systematically observed records. As tree-ring-based flood research expands to take advantage of its unparalleled temporal and spatial resolution when compared with other types of paleorecords, and its ability to provide regional connectivity between past flood events and systematically gauged flood time series, it has the potential for providing exciting new insights into interpreting the climatic drivers of extreme flood events and consequently improving future predictions of flood hazards.

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