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A new methodological protocol for the use of dendrogeomorphological data in flood risk analysis

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ABSTRACT

Dendrogeomorphology uses information sources recorded in the roots, trunks and branches of trees and bushes located in the fluvial system to complement (or sometimes even replace) systematic and palaeohydrological records of past floods. The application of dendrogeomorphic data sources and methods to palaeoflood analysis over nearly 40 years has allowed improvements to be made in frequency and magnitude estimations of past floods. Nevertheless, research carried out so far has shown that the dendrogeomorphic indicators traditionally used (mainly scar evidence), and their use to infer frequency and magnitude, have been restricted to a small, limited set of applications. New possibilities with enormous potential remain unexplored. New insights in future research of palaeoflood frequency and magnitude using dendrogeomorphic data sources should: (1) test the application of isotopic indicators ($^{16}O/^{18}O$ ratio) to discover the meteorological origin of past floods; (2) use different dendrogeomorphic indicators to estimate peak flows with 2D (and 3D) hydraulic models and study how they relate to other palaeostage indicators; (3) investigate improved calibration of 2D hydraulic model parameters (roughness); and (4) apply statistics-based cost–benefit analysis to select optimal mitigation measures. This paper presents an overview of these innovative methodologies, with a focus on their capabilities and limitations in the reconstruction of recent floods and palaeofloods.

Key words | dendrogeomorphology, flood hazard, natural risk, palaeoflood, roughness, tree-rings

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INTRODUCTION

Floods are among the natural catastrophes and disasters that cause the highest number of victims, injuries and displacements as well as economic losses in goods and infrastructure. This is the case both in Spain and worldwide, as shown by the results of the floods affecting many countries over recent decades; in Spain alone, flood damage totalling 1% of GDP has caused more than 215 deaths in the last 20 years. The wide-scale flooding that took place in central Europe in 2002 was the turning point for the EU institutions concerned with this problem, leading to the new EU Directive initiative. In Europe, lowland floods are rarely associated with fatalities; in contrast, flash floods often result in loss of life (Gaume *et al.* 2009).

In mountain torrents the traditional methods used for flood hazard analysis (hydrological–hydraulic, palaeohydrological and geological–geomorphological) present enormous scientific uncertainties because of the lack of availability of input data. Normally, in these areas there are very few meteorological and flow gauge stations, or even none at all; their space-time validity may be heterogeneous due to altitude distribution (concentrated in lower level urban areas), and the time series could be discontinued or statistically not representative when fewer than 30 data samples are available. Historic and palaeohydrological data are often used to complete the systematic data log (Benito & Thorndycraft 2004); however, many of the

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analysed areas do not have available documentation on historic flooding as they are a considerable distance from administrative centres and document production centres. There are often no records of flood deposits either, as there are no debris materials in the source area, or no appropriate deposit-prone or retention areas (because of the high steep dynamic velocities). As a result, in the absence of input data, it is very difficult to apply reliable statistical analyses or hydrometeorological models that are adequately calibrated and validated. In the upper basins, conditions for stable human activities such as agriculture and industry are less favourable, significant forest areas have survived and in almost all high-gradient river beds, trees and riparian or other species can be easily found on or near river banks. The growth distribution pattern and single trees of these plant species are affected by the interference of flash floods occurring in these river courses and on their banks.

Dendrogeomorphology (Alestalo 1971) uses information sources recorded in the roots, trunks and branches of trees and bushes located at specific geomorphological points (river banks, bars, flood plains, etc.), to complement (or even replace) the record of flash floods that have occurred in a water stream (Díez Herrero *et al.* 2007). This scientific analysis involves the following research: finding examples with ideal dendro-evidence (exposed roots, adventitious branches, impact scarring, etc.); species selection with homogeneous growth; planned sampling of ring sequences; study of plant anatomy searching for characteristic signatures of flash flood events; synchronization of ring sequences for event dating; including events to better fit the frequency distribution function; hydraulic modelling of the site to estimate flow rates; assigning magnitudes to the estimated frequencies. This allows systematic record data series to be extended, completed or even replaced using proxy data evidencing physical events, not statistical models.

The key aim of this paper is therefore to propose a methodological scheme or protocol for the use of dendrogeomorphological data in flood risk analysis. The objective of this methodological protocol is to improve frequency and magnitude estimates for flash floods and enable the implementation of more effective preventive measures for mitigation of related risks. To achieve this aim the specific objectives are to: (1) review the application of different data sources and scientific methods resulting from dendromorphological analysis; and (2) analyse the preliminary results from case studies in which this protocol is followed.

BACKGROUND AND STATE OF THE ART

Dendrogeomorphology is a relatively recent branch of science, especially compared with other closely related sub-disciplines such as dendroclimatology. In fact, both derive from dendrochronology, the science of dating tree-rings to characterize and synchronize environmental changes that have taken place, or for dating archaeological remains. The origins can be traced back to Leonardo da Vinci's observations in the late 15th and early 16th centuries (France manuscripts M 78v and 79r), but it was not until the early 20th century that the theoretical bases were established (Douglass 1909, 1914). However, its laws and principles, although originating in the 18th century with theories such as uniformitarianism, were not explicitly formulated until the 1970s (Fritts 1976): uniformitarianism, limiting factors, ecological range, aggregate tree-ring growth (Cook 1990), site selection, replicate measurement and cross-dating.

The early dendrogeomorphological studies on the relationship between tree-rings and geomorphological processes date from the 1960s (La Marche 1963), but it was not until a few years later that the first publications appeared using this term (Alestalo 1971). In general, these dealt with the application of dendrochronological techniques to the study of erosive processes of soils, snow avalanches, slope mass movements (rockfalls, rock avalanches, landslides, etc.) and surface dating, among others.

The application of dendrogeomorphological analyses to torrent dynamic-related events such as debris flows and flash floods dates back to the same time. The earliest papers on these applications also date from the 1960s (Sigafoos 1964; Harrison & Ried 1967), but it was not until the 1980s that these became standard, with the papers by Yanosky (1982a, 1982b, 1983, 1984), Hupp (1984, 1986, 1988), Hupp *et al.* (1987), Gottesfeld & Gottesfeld (1990), McCord (1990) and Gottesfeld (1996). These techniques and data sources have since become more widely used, although largely limited in geographical terms to

North America and Central Europe (Astrade & Bégin 1997; St. George et al. 1999, 2002; St. George 2010; Stoffel & Wilford 2012). These include the methodological contributions of C. R. Hupp, particularly the book chapter by Hupp (1988). In this contribution he includes the only classification of flood dendrogeomorphological evidence (FDE) (limited to six types) prior to this article. Other book chapters by Yanosky & Jarrett (2002) and by St. George (2010) also provide an overview of the main contributions of dendrogeomorphology to hydrological studies, but focus on aspects of the frequency of extreme events, and on one type of magnitude indicator, respectively. The other publications are simply case studies, and do not include a methodological proposal apart from short sections on materials and methods.

With an accumulation of more than 40 years' experience in these studies, the current state of the art in terms of methods and knowledge is the result of the evolution and recent fine-tuning of techniques in the following three aspects:

- Botanical features: in early studies only external evidence was used, such as corrosion scarring, bifurcations at the base of the trunk, adventitious branches and eccentric growth; nowadays, however, many more tree-ring pattern growth anomalies are used; these are called growth disturbances (GD), such as the lines formed by traumatic resin ducts (TRDs) or sudden variations in tree-ring width (Bollwschweiler et al. 2008b; Ruiz-Villanueva et al. 2010a).
- Detail of the information extracted: formerly, tree-rings were only studied as indivisible elements, whereas nowadays, plant histology and plant cytology techniques are applied (Ballesteros et al. 2010a, 2010b) that allow zone rescaling within the tree-ring and identification of even the season and month when the disturbance occurred (Stoffel et al. 2006) and differentiation between various processes in mountain areas (avalanches, flash floods, debris flows, etc.).
- New data from dendrogeomorphological analysis, from the classical estimation of flood discharges, from simple equations (Yanosky & Jarrett 2002) to the calibration of interesting flow parameters such as roughness (Ballesteros et al. 2011b).

This means that in the current state of the art, dendrogeomorphological analysis techniques require the study of a wide range of elements, the use of synchronization and the application of microscopic techniques to extract the maximum information on the event, its origin and dating. Good examples of some of the most recent studies including advances in scientific knowledge are: Gottesfeld (1996), Kozlowski (1997), Yanosky & Jarrett (2002), Coriell (2002), Stoffel, Bollschweiler and Ehmisch (Stoffel et al. 2003, 2005, 2006, 2008; Bollschweiler et al. 2006, 2008a, 2008b; Stoffel & Wilford 2012) and Zielonka et al. (2008). A summary on recent state-of-the art research in dendrogeomorphology is given in Stoffel & Bollschweiler (2009) and Stoffel et al. (2010).

FIRST METHODOLOGICAL PROPOSAL: CLASSIFICATION OF FLOOD DENDROGEOMORPHOLOGICAL EVIDENCE

As mentioned above, dendrogeomorphological techniques have been applied to the analysis of flood risks for more than four decades. As there is no classification or any commonly accepted nomenclature of dendrogeomorphological evidence in use today, and our review of many studies revealed inconsistencies in the description of dendrogeomorphic data, we elaborated a simplified classification of evidence used in flood analysis. Therefore, this system would facilitate realization of cross studies and spatial correlation of the results, and it would also be useful as a guide to novice researchers in this field, providing a basic doctrinal corpus.

The conductive thread of this classification is the spatial scale of the evidence (from macro- to microscopic, from kilometres to microns) and the scale of studied elements (from forest communities and vegetal formations to changes in cell structure). More than 29 types of disturbance signs have been distinguished and hierarchically arranged, with 15 of them referring to entire individuals (tree or bush) or their parts (trunk, branches or roots). The classification has a cross-tabular shape (Table 1) and is complemented with graphics of the evidence, both in the form of sketches (Figure 1) and pictures from field examples (Figure 2).

Table 1 | Proposal for classification of the main types of flood dendrogeomorphological evidence (FDE) useful in the study of past floods, depending on the scale of the studied element (modified from Díez-Herrero *et al.* (2009))

Spacial scale		Studied element			Type of dendrogeomorphological evidence		No.
km	Macroscopic	Bottomland vegetation patterns			Species distribution pattern		FDE 1
hm							
					Coverage distribution pattern		FDE 2
					Ages distribution pattern		FDE 3
		Individual (tree or bush)	Complete tree or bush		Candelabra growth ('Sigafoos' trees)		FDE 4
					Tilted and overturned trees		FDE 5
					Decapitated trees (tops missing)		FDE 6
			Part of tree or bush	Trunk	Stripped bark with callus marks	Scars by sediment load impact	FDE 7
dm						Branches torn off	FDE 8
						Scraping from other falling trees	FDE 9
M					Bark erosion		FDE 10
					Elbows and angles (sharp changes in the trunk growth direction		FDE 11
					Sudden narrowings in trunk		FDE 12
					Bifurcations		FDE 13
					Sprouts from buried trunks and roots		FDE 14
dm				Branches	Sharp changes in the branch growth direction		FDE 15
					Sprouting from burried trunk		FDE 16
				Roots	Exposed roots	Stripped bark and erosion	FDE 17
cm						Float roots without substrate contact	FDE 18
					New roots from buried trunks		FDE 19
	Mesoscopic	Tissues, wedges and slices		Rings	Eccentric growths (reaction wood)		FDE 20
					False or absent tree rings		FDE 21
mm					Discontinuities, erosion, and internal scars		FDE 22
				Tissues	Changes in tree-ring parameters (width, % early wood, late wood, etc.)		FDE 23
	Microscopic	Thin slice (microslices)			Ratio parenchyma-lignification tissue		FDE 24
					Size and density of vessels		FDE 25
				Cells	Changes in cell parameters	Size and morphometry of cell lumens	FDE 26
						Cell wall thickness	FDE 27
					Appearance and/or abundance of special types of cells	Traumatic resin ducts (TRDs)	FDE 28
mm						Fibre-tracheid	FDE 29
						Traumatic structures in cell wall	FDE 30
Å	Atomic	Cell wall		Cellulose	Isotopic fractionation	$^{18}O/^{16}O$ ratio	FDE 31

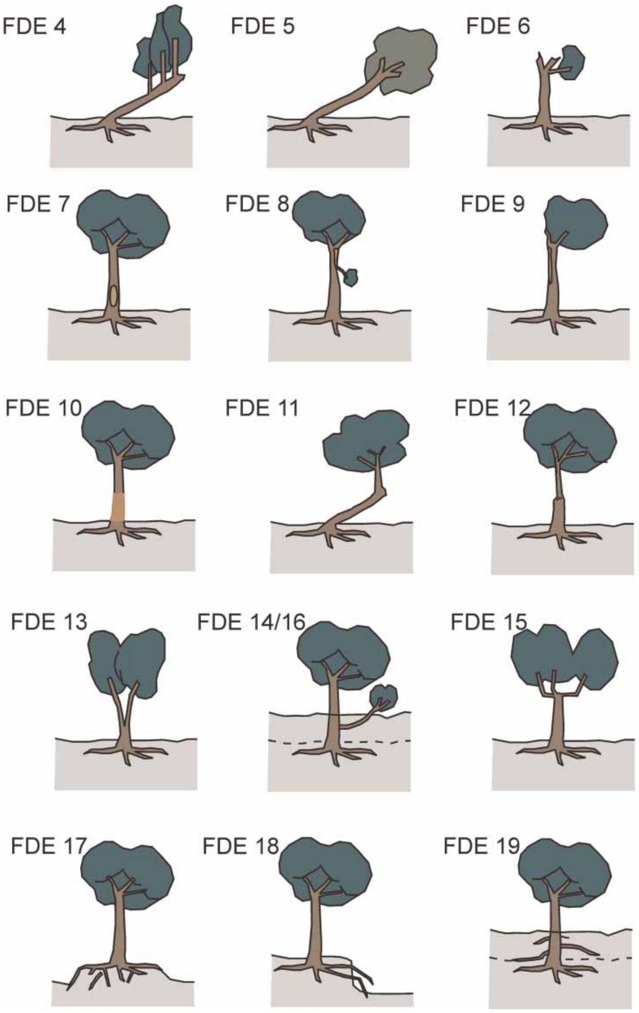

Figure 1 | Types of the main individual macroscopic dendrogeomorphological evidence useful in the study of past floods: FDE 4, 'candelabrum' growths (Sigafoos trees); FDE 5, tilted tree with feet tipped over; FDE 6, decapitation; FDE 7, scars caused by sediment load impact; FDE 8, branches torn off; FDE 9, grazes caused by falling boulders; FDE 10, erosion on the trunk; FDE 11, trunk bends and angles; FDE 12, sudden narrowing of trunk; FDE 13, bifurcations; FDE 14/16, re-growth from buried trunks; FDE15, bends and angles in branches; FDE 17, exposed roots with stripped bark and eroded surface; FDE 18, exposed roots without contact with substratum; FDE 19, new roots from buried trunks.

However, not all signs appear to be equally useful for the reconstruction of magnitudes or frequencies of past flood events. Using a cross table (Table 2), the most significant signs are shown in the sense that they provide the date as well as the area affected by an event, the minimum levels reached that can later be used for the estimation of peak flows with hydraulic modelling and simplified equations (e.g., critical flow, super-elevation) (e.g., Elleder *et al.* 2013).

SECOND METHODOLOGICAL PROPOSAL: A 15-TASK WORKING PLAN WITH ADVANCED TECHNIQUES

A working plan has been drawn up structured into 15 activities or tasks and its relationships and links as shown in Figure 3. To carry out the activities and tasks envisaged in the working plan, simultaneous and complementary analysis and synthesis-based methodological approaches may be adopted with a sequential combination of field data acquisition methods, in-laboratory study protocols, and desk-based processing and analysis methods.

The first steps of the field data acquisition, i.e., geomorphological analysis (task 1) and flora characterization (task 2) should be carried out using classical methods that do not require specific adaptations or additional explanations. Species sampling (task 3), comprising sampling of individual examples of trees and bushes, should start with a rigorous and objective selection, based on external characteristics which can be used to provide evidence for interference between the sample tree and the river dynamics (see the previous section). The collection of detailed topographical data (task 4) also uses conventional methods and standardized techniques (GPS receivers in differential mode, total stations, 3D terrestrial laser scanner).

Neither is there anything new in laboratory work methodologies, as they are standardized procedures in dendrochronological analysis (Picher 1990; Wilford *et al.* 2005). This is the case of sample preparation (task 5) and tree-ring counting and measurement (task 6). However, some new methodological techniques are required for the anatomical and histological study (task 7) focused on the detection of past flood events. Anomalies in tissues and cells associated with flash flood events should be observed, with special emphasis on: cell dimensions (radial length and tangential width of parenchymal cells, vessels, fibres for broad leaves and tracheids for conifers; e.g., Stoffel & Hitz 2008), cell lumen, cell wall thickness, percentage of latewood, resin ducts (lines caused by traumatisms, TRDs; see Bollschweiler *et al.* 2008a, 2008b; Schneuwly *et al.* 2009a, 2009b), existing anatomical elements of traumatic origin (e.g., tyloses, sticky deposits) or the existence of intra-annual density fluctuation. Another source of 3D anatomical data

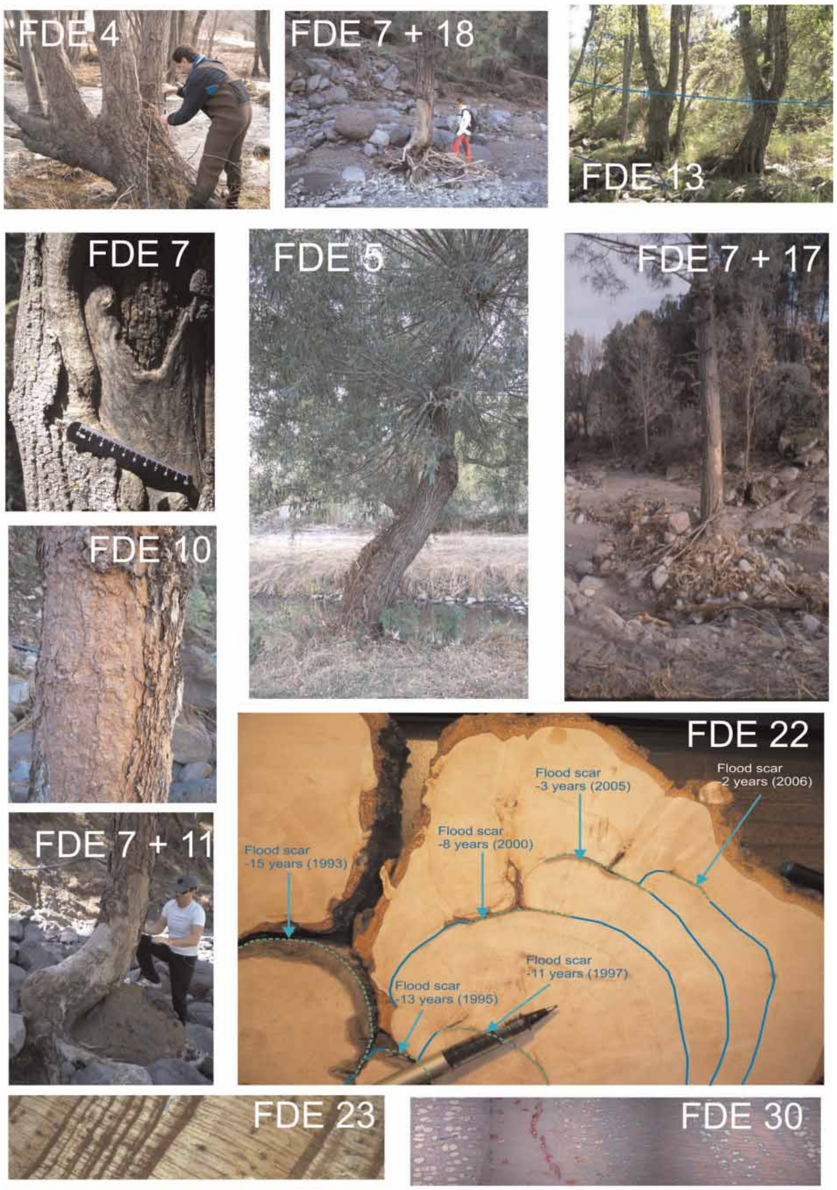

Figure 2 | Examples of the types of the main dendrogeomorphological evidence useful in the study of past floods.

could be the tomographic analysis of portions of tree trunks, using sophisticated medical devices. Finally, variance analysis (ADEVA) should be performed on the different variables considered in anatomical analysis to verify (or disprove) statistically significant differences between different mean groups. Variogram analysis should be applied to explore 3D intrinsic structure of cell data sampled at different distance intervals and directions (Bianchi & Zheng 2009; Remy *et al.* 2009).

Most desk-based data processing and analysis methods are classical and standard from dendrochronological or hydrological research; for example, series synchronization and tree-ring dating (task 9), hydrometeorological modelling of river basins (task 11), hydraulic modelling of reaches (task 12; Lang *et al.* 2004) or mapping flash flood hazard areas and risk maps (task 14; Díez-Herrero *et al.* 2009). Others methods do have peculiarities for their application to the analysis of past floods.

Table 2 | Use of flood dendrogeomorphological evidence (FDE) types and their combinations for the study of the frequency and magnitude of past floods. Type of information conveyed and degree of utility for each sign or combination in the study of flood hazard: black, high utility; grey, medium; white, none (modified from Díez-Herrero *et al.* (2009))

		Temporal considerations							
		Unique events			**Magnitude considerations**				
FDE/FDEs		**Dating**	**Seasonality**	**Frequency**	**Extent**	**Flow depth**	**Sediment load**	**Energy**	**Duration**
FDE 1		▨		▨	■	▨	▨	▨	▨
FDE 2		▨		▨	■	▨	▨	▨	▨
FDE 10					■	■	▨	▨	
FDE 23	FDE 3	■		■	■	▨	▨	▨	
	FDE 4	■	▨	■	■	▨	▨	▨	
	FDE 5	■	▨	■	■	▨	▨	▨	
	FDE 6	■	▨		■	▨	▨	▨	
	FDE 7	■	▨	■	■	■	▨	■	
FDE 8		■	▨	■	▨	▨	▨	▨	
FDE 9		▨	▨	▨	▨			▨	
FDE 11		■	▨	■	■	▨	▨	▨	
FDE 12		■	▨	■	■	▨	▨	▨	
FDE 13		■	▨	■	■	▨	▨	▨	
FDE 14		■	▨	■	■		■	▨	
FDE 15		■	▨	■	■	▨	▨	▨	
FDE 16		■	▨	■	■		■		
FDE 19		▨		▨	■		■		
FDE 20	FDE 17	■	▨	■	■		▨	▨	
	FDE 18	■	▨	■	■	▨	▨	▨	
	FDE 5	■	▨	▨	■	▨	▨	▨	
FDE 7/FDE 21		■	▨	▨	■	■	▨	■	
FDE 22 28-30	FDE 17	■	▨	■	■		▨	▨	
	FDE 7	■	▨	■	■	■	▨	■	
FDE 24		■		■	■				▨
FDE 25		■	▨	■	■				▨
FDE 24–28 27–29	FDE 7	■		■	■	■	▨	■	
FDE 17		■		■	■		▨	▨	
FDE 31		■	■	■	■		▨	▨	▨
FDE 32		■	■	■	■				▨

This is the case for task 10, flood event detection and dating in tree-ring series. From the synchronized tree-ring series we can proceed to the dating of the anatomical elements associated with torrent phenomena (GDs, such as TRDs, wounds, callus tissue, reaction wood, reduced or increased growth); and obtain a list or database of flash flood events with assigned dates, indicating whether these are definite or approximate dates, and the type of evidence marking maximum, minimum or exact level. Similarly, depending on what part of the tree-ring the GDs (late or earlywood) are situated, it is even possible to infer the season of the year (at a seasonal level and sometimes to the precise month) in which the event took place. The possible identification of flash flood events that caused unearthing and exposure of the tree root system (e.g., by erosion of river banks or pedestal effect on bars and islands), and which may have led to reduced leaf system production (crown) should also be investigated, observing possible

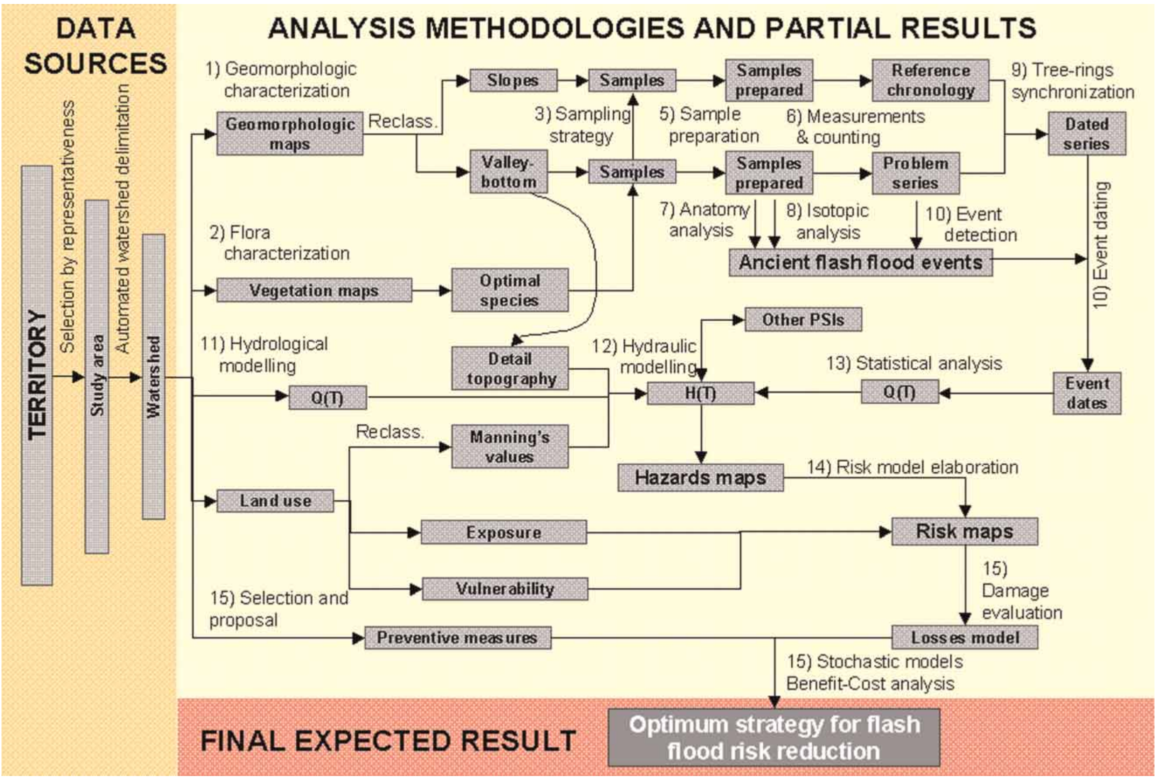

Figure 3 | Chart summarizing the 15 activities or tasks of the methodological proposal, from the data sources to the final expected results, and their mutual relations.

changes in the tree-ring growth pattern at the standard height (1.30 m). These dates, especially those that are repeated and common, should be contrasted with recent historic records of intense precipitation and flooding where hydrometeorological information exists. This information should be used to calculate similarity indices and conditional probabilities. To calibrate the elements used for detecting and dating events, the same methods and data sources should be used as applied to recent events studied in detail, from which many effects on riverbank vegetation are conserved.

Also flood frequency analysis (task 13), using the combination of systematic and palaeoflood data from dendrochronological sources, has some particularities. When the dates of the flood events and their estimated flows are available, these can be used to produce a statistical analysis to allow a frequency distribution function adjusted to these flows. For this, different formulas can be used to assign sample probability to different events, depending on whether they are exact, minimum or maximum levels, and on their degree of certainty (classified as EX, LB, UB and DB type); and specific frequency distribution functions should be used (for both stationary and non-stationary models) based on setting thresholds or ranges, which have already been successfully used for including historic and palaeohydrological data (Francés 2004; Macdonald 2013). To facilitate these analyses, various computer applications that implement these formulas can be used comparatively, with programs including FRESH (University of Québec; Ouarda *et al.* 2004), AFINS (*Grupo de Investigación de Hidráulica e Hidrología*; UPV) and MAX (Stedinger *et al.* 1988). Finally, the same analyses should be carried out including the data from the dendrogeomorphology in the systematic record flow series from the nearby measuring stations, observing the possible improved fit by applying different statistical tests (Kolmogorov-Smirnov, PPCC, L-moments ratio, etc.).

Finally, our methodological proposal also includes improvements and new methods of cost–benefit analysis for risk mitigation measures. From the results of the maps and risk analysis, a detailed study should be made of all the mitigation measures that can reasonably be applied in each case (predictive, preventive and corrective), evaluating the cost of applying each individually or in combination. When this battery of measures and possible logical combinations is available, their effects should be input into the hydrometeorological models, to study to what extent and in what conditions a reduction of risk levels could occur. Geostatistics and geographic information systems should be integrated for assessment of socioeconomic factors related to flood risk management. From these two estimates, the cost of the measures and the benefits of their application, complex cost–benefit analyses should be produced, using stochastic and geostatistic methods to take into account their spatial dimension (Sánchez-Silva 2004; Zhai & Ikeda 2008); to do this, computer-based tools should be used as specific developments for the MATLAB program package. In short, the aim of this analysis should be to integrate the concept of sustainability of these preventive measures with essential aspects related to risk calculation, definition of acceptability criteria and the optimization of investment. The results indicate optimum measures for minimizing risks of flash floods in terms of cost–benefit analysis (Ballesteros *et al.* submitted).

INITIAL RESULTS AND DISCUSSION OF ADVANTAGES AND LIMITATIONS

Both methodological proposals described and explained above are not only theoretical exercises. They have been applied in different projects and study areas (Figure 4), mainly in Spain, but also in other areas of Europe such as the United Kingdom (Ruiz Villanueva *et al.* 2010b) or Poland.

The first results have been published over the last 3 years, or will be published soon, in some of the most prestigious journals, both in the botanic thematic category (*Tree Physiology, Tree-Ring Research*, etc.) and in hydrologic–geomorphological scope (*Journal of Hydrology, Hydrological Processes, Water Resources Research, Water Resources Management, Geomorphology, Catena*, etc.); i.e., see the publications of Ballesteros *et al.* (2010a, 2010b, 2011a, 2011b, 2012, submitted), Ruiz-Villanueva *et al.* (2010a) and Genova *et al.* (2011).

Nevertheless, this is the first time that well-developed methodological proposals have been published. The necessarily brief methodology section of the papers has prevented proper development of specific aspects of the analysis carried out (St. George *et al.* 1999). Such detailed explanation is necessary for two reasons: to allow other research teams to follow these techniques; and more importantly, to allow other scientists to replicate the analysis outlined in this work, to ensure they achieve the same results. For this reason, we consider it important to explain all the details of our advanced methods, and bring them to the scientific community so they can be corrected and completed.

Some of the methodologies presented are classical techniques that require no further discussion, such as tasks 1, 2, 4 and 11 to 15. Another group is pertinent to the

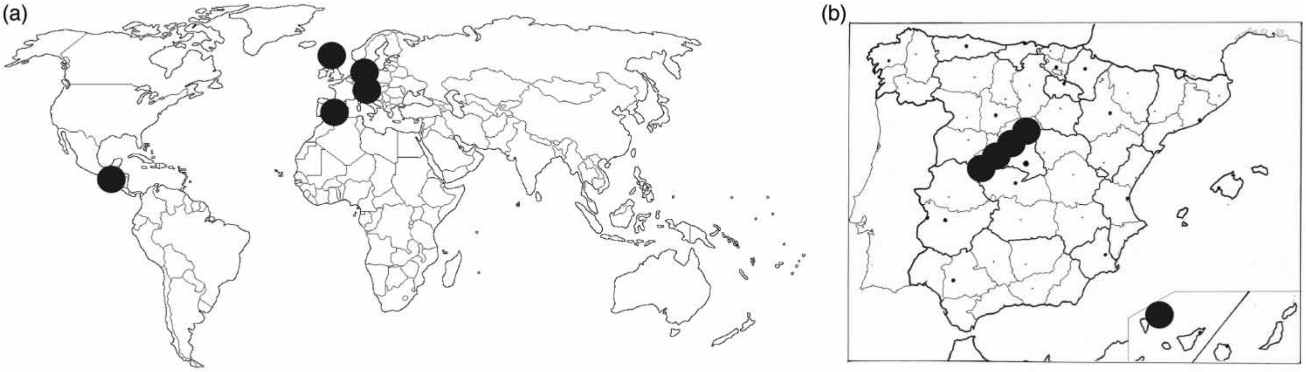

Figure 4 | Location of study areas where advanced dendrogeomorphological methods are being applied to the study of past floods: (a) in the world, Spain, Switzerland, United Kingdom, El Salvador and Poland; (b) in Spain, Navaluenga, Arenas de San Pedro, Guisando Segovia, Pajares de Pedraza, Taburiente and Valsain.

dendrochronological field and these tasks (3, 5, 6, 7 and 9) are well developed in the scientific literature (Picher 1990; Wilford *et al*. 2005) but for other applications (palaeoclimatology, vegetation dynamics, etc.). Finally, for another set of tasks (8 and 10), the relationship of linked tasks and the classification of evidence are described in detail here for the first time and require some discussion of their advantages and limitations.

One of the most innovative tasks that could be included in the second methodological proposal is isotope analysis in alpha-cellulose (Figure 3, task 8). This task is still at the development stage, and has not yet been tested, calibrated and validated. It should therefore be considered as a working hypothesis, rather than a methodological step. To analyse the isotope contents of the tree-ring wood for specific stable isotopes (^{16}O, ^{18}O, ^{13}C, etc.), the following procedures should be carried out or requested from specialized laboratories: samples of late and/or early wood from specific tree-rings; extraction of alpha-cellulose from the wood; measurement of the $^{16}O/^{18}O$ isotope ratio and interpretation of the results. The aim of this novel technique is to study the relationship between the above ratio in the tree-ring wood corresponding to a particular year with flash flood events and the ratios measured in rainfall recorded in the main precipitation events of that year or season (taken from the CEDEX national measurement network). The aim of this comparison is to establish possible relationships between both ratios to study the meteorological origin (of frontal, of convective, of orographic, etc.) of the precipitation that generated the flash flood from tree-ring wood analysis, allowing two or more past event populations to be differentiated and their frequency and magnitude to be examined separately (Figure 5).

We are beginning to study the $^{16}O/^{18}O$ ratio patterns of different types of precipitation in central Spain corresponding to recent well-known flood events. These singular events will be selected looking for vegetative periods in which only one type of precipitation has been described in the

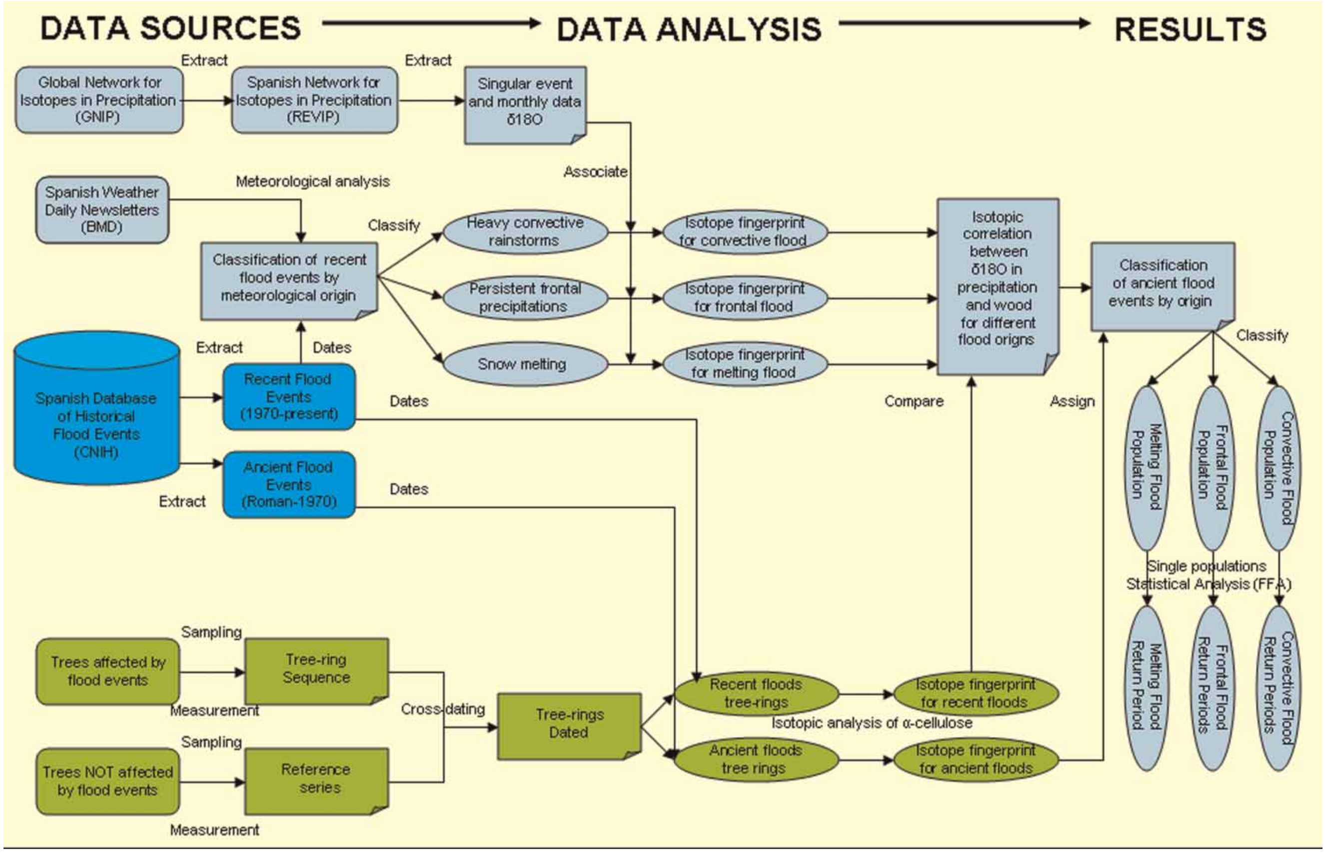

Figure 5 | Methodological procedure framework for the analysis of isotopes in tree-ring alpha-cellulose and its use for improving flood frequency analysis.

meteorological reports. Later, the alpha-cellulose $^{16}O/^{18}O$ ratio from the wood sequence used for dating the flood event by dendrochronological techniques will be analysed. Both isotopic ratios will be compared looking for statistical relations. These results will be used to extrapolate this relation to the entire tree-ring sequence, completing the past flood record and their classification in two or three event populations. The last step (equivalent to task 13) will be frequency analysis of each single population, and comparison with traditional frequency analysis of the entire flood dataset.

The proposed classification of dendrogeomorphological evidence applied to flood risk analysis is an important advance with respect to earlier classifications (Hupp 1988), because it is not a simple list of evidence without order and criteria. On the contrary, this proposal uses a clear criterion for the type of evidence, its spatial dimension and the element upon which the analysis is performed. This allows the potential user to easily locate its study elements, and the designations are internationally comparable. Furthermore, it has expanded from four or five evidence types of earlier classifications, to more than 30 different types, increasing the range of possibilities for study. Among the limitations is that the study of plant communities as FDE is not just a dendrogeomorphological analysis using its own techniques. Other aspects of population dynamics, species distributions and densities, etc., which are not studied exclusively in tree-ring dendrochronology, must also be taken into account.

The assignment of data obtained for each type of evidence (Table 2), although based on scientific literature and our own experience, remains hypothetical at present as very little work has been done to demonstrate validity. It would therefore be interesting to explore new areas with suitable studies, for example, using the angle of tilt of trees to obtain previous flood energy levels and thus estimate the water depth of palaeofloods.

CONCLUSIONS

Although dendrogeomorphological techniques have been used for the study of floods for more than 40 years, proposals for methodological approaches can still be advanced to improve risk analysis. Two of these proposals are classification of dendrogeomorphological evidence and a working schema comprising 15 tasks, with some additional innovative techniques. The first proposal enables studies to normalize and standardize nomenclature improving the possibility of obtaining data on past floods. The advanced methods of the working schema, such as the isotope analysis of tree-rings, can improve flood frequency analysis and reduce uncertainties in risk analysis. Thus it is possible to obtain very accurate and reliable information from past floods and help prevent future flooding using dendrogeomorphological techniques.

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