Chapter 3

Palaeoflood Hydrology: Reconstructing Rare Events and Extreme Flood Discharges

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ABSTRACT

The estimation of rare, large magnitude floods is problematic due to short gauging station records and their limited spatial distribution. The instrumental record can be lengthened by hundreds or thousands of years by estimating discharges of past floods using geological and botanical evidence (palaeostage indicators) left by flood waters. In the former, stratigraphic sequences of sand and silt deposited in slackwater and eddy sedimentary environments are described and dated by geochronological methods (radiocarbon and luminescence techniques). In the later, flood impacts on trees producing scars and other damages (e.g., candelabrum trees) are identified and dated using tree-ring counting. These palaeostage indicators enable to calculate flood discharges using hydraulic modelling, and both flood ages and magnitudes are the input data necessary for improving flood frequency analysis. The scientific and technological interest of these studies is evident for design purposes of critical structures (dams, bridges), risk planning, and for understanding the response of flood patterns to climate change.

3.1 INTRODUCTION

The availability of discharge records of sufficient length is always a major concern for the probabilistic analysis of flood hazards, particularly when the return intervals of floods exceed the length of systematic stream gauging. Longer term flood records can be obtained from human observations during the historical period, or from geological and botanical indicators of flood stage (e.g., flood sediments and damage to vegetation). Flood information obtained outside stream gauging is considered nonsystematic, although, in

Hydro-Meteorological Hazards, Risks, and Disasters. http://dx.doi.org/10.1016/B978-0-12-394846-5.00003-5

many instances, preinstrumental records fulfil the requirements of homogeneous and continuous flood series (Baker, 2008; Brázdil et al., 2006). Often past flood evidence refers to exceptional or rare floods preserved in narrative written sources (annals or chronicles) or as geological–botanical proxy evidence. The reconstruction of the timing and magnitude of these large floods provides valuable data to improve substantially our understanding of hazardous floods.

Flood hydrologists have traditionally used indirect discharge measurements based on field evidence of high-water marks (HWM) (e.g., drift wood, leaves, foam lines) and hydraulic energy equations for computing discharge as a means to extend flood records into the past or to obtain additional discharge data after the passage of a flood (Benson and Dalrymple, 1967). However, woody debris evidence tends to disappear rapidly after the flood, particularly in humid regions and, moreover, differentiation of water marks from different floods is a complicated task after some weeks from the flood peak. Kochel and Baker (1982) observed that "sediments deposited in the backwaters of large floods may accumulate thick sequences in tributary mouths" which can be interpreted in terms of flood frequency based on radiocarbon dating. These authors coined the term "palaeoflood" applied to events that occurred prior to the systematic gauging record and their magnitude and timing are estimated by indirect hydraulic, geological, geomorphological, sedimentological, and botanical methods. Consequently, palaeoflood hydrology is the reconstruction of the magnitude and frequency of recent, past, or ancient floods using geological (physical) evidence (Baker et al., 2002). The term "palaeo" has sometimes contributed to the general misconception that palaeoflood techniques are only used for estimating very old floods (geological scales). However, most palaeoflood studies involve prehistoric (past 5,000 years), historic (past 2,000 years), and even modern flood analysis in ungauged basins (Benito and O'Connor, 2013). Consequently, it is not the timescale of flooding that defines palaeoflood hydrology but the fact that flood evidence derives from the lasting physical effects of floods on natural recording indicators (palaeostage indicators, PSI's). Other nonsystematic records include historical floods or floods recorded from human observations and documents, that is, a manuscript, a piece of printed matter (book, newspaper), a picture or an artefact (a flood mark or an inscription on a building), which refers to the stage or impacts of hydrological extremes (Brázdil et al., 2006).

Over the past 30 years, palaeoflood hydrology has achieved recognition as a new branch of geomorphology and hydrology, developing new tools and applications for the study of extreme events in relation to climate change, water resources, and flood hazard assessment (Baker and Kochel, 1988; Baker, 2008). In a broad sense, palaeoflood studies involve multidisciplinary research addressing geological palaeostage indicators (stratigraphy, chemical analysis, radiometric techniques) and biological flood markers (dendrochronology, palynology, biomineralogy, lichenometry). Flood reconstructions based on geological and biological indicators have been successfully applied in several regions of the world (Figure 3.1). Palaeoflood studies in bedrock rivers, based on sedimentological indicators, gained scientific acceptance in the early 1980s, mainly under the auspices of Prof. Victor R. Baker and his students, focusing largely on the southwestern United States (e.g., Kochel et al., 1982; Ely and Baker, 1985; Partridge and Baker, 1987; Webb et al., 1988; O'Connor et al., 1986, Jarrett, 1990; Knox, 1985, 1999), and later extended to other parts of the world (Figure 3.1). Pioneer research on dendrogeomorphological palaeoflood indicators was carried out by Sigafoos (1964) in the eastern USA, and later extended to other sites in North America (USA and Canada), and Europe (Figure 3.1).

Recent advances in palaeoflood hydrology are the result of new applications and progress in computing science and new techniques related to computational fluid dynamics, remote sensing, geochronological and isotopic methods, environmental tracers, geophysical data acquisition and analysis, among others (Woodward et al., 2010). This chapter aims to describe different techniques available for extending the flood record back in time, as well as some fields of application of these palaeoflood data to solve different scientific and engineering problems.

3.2 PALAEOFLOOD APPROACHES AND METHODOLOGY

The primary goal of palaeoflood hydrology is to extend flood records (magnitude and timing) over centuries or millennia (Baker, 2008). Long-term flood records are of interest for flood hazards, understanding climate change impacts and for the assessment of water resources. These different palaeoflood applications are carried out through a common methodological framework for palaeoflood data collection and further applications follow specific methodological procedures (Benito and Thorndycraft, 2005). In palaeoflood data collection the methodological approach is dictated by river channel type (bedrock vs alluvial rivers), channel slope, and by the characteristics of the available PSIs.

The geomorphological characteristics of the studied reach may limit the quantity of PSIs and therefore the quality of discharge estimations. Bedrock channels provide the most suitable conditions for extending flood records as sediment deposition is favored by the sharp energy—flow changes between expansion and constriction reaches. Moreover, discharge estimations from stage indicators are more accurate under fixed-bedrock channel geometry. Alluvial rivers contain rich stratigraphic archives from which we may reconstruct flood history but discharge estimations in erodible channels lose accuracy. Alluvial rivers are here defined as streams with channel(s) flowing over alluvium with adjacent floodplain areas and alluvial fans. Mountain streams typically flow on bedrock or cemented alluvium, although the high flow—energy characteristics and coarse sediment size limit palaeoflood

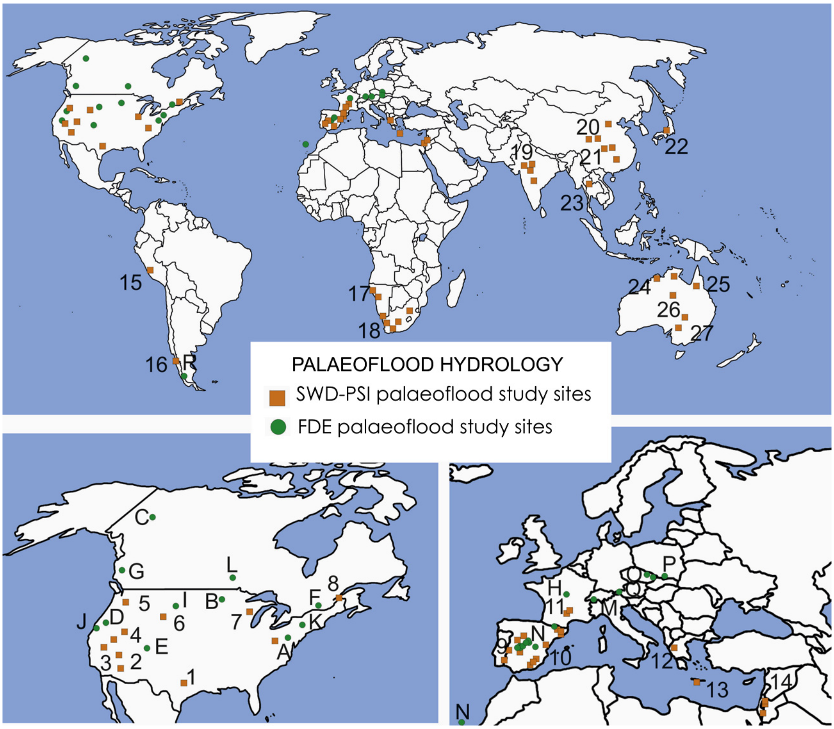

FIGURE 3.1 Global distribution of the most representative studies on palaeoflood hydrology that used slackwater flood deposits (SWD-PSI) and flood dendro evidence (FDE). Many more studies have been carried out in most of the areas than the indicated by the selected references. *SWD-PSI* (orange squares): 1. West and central Texas (Kochel et al., 1982); 2. Arizona and Utah (Ely and Baker, 1985; Partridge and Baker, 1987; Webb et al., 1988; Enzel et al., 1994; O'Connor et al., 1994; House et al., 2002; Webb et al., 2002); 3. California (Enzel, 1992); 4. Oregon and Idaho (Chatters and Hoover, 1994; Ostenaa et al., 2002; O'Connor et al., 2003); 5. Colorado (Jarrett and Tomlinson, 2000); 6. South Dakota (Harden et al., 2011); 7. Eastern USA (Springer and Kite, 1997; Kite et al., 2002); 8. Eastern Canada (Saint-Laurent et al., 2001); 9. Portugal (Ortega and Garzón, 2009); 10. Spain (Benito et al., 2003a, 2010; Thorndycraft et al., 2005a,b, 2006; García-García et al., 2013); 11. France (Sheffer et al., 2003, 2008); 12. Greece (Woodward et al., 2001); 13. Crete (Macklin et al., 2010); 14. Israel (Greenbaum et al., 1998, 2000, 2002); 15. Peru (Wells, 1990; Magilligan and Goldstein, 2001); 16. Chile (Dussaillant et al., 2010); 17. Nambia (Heine, 2004; Heine and Völkel, 2011; Grodek et al., 2013); 18. South Africa (Smith and Zawada, 1990; Smith, 1992; Zawada, 2000; Zawada and Hattingh, 1994; Benito et al., 2011a,b); 19. India (Ely et al., 1996; Kale et al., 1997, 2003; Kale and Baker, 2006); 20. Northeastern China (Zha et al., 2009, 2012; Huang et al., 2010, 2011; 2012a,b; Yang et al., 2000); 21. Central-Southeastern China (Zhang et al., 2013; Huang et al., 2013); 22. Japan (Jones et al., 2001; Grossman, 2001; Oguchi et al., 2001); 23. Thailand (Kidson et al., 2005a,b); 24. Northcentral Australia (Baker and Pickup, 1987; Sandercock and Wyrwoll (2005); 25. Northwestern Australia (Wohl et al., 1994); 26. Central Australia (Baker et al., 1983, 1985, 1987; Pickup et al., 1988; Pickup, 1991; Patton et al., 1993); 27. Southeastern Australia (Saynor and Erskine, 1993; Erskine et al., 2002). *FDEs* (green circles): A. Potomac River, Virginia and Maryland, USA (Sigafoos, 1964; Yanosky, 1982a, 1982b, 1983, 1984); B. North Dakota, USA (Harrison and Ried, 1967); C. Mackenzie Mountains, Northwest Territories, Canada (Butler, 1979); D. Mount Shasta, northern California, USA (Hupp, 1984;

techniques to botanical indicators (tilting and tree scars). Depending on the purpose of the research, some studies may require a complete palaeoflood record over some period of time, whereas others will focus on assessing the largest events possible within a catchment.

The methodological steps to conduct a standard palaeoflood study include (1) a preliminary inventory of potential sites using aerial photographs; (2) field visit and survey for the identification and selection of flood indicators (flood deposits, botanical indicators, and erosion marks); (3) at the selected sites, detailed descriptions of flood evidence, that is, stratigraphical description with emphasis on identifying flood units or tree coring for botanical evidence; (4) sample collection for age dating; (5) topographical survey of studied river reaches, with exact location and elevation of PSIs; (6) hydraulic modelling and discharge estimation; (7) comparison with available historical or systematic data; and (8) flood frequency analysis (FFA).

A preliminary inventory of potential areas for flood deposition and disturbed trees can be drawn up using aerial photograph interpretation. This preliminary identification of potential sites will limit the number of river reaches to be visited in the field. One of the most challenging tasks in palaeoflood studies is the field identification of flood evidence from which to estimate maximum flood stages for a particular river reach. This includes a close inspection to determine (1) the bedload being transported during a flood event (flood bars and large isolated boulders); (2) the identification of PSIs associated with flood events of different magnitudes (geological and botanical); and (3) the indication of maximum flood stage based on sedimentary, erosional, or pedological evidence. These flood stage indicators may be interpreted as follows: (1) close to peak flood stage (peak discharge level); (2) minimum flood stage; and (3) within a known flood level range. Hydraulic calculations based on rating curves (stage-discharge) will be used to assign a minimum discharge value to all/most flood indicators. FFA combines systematic and nonsystematic records, where palaeoflood data are treated as censured records over a stage-discharge threshold for a specific time period.

Hupp et al., 1987); E. Kanab Creek (Utah) and Arizona, USA (McCord, 1996); F. Upper St-Lawrence Estuary, Quebec, Canada (Begin et al., 1991); G. British Columbia (Gottesfeld, 1996); H. Saone River, France (Astrade and Bégin, 1997); I. Missouri River, Montana, USA (Scott et al., 1997); J. Eel River, California, USA (Sloan et al., 2001); K. Middlebury River Gorge, Vermont, USA (Coriell, 2002); L. Red River, Manitoba (Canada) and Red River of the North, North Dakota and Minnesota, USA (St. George et al., 2002; St. George, 2010); M. Ritigraben, Switzerland (Stoffel et al., 2003; Stoffel and Wilford, 2012); N. Navaluenga, Venero Claro, Guisando, Arenas de San Pedro, Segovia, Pajares de Pedraza, Peralejos de las Truchas and Valsaín (Central Spain) and Caldera de Taburiente (Canary Islands), Spain (Díez-Herrero et al., 2007, 2013b; Ballesteros Cánovas et al., 2010a,b, 2011a,b, 2013a; Ruiz-Villanueva et al., 2010, 2013); O. Bila Opava River and Moravskoslezsk, Beskydy Mts., Czech Republic (Malik and Matyja, 2008; Silhan, 2012); P. Tatra Mountains, Poland (Zielonka et al., 2008; Kundzewicz et al., in press); Q. Gratzental, Tyrol, Austria (Mayer et al., 2010); R Patagonian Andes, Argentina (Stoffel et al., 2012).

3.3 GEOLOGICAL AND BOTANICAL PALAEOFLOOD DATA

Geological and botanical flood indicators can be divided into two categories: (1) HWM and (2) PSIs. HWMs include mud, silt, seed lines, and flotsam (e.g., fine organic debris, grass, woody debris) representing the peak stage of a recent flood (Benson and Dalrymple, 1967). Preservation of fine organic debris is limited to weeks in humid climates and to a few decades in semiarid and arid climates (Williams and Costa, 1988).

PSIs are geological and botanical evidence left by flood waters (Kochel and Baker, 1988: Webb and Jarrett, 2002; Benito and O'Connor, 2013). The most common types of palaeostage evidence are the following:

Slackwater flood deposits (SWD) are fine sediments (sand and silt) transported as suspended load during floods, and deposited on slackwater flood areas (Kochel and Baker, 1982). SWDs are the most frequently used PSIs in bedrock river systems, typically placed at lower elevation than HWM. These sediments may be preserved for centuries or millennia when protected from post-flood erosion. At preserved sites, the accumulation of successive flood sediment layers provides excellent palaeoflood records.

Flood dendro evidence (FDE), including tree scars and damage to riparian trees (sprouting from tilting stems, eccentric ring growth), has been effectively used for documenting flood magnitude and the frequency of palaeofloods (Sigafoos, 1964). Recent studies of anatomical changes developed following flood damage open new research perspectives to detect the occurrence of extreme floods in trees with nonevident physical damage (Yanosky and Jarrett, 2002; Ballesteros Cánovas et al., 2010a,b).

Silt lines are subhorizontal linear deposits of silt- and clay-sized particles that line some portion of the bedrock canyon walls, rocks, and trees (Jarrett, 1985). These lines have been interpreted as derived from the suspended load of the flooded stream, left as the flood waters percolated into the bedrock, and serve as excellent PSIs (O'Connor et al., 1986).

Organic drift, including branches, leaves, and seeds, left stranded at the high-water line when water recedes. The finer organic drift (leaves, cornstalks, and seeds) are better flood stage makers than would be some scattered clumps of large drift (Benson and Dalrymple, 1967). Careful selection of proper organic drift is important to avoid affection by velocity head, as the marks upstream of obstacles (trees, buildings, rocks) will be overelevated and marks on the downstream side may be lower than normal. A mound (>20 cm) of fine organics at the very edge of the channel in slow velocities is considered an excellent flood stage indicator. The main problem is the poor preservation of organic drift.

Boulder deposits are PSIs in high-energy environments and/or high-slope streams (Jarrett and Malde, 1987). Boulder bars have been extensively used to estimate flood discharges in mountain streams together with flood-related scars on trees (Jarrett, 1990).

Scour marks and trimlines at high elevation on slope alluvium and soils are considered as evidence of the largest flood(s) occurring in a river reach, although their interpretation may be ambiguous and difficult to accurately decipher (Webb and Jarrett, 2002).

Some researchers have reported height differences of PSIs in relation to actual flood water depths (Kochel, 1980; Springer and Kite, 1997; House et al., 2002). In a systematic analysis of flood marks (PSI and HWM) in rivers in the United States, Jarrett and England (2002) concluded that, in short reaches, the elevation at the top of some flood sediments (PSIs) essentially equals the height of HWMs (with an average deviation of +15 mm in 192 observations), with almost no deviation when using deposits located at the channel margins. Nevertheless, further studies are needed to systematically evaluate the discrepancy between PSIs and actual water surface elevations for different river characteristics and climatic regions. The following section provides a detailed description of the most commonly used geological and botanical PSIs, namely slackwater flood deposits and dendrochronological analysis of tree scars.

3.3.1 Sedimentological Indicators

SWDs are composed of silts and sands with high settling velocities that accumulate relatively rapidly from suspension during major floods (Baker et al., 2002). The sedimentation is favored by sharp changes in flow energy conditions between the main flow in the channel and the valley margins. In these marginal areas and during flood stages, eddies, back-flooding and water stagnation occur, which significantly reduces flow velocities (<1 m s^{-1}) and favors deposition of suspended clay, silt, and sand (Figure 3.2).

Successful palaeoflood reconstruction over long periods of time depends upon (1) an appropriate sediment source or the presence of finegrained sediments within the catchment area and (2) the preservation conditions. Catchment geology dominated by granite and/or sandstones provides an abundant source of fine-grained material to be transported as suspended sediment during flood events. The deposition and preservation conditions are controlled by flood erosion/sedimentary processes and by post-flood erosion processes (slope and tributary erosion). The most common depositional environments include (1) rock shelters or caves in bedrock walls (Figure 3.2(a)); (2) channel expansions (Figure 3.2(b)); (3) channel bends; (4) back-flooded tributary mouths and valleys (Figure 3.2(c) and (d)); (5) obstacle shadows where flow separation causes eddies (Figure 3.2(e)); (6) channel widening (Figure 3.2(f)); and (7) on top of high alluvial or bedrock surfaces that flank the channel (Kochel et al., 1982; Ely and Baker, 1985; Baker and Kochel, 1988; Benito et al., 2003a; Sheffer et al., 2003; Thorndycraft et al., 2005a; Benito and Thorndycraft, 2005).

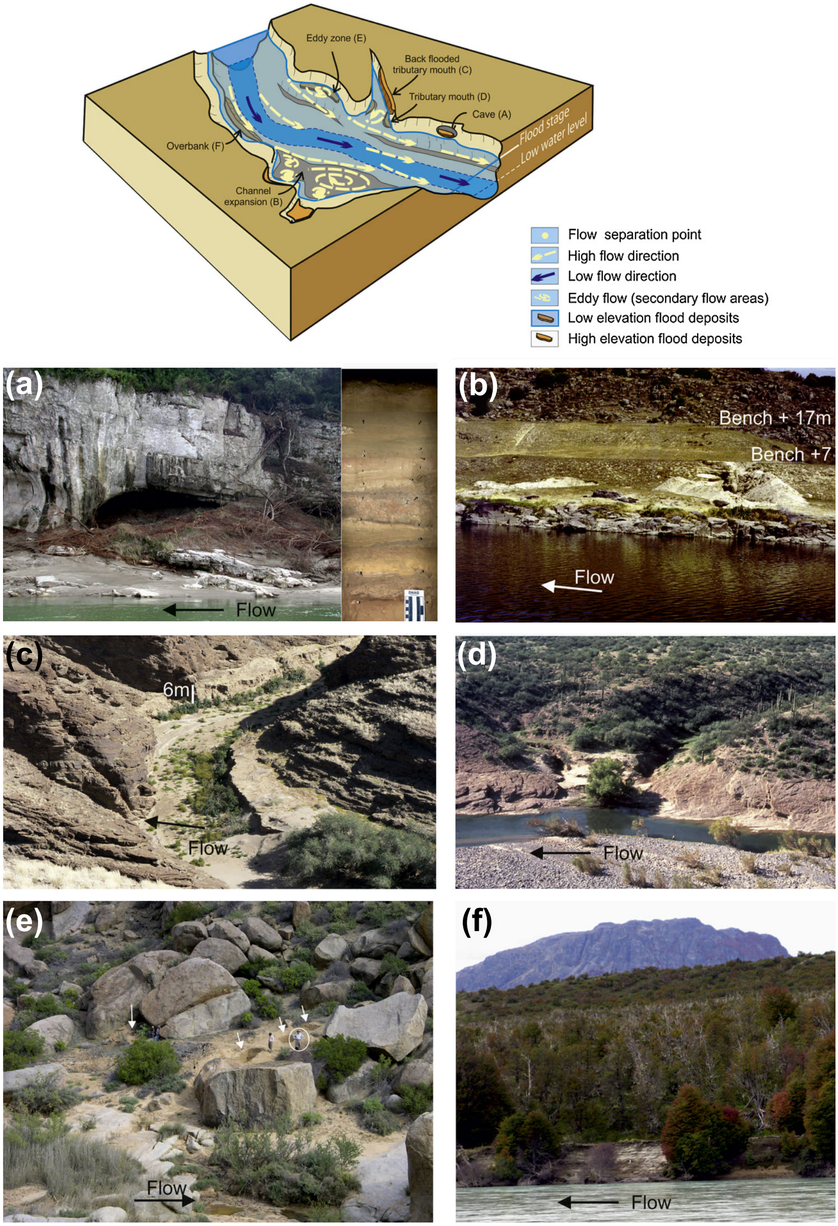

FIGURE 3.2 Upper part: Block diagram illustrating the location of sedimentary environments related to flood deposition (modified from Benito et al., 2003b). Photos: Field examples of palaeoflood stage indicators. (a) Rock shelter infilled with SWDs in the Gorge of the Gardon River (France) and stratigraphy of flood deposits within the cave (Sheffer et al., 2008). (b) Flood benches, at 17 and 10 m above the present channel bottom, deposited in an expansion reach of the Tagus River gorge (Central Spain; Benito et al., 2003a). (c) SWDs along a back flooded tributary

Flood deposition in narrow reaches is usually flushed away by subsequent flooding, although flood traces of the largest floods can be found. In narrow reaches, preservation of slack water palaeoflood deposits is optimized when they are deposited in rock shelters or rock overhangs (Figure 3.2(a)), protected from slope runoff and bioturbation. Typical slack water locations include areas upstream of tributary junctions (Figure 3.2(c) and (d)) and in transition reaches from channel expansion to constrictions (Figure 3.2(e)). In these settings, low-energy conditions favor the deposition of thick, high-standing flood deposits with bench morphology (Figure 3.2(b), (d) and (e)). Flood deposit benches are formed by vertical accretion of slackwater sediments deposited by successive floods. Deposition of a flood layer raises the minimum flood water level required for deposition of a new flood layer, meaning that a rising threshold or self-censoring level occurs over time (Kochel and Baker, 1982; House et al., 2002). Small floods may develop low elevation inset benches that are more susceptible to erosion during subsequent floods.

Individual flood beds commonly pinch out into the valley side as the layer rises in elevation. A transversal trench to the flood bench may expose complex disposition of bed contacts in response to the location and energy of recirculation eddies and sediment pulses delivered during floods. Flood benches may contain biased stratigraphic records with the higher flood bench containing a record of the largest palaeofloods over long periods of time, and the lowest benches recording more recent smaller floods.

The stratigraphical description of SWDs requires a major emphasis on interpreting the breaks and contacts between flood layers, and sedimentary structures (Baker and Kochel, 1988; Enzel et al., 1994; Benito et al., 2003a). The general criteria for identification of multiple flood layers are the following:

1. Identification of a distinct clay layer at the top of a flood unit, this representing the waning stage of a flood;
2. Deposition of a layer of sediments not deposited by a river flood that marks a clear boundary between two successive flood units. These may be colluvial, deposits falling from cave roof, or interbedded coarse tributary alluvium (couplets);
3. Bioturbation (plant and animal activity) that is indicative of an exposed sedimentary surface after the flood has passed;

of the Kuiseb River (Namibia; Grodek et al., 2013). The black arrow indicates the main flow direction through the Kuiseb River gorge. (d) Flood deposits at tributary mouth due to eddy circulation during flood stage in the Verde River, Central Arizona (Ely and Baker, 1985). (e) SWDs at eddy zone formed at the lee side of rock fall boulders in lower sector of the Buffels River (Namaqualand, South Africa; Benito et al., 2011a,b). (f) Flood deposits at overbank sedimentary environment in the Baker River, downstream of the confluence with the Colonia River (Patagonia region, Chile).

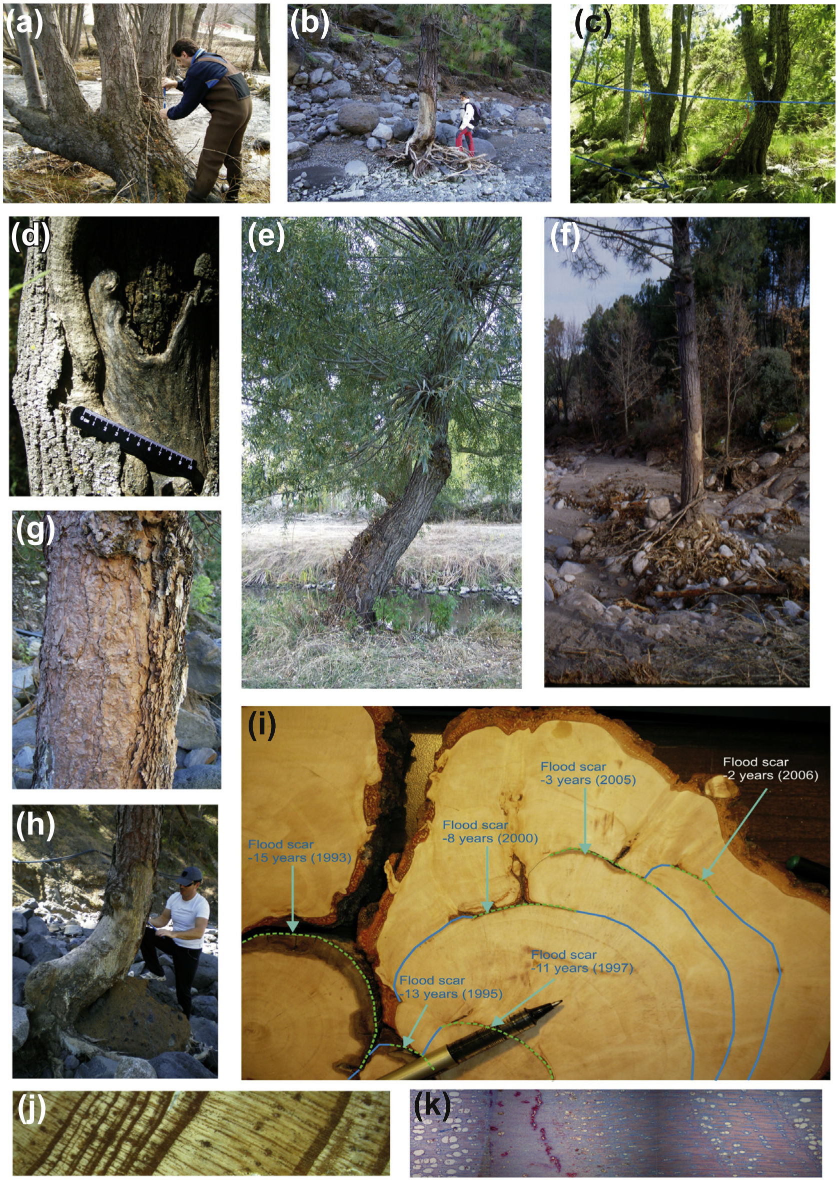

FIGURE 3.3 Examples of the most common types of dendrogeomorphological evidence useful in the study of past floods (FDEs): (a) candelabra growth ('Sigafoos' trees, Navaluenga, Central Spain); (b) scar and exposed floating roots, Taburiente (La Palma, Canary Islands); (c) bifurcations in tree stems, Navaluenga (Spain); (d) scars (stripped bark with callus marks) caused by sediment load or woody debris impacts, Venero Claro (Central Spain); (e) tilted and overturned tree, Pajares de Pedraza (Central Spain); (f) scars and exposed roots with stripped bark and erosion, Venero Claro, Spain; (g) bark erosion by abrasion, Taburiente (La Palma, Canary Islands); (h) scar and elbows and angles (sharp changes in the trunk growth direction; Taburiente, La Palma, Canary

4. An erosional boundary where the surface of an older flood unit has been eroded by a later flood event;
5. A change in the physical characteristics of the flood units, such as sediment color or particle size, that may be brought about by factors such as differing sediment source or differing energy conditions during separate flood events. This criterion is not always valid by itself and may need additional corroboration by other flood break indicators.
6. Development of palaeosols and changes in sediment hardness and mud cracks indicating soil-surface exposure.

Sedimentary structures developed within individual flood units provide valuable information on flow energy and sediment pulses during floods (McKee, 1938; Kochel and Baker, 1988; Benito et al., 2003b). The most systematic analysis of sedimentary structures associated with SWDs has been described by Benito et al. (2003b). In the flow separation zones textures are dominated by medium to coarse sand with sedimentary structures ranging from upper high-energy parallel lamination to large-scale planar or trough cross-bedding, ripple lamination, or massive intervals. In secondary flow areas toward the valley side, texture is dominated by silty sand and sandy silt, with weak stratigraphical breaks due to minor changes in texture and massive structure. Inside caves and rock shelters, characteristic sedimentary sequences are dominated by reverse flow structures (e.g., climbing ripples migrating upstream) due to eddies with a high sand concentration.

3.3.2 Botanical—Dendro Indicators

3.3.2.1 Dendrogeomorphology

Dendrogeomorphology uses information from flood damage and impacts recorded in tree trunks—stems, branches, and exposed roots of riparian forest communities (trees and bushes) located at river banks, bars, and floodplains. FDE includes more than 29 types of evidence produced by flooding. According to Díez-Herrero et al. (2007, 2013a), FDE can be classified by the spatial scale of the evidence (from macro- to microscopic, from kilometers to microns) and the scale of studied elements (from forest communities and vegetal formations to changes in cell structure and isotopic ratios). Examples of the most common FDE (impact scarring, candelabrum trees, exposed roots, adventitious branches, etc.) are shown in Figure 3.3.

Flood studies using FDE involve the following research protocol (Díez-Herrero et al., 2007, 2013a; Figure 3.4): (1) finding dendro evidence in

Islands); (i) internal scars and discontinuities, Arenas de San Pedro (Central Spain); (j) changes in tree-ring parameters (width, percent early wood, latewood, etc.); and (k) traumatic structures in wood tissues. See, for more details, Díez-Herrero et al. (2007, 2013a). All examples from Spanish study sites (Díez-Herrero et al., 2013b).

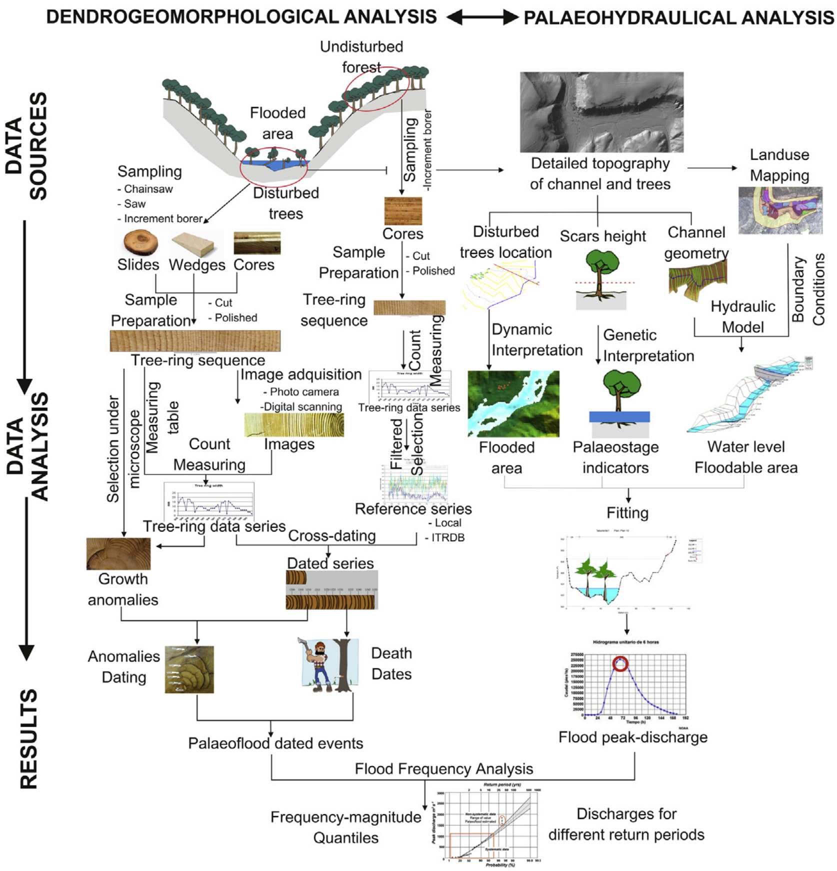

FIGURE 3.4 Scheme summarizing the main activities or tasks of both, the dendrogeomorphological and palaeohydraulic methodologies, from the data sources to the final expected results through analyses, and their mutual relations.

bottomland trees; (2) selection of tree species with homogeneous growth; (3) planned sampling of tree-ring sequences; (4) study of plant anatomy in search of characteristic signatures of past flood events; (5) synchronization of tree-ring sequences, by means of cross-dating, for past flood event dating; (6) hydraulic modelling of the river reach to estimate flow discharges using PSIs in trees; (7) assigning magnitudes to the estimated frequencies; and (8) combining palaeodischarges with systematic or modelled discharges to improve the frequency distribution function.

Dendrogeomorphological data have mainly been used for the characterization and dating of past floods (with annual precision) and the identification of time periods with different flood frequency (Coriell, 2002). These dendropalaeostage indicators can be used to estimate the magnitude of past floods either by computing the peak flow using simple equations or by means of complex hydraulic models (Ballesteros Cánovas et al., 2011a). Palaeodischarges can be used for FFA using statistical functions (Ballesteros Cánovas et al., 2011a; Ruiz-Villanueva et al., 2013). Other palaeohydrological information derived from fluvial dendrogeomorphology includes the duration of the flood (hydrograph base time), meteorological origin (based on isotopic fractionation), and runoff genesis (Díez-Herrero et al., 2013c).

The dendrogeomorphologic indicators traditionally used (mainly scar evidence) and their use to infer flood frequency and magnitude have been restricted to a small, limited set of applications. New research opportunities in palaeoflood hydrology using dendrogeomorphologic data sources can be found in (1) the application of isotopic indicators ($^{18}O/^{16}O$ ratio) to interpret the meteorological origin of past floods (Díez-Herrero et al., 2013c); (2) the use of different dendrogeomorphic indicators (i.e., tilted trees, Ballesteros Cánovas et al., 2013b; or X-ray computed tomography techniques, Guardiola-Albert et al., 2012) to estimate peak flows with 2D and 3D hydraulic models; (3) improvements to the calibration of hydraulic model parameters (roughness); and (4) the application of statistics-based cost—benefit analysis to select optimal mitigation measures (Ballesteros Cánovas et al., 2013a).

The successful reconstruction of palaeoflood records from botanical evidence depends on the presence of bottomland trees of appropriate tree species for dendrochronological analysis, and the existence of external indicators of flood damage. Another limitation is the lack of statistical representativeness of the FDEs that depend on spatial distribution (i.e., number of replications and homogeneity along the river reach), and on the age distribution of available trees to determine the temporal length of the data series. Several sources of uncertainty can affect the dendrogeomorphological results applied to past flood characterisation: (1) mistakes in tree-ring dating due to cross-dating interference (double, false or missing tree-rings, multiple density bands, etc.); (2) inadequate interpretation of the observed height of the FDEs as PSIs; and (3) the complex reconstruction of hydraulic boundary conditions of past flood hydrodynamics around trees.

3.3.2.2 Lichenometry

Another group of palaeoflood techniques rooted in botany ecology are based on lichens and lichenometric dating of bedrock surfaces and deposits exposed to floods. The presence of lichens on boulders in the river channel can be used to date the last mobilization of the blocks (Gob et al., 2003), estimate flood competence (Gob et al., 2005, 2010), frequency (Macklin and Rumsby, 2007; Macklin et al., 2010), and magnitude based on palaeocompetence equations (Johnson and Warburton, 2002). By using size—frequency diagrams and regional growth curves calibrated with dated reference points, it is possible to determine the past flood event responsible for the last mobilization of each boulder covered with lichens (Gob et al., 2010). The first step is always to establish a lichenometric growth curve characteristic of each lichen species and subspecies used for the area studied (Jacob et al., 2002). The secular growth rate of the lichen colonies is obtained from tombstones and old monuments (buildings, rocky surfaces, megaliths). Lichens on canyon walls and terraces can also be used to date the incision phases or abrasion phases linked to floods and thereby date the floods and their boundaries, which are used in turn to infer magnitudes (Gregory, 1976).

The uncertainties in lichenometry studies are related to the data sources (lichen colonies) and the methodology itself. Errors in lichen measurements, their proper identification (species and subspecies), and the characterization of the growth curve bring uncertainties in flood dating. In addition, another source of error can come from the nonrenovation of lichen colonies after flood events, because of their varying level of susceptibility to stream power, abrasion, or the period of immersion required for mortality (Marsh and Timoney, 2005); and the complex patterns of overwashing and reworking (McEwen and Matthews, 2013). These uncertainties can be reduced by the simultaneous use of a combination of different data sources and palaeohydrological methods (Johnson and Warburton, 2002).

3.4 DATING PALAEOFLOOD EVIDENCE

Some flood layers within a stratigraphic profile should be dated to determine temporal flood behavior and recurrence. The methods applied to date palaeoflood sediments can be divided into three categories: (1) relative; (2) numerical correlated; and (3) numerical (Jacobson et al., 2003).

Relative methods allow a first diagnosis about the age of sediments and other flood indicators and help to decide the strategy and targets for other dating techniques. Common relative methods applied to alluvial methods include stratigraphic position, weathering characteristics, pedogenesis, and morphological position (inset or superimposed levels).

Numerical correlated are hybrid methods aiming to estimate numerical ages through presence or absence of diagnostic properties (e.g., weathering) or elements (e.g., pollen, tephra, macrofossils, and archaeological artifacts). These diagnostic features can be used for the correlation and dating of different stratigraphic profiles.

Numerical dating methods aim to provide an estimate of the time elapsed since sediment deposition. Radiocarbon dating is a standard absolute dating tool employed in palaeohydrologic work (e.g., Baker et al., 1985). Radiocarbon analysis measures the decay of the radioactive ^{14}C isotope in organic samples (animals and plants) since the time they died. Organic material such as wood, charcoal, seeds, and leaf fragments transported by floods are commonly deposited in conjunction with detrital sediment in slackwater sequences. The radiocarbon method is limited to the range ~200 years to 55,000 years BP. Radiocarbon dating can be carried out in two ways: conventional and accelerator mass spectrometry (AMS). The conventional radiocarbon method measures the remaining ^{14}C activity in a sample, and compares it to atmospheric ^{14}C, assuming that the level has not changed. This conventional method utilizes only a small number of atoms that decay during the experiment, and therefore a large sample (a few grams) is necessary. The AMS method utilizes every atom of the nuclide in the sample, allowing extremely small samples (a few milligrams) to be dated. Radiocarbon dates are given in radiocarbon years before present that need to be calibrated to calendar years to account for secular variations in radiocarbon production in the atmosphere (Stuiver, 1982). Precise curves of radiocarbon ages have been established for calibrating radiocarbon results (e.g., Reimer et al., 2013), although anthropogenic emissions into the atmosphere pose special problems in obtaining precise calibration of ages of less than 200 years.

In flood deposits, common sample material for radiocarbon analysis includes charcoal, seeds, wood, twigs, peat, shells, bones. The sample should be taken and sent in glass, plastic, or aluminum foil, preferably in dry and dark conditions. During collection special attention should be given to the sample location within the stratigraphic profile as well as the potential postflood impact of biological or human activities. In most studies, it is assumed that the radiocarbon age is close to the flood date, although strictly the radiometric date should be considered as a maximum limiting age. Dating of multiple samples along a stratigraphical profile can prove the validity of the assumption.

The optically stimulated luminescence (OSL) method (Aitken, 1998; Wintle and Murray, 2006) is a dating technique that indicates the burial time of deposits, principally quartz and feldspar minerals. In OSL dating, the time when the sediment was last exposed to direct sunlight (bleached) is determined. For the purposes of dating flood deposit sequences, the general assumption is that the sediment was last exposed to light during transport prior to deposition. Luminescence dating might be limited if the sediment to be measured has been heterogeneously exposed to light prior to being buried and shielded from daylight. In these cases, the measurement of multigrain aliquots would lead to overestimation of the burial dose and thus overestimation of the age. Developments in instrumentation are reducing the sample size to individual grains (Duller and Murray, 2000; Bøtter-Jensen et al., 2000) from which the heterogeneity within the grain population can be analyzed. This involves the use of statistical methods and the so-called minimum age models to estimate the true burial dose making the analysis more complex. Moreover, new analytical protocols have considerably improved the application of OSL dating (Murray and Wintle, 2000; Wintle and Murray, 2006), resulting in numerical ages known to 5−10 percent, even for young deposits (<300 years) (e.g., Ballarini et al., 2003; Duller, 2004; Medialdea et al., 2014). OSL dating can be an important tool, especially for deposits: (1) containing little or no organic material; (2) older than 40,000 years, the range of radiocarbon dating; or (3) younger than 500 years old, so that radiocarbon dating cannot

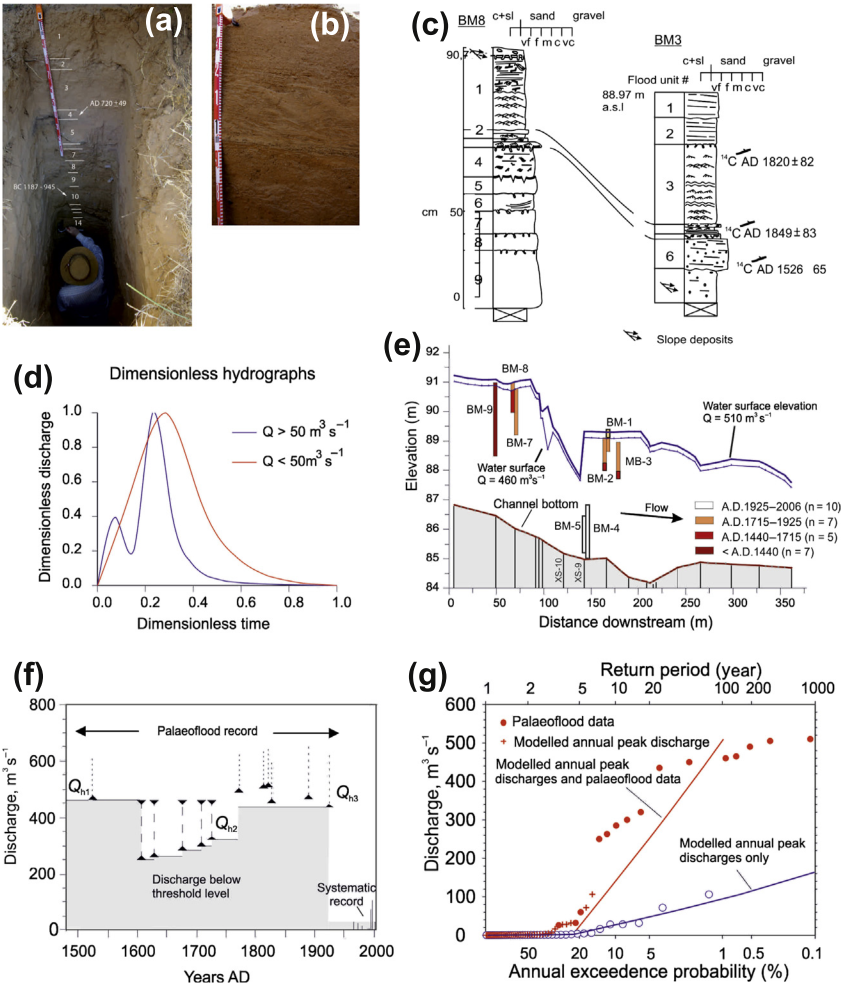

FIGURE 3.5 Buffels River palaeoflood case study in Messelpad reach based on data after Benito et al., 2011a,b. The general view of the Messelpad study reach and location of three profiles is shown in Figure 3.2(e). (a) View of the BM9 pit in Messelpad with indication of the stratigraphic units and radiocarbon dating results. (b) Lower part of slackwater unit 3 in BM8 profile (Messelpad) showing an organic detrital laminae and climbing ripples with both upstream and downstream flow direction (indicative of eddy circulation). (c) Two stratigraphic profiles of the Messelpad reach indicating dated samples (radiocarbon dates in years AD) and proposed correlations between sections. (d) The dimensionless hydrographs selected from a set of modelled hydrographs for small floods (<50 m^3 s^{-1}) and large floods (<50 m^3 s^{-1}). Probabilistic hydrographs were scaled to match the peak discharges obtained from the FFA (showed in F) (e) Longitudinal profile of the stream channel bed and water surface profiles obtained from HEC-RAS model for the highest palaeoflood deposits (510 m^3 s^{-1}) and for a reference discharge of 460 m^3 s^{-1}. Stratigraphic profiles are represented as vertical bars, with colors sketching sections of the columns with different age. (f) Palaeoflood and modelled discharges at Messelpad reach. Palaeofloods data are shown as triangles that show minimum discharge values above discharge

yield precise results. Samples are collected by hammering opaque PVC cylinders (internal diameter ~5 mm and length ~30 cm) into a cleaned vertical exposure until completely filled with sediment. Upon extrusion from the cliff face, these cylinders are sealed using thick duct tape. Extra sand subsamples for each sample are packed into airtight plastic containers holding approximately 200 g. These subsamples are to be used for determining the water content and the dose rate at the sample location. The cylinders of OSL samples are extruded under subdued red laboratory light and from them quartz grains with sizes of 180–250 µm are extracted using routine laboratory procedures (Porat, 2006).

Ideally, each flood unit should be dated, although in practice scarcity of datable material and high dating costs are the most common limiting factors on the number of samples. A first assessment based on relative age indicators such as degree of soil development, slope accumulation, and archaeological material may facilitate the decision-making process when choosing an age sampling strategy. It is advisable to separate the flood stratigraphy in sequences or sets and spend time and resources on dating the base and top of each sequence. The same applies to flood benches. Additional efforts should target the date of the largest floods and nonexcedence time intervals. Documentary and historical flood data is highly valuable to understand palaeoflood chronology (Benito et al., 2003b; Brázdil et al., 2006; Thorndycraft et al., 2006).

The problems of dating recent deposits (the past 150 years) with radiocarbon dating were solved using the analysis of modern radionuclides such as cesium-137 and lead-210 (Ely et al., 1992; Thorndycraft et al., 2005b). Cesium-137 is an artificial isotope that was introduced into the atmosphere during nuclear bomb testing in the 1950s. Since then, cesium-137 has been deposited on the land surface (including soils and sediments) from atmospheric fall-out. The presence of cesium-137 in flood sediments indicates a post-1950 age for the flood event. Sample techniques consist in collecting 100 gr of fresh sediment at 10–20 cm intervals down to a reasonable depth, informed by the results of other age dating controls. In the Llobregat flood deposits, samples were taken at the central portion of the flood units or at the upper and lower parts, depending on the unit thickness (Thorndycraft et al., 2005b).

3.5 PALAEOFLOOD DISCHARGE ESTIMATION

The water levels associated with the different flood units (Figure 3.5(a) and (b)) can be converted into discharge values (Lang et al., 2004), which is the

thresholds (shaded areas). Palaeoflood data within a discharge range are represented by the discontinuous lines between the normal and inverse triangles. The horizontal shaded areas represent the discharge threshold values used in the FFA. (g) Two component extreme value distribution fitted to annual series of modelled discharges and palaeoflood information (censored data) for Messelpad sites.

random variable used in the statistical analysis (Francés, 2004). The elevation of the uppermost contact of each flood unit represents the minimum water surface elevation during the flood event (Figure 3.5(b)). Cross-sections and flood deposit elevations, the input data for the hydraulic models, are surveyed along the study reaches. The discharge is obtained by trial and error using the appropriate hydraulic model by comparison between the observed water levels and the simulated ones (Figure 3.5(d)). A number of formulae and models exist to estimate past flood discharge from a known water surface elevation (O'Connor and Webb, 1988; Webb and Jarrett, 2002; Lang et al., 2004), ranging from simple hydraulic equations to one- or multidimensional hydraulic modelling. Most palaeoflood studies assume one-dimensional flow based on (1) uniform flow equations (Manning and Chézy equations); (2) critical flow conditions (King, 1954; Bodoque et al., 2011); (3) gradually varied flow models; and (4) one-dimensional St Venant equations. The selection of an appropriate approach for a particular site depends on local hydraulic conditions (Webb and Jarrett, 2002).

These models assume a fixed bed, and data required include slope, roughness (generally Manning's n), cross-sectional geometry and, for the step-backwater method, a boundary condition upstream or downstream depending on the flow type. The three principal sources of error are (1) the assumption that present channel geometry represents the channel conditions at the time of flooding and (2) an underestimate of the palaeodischarge due to the unknown level of the floodwaters above the palaeostage indicator (sediment, tree scar). The first error, that of cross-sectional stability, is substantially reduced by conducting palaeoflood studies in bedrock gorge reaches, where available. Bedrock channel geometry is significantly more stable than alluvial floodplain channels, for example, and will not have been substantially altered over the past centuries or millennia (Figure 3.2(e)). In case of uncertainty regarding the flow-boundary geometry, it is important to consider the plausible changes in channel geometry at the time of flooding and, consequently, provide a range of palaeoflood discharges. The unknown water depth above the flood sediments can be approached by a study of the sedimentology of the flood deposits (Benito et al., 2003a), which can enable interpretations regarding flow velocities and energy conditions at the site of deposition, thus allowing inferences to be made regarding the level of the water above the deposits.

The most common palaeoflood analysis situation is that of gradually varied flow at a steady state (constant discharge) for which depth varies with distance but not with time (O'Connor and Webb, 1988; Webb and Jarrett, 2002). The discharge of the different flood units/features is typically estimated by computing the water surface profiles for various hypothetical discharges using the step-backwater method (Chow, 1959), which solves the conservation of mass and energy equations in their one-dimensional forms (Figure 3.5(d)). Two-dimensional hydraulic models have been used for palaeodischarge estimation (Denlinger et al., 2002; Ballesteros Cánovas et al., 2011a,b). By comparing the model-generated profiles to the PSIs (e.g., slack water flood deposit elevations) minimum palaeodischarges are specified. Available public-domain computer routines, such as U.S. Army Corps of Engineers HEC-RAS (Hydraulic Engineering Center, 2010) software, allow for rapid calculation of water surface profiles for specific discharges, and energyloss coefficients.

3.6 FLOOD FREQUENCY ANALYSIS USING PALAEOFLOOD DATA

FFA with systematic data assumes that the distribution of the unknown magnitudes of the largest floods is well represented by the gauged record or that it can be obtained by statistical extrapolation from recorded floods (usually modest floods). However, the limit of credible statistical extrapolation relative to the typical length of gauged discharges (40–50 years) corresponds, at best, to a period of 200 years (England et al., 2006). The value of palaeoflood records is their potential for incorporating physical evidence of rare floods and limits to their largest magnitude (Figure 3.5(e)). The use of historical and palaeoflood information gives rise to two specific problems: (1) nonsystematic data (only the major floods remain known); and (c) nonhomogeneous data (hydroclimatically induced nonstationarity due to natural climatic variability within the past 1,000–10,000 years). These problems are discussed in detail by Redmond et al. (2002), Benito et al. (2004), Francés (2004).

In hydrology, flood observations reported as having occurred above some threshold are known as censored data sets (Leese, 1973). Palaeoflood information is considered data censored above a threshold (Figure 3.5(e)) and it is assumed that the number of k observations exceeding an arbitrary discharge threshold (X_T) in M years is known, similar to the partial duration series (Stedinger and Cohn, 1986; Francés et al., 1994). The value of the peak discharge for palaeofloods above X_T may be known or unknown. Palaeoflood data are organized according to different fixed threshold levels exceeded by flood waters over particular periods of time. Estimated flood discharges obtained from the minimum high-water palaeoflood indicators and maximum bounds (nonexceeded threshold sense; Levish et al., 1997) can be introduced as minimum and maximum discharge values (Figure 3.5(e)). Estimates of statistical parameters of flood distribution functions (e.g., Gumbel, LP3 or upper-bounded statistical models; Botero and Francés, 2010) are calculated using maximum likelihood estimators (Leese, 1973; Stedinger and Cohn, 1986; Figure 3.5(f)), the expected moment algorithm (Cohn et al., 1997), and a fully Bayesian approach (O'Connell et al., 2002; Reis and Stedinger, 2005), providing a practical framework for incorporating imprecise and categorical data as an alternative to the weighted moment method (U.S. Water Resources Council, 1982).

Before the statistical analysis is carried out, the general characteristics and stationarity of the flood series must be considered. The temporal changes in the trajectory and statistics of a variable may correspond to natural, low-frequency variations of the climate's hydrological system or to nonstationary dynamics related to anthropogenic changes in key parameters such as land use and atmospheric composition. Flood record stationarity from censored samples (systematic and/or nonsystematic) can be checked using Lang's test (Lang et al., 1999). This test assumes that the flood series can be described by a homogenous Poisson process. The 95 percent tolerance interval of the cumulative number of floods above a threshold, or censored, level is computed. Stationary flood series are those remaining within the 95 percent tolerance interval (Naulet et al., 2005). Recent advances in FFA have focused on modelling time series under nonstationary conditions, such as Generalized Additive Models for Location, Scale and Shape parameters (GAMLSS; Rigby and Stasinopoulos, 2005). The GAMLSS approach is able to describe the temporal variation of statistical parameters (mean, variance) in probability distribution functions (Gumbel, Lognormal, Weibull, Gamma). The statistical parameters may show increasing/decreasing trends that can be modelled using time as covariate (characterizing the trend or as a smooth function via cubic splines; Villarini et al., 2009), or they can be related to hydroclimatic covariates such as climatic indices that reflect low-frequency climatic variability (e.g., Pacific Decadal Oscillation, North Atlantic Oscillation, Arctic Oscillation; López and Francés, 2013). The application of these nonstationary models to palaeoflood hydrology requires a characterization of the occurrence rate (covariate) during the recorded period.

3.7 ESTIMATION OF PALAEOFLOOD VOLUME

Extreme flood hydrographs are needed for different engineering applications, such as risk analysis for dam safety (Nathan and Weinmann, 1999; Swain et al., 2006) or estimating floodwater recharge into alluvial aquifers (Greenbaum et al., 2002; Benito et al., 2011b). Extreme flood hydrographs are characterized by four major factors: peak, volume, duration, and shape (e.g., Yue et al., 2002). The few attempts to derive hydrographs from palaeoflood studies have used probabilistic hydrographs (England, 2003; Benito et al., 2011b). A probabilistic hydrograph is defined as one that preserves a peak discharge exceedance probability and dependence between volume and peak for a fixed duration (England, 2003). Probabilistic hydrographs are developed from scaling streamflow observations, or from rainfall–runoff models. This approach requires (England, 2003) (1) a peak discharge–probability analysis; (2) an extreme storm duration probability relationship; (3) correlation between peak discharge and maximum mean daily flow, and (4) observed hourly flow hydrograph(s) in natural regime.

Peak discharge probability relationships, hourly flow data and daily mean streamflow data, are used to construct probabilistic hydrographs. The peak discharge probability relationship uses data from gauge stations or from rainfall–runoff modelling combined with palaeoflood discharges (Figure 3.5(f)). Flood runoff duration can be obtained either from observed extreme storm duration (assuming a close similarity of storm and runoff duration) or based on the most common observed occurrences of peak duration at the study basin. The hydrograph shape is reproduced from averaged unit hydrographs (Cudworth, 1989) or based on mean dimensionless hydrographs (Craig and Rankl, 1978). The mean dimensionless hydrographs may be constructed by visually selecting a representative shape of observed or modelled hydrographs of large floods (Benito et al., 2011b, Figure 3.5(c)). The probabilistic hydrographs are then scaled to represent the estimated duration (from peak duration frequency distribution) and dimensionless hydrograph shape corresponding to the peak discharge calculated for different flood quantiles (Figure 3.4(c); Table 3.1).

3.8 APPLIED PALAEOFLOOD HYDROLOGY

Palaeoflood hydrology has been successfully applied to engineering and flood hazard studies (Benito and Thorndycraft, 2005), including (1) major improvements in flood risk assessment (House et al., 2002; Benito et al., 2004); (2) determination of the maximum limit of flood magnitude (Enzel et al., 1993) and nonexceedences to test the consistency of probable maximum flood (PMF), and safety risk analysis of critical facilities (e.g., dams, wastewater facilities, and power plants; Levish et al., 1996, 2003; Benito et al., 2006; Greenbaum, 2007); (3) understanding of long-term flood–climate relationships (Ely et al., 1993; Ely, 1997; Knox, 2000; Redmond et al., 2002; Thorndycraft and Benito, 2006; Benito et al., 2008); and (4) assessing the sustainability of water resources in dryland environments where floods are an important source of water for alluvial aquifer recharge (Greenbaum et al., 2002; Benito et al., 2011b).

3.8.1 Palaeofloods as an Analogue of Present and Future Flood Disasters

Palaeoflood hydrology has demonstrated in a number of cases that present catastrophic floods were already produced in the recent past (a few hundred years). In the Black Hills of South Dakota, on June 9–10th, 1972 an extreme convective rainfall of around 380 mm of rain in 6 h produced peak discharges of 1,461 $m^3\ s^{-1}$ in Boxelder Creek (drainage area of 303 km^2) and 883 $m^3\ s^{-1}$ in Rapid Creek (drainage area 135 km^2) upstream of Rapid City producing 238 casualties (Schwarz et al., 1975). This 1972 flood discharge represents a high outlier for the gauge records of the Black Hills region, but sedimentological

TABLE 3.1 Instrumental, Palaeoflood, the 10,000-year Return Period and Probable Maximum Flood (PMF) Discharges for Various River Basins in the USA and Spain. The 10,000-year Return Period Discharges Were Estimated Using the Palaeoflood Data in Each Basin (Benito and Thorndycraft, 2005)

Location	Drainage Basin Area (km^2)	Largest Instrumental Flood ($m^3\ s^{-1}$)	Length of Palaeoflood Record (years)	Largest Palaeoflood Discharge ($m^3\ s^{-1}$)	10,000-year Palaeoflood Discharge ($m^3\ s^{-1}$)	PMF Discharge ($m^3\ s^{-1}$)
Santa Ynez River, California (USA)[a]	1,080	2,265	2,900	2,550	2,690	13,060
Ochoco Creek, Oregon (USA)[b]	764	–	10,000–15,000	285	285	4,785
Crooked River, Oregon (USA)[c]	6,825	–	8,000–10,000	<1,100	1,100	7,225
South Fork Ogden River, Utah (USA)[c]	210	53	400	70	<215	3,075
Llobregat River (NE Spain)[d]	3,370	2500	2,800	4,680	–	18,985[e]
Caramel River (SE Spain)[d]	372	170	1,985	1,616	3,450	5,786

[a]*Data from Ostenaa et al., 1994 in Levish et al., 1996.*
[b]*Data from Ostenaa and Levish, 1996.*
[c]*Data from Levish et al., 1996.*
[d]*Data from Benito and Thorndycraft, 2005.*
[e]*Data from Francés (written communication, 2003).*

evidence of former floods deposited within rock shelters showed that similar magnitude floods have occurred at least five to seven times over the past 1,000 years on both creeks (Harden et al., 2011). In this case, as in others, palaeoflood analysis is a suitable deterministic means to provide a long-term perspective of the largest floods occurring at specific catchments.

Another further application of palaeoflood hydrology for the prevention of future flood disasters and the rational assessment of mitigation strategies is the incorporation of palaeoflood data in economic risk analysis. Few examples of these studies exist worldwide; one of them is the cost—benefit flood risk analysis made by Ballesteros Cánovas et al. (2013a) in the village of Navaluenga (Central Spain). Nonsystematic data derived from a dendrogeomorphological study of riparian trees were included in the FFA, improving the statistical function for flood estimation of medium and high recurrence periods. Flood damage was assessed by means of depth-damage functions, and the flooded urban areas were analyzed by applying a 2D hydraulic model. The best defense strategies were obtained via a cost—benefit procedure, where uncertainties derived from each analytical process were incorporated, based on a stochastic approach to estimating expected economic losses. The results showed that large structural solutions are not economically viable when compared with other smaller structural measures, presumably because the preestablished location of dams in the upper part of the basin is unable to laminate the flow generated in the headwaters. This analysis shows that uncertainties derived from nonsystematic data (i.e., tree-ring analysis) included in the flood frequency definition can be used in flood risk assessment.

3.8.2 Palaeoflood Hydrology Applied to Dam Safety

Dams are designed, constructed, and modified, when necessary, such that a catastrophic failure is prevented during a large flood. The design flood refers to the flood magnitude for which spillways and energy dissipating structures were designed, with a safety margin provided by the freeboard. Past experience indicates that overtopping represents more than 40 percent of dam failures, showing that extreme floods constitute an important risk for dam safety (ICOLD, 1995). The ICOLD (1995) recommends the estimation of a flood discharge return period of 1,000 years for the design of spillways, and 10,000 years for the safety of the dam structure. The estimation of such low frequency floods is based on either probabilistic or deterministic approaches. Probabilistic methods (statistical analysis and hydrometeorologic estimations) involve extrapolation of hydrological and meteorological instrumental records, and occasionally the use of historical data. The deterministic approach, particularly the estimation of the probable maximum flood (PMF), is nowadays a common practice in dam design. The rationale behind the PMF is the existence of a hydroclimatic limit to the supply of moisture to river basins through storms and precipitation, which has led to discussion on whether there is an upper limit of flood magnitude, duration, and volume that a specific drainage basin can generate (Wolman and Costa, 1984). The designed largest flood is then routed downstream by using watershed models (National Research Council, 1985). By definition, the PMF has no return period but arbitrarily it was assigned a return period of 10,000 to 1,000,000 years at the upper and lower confidence limits for FFA (National Research Council, 1985).

Palaeoflood studies, including those performed for dam safety purposes by the U.S. Bureau of Reclamation, show that the upper limit for palaeoflood magnitude is of an order of magnitude smaller than that implied by PMF calculations (Enzel et al., 1993; Levish et al., 1996). Studies performed in Spain show similar conclusions in the Llobregat and the Caramel river basins (Benito et al., 2006). In these studies the extrapolated discharges of the 10,000 year palaeoflood return period are between 5 and 20 percent of the calculated PMF for the United States (Levish et al., 1996) and around 60 percent for the Spanish case studies (Table 3.2), indicating that the calculated PMF discharges are very large overestimates. The value of PMF for dam safety studies is uncertain due to the lack of physical potential for these basins to generate the calculated peak discharges. Estimated discharges from the physical evidence left by floods over periods of thousands of years provide more realistic results, which can be combined with gauge station data using appropriate statistical tools and can subsequently be of great value for the planning of large-scale hydrological projects (e.g., Ostenaa et al., 1994; Ostenaa and Levish, 1996).

3.8.3 Flood Hazards in the Context of Climate Change

Climate affects flooding across a wide spectrum of spatial and temporal scales (Redmond et al., 2002). Temporal changes in flood magnitude and frequency have been described via instrumental (Robson et al., 1998), documentary/historical (Glaser et al., 2010), and palaeoflood records (Ely et al., 1993; Benito et al., 2008). Long-term palaeoflood records have revealed secular to multidecadal variability in flood patterns that may affect their frequency, magnitude, seasonality, and cause (e.g., Ely et al., 1993; Macklin et al., 2006; Benito et al., 2008; Glaser et al., 2010). A major driver for this flood variability is climate (Knox, 1999, 2000; Redmond et al., 2002), although land use changes could affect runoff generation conditions at basin scale, particularly (but not exclusively) during the nineteenth century (Greenbaum et al., 2000; Benito et al., 2010).

Periods with a higher frequency of large floods are interpreted as a result of changing atmospheric circulation patterns modulated by climate variability on decadal and secular timescales (Hirschboeck et al., 2000). In the Mediterranean region, palaeoflood records supported by documentary evidence indicate that periods of region-wide flooding can be identified in the second,

TABLE 3.2 **Floodwater Recharge into the Spektakel Alluvial Aquifer in the Lower Buffels River (South Africa) Based on the Study by Benito et al., 2011b**

Return Period, years	Peak Discharge, $m^3\ s^{-1}$	Duration, days	Hydrograph Volume, mm^3	Potential Infiltration, mm^3	Infiltration to Saturation[(a)] WT: 3 m, mm^3	Infiltration to Saturation[(b)], mm^3
5	23	6	4.2	4.2	4.2	4.20
10	140	12	27	11	9	11.83
25	287	12	54	17	9	13.60
50	397	12	76	18	9	13.60
100	505	12	97	21	9	13.60
500	752	12	144	23	9	13.60

First and second columns: flood quantiles for different return periods at messelpad reach (~5 km upstream of spektakel aquifer reach), obtained using a two-component extreme value (TCEV) distribution fitted to the combined modelled and censored palaeoflood data. Third and fourth columns: characteristics of the probabilistic hydrographs (duration and volume) based on dimensionless hydrographs and fix duration of 6 days to small floods ($<50\ m^3\ s^{-1}$) and 12 days for large floods ($<50\ m^3\ s^{-1}$). Fifth column: potential infiltration considering all the possible infiltration for the given probabilistic hydrograph assuming a limitless capacity of the aquifer. Sixth and seventh columns: infiltration to saturation estimated for two starting conditions assuming (a) a water table at 3 m below the surface and (b) a depleted aquifer conditions at the time of flooding. Floodwater recharge of this alluvial aquifer in Africa's dryland region may be enhanced keeping a low water table during wet years.

sixth–seventh, tenth, late fifteenth, and late eighteenth centuries AD, which all coincide with relatively wet and cold climatic conditions (Macklin et al., 2006; Thorndycraft and Benito, 2006; Benito et al., 2008; Luterbacher et al., 2012). Glaser and Stangl (2004) found that multidecadal (range of 30–100 years) increases or decreases in flood frequency have occurred several times in Central-western Europe. For instance, flood events in the Pegnitz and Main rivers in Southern Germany were more frequent in the second half of the sixteenth century than in the second half of the twentieth century. In the western United States, an increased frequency of high-magnitude palaeofloods coincides with periods of cool, wet climate, whereas warm intervals, such as the Medieval Climatic Anomaly, correspond to dramatic decreases in the number of large floods (Ely et al., 1993). In this region, a positive relationship between palaeofloods and long-term variations in the frequency of El Niño events is evident at least over the past 3,000 years (Ely, 1997).

The temporal change in flood frequency/magnitude may affect the assumption of stationarity of the statistical parametric models on which the random variable (flood discharge) is independently and identically distributed (Lang et al., 1999; Redmond et al., 2002). This assumption is being questioned because of the ways in which climate change and land use may alter flood hydrology (Milly et al., 2008). Palaeoflood and documentary records can be used to test this assumption of stationarity from the analysis of long-term flood records (Benito et al., 2011a; Grodek et al., 2013), their magnitude–frequency patterns, and their links to local and regional driving mechanisms (natural and anthropogenic).

3.8.4 Floodwater Recharge by Extreme Floods

In many arid environments, the availability of water resources for natural ecosystems and human societies depends on floodwater infiltrating into alluvial aquifers (indirect recharge). As floods are rare in the gauged records, limited data exist on which to base an evaluation of the long-term frequency of the recharging events, data that are of crucial importance for integrated water resource management. In recent years new methodologies have been developed, combining flood and palaeoflood records with data on modern transmission losses, to estimate shallow aquifer recharge processes. The approach was first successfully applied in the Negev Desert, with quantitative data provided on the volume of water lost during floods through transmission losses (Greenbaum et al., 2002). In the framework of the WADE Project, funded by the European Commission, instrumental records on the temporal variation of water content in the vadose zone during recharging floods (Dahan et al., 2003, 2008) were used to calibrate a model for long-term recharge estimation from palaeofloods (SWDs) linked to the isotopic composition of groundwater (Benito et al., 2011a,b). A major factor controlling the recharge is the infiltration rate of the channel bed. In alluvial channels with a limited infiltration rate (e.g., Kuiseb River, Namibia; 8.5–10 mm/h) flow duration and channel characteristics (length and width) become important factors in determining infiltration and total recharge volume (Morin et al., 2009; Grodek et al., 2013). In the Buffels river (South Africa; 10–60 mm/h) with a higher infiltration rate the effect of flood duration becomes less important and at the same time infiltration volume becomes more dependent on the magnitude of the flow and the size of the aquifer (Benito et al., 2011a,b). In the South African case, reconstructed palaeofloods were up to five times greater than the largest modelled peak discharges over the period 1965–2006. Dimensionless hydrographs scaled to the probabilistic flood discharge showed that small floods (return periods of 5–10 years) were able to fully saturate the alluvial aquifers (floods exceeding *ca* 120–140 $m^3 s^{-1}$ and 12 days duration; Benito et al., 2011b; Table 3.2).

3.9 CONCLUSIONS

Palaeoflood hydrology is a young and evolving discipline that has received criticism mostly because of misconceptions that persist in parallel disciplines, particularly in conventional hydrology. A review of the basic criticisms and their discussion can be found in Baker et al. (2002). Theoretical difficulties to be solved in the combined use of systematic and nonsystematic information stem from (1) methodological complexity and uncertainties associated with the reconstruction of the catalogue of palaeoflood data and (2) the influence and evidence of nonstationarity in long timescale flood records.

The methodological complexity associated with reconstructing past flood records can be solved by selecting the most appropriate settings, such as bedrock canyons for palaeoflood analysis, using SWDs. In terms of pure scientific research it is of interest to reconstruct the most complete catalogue of past floods and estimate the most accurate peak discharges possible so that issues such as the water depth above SWDs become of key importance. In practice, however, the critical issue for flood risk estimation is not the accurate compilation of the whole past flood record, but the frequency of floods that might have an impact on human activities. In this case, the number of floods exceeding or not exceeding a surface or altitudinal level during a time period, which represents stage and subsequently discharge limits, may result in a significant improvement in FFA.

A major effort must be focused on FFA for managing this nonsystematic and, even more importantly, nonstationary information. Different statistical tools, such as the maximum likelihood and Bayesian methodologies, have been successful in managing nonsystematic data, even data with a high degree of uncertainty regarding peak discharge values, which have been solved using censuring levels and thresholds. In the analysis of nonstationary flood series it is also critical to reach a better understanding of flood-producing mechanisms and flood—climate links during different time periods. A change in flood-generating mechanisms, or in flood frequency patterns, can be related to climatic variations and, therefore, a study of these variations, quantifying the frequency of climatic patterns responsible for flooding, is required. Another source of nonstationarity is related to land use and land cover changes (vegetation and soil moisture) that affect the response of a catchment to rainfall. As with other sedimentary records, a detailed analysis of geochemical and vegetation proxies (e.g., pollen and phytoliths) may provide insight into environmental changes in the studied basin at the time of flooding. Ultimately, nonstationarity in FFA is a problem with both systematic and/or nonsystematic records (Baker et al., 2002).

ACKNOWLEDGMENTS

The research conducted in this study was supported by the Spanish Inter-Ministry of Science and Technology (CICYT), through the projects CLARIES (CGL2011-29176) and MAS Dendro-Avenidas (CGL2010-19274); and the National Parks Research Program (MAGRAMA), through the project IDEA-GesPPNN (OAPN 163/2010).

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