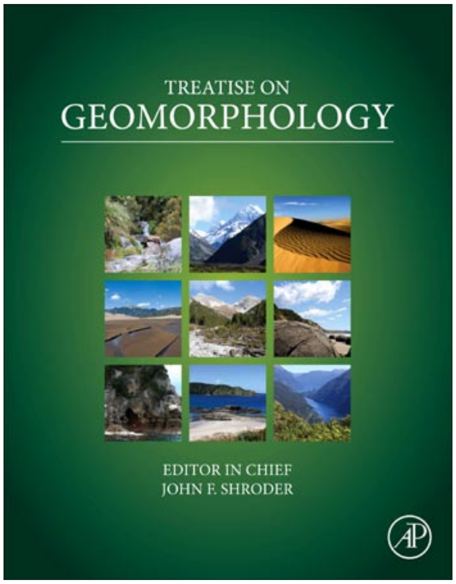

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9.24 Quantitative Paleoflood Hydrology

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Abstract

This chapter reviews the paleohydrologic techniques and approaches used to reconstruct the magnitude and frequency of past floods using geological evidence. Quantitative paleoflood hydrology typically leads to two phases of analysis: (1) documentation and assessment of flood physical evidence (paleostage indicators); and (2) relating identified flood evidence to flood discharge, based on hydraulic calculations. Most paleoflood studies rely on stratigraphic sequences of fine-grained flood sediments deposited in slackwater and eddy environments in bedrock rivers to enable calculation of robust palaeodischarge estimates for floods that occurred during recent centuries or millennia. Geochronological developments such as optically stimulated luminescence age dating, together with radiocarbon techniques, are key for structuring the paleoflood discharge data into different threshold levels that are exceeded by floodwaters over specific periods of time, providing the input data necessary for flood-frequency analysis. The value of paleoflood data is the potential to include physical evidence of rare floods and limits on their largest magnitude, with direct applications for different scientific and engineering problems, including: (1) risk assessments for critical structures such as nuclear facilities, dams, or bridges; (2) understanding of the recurrence of geomorphically effective flows; and (3) assessment of nonstationarity in the frequency of large floods due to climate, land-use, or other changes.

9.24.1 Introduction

Paleoflood hydrology (Kochel and Baker, 1982) is the reconstruction of the magnitude and frequency of past floods using geological evidence (Baker et al., 2002). Over the last 30 years, paleoflood hydrology has achieved recognition as a new branch of geomorphology and hydrology (Baker et al., 2002; Baker, 2008; Benito and Thorndycraft, 2005), employing principles of geology, hydrology, and fluid dynamics to infer quantitative and qualitative aspects of unobserved or unmeasured floods on the basis of physical evidence left in their wake (House et al., 2002a; Saint-Laurent, 2004) (*see* Chapter 9.26). Flood indicators include various types of geologic evidence (flood deposits and geomorphic features) and flotsam deposits, as well as physical effects on vegetation. Resulting inferences can include timing, magnitude, and frequency of individual floods at specific sites or for specific rivers, as well as conclusions regarding the magnitude and frequency of channel-forming floods. The obvious benefit of paleoflood studies is obtaining information on floods from times or locations lacking direct measurements and observations. Findings from paleoflood studies support flood hazard assessments as well as understanding of the linkages between climate, land-use, flood-frequency, and channel morphology.

The primary goal of paleoflood hydrology is to acquire information on extreme floods by inferring their hydrological parameters (usually flood discharge) from physical evidence, thereby contrasting with standard flood hydrology based on direct measurements of hydrologic phenomena. Paleoflood studies involve many different techniques, the selection of which is mainly guided by (1) attributes of the river system and (2) the purpose of the flood study. The physical characteristics of a river system dictate the type, longevity, and fidelity of paleoflood records. The purpose of a flood study gives priority to relevant evidence and analyses of paleostage indicators (PSIs) and hydraulic properties.

Paleoflood studies typically take one of two forms: (1) analyses focused on determining quantitative information for specific events, such as the timing, peak discharge, and maximum stage of an individual flood or floods; and (2) studies

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investigating more general spatial and temporal patterns of flooding, commonly to assess relations among climate, land use, flood frequency and magnitude, and geomorphic response (such as channel morphology or floodplain sedimentation and erosion processes). Both types of investigations share approaches and techniques, but, in general, studies of specific paleofloods are most typically conducted in bedrock or otherwise confined river systems for which preservation of stratigraphic and geomorphic records of individual floods are more likely (Kochel and Baker, 1982), although many studies have obtained valuable paleoflood information for alluvial rivers (Knox, 1999; Knox and Daniels, 2002). Studies relating channel form or floodplain morphology to past flood characteristics more typically are conducted for alluvial river corridors, and follow from the classic studies of Schumm (1968) and Dury (1973). The remainder of this chapter focuses on techniques and approaches for obtaining quantitative information on specific floods – as this has been the main emphasis of most paleoflood studies of the last 30 years – and provides example applications for different scientific and engineering problems.

9.24.2 Quantitative Paleoflood Hydrology

Quantitative paleoflood hydrology relies on identification of evidence of flooding in conjunction with application of hydrodynamic principles to determine flow magnitude. These two aspects of investigation typically lead to four phases of analysis: (1) documentation and assessment of flood evidence; (2) determination of paleoflood ages; (3) estimation of flow magnitude, typically peak discharge, associated with flood evidence; and (4) incorporation of paleoflood data into the flood-frequency analysis. The first component is geological and archival, requiring classic tools of historical research, geomorphology, stratigraphy, and sedimentology and the second involves geochronology in order to identify and date physical evidence of flooding. The third component requires employing hydraulic and hydrodynamic analyses, many drawn from engineering applications, to assign a flow magnitude to discovered evidence. Paleoflood discharge data can be incorporated together with instrumental records into a flood-frequency analysis to determine peak flows associated to probability quantiles. These paleoflood studies generally are more successful and have fewer uncertainties in fluvial systems with resistant boundaries, such as bedrock or semi-alluvial channels. These environments, because of stable depositional sites, tend to have longer and clearer stratigraphic records of floods – sometimes exceeding several thousand years – and have stable boundary conditions, leading to greater confidence in using present topography to determine past hydraulic conditions.

These types of paleoflood studies in bedrock rivers gained traction in the late 1970s and early 1980s, primarily under the auspices of Prof. Victor R. Baker and his students. These studies focused on the southwestern United States, including Texas (Kochel et al., 1982), Arizona (Ely and Baker, 1985; Partridge and Baker, 1987; Ely et al., 1993; House et al., 2002b), and Utah (Webb et al., 1988; O'Connor et al., 1986). Other practitioners were active in Colorado (Jarrett, 1990), Wisconsin (Knox, 1985), Washington (Chatters and Hoover, 1986), and Southern California (Enzel, 1992). Subsequently, such studies expanded to other countries including Australia (Pickup et al., 1988; Wohl, 1992; Wohl and Fuertsch, 1994), India (Kale et al., 1994, 2000), South Africa (Smith, 1992; Zawada, 2000), Israel (Greenbaum et al., 2000), Peru (Wells, 1990), Spain (Benito et al., 2003a, 2008; Thorndycraft et al., 2005a), France (Sheffer et al., 2003, 2008), and Thailand (Kidson et al., 2005). Some aspects of these techniques have been also applied to water flows on Mars (e.g., Baker and Milton, 1974; Baker, 1978; Komatsu and Baker, 1997; Burr et al., 2002).

Most of these studies were carried out in semi-arid and arid regions. In general, paleoflood studies show that: (1) flood discharges estimated for paleofloods have generally exceeded those of the observation record (Enzel et al., 1993); and (2) in certain areas, very large floods cluster on timescales of decades and centuries, interpreted as a flood response to climate variability (Ely et al., 1993; Knox, 2000; Benito et al., 2003a).

9.24.2.1 Development of Paleoflood Records

Paleoflood records can be reconstructed from two basic types of physical evidence: high-water marks (HWMs), and PSIs. HWMs include mud, silt, seed lines, and flotsam (e.g., fine organic debris, grass, and woody debris) that closely mark peak flood stage (**Figure 1(a)**). This type of evidence typically only persists for weeks, in humid climates, and to several years, in semi-arid and arid climates (Williams and Costa, 1988). By contrast, PSIs provide longer-lasting evidence of peak flow stages, and typically consist of fine-textured flood sediment (slackwater flood deposits (SWDs); **Figure 1(e)**), gravel and boulder bars, silt lines, and erosion features (Baker, 1987; Kochel and Baker, 1988; Webb and Jarrett, 2002), as well as botanical evidence such as scars on riparian trees. Depending on the environment, such evidence can persist for several millennia (Kochel and Baker, 1982).

Silt lines are subhorizontal linear deposits of silt- and clay-sized particles traced along some portion of the bedrock canyon walls, providing clear evidence of maximum flood stage (**Figure 1(a)**). These lines have been interpreted as derived from suspended load of the flooded stream, being left as the flood waters covered, and, in places, percolated into the bedrock valley margins (O'Connor et al., 1986). High-level scour marks and trimlines on valley-margin colluvium and soils may result from erosion of largest(s) floods (**Figure 1(b)**), although their interpretation may be ambiguous (Webb and Jarrett, 2002). In high-gradient streams, coarse boulder deposits are the most common large-flood deposits and can also serve as PSIs (Jarrett, 1990). Botanical flood evidence include flood scars and other flood-related effects on riparian trees (sprouting from tilting steams, eccentric ring growth; Sigafoos, 1964), which have been used effectively for reconstructing regional flood magnitude and frequency (McCord, 1990, 1996). Recently, Yanosky and Jarrett (2002) described new techniques to infer flood history from tree-ring anatomical changes.

The most complete paleoflood records generally result from analysis of stratigraphic sequences of fine-grained flood

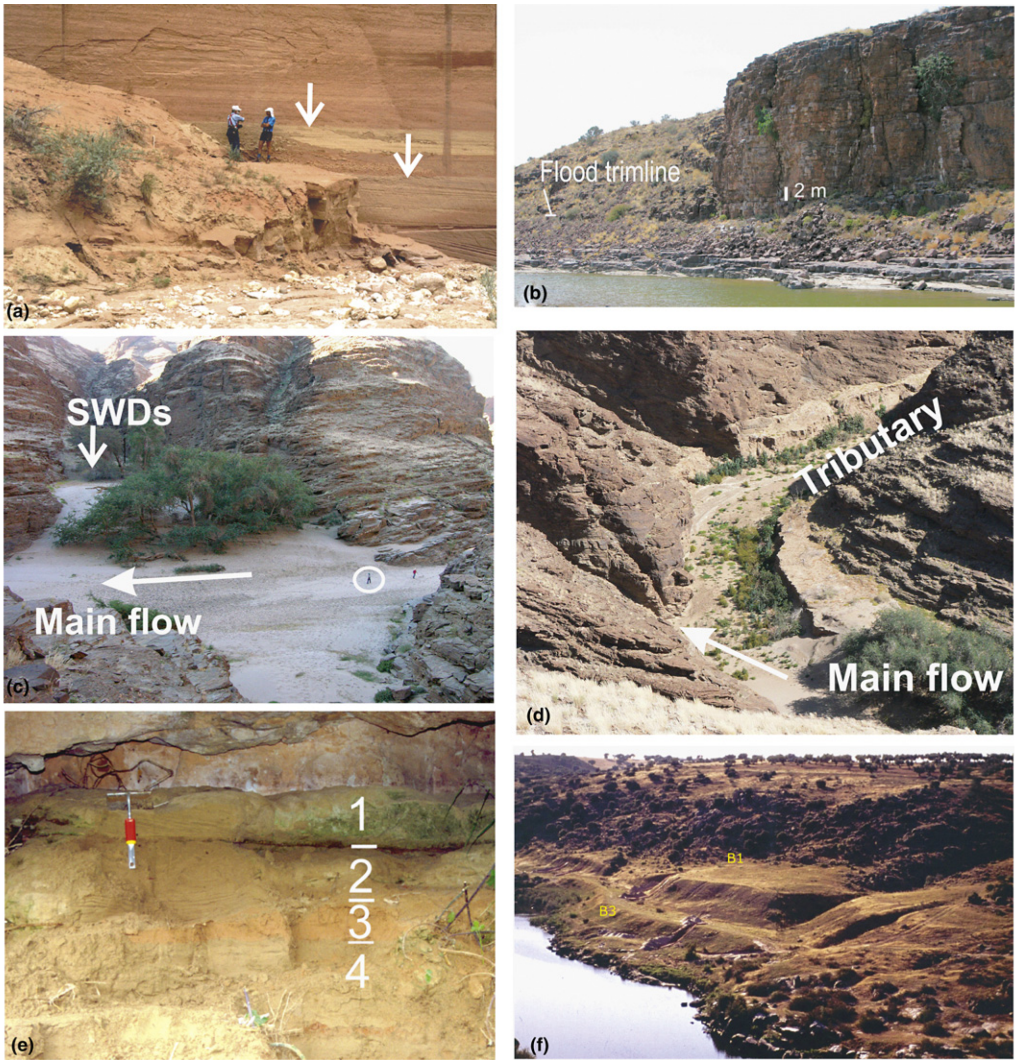


Figure 1 Field examples of paleoflood-stage indicators. (a) Silt lines preserved on canyon walls, Buckskin Gulch (Utah). (b) Flood trimline on coarse colluvium deposits, upper Fish River catchment (Namibia). (c) Flood bench at a backwater-flooded tributary of the Kuiseb River (Namibia). (d) Slackwater flood deposits (SWD) at tributary mouth due to eddy circulation during flood stage (Kuiseb River, Namibia). (e) Rock shelter infilled with slackwater flood deposits in the Llobregat River (NE, Spain). (f) Flood benches, at 17 and 10 m above the present channel bottom, deposited in an expansion reach of the Tagus River gorge (Central Spain).

deposits occurring in slackwater and eddy environments (**Figure 1(c)**). SWDs are fine-grained sedimentary deposits that accumulate from suspension during floods (Baker et al., 2002). Slackwater sedimentation areas include flooded valley margins subject to eddies, back flooding, flow separation, and water stagnation during high stages. The significant reduction on flow velocities in these areas ($<1\ \mathrm{m\ s^{-1}}$) promote rapid deposition of the fine-grained fraction of the suspended load. The resulting SWDs commonly contain sedimentary structures and textures reflecting flow energy, direction, and velocities.

Slackwater depositional environments (**Figure 2**) commonly include: (1) areas of channel widening (**Figure 1(f)**); (2) severe channel bends; (3) obstacle hydraulic shadows where flow separation causes eddies; (4) alcoves and caves in bedrock walls (**Figure 1(e)**); (5) back-flooded tributary mouths and valleys (**Figures 1(c)** and **1(d)**); and (6) 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). In narrow reaches, preservation of SWDs is enhanced when they are deposited in valley side caves, alcoves, or rock overhangs (**Figure 1(e)**).

Stratigraphic description of flood sequences requires emphasis on breaks and contacts indicative of individual flood events, and sedimentary structures (**Figure 3**). Individual flood units can be identified within a sedimentary profile recording a number of flood events using one, or a combination, of any of the following criteria (e.g., Baker and Kochel, 1988; Enzel et al., 1994; Benito et al., 2003a):

1. Identification of a distinct silt to clay layer at the top of a flood unit, this representing the waning stage of a flood.

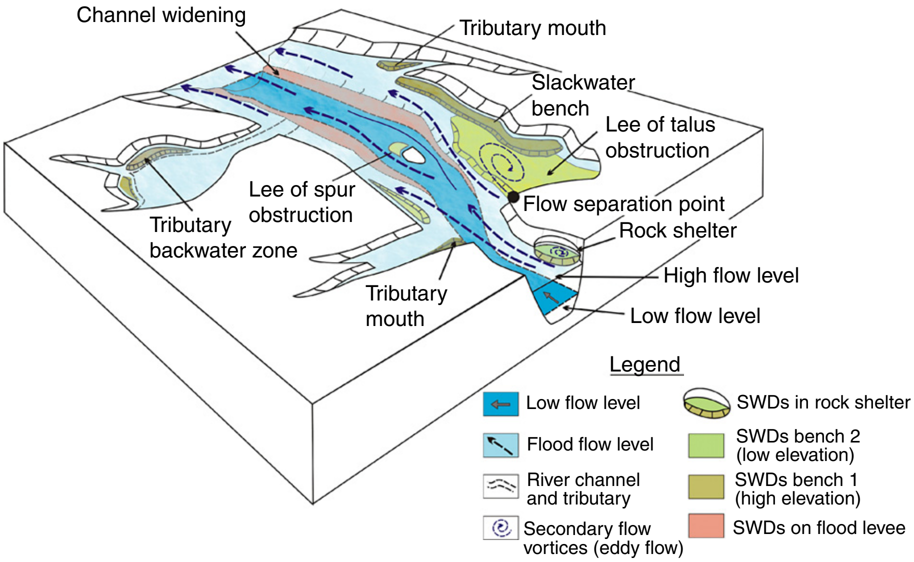


Figure 2 Block diagram illustrating the location of sedimentary environments related to flood deposition. Modified from Benito, G., Sánchez, Y., Sopeña, A., 2003b. Sedimentology of high-stage flood deposits of the Tagus River, Central Spain. Sedimentary Geology 157, 107–132.

2. Intervening layers of sediments deposited by non-flood processes (e.g., slope deposits, cave roof-fall, or tributary alluvium) separating deposits of main-stem floods.
3. Bioturbation (plant and animal activity) indicative of an exposed sedimentary surface after the flood has passed.
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 colour 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 support by other indicators of subaerial exposure.
6. Development of paleosols and associated pedogenic alterations to sedimentary units.

Sedimentary structures developed within individual flood units provide valuable information on the flow energy and sediment pulses during floods (McKee, 1938; Kochel and Baker 1988; Benito et al., 2003b; e.g., **Figure 3(b)**, unit iii). Within high-energy eddy zones, sedimentology typically consists of medium to coarse sand with high-energy parallel lamination, large-scale planar or trough cross-bedding, ripple lamination, and massive intervals (**Figure 3(a)**). Within more low-energy slackwater areas, textures are dominated by silty sand and sandy silt, with parallel lamination (**Figure 3(b)**). Inside caves and rock shelters, sedimentary sequences commonly contain current ripples and climbing ripples, the latter indicating a high-suspended sediment concentration in the floodwater during deposition.

A complementary technique for sedimentological analysis consists of preparation of sediment peels of selected portions of the stratigraphic profile (Hattingh and Zawada, 1996; Benito et al., 2003b, 2010). Sediment peels are made by adhering sediments from a planar exposure of slackwater sediment outcrop onto fabric (Hattingh and Zawada, 1996), preserving a coating of sediment and their sedimentary structures (**Figure 3(a)**). This technique allows a very detailed description and analysis of textural variations and sedimentary structures for individual flood units as well as improving interpretation of hydrodynamic changes such as flow velocity during flood events (Benito et al., 2010).

In studies of extreme floods ($<0.1\%$ probability of annual exceedance), sedimentary or botanical flood evidence may not suffice to provide compelling evidence of the largest floods occurring at specific rivers or sites. Understanding such low-probability floods is important for flood protection design of sensitive infrastructures such as dams, nuclear power plants, or tailing dams from radioactive mining. Recently, a new corpus of paleoflood studies have focused on providing indicators of noninundation surfaces (elevations inferred not to have been flooded for a specific time period) to define nonexceedance paleohydrological bounds (Levish et al., 1996; Ostenaa et al., 1994; England et al., 2006). A paleohydrologic bound is defined as a time interval during which a paleostage has not been exceeded sufficiently to modify a terrace or abandoned floodplain surface (nonexceedance discharge threshold; Levish et al., 1996). Stable terraces have been used as field expression of upper limits of flooding over a time interval established by geochronological means (England et al., 2010). The objective is to estimate a flood discharge that has not been attained or exceeded over a specific time period (Levish et al., 1996). Such bounds can significantly constrain the tail of flood-frequency distributions and, in many cases, lead to more robust frequency and magnitude estimates of rare and large floods (O'Connell et al., 2002). However, a nonexceedance bound does not imply that the estimated peak discharge has ever occurred or that such a flood is even physically possible.

As explained in detail by Levish (2002), surfaces are identified for which there is compelling evidence that they have not been eroded or modified by floods for a lengthy period. Such evidence typically includes pedogenic alteration but can include the presence of volcanic tephra or other landscape features readily affected by inundation. The period of noninundation is determined using standard geochronologic techniques such as described in Section 9.24.2.2. The discharge associated with such paleohydrological bound is estimated using the feature elevation (as elaborated in Section 9.24.2.3). The most rigorous assessments account overtopping depths required for initiating erosion or deposition of the stable terrace surface either by considering shear-stress or stream-power conditions (e.g., Andrews, 1984; Baker and Costa, 1987) or by comparing with effects of historical floods (England et al., 2006). The method has been used extensively by the U.S. Bureau of Reclamation (Levish et al., 1996; Ostenaa et al., 1994; England et al., 2010) in applying paleohydrological analysis toward dam-safety assessments.

9.24.2.2 Paleoflood Age Determination

Dating of sedimentary flood units and intervening deposits is a key task supporting analysis of temporal flood behavior and recurrence. Dating methods applied in paleoflood hydrology can be divided into three categories (Jacobson et al., 2003): numerical, relative, and hybrid correlated. Development of a timescale sequence of paleofloods requires, in most cases, a combination of methods mostly relying on multiple numerical ages at individual sites from flood-sediment layers and interbedded and bounding deposits such as colluvium and soils. Numerical ages pin chronologies mainly established by deposit stratigraphy and site-to-site correlations based on deposit characteristics and sequences.

Numerical dating methods aim to establish the timing of individual floods, typically by radiocarbon and optically stimulated luminescence (OSL). Radiocarbon dating is the most common absolute dating tool employed in paleohydrologic work (e.g., Baker et al., 1985). Organic materials such as wood, charcoal, and seeds leaf fragments are entrained by floods and commonly deposited in conjunction with clastic sediment in slackwater sequences. Additionally, flood deposits may cover vegetation or organic cultural materials, as well as, in turn, be covered by vegetation and organic detritus. All these types of materials can be radiocarbon dated, thereby providing information on the age of enclosing or bounding flood deposits. Organic materials most likely to provide high-fidelity constraints on flood ages are those not likely to have persisted for a long period of time before deposition, such as seeds, fine organic detritus, and twigs. Commonly, however, radiocarbon dating is performed on charcoal contained within flood deposits, which can persist for hundreds or thousands of years prior to incorporation within a flood deposit (Blong and Gillespie, 1978).

For most studies, it is assumed that radiocarbon ages from detrital material within flood deposits closely approximates the flood date, although the most conservative assumption is that the radiometric date provide a maximum limiting age for the enclosing deposit. This is particularly the case for radiocarbon dates from detrital charcoal. Dating of *in situ* organic materials, such as charcoal from ground fires between affected surfaces bracketed by flood deposits, or pedogenic carbon between flood deposits, can provide robust constraints on the timing of flood sequences. As for most geologic investigations, dating of multiple organic materials and multiple deposits within a stratigraphic profile can increase the confidence of flood age determinations. The 5730 year half-life of ^{14}C limits radiocarbon dating to deposits less than 40 000 years. Also, radiocarbon dating suffers from significant imprecision for the period AD 1650–1950 because of the significant fossil fuel burning and introduction of variable amounts of ^{14}C into the atmosphere during the industrial revolution.

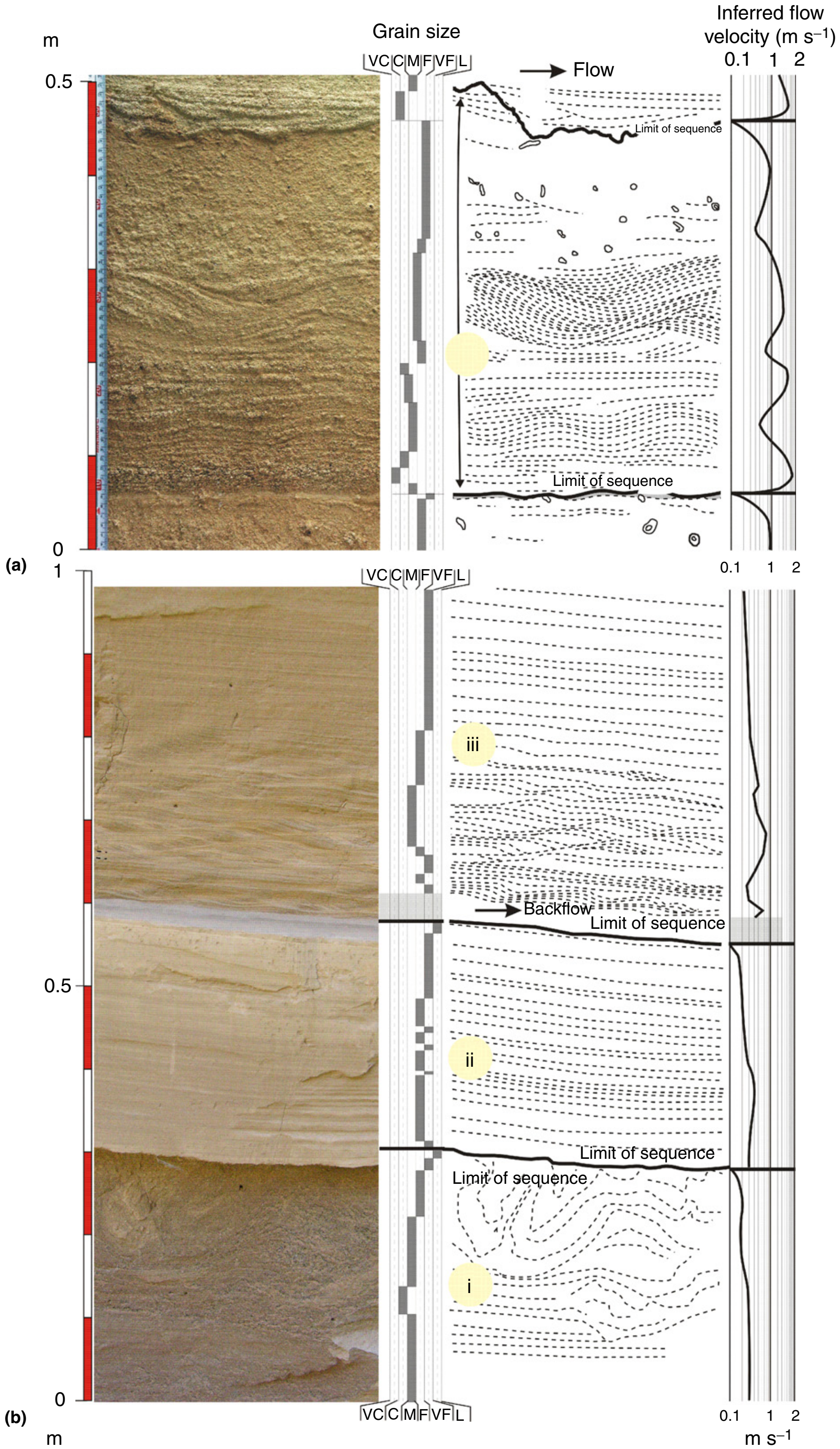
The OSL method (Aitken, 1998) is a dating technique that indicates the burial time of deposits, principally quartz and feldspar minerals. This approach allows determination of when sediment was last exposed to light (bleached). For the purposes of dating sequences of flood deposits, the general presumption is that the sediment was last exposed to light prior to deposition. Sampling and analysis involves several steps of collecting and analysis of sand-sized sediment from a target deposit without inadvertent exposure to light (Porat, 2006). Developments in OSL instrumentation are reducing the sample size to individual quartz and feldspar grains (Duller and Murray, 2000; Bøtter-Jensen et al., 2000). Moreover, new analytical protocols have improved the application OSL dating for alluvial deposits (Murray and Wintle, 2000; Wintle and Murray, 2006), resulting in numerical dating with age uncertainties within 5–10%, even for young deposits (<300 years) (Ballarini et al., 2003; Duller, 2004; Arnold et al., 2009). Recent research also has highlighted the importance of selecting suitable sample locations (Rodnight et al., 2006). The technique can be hampered in situations: (1) in which the proper species of quartz are not present in the deposits; and (2) for floods where the transported sediment was not bleached by exposure to light, either because of high turbidity levels or because the flood occurred at night. However, under appropriate conditions, OSL dating can be an important tool, especially for deposits: (1) containing little or no organic materials; (2) older than the range of radiocarbon dating (>40 000 years); or (3) younger than 300 years old so that radiocarbon dating cannot yield precise results.

Dendrochronology has supported several paleoflood studies because of the well-understood responses of tree growth to damage of the bark and wood-forming tissues, buds, and leaves, and to radial growth following partial uprooting of the trunk (Yanosky and Jarrett, 2002; Ballesteros et al., 2011) For situations when flood damage or effects can be related to tree-ring chronologies derived from the affected tree or from established regional chronologies, flood ages can commonly be determined to the specific year and, in some instances, a specific season (Sigafoos, 1964; Jacoby et al., 2008; Ruiz-Villanueva et al., 2010).

Lichenometry can provide numerical dates for flood bars and erosion of alluvial surfaces by floods, particularly over the last 500 years (Innes, 1985). The first application of lichenometry to flood studies was carried out by Gregory (1976) to define and date flood boundaries using lichens present on bedrock and river banks. Subsequent applications to date flood events and phases of recent fluvial activity have been carried out by Harvey et al. (1984), Gob et al. (2008), and Macklin and Rumsby (2007). The most common lichen used is genus *Rhizocarpon*, particularly *Rhizocarpon geographicum*, as well as the genus *Xanthoria*. Such dating requires determination of lichenometric growth curves for the specific location and lichen species. These are typically derived from lichen measurements on rock surfaces of known age, commonly tombstones and old monuments (Gob et al., 2003).

Lichenometry has not been widely used for palaeoflood studies probably because it is limited to bouldery bars in mountain streams where other techniques, such as dendrochronology, can be readily applied.

Radiocarbon and OSL dating can be supplemented with analysis of modern radionuclides such as cesium-137 and lead-210 (Ely et al., 1992; Thorndycraft et al., 2005b; Stokes and Walling, 2003). Both of these isotopes were introduced



into the atmosphere during nuclear bomb testing in the 1950s. Their presence in flood deposits signifies a post-1950 age, and offers a less-expensive technique to distinguish modern flood deposits from older ones. Likewise, human artifacts, such as beer cans (House and Baker, 2001), pottery (Benito et al., 2003a), and other archaeologic materials can provide numeric age constraints on enclosing deposits.

The largest floods generally greatly affect landscapes, commonly leaving a multiple cultural, physical, and botanical records. In particular, assessment of effects of historical floods may help in optimizing the dating strategy and minimizing analysis costs. The establishment and growth of riparian vegetation along river corridors are controlled by hydrogeomorphic processes (Bedinger, 1971; *see* Chapter 9.14), including flood magnitude and duration, flow velocity, and sediment transport fluxes (Osterkamp and Hupp, 1984). Resulting botanical conditions provide a context for linking flood sediments and geomorphic surfaces with flood timing and magnitude. Along rivers, caves, rock shelters, and flood benches are commonly the sites of recurrent human occupation. At such sites, archaeological features may be used to infer floods and date flood episodes.

9.24.2.3 Paleoflood Discharge Determination

Relating paleoflood evidence to flood discharge is a critical component of most quantitative paleohydrologic studies. The approach for assessing discharge can range from application of simple hydraulic or sediment transport formulae applied to single cross sections to sophisticated two- or even three-dimensional modeling, depending on study objectives, site conditions, and available information and resources. Two primary approaches lead to quantitative estimates of peak discharges from paleoflood deposits: (1) flow competence criteria typically evaluated relative to coarse bedload transported by the flood; and (2) flow estimates from hydraulic analysis based on the elevation of deposits relative to local channel geometry.

9.24.2.3.1 Paleocompetence

Paleocompetence techniques rely on selective sorting of particles being transported by floods, usually coarse-clastic deposits, and are appropriate for estimating the magnitude of singular events (see Jacobson et al., 2003). They have been used commonly for exceptional floods from Pleistocene glacial, volcanic-, and landslide-dammed-lake outburst floods (O'Connor, 1993; Waythomas et al., 1996; Manville et al., 2007; Manville, 2010), as well as from flash floods from meteorological events (Costa, 1984). Flow competence evaluation is based on selective-entrainment relationships (empirical and physically based equations), usually based on the largest clasts (Carling, 1983; Costa, 1983) providing mean-flow stress, velocity, and discharges per unit flow width. Reviews of flow competence methods, including their application and uncertainties, are provided by Maizels (1983), Williams (1983, 1984), Komar (1989, 1996), Komar and Carling (1991), Wilcock (1992), and O'Connor (1993).

Although competence approaches can be used over a broad range of fluvial environments, they typically can only provide imprecise estimates of paleohydraulic values because of the uncertainties in the relations between flow-strength variables (generally velocity, shear stress, or stream power) and transported clast size. Moreover, discharge can only be estimated for situations in which there is independent knowledge of cross-section geometry to apply retrodicted flow-strength variables. Other deficiencies and constraints of the competence approach include difficulties in adequately sampling or characterizing the largest particles, ensuring that measured clasts were indeed transported by water flow (as opposed to debris flow or mass movement), and ensuring that available sources of transported clasts include the entire range that the flow was competent to transport.

9.24.2.3.2 Hydraulic analysis

Hydraulic analysis is the basis for discharge estimates for most quantitative paleohydrologic studies, especially where flood histories are reconstructed from stratigraphic sequences of fine-grained flood deposits. In most analyses, discharge estimates follow from the assumption that the position of paleostage evidence relates closely to the maximum stage attained by an identified flood. This assumption is difficult to verify (Jarrett and England, 2002), although several investigators have reported height differences between flood indicators and actual flood water depth for modern floods (Kochel, 1980; Springer and Steven Kite, 1997; House et al., 2002b). In a systematic analysis of flood indicators left by modern floods in North American mountain rivers, Jarrett and England (2002) concluded that flood sediment elevations matched maximum flood stages, especially for deposits left at channel margins. Uncertainties in the fidelity of paleoflood stage evidence to actual maximum stages can be assessed in conjunction with most discharge estimation procedures.

Figure 3 Selected flood sequences from slackwater flood deposits, interpretation of sedimentary structures, grain size, and inferred flow velocity. (a) Photograph of lacquer peel (50-cm high) of slackwater flood deposits from the Guadalentín River (Spain). The sequence (i) shows, at the base, coarse to medium grain size with parallel lamination and three dimensional bedforms that resemble hummocky cross-stratification. This fining upward sequence culminates with parallel lamination and bioturbated sand that locally includes clay chips. This sedimentary sequence is inferred to have resulted from extreme floods with high stream flow velocity (>1 m s^{-1}) even in these ineffective flow areas. (b) Field photograph of slackwater flood deposits within a back-flooded tributary environment showing three flood units (Kuiseb River, Namibia, site K-400). The lower sequence (flood i) contains parallel lamination deformed by fluid escape structures or convolute bedding due to density inversion. The intermediate sequence (flood ii) is composed of fine to very fine sand with parallel lamination produced by aggradation on a plane bed, and a clayey silt layers at the top of the flood unit. The upper sequence (flood iii) contains fine-grained sand with in-phase climbing ripples, overlain by very fine-grained sand with parallel lamination. The lower ripple structures show lamina dipping up the tributary valley deposited during the rising flood stage of the Kuiseb River. The upper sand with parallel lamination was deposited later during the same flood, but near the time of peak stage when slow-moving or stagnated water at the tributary promotes sedimentation. Reproduced from Benito, G., Rico M., Sánchez-Moya Y. Sopeña, A., Thorndycraft V.R., Barriendos, M., 2010. The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentín River, southeast Spain. Global and Planetary Change 70, 53–63.

A number of formulae and models are available to estimate flood discharge from known water-surface elevations (O'Connor and Webb, 1988; Webb and Jarrett, 2002; Kutija, 2003; Lang et al., 2004), ranging from simple hydraulic equations to one- or multidimensional hydraulic modeling. Most paleoflood studies assume one-dimensional flow with calculations based on: (1) uniform flow equations (e.g., Manning equation); (2) critical flow conditions (King, 1954); (3) gradually varied flow models; and (4) one-dimensional St Venant equations. In complex reaches, multidimensional modeling may reduce uncertainties associated with reconstructing flood discharge (Denlinger et al., 2002; Wohl, 2002). As described in particular by Webb and Jarrett (2002), the appropriate approach for a particular site depends on local hydraulic conditions.

These formulae and models are applied to estimated channel geometry and roughness conditions for the time of the flow of interest. For late Holocene floods in bedrock-bound fluvial systems, the present valley geometry is commonly assumed to adequately represent the channel conditions at the time of flooding (e.g., Ely and Baker, 1985; O'Connor et al., 1986; Webb et al., 1988; Greenbaum et al., 2000; Benito et al., 2003a; Thorndycraft et al., 2005a; Sheffer et al., 2008). However, because channel geometry is the single most important factor in calculating discharge for a particular stage, assessment of this assumption is important for overall uncertainty analysis. Hydraulic analysis of paleofloods in river channels for which flow-boundary geometry is uncertain requires specific consideration of plausible ranges of channel geometry at the time of flooding. This is the case for alluvial or bedrock rivers where there has possibly been incision, widening, or alluviation since the flood paleostage evidence was emplaced.

The Manning's equation is applied for uniform flow conditions of straight channels of even gradient and regular width (Chow, 1959). In mountain streams with slopes ranging from 0.002 to 0.052 $\mathrm{m\,m^{-1}}$, Jarrett (1984, 1987) developed an equation that uses energy gradient (S) and hydraulic radius (R) to predict an n value of $n = 0.32\,R^{0.38}S^{-0.16}$. The Manning's equation may be reformulated for estimating velocity and discharge in high-gradient natural channels (Jarrett, 1985). This equation has been applied successfully for discharge estimates based on heights of tree scars and gravel bars (Jarrett, 1985; Rico et al., 2001).

Another special flow condition is that of critical flow, which arises when flow is constricted or subject to substantial slope increase and passes through a state of minimum specific energy $(v/(gd_c)^{1/2} = 1$, where v is flow velocity, g the gravitational acceleration ($g = 9.8\ \mathrm{m\ s^{-2}}$), and d_c the critical depth) as it funnels through or drops over the channel contraction or slope break. If such conditions can be identified and associated with paleostage evidence, they can provide robust discharge estimates (Webb and Jarrett, 2002) because the overriding factor in controlling flow in such stable bedrock conditions is channel geometry. A common situation in bedrock fluvial systems is flood sediment accumulation upstream of constrictions, where flow is controlled by the constriction, promoting upstream hydraulic ponding and deposition of the suspended sediment and bedload. In these situations, the maximum-stage evidence can be related to discharge by assuming critical flow in the channel contraction, and assuming that the elevations of the flood deposits in the controlled reach upstream indicate the total mechanical energy of the flow (e.g., O'Connor et al., 2001). Critical flow conditions are especially common in steep mountain streams, with alternating pool and steep reaches that result in longitudinal accelerations and decelerations through the critical threshold (Grant, 1997). The critical flow method requires the field selection of sections fulfilling conditions of critical flow (Chow, 1959) but, in contrast, does not depend on the arbitrary estimation of variables such as roughness or slope (Jarrett, 1987; O'Connor and Costa, 1993; Benito et al., 1998). Quick assessments of paleoflood discharges can be achieved by application of critical flow formula for common cross-section geometries as summarized in **Table 1**.

Table 1 Critical flow equations for different cross-section geometries

Rectangular:	$Q = g^{1/2} w_c d_c^{3/2} = g^{1/2}\left(\frac{2}{3}\right)^{3/2} bh^{3/2} \approx 1.7\,bh^{3/2}$
Triangular:	$Q = g^{1/2}\left(\frac{1}{2}\right)^{3/2} w_c d_c^{3/2} = g^{1/2}\left(\frac{1}{2}\right)^{3/2}\left(\frac{4}{5}\right)^{5/2} bh^{3/2} \approx 0.6\,bh^{3/2}$
Parabolic:	$Q = g^{1/2}\left(\frac{8}{27}\right)^{3/2} w_c d_c^{3/2} = g^{1/2}\left(\frac{2}{9}\right)^{1/2}\left(\frac{3}{4}\right)^{3/2} bh^{3/2} \approx 1.0\,bh^{3/2}$

Derived from King (1954: p. 8.8–8.11), where g is gravitational acceleration, d_c the critical depth for specific energy h, and w_c the top width of flow at critical depth d_c, and b the channel width at stage h. The approximations are valid for terrestrial ($g = 9.8\ \mathrm{m\ s^{-2}}$) conditions only.

The most common paleoflood analysis situation is that of gradually varied flow (O'Connor and Webb, 1988; Webb and Jarrett, 2002). River channels are typically irregular in shape and surface roughness, leading to nonuniform flow conditions. In low-gradient and larger river systems, critical flow conditions may not be achieved in the absence of significant valley constrictions. The simplest gradually varied flow analyses assume a steady state (constant discharge) for which flow depth varies with distance but not with time (Chow, 1959). For such situations, calculation of water-surface profiles are based on the resolution of the conservation of mass and energy equations in their one-dimensional forms. The step-backwater method (Chow, 1959; Henderson, 1966) for gradually varied water-surface profile computation is the typical approach used to relate paleoflood evidence to discharge (O'Connor and Webb, 1988). Available public-domain computer routines, such as the U.S. Army Corps of Engineers HEC-RAS (Hydrologic Engineering Center, 2010) software, allow for rapid calculation of water-surface profiles for specified discharges, and energy-loss coefficients. From these calculations, water-surface elevations are computed by trial and error at specific cross sections for a given discharge. Multiple analyses can provide synthetic stage-discharge ratings at sites of interest, thus providing a basis for estimating paleoflood discharge from the elevation of a deposit or other high-water evidence. Uncertainties in flow-modeling parameters can be evaluated for their resulting influence in paleoflood discharges by testing outcomes of plausible ranges of Manning's n values and possible changes in channel geometry.

Recent paleoflood studies have overcome some specific problems of traditional one-dimensional hydraulic models (Cunge et al., 1980; Bates and De Roo, 2000) through application of two-dimensional hydrodynamic models (Denlinger et al., 2002). Advances in modeling approaches, computational software, and high-resolution topographic data acquisition now make such models more practical for applied paleoflood studies. Several such two-dimensional models including SRH2D model (Lai, 2008, 2009) have been used extensively for paleoflood studies by the U.S. Bureau of Reclamation (see Bauer and Klinger, 2010). These models typically take advantage if high-resolution digital elevation models, such as those derived from terrestrial or airborne laser altimetry, to produce better estimates of flow stage and velocity associated with large flows, particularly in environments of substantial secondary and cross-valley flow currents (Denlinger et al., 2002). As these hydraulic models and their interfaces advance, coupled with greater availability of high-resolution topography, application of multidimensional models to paleoflood studies will become increasingly common.

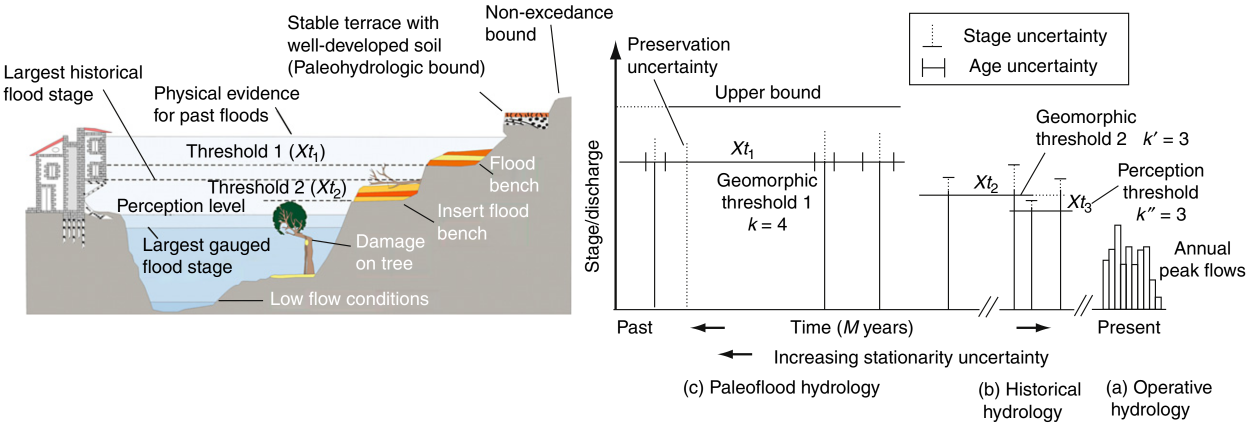
9.24.2.4 Flood Frequency Analysis

A common objective of paleoflood analysis is better estimates of flood frequency. Such analyses can support: (1) risk assessments for critical structures such as nuclear facilities, dams, or bridges for which knowledge of infrequent large-magnitude floods is important (Ostenaa et al., 1994; Levish et al., 1996; England et al., 2006; Benito et al., 2006); (2) understanding of the recurrence of geomorphically effective flows (e.g., O'Connor et al., 1986, 1994); and (3) assessment of nonstationarity in the frequency of large floods due to climate, land-use, or other changes (Ely et al., 1993; Ely, 1997; Redmond et al., 2002).

The value of paleoflood records is the potential to incorporate physical evidence of rare floods and limits on their largest magnitude (Figure 4). Conventional flood-frequency analysis assumes that the distribution of the magnitudes of the largest floods is well represented by the gauge record. However, the limit of credible statistical extrapolation relative to the typical stream gauge record length corresponds, in the best case, to the flood of 200 years return period (England et al., 2006).

In statistical analysis, stream-flow monitoring data are considered systematic information, whereas flood observations reported as having occurred above some threshold are known as censored data sets (Leese, 1973). Most paleoflood information is of this censored type, because floods of only certain magnitudes (typically large) are preserved in geologic records. Such data are similar in a sense to partial duration series, where k observations exceeding arbitrary-specified discharge threshold (Xt) in M years are known (Figure 4). Concerning the floods below Xt, their exact values are not known, except that they were smaller than Xt.

Current statistical approaches to incorporating paleoflood data typically result in flood observations being organized according to different discharge thresholds (Xt_1, Xt_2, ...) over particular periods of time (Figure 4). Additionally, current analysis algorithms allow observations to be classified



Data source	Data characteristics	Flood timing	Flood stage/discharge	Recod length scale
(a) Operative hydrology	Gaged records: Annual maximum/ partial duration series	Known date	Flood stage known/ eventually problems with large stages	Decades
(b) Historical hydrology	Documentary archives, recorded marks, observed stage, newspapers	Known date (year)	Stage known or not: censored data with stage above perception level	Centuries
(c) Paleoflood hydrology	Slackwater flood deposits, silt lines, boulder berms, erosion lines, scars and damage on tress	Geochronologically known or unknown	Minimum stage known; censored data with stage above geomorphic level	Millenia

Figure 4 Multiple sources of evidence for extending flood records beyond instrumental records. Left: sketch of a cross section showing various paleostage indicators and flood deposits, and buildings affected by historical floods. For historical hydrology, only floods exceeding perception thresholds, typically with socioeconomic disruption, are recorded, whereas for paleoflood hydrology, stratigraphic records relate more closely to geomorphic thresholds. Right: organization of historical and paleoflood data, using the described thresholds, and multiple types of observations to support flood frequency analysis. Upper bound stages from paleohydrologic bounds may be used to limit the maximum discharge non-exceeded over certain time periods. The past flood data is combined with gauge flow records (operative hydrology). Below: table showing data source characteristics, timing, stage information, and typical temporal framework of systematic and nonsystematic data (paleoflood and documentary flood data).

categorically as to the types of associated information. These include, following Stedinger and Cohn (1986), Francés et al. (1994), and Naulet (2002):

1. *Exact*. The flood at time *t* is exactly known. Such floods would include those in systematic-gauging records as well as for floods with enough information to reconstruct the peak discharge and timing. Such information typically results from historical observations, from well-reserved HWMs associated with recent flooding, or from dendrochronological records in exceptional cases.
2. *Lower bounds*. It is known that a certain number of floods exceeded a specific discharge, *Xt*, over a specific period. This is the most common outcome of typical paleoflood analyses of stratigraphic sequences.
3. *Upper bounds*. It is known that no floods exceeded a certain discharge over a specific time period. These constraints can result from inferences regarding nonexceedance bounds, such surfaces or features known have not been flooded. Although such inferences can constrain the tails of calculated frequency distributions, they can be subject to uncertainty when applied to geologic records because of the variety of mechanisms by which large floods may fail to leave a record or to alter a flood sediment (e.g., by soil development). Such upper bounds are most reliable in conjunction with historical records, where there is human knowledge of whether or not certain features (such as specific buildings or bridge decks) have been inundated.
4. *Double bounds*. For situations where both lower and upper bounds are known for specific periods.

Several statistical methods have been applied to estimate distribution function parameters for paleoflood data sets (Ouarda et al., 1998; Francés, 2004). The most efficient methods to incorporating imprecise and categorical data are: (1) maximum likelihood estimators (Leese, 1973; Stedinger and Cohn, 1986); (2) the method of expected moments (Cohn et al., 1997; England et al., 2003a); and (3) Bayesian methods (Kuczera, 1999; O'Connell et al., 2002; O'Connell, 2005; Reis and Stedinger, 2005). Some examples of employing these techniques for flood-frequency analysis using both gauged and paleoflood records include O'Connor et al. (1994), Bureau of Reclamation (2002), England et al. (2003b), Levish et al. (2003), Hosman et al. (2003), Thorndycraft et al. (2005a), O'Connor and Driscoll (2007), and England et al. (2010). Recent studies by Fernandes et al. (2010) and Botero and Francés (2010) have explored using upper-bounded statistical distributions in combination with gauge, historical, and paleoflood data. In nearly all cases, the addition of paleoflood information greatly improves estimates of low-probability (long return period) floods, most commonly indicated by markedly narrower confidence limits about flood quantile estimates.

Employing long geologic or historic records for flood-frequency analysis can introduce the question of flood stationarity, because cyclic and climatic and land-use conditions can affect the relevance of past flooding as a predictor of future flooding. Whether or not this is an issue in a particular case depends on the specific question (and timescale) involved, and is discussed by Redmond et al. (2002) and Francés (2004). Paleoflood 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's process. The 95% tolerance interval of the accumulative number of floods above a threshold, or censored, level is computed. Stationary flood series are those remaining within the 95% tolerance interval (Naulet et al., 2005; Sheffer et al., 2003).

9.24.3 A Paleoflood Case Study: The Llobregat River

To illustrate a paleoflood analysis from start to finish, we describe an assessment of flood risk analysis for the Llobregat River (NE Spain) at Monistrol de Monserrat ($\sim$50-km NW of Barcelona). This summary is derived from the complete report of Thorndycraft et al. (2005a). The Llobregat River has a typically Mediterranean regime with extreme seasonal variations. Flood peaks are sometimes 100 times greater than the mean annual discharge of 21 $m^3\,s^{-1}$. In the studied reach (2.5 km in length), the channel drains 3370 km^2 and is confined to a bedrock canyon with vertical walls as the river trends south through Eocene conglomerates. Slackwater flood sediments have been deposited and preserved in six valley side rock alcoves developed within the predominantly horizontal rock strata. Stratigraphic and sedimentological analyses of the deposits were carried out both in the field and the laboratory, supported by 80 cm $\times$ 50 cm sediment peels of the stratigraphic profiles (Thorndycraft et al., 2005a). Flood chronology was determined by radiocarbon and cesium-137 dating (Thorndycraft et al., 2005b).

The SWDs of the Llobregat River are composed predominantly of very fine to fine-grained sand with parallel laminations alternating with climbing ripples in drift and climbing ripples in phase. In total, 46 individual flood units have been identified in six stratigraphic profiles. The number of flood units preserved at the different sites reflects relationships between flood magnitude and frequency, with greater numbers of modern flood events located in the lower-elevation alcoves (relative to the channel bottom) such as Alcove E. The highest elevation site, Alcove C (**Figure 5(a)**), contains a single flood unit with a radiocarbon date of cal. AD 1516–1642. This date and the exceptional altitude (16-m above the river bed), when cross-referenced with the documentary flood record from the Llobregat River, imply that this unit was most likely deposited by the 1617 flood (Thorndycraft et al., 2005a), the largest flood of the last seven centuries according to historical flood observations. The next oldest dated sediments are from Alcove F (**Figure 5(a)**), with the basal flood unit (F1) dated to 185$\pm$55 BP (cal. AD 1790$\pm$92). This date is in a range of poor radiocarbon dating resolution (Trumbore, 2000); it is likely, however, that the sequence dates to the nineteenth century. The best dating control for the recent slackwater sequences was provided by ^{137}Cs analysis, as the most recent sediments could be assigned only as modern, based on the radiocarbon results alone. The benefit of the cesium analyses is that it permits the modern sedimentary record to be divided between those flood units deposited before or after the mid-1950s. At the majority of the sites, the measured ^{137}Cs was associated with sediment mobilized from the upstream catchment by erosion and

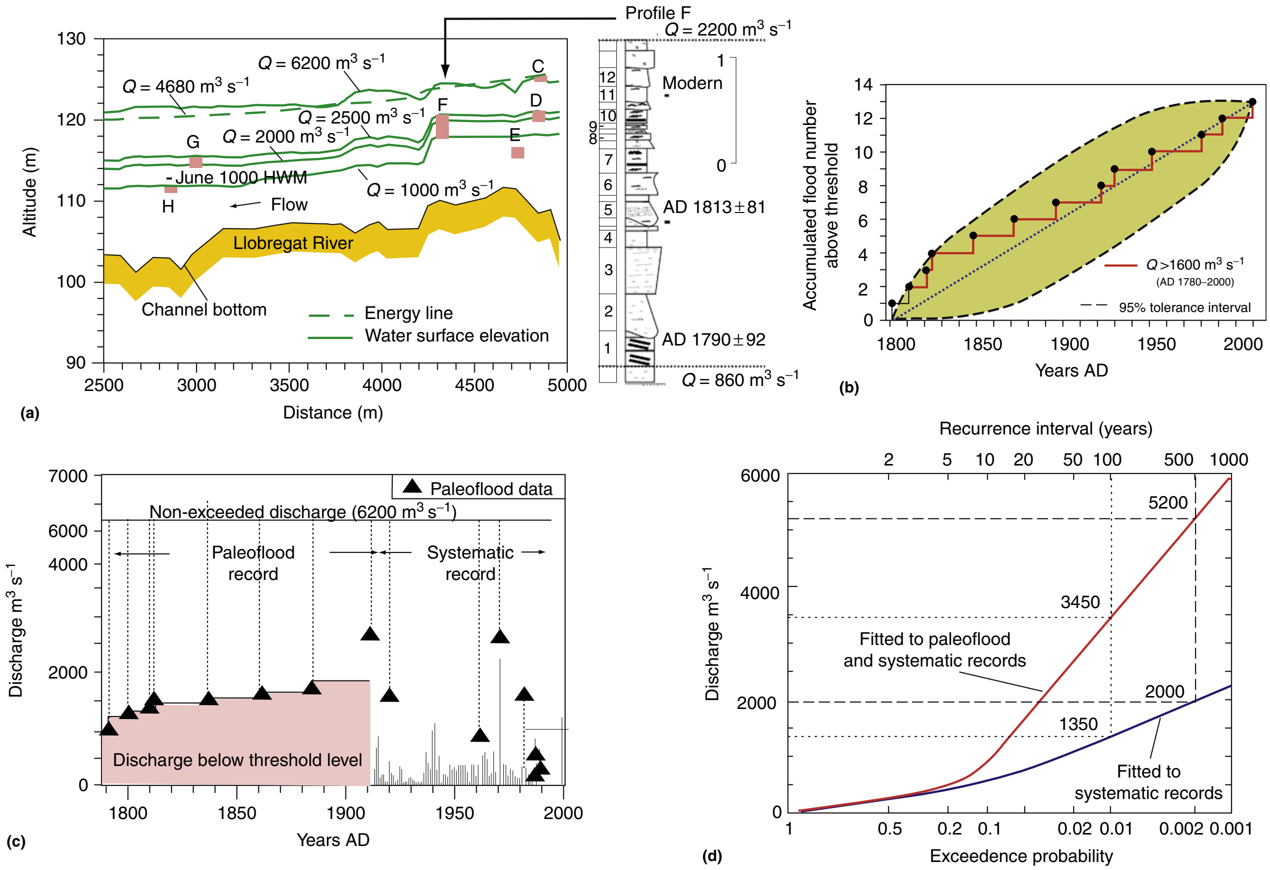


Figure 5 Llobregat paleoflood case study based on Thorndycraft et al. (2005a). (a) Calculated water-surface and energy line elevations for selected discharges related to the mapped palaeostage indicators (slackwater flood deposits) at alcoves C–H along the Monistrol study reach. The elevation of debris and silt lines left above Alcove H by the June 2000 flood is also indicated. This data were used to calibrate the hydraulic model at this reach. (b) Poisson's test on the time flood process in the Llogregat record for the period 1790–2003, for floods exceeding a discharge threshold of 980 $m^3\ s^{-1}$. Note that the flood series (central line connecting points) remain within the 95% tolerance interval (outside enveloped curves). (c) Organization of historical systematic and paleoflood data from the Llobregat River at Monistrol, for flood frequency analysis. Modified from Botero, B.A., 2006. Estimación de Crecidas deal to periodo de retorno mediante funciones dedistribución conlímite superiore información nosistemática. Ph.D. Thesis, Polytechnical University of Valencia, 223 pp. (d) Two component extreme-value distribution fitted with systematic data (blue line) and systematic and paleoflood data (red line). Discharge values in cubic meters per second are shown for return intervals of 500 years and 100 years based on the two frequency analyses. Discharge values from the distribution fitted with paleoflood data are more than twice those based only on the systematic flood series. Moreover, the 500-year discharge value of 5200 $m^3\ s^{-1}$ is on the same order of magnitude of a discharge of 4680–6200 $m^3\ s^{-1}$ estimated for the AD 1617 flood, despite this event not being included in the flood frequency analysis.

transported to the alcoves during floods, permitting the dating of post mid-1950s flood deposits (Thorndycraft et al., 2005b). Alcove E contains the most modern flood units, with 10 units postdating the mid-1950s, reflecting its close proximity to the river channel. In conjunction with the gaged record, ^{137}Cs data from Alcoves D, G, and H indicate that only the largest two, two, and three post mid-50s floods reached these alcoves, respectively.

Discharges associated with the flood units at each site were estimated by computing water-surface profiles for hypothetical series of specified discharges run using the HEC-RAS one-dimensional model. The initial water-surface elevation was set at a constricted section 2.5-km (Cairat Gap) downstream of the studied reach, for which critical flow was assumed. These calculated water-surface profiles were compared to the elevations of the flood deposits along the Monistrol study reach (**Figure 5(a)**). For this reach, the calculated water-surface profile for a discharge of 6200 $m^3\ s^{-1}$ matches the highest slackwater deposits of the C1 unit (**Figure 5(a)**). A more conservative estimate of the discharge associated with this deposit results from consideration of the calculated energy surfaces (stage plus velocity head), recognizing that some deposits will be emplaced at higher elevations than the cross-sectional average water-surface stage because of the two-dimensional nature of flood flows. In this case, a discharge of 4680 $m^3\ s^{-1}$ results in an energy surface matching the deposit elevation and was considered to provide a more accurate estimate of the emplacing discharge (Thorndycraft et al., 2005a). The ranges of estimated discharges required for floodwaters to reach either the base or the roof of the alcoves are indicated in **Figure 5(a)**. There are a number of alcoves (D, F, and G) along the study reaches that require discharges in excess of

2000 $m^3 s^{-1}$ to overtop the flood sediments. Only two alcoves (E and H) were inundated by the June 2000 flood event, with a measured peak discharge of 1200 $m^3 s^{-1}$, where maximum stage was marked by silt lines on the gorge wall and fissures in the rock filled with debris (**Figure 5(a)**). The SWDs and associated paleodischarge estimates provide strong evidence of ancient floods with discharges greater than those recorded in the gauge station ~3-km upstream for which measurements extend back to 1913.

The paleoflood records from this reach were combined with the nearby gaged record to estimate flood frequency. For this analysis, the key information were the exact information on annual flood peaks from the 1913–2000 gauged record, the 12 paleofloods since AD 1790 (radiocarbon dated at site F1) for which lower bounds were specified, and an upper bound derived from the inference that the flood discharge estimated for the 1617 flood has not been exceeded over the last 220 years of the paleoflood record considered in the analysis. Timing and discharges of paleoflood and gauged records are represented in **Figure 5(c)**. The shaded area indicates the time and discharge domain of the censoring level, which changes as flood deposits accumulate – only floods overtopping a sequence of flood deposits can leave a record (**Figure 5(c)**). Seven floods with minimum discharges of 860–2200 $m^3 s^{-1}$ were deposited in Alcove F prior to the gauge record. In the twentieth century, four floods exceeded 1600 $m^3 s^{-1}$ (1913, 1919, 1971, and 1982) and at least two reached 2500 $m^3 s^{-1}$ (likely 1913 and 1971 floods). Tentative ages were assigned to the paleoflood units (and corresponding censoring thresholds) based on documentary records of known floods (**Figure 5(c)**). Lang's stationarity test was passed for the Llobregat combined flood record covering the period 1790–2003 with a lower threshold discharge of 980 $m^3 s^{-1}$ (**Figure 5(b)**).

Multiple probability distribution functions were fit to the reconstructed flood data series with statistical parameters estimated by the maximum likelihood method (Stedinger and Cohn, 1986). The distribution function with the best fit to the data was the two component extreme value distribution (**Figure 5(d)**). The incorporation of the paleoflood data into the frequency analysis increases the flood quantile estimates for the Llobregat River substantially – by a factor of two for annual exceedance probabilities less than 0.05 (**Figure 5(d)**). The largest paleoflood discharge (Alcove C, likely of 1617 flood) is associated with a return period of ~500 years, whereas one of the two largest floods of the twentieth century (1971) represents a return period of *c.* 50-year flood (**Figure 5(d)**). The fitted distribution based on paleoflood and systematic data shows a characteristic dog-leg shape generally generated by heterogeneous distributions composed of a mixture of two or more populations (Alila and Mtiraoui, 2002). Differences between the populations may be the result of a number of factors, including seasonal variations in the flood-producing mechanisms (such as autumn floods instead of winter-spring floods) and changes in weather patterns resulting from low-frequency climate shifts.

This paleoflood analysis illustrates the common situation of the gauging station data not being fully representative of the largest floods affecting a river basin. Here, the hydrological series is too short to make informed decisions regarding flood risk for infrequent floods and that paleoflood data can provide valuable and quantitative information on flooding over longer timescales.

9.24.4 Concluding Remarks and Perspectives

This chapter has reviewed techniques and approaches for obtaining quantitative information on specific past floods from the geologic record, and describing strengths and limitations of various analysis methods. Paleoflood hydrology has gained recognition among hydrologists and engineers as a valuable tool to extend flood series data back beyond the gage record and thereby provide better estimates of the frequency and magnitude of rare floods. The extension of the flood record of rare floods to centuries and even millennia has major applications for different scientific and engineering problems, including: (1) flood hazard assessment based on flood-frequency analysis of sites with continuous flood deposition at a site (data censored over threshold) (O'Connor et al., 1986; Hosman et al., 2003; Benito et al., 2006); and (2) determination of maximum flood discharge over a time framework as evidence for a deterministic approach (Enzel et al., 1993) to estimate the probable maximum flood and safety risk analysis of critical facilities (such as dams and wastewater facilities and power plants; Levish et al., 1996; Benito et al., 2006; Greenbaum, 2007). Considering ongoing discussions as to how climate change may affect flood occurrence at regional and local scales, paleoflood hydrology can provide a perspective by showing how flood magnitude and frequency have responded to past climate shifts over millennia timescales (Ely et al., 1993; Ely, 1997; Knox, 2000; Redmond et al., 2002; Thorndycraft and Benito, 2006), and how flood patterns have varied in relation to different modes of atmospheric circulation, including El Niño Southern oscillation (Ely et al., 1993) and North Atlantic oscillation (Benito et al., 2008). Additionally, floods in dryland environments have been recognized as a fundamental water resource for human systems and ecosystems, opening new paleoflood research to assess long-term water infiltration into alluvial aquifers (Greenbaum et al., 2002; Grodek et al., 2007; Benito et al., 2011a, 2011b). Advances in paleoflood science are expected to benefit from improvements in geochronological methods (such as optically stimulated luminescence) and better topographic information (such as LiDAR). One of the key elements for successful paleoflood studies is to find the most appropriate sedimentary environments in which the geological and botanical records of floods are complete and preserved over hundreds of years. Multidisciplinary studies combining marine and lake records with more conventional SWD records can provide further insight into flood frequency and magnitude in relation to climate and environmental changes at basin scale. Other areas ripe for investigation include better understanding of the links of the sedimentary sequences and local hydraulics that can lead to a better estimation of the water depth and flow energy required to reproduce the sedimentary structures, methods to relate suspended sediment concentration with flood unit thickness, and techniques for obtaining information about flood hydrograph characteristics from deposit characteristics.

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Biographical Sketch

Gerardo Benito, PhD in geosciences (1989) from the University of Zaragoza (Spain), was associate research fellow at the University of Arizona (1989–92), and since 1992 a member of the research staff at the Spanish National Research Council (CSIC), holding currently a research professor position. His research interests are within Quaternary Geology, with emphasis in palaeohydrology and geomorphology, and particularly on the study of past and recent floods. Regarding the latter, his works have focused on flood hazards in relation to climate and environmental changes, with field sites in Europe, North and South America, and Africa. Dr. Benito is currently president of the Global Continental Palaeohydrology group of INQUA, leader of Focus Area 'Hydrological Change and Climate' in INQUA, Spanish delegate in Past Global Changes (PAGES) and member of the IGBP-Spain and INQUA-Spain committees. His research activity is combined with active participation as lead author of the IPCC special report on 'Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation' (SREX), and of the IPCC 5th assessment report, WG II Impacts, Adaptation and Vulnerability.

Jim O'Connor is a Research Hydrologist at the U.S. Geological Survey Oregon Water Science Center in Portland, Oregon, USA. He is a U.S. Pacific Northwest native interested in the processes and events that shape the remarkable and diverse landscapes of the region. Following this interest with a Geological Science major at University of Washington and MS and PhD degrees at University of Arizona (1990), he has spent the last 20 years focused on fluvial geomorphology and Quaternary geology, primarily in the western United States.