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Palaeoflood hydrology and its role in applied hydrological sciences

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Abstract

This paper is a review of the methodology of palaeoflood hydrology. In particular, we focus on recent developments and the credibility of the palaeoflood data produced. The use of slackwater flood deposits as a physical record of water surface elevations reached by past floods enables the calculation of robust palaeodischarge estimates for floods that occurred during recent centuries or millennia. Over these time intervals the chronological precision from numerical age dating, such as radiocarbon, is sufficient for the structuring of the palaeoflood discharge data into different threshold levels that are exceeded by floodwaters over specific periods of time, the input data necessary for new methodologies of flood frequency analysis. The value of palaeoflood hydrology to hydrological sciences is discussed through its application in varying multidisciplinary research themes. We demonstrate the use of palaeoflood hydrology in: (1) flood risk estimation; (2) determination of the maximum limit of flood magnitude and non-exceedances as a check of the probable maximum flood (PMF) and its application in producing regional, long-term envelope curves; (3) Holocene climatic variability and (4) assessing sustainability of water resources in dryland environments where floods are an important source of water to alluvial aquifers.

Keywords: Palaeoflood hydrology; Flood geomorphology; Flood hazards; Flood frequency analysis

1. Introduction

Palaeoflood hydrology is the reconstruction of the magnitude and frequency of recent, past, or ancient floods using geological evidence (Baker et al., 2002). The term '*palaeo*' has contributed to the general misconception that palaeoflood techniques are only used for estimating very old floods over geological timescales. However, most palaeoflood studies involve the study of the last 5000 years with an emphasis on the last millennium, or even the last 100 years in ungauged basins. It is not the time scale of flooding that defines palaeoflood hydrology but the fact that flood evidence is derived from the lasting physical effects of floods on natural indicators, for example slackwater flood deposits or scour lines.

J Harlem Bretz (Bretz, 1929; Bretz et al., 1956) was the first scientist to use geological evidence intensively to elucidate information about past floods during his studies of the pathways followed by the cataclysmic outburst floods from Pleistocene Lake Missoula. However, the term and concepts of palaeoflood hydrology were formally introduced by Kochel and Baker (1982). Over the last 20 years, palaeoflood hydrology has achieved recognition as an interdisciplinary branch of geomorphology

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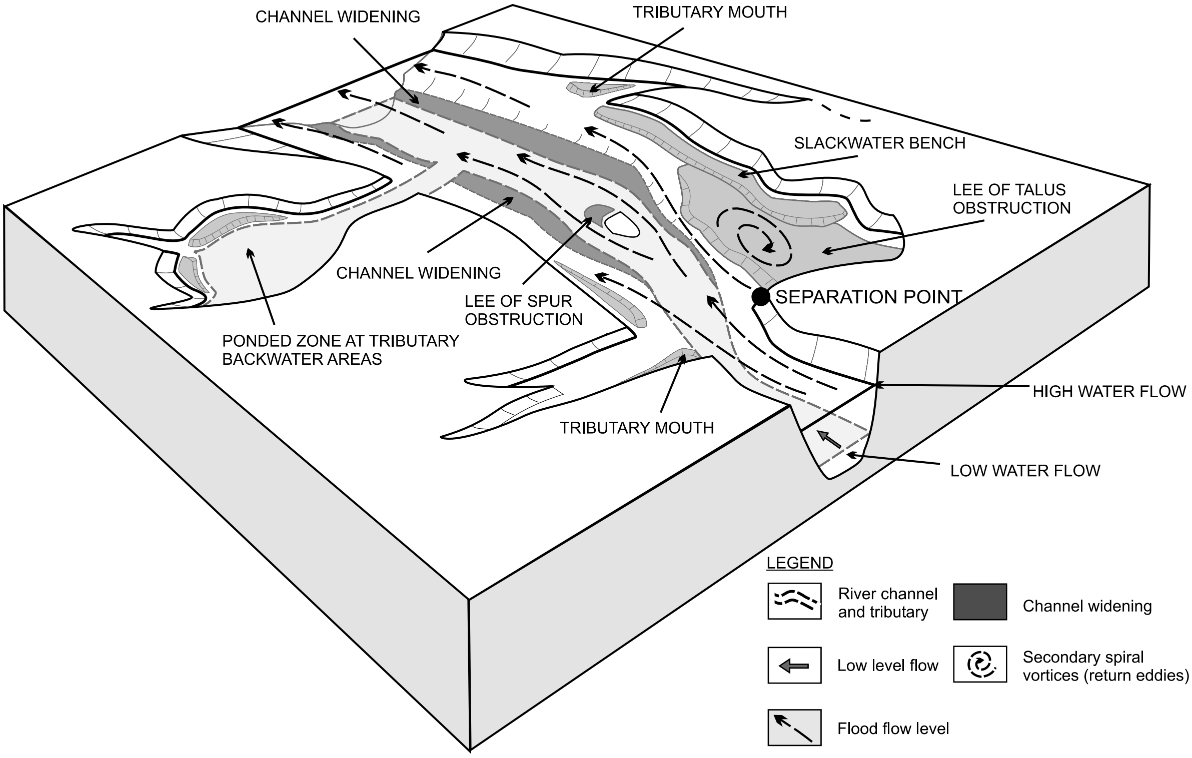

Fig. 1. Block diagram displaying the location of sedimentary environments related to flood deposition (modified from Benito et al., 2003b).

and hydrology. The most accurate palaeoflood technique is based on the identification of high-water marks and palaeostage indicators (PSIs). Common evidence of flood palaeostage includes flood sediments (Fig. 1), erosional landforms (stripped soils, flood scarps, high-flow channels) and other high-water marks such as drift wood and damage to vegetation. These palaeoflood indicators can be correlated to define the palaeoflood water surface profiles along the river channel. Hydraulic computations using either one- or two-dimensional hydraulic models can provide a good estimation of the discharges associated with the palaeostage indicators (O'Connor and Webb, 1988; Webb and Jarrett, 2002; Denlinger et al., 2002). Together with absolute age dating, this allows the reconstruction of flood magnitude and frequency over an extended period of time. Palaeoflood hydrology has been applied successfully in many regions of the world to lengthen flood records beyond that of the instrumental gauging station data, for example in the USA (Kochel et al., 1982; Ely and Baker, 1985; O'Connor et al., 1994), Australia (Baker and Pickup, 1987; Pickup et al., 1988), India (Ely et al., 1996; Kale et al., 2000), Israel (Greenbaum et al., 2000), Spain (Benito et al., 2003a; Thorndycraft et al., this issue), France (Sheffer et al., 2003a), Greece (Woodward et al., 2001), South Africa (Zawada, 1997), China (Yang et al., 2000) and Japan (Jones et al., 2001).

Recent studies of past floods in Europe have shown good synergies between palaeoflood studies and those recorded not only in the modern instrumental record but also catalogued over centuries in documentary records (Benito and Thorndycraft, 2004). These historical flood records may be found in public and ecclesiastic archives, local chronicles, oral history and may include epigraphical records (stone-marks indicating the elevation of past floods), historical photography, old cartography and paintings. These three principal sources of past flood data (palaeofloods, historical floods and the systematic record) in many European basins may overlap (e.g. Sheffer et al., 2003a) and, therefore, ensure a reliable, well-documented flood record that can be used to improve flood risk estimation.

The aims of this paper are: (1) to present a review of the methodology of palaeoflood hydrology and a critical discussion of the associated errors, updating the 1980s review of Baker (1987); and (2) to highlight the current role of palaeoflood hydrology in applied hydrological sciences. Recent research projects have focused on using palaeoflood data for: (1) improving flood risk estimation; (2) improving flood frequency analysis associated with design discharges used in the planning of large scale hydrological projects, such as dams; (3) determining flood–climate relationships; and (4) in assessing long-term water resources in semi-arid and arid regions which rely on floodwaters as an important means of recharging shallow alluvial aquifers.

2. Methodological approaches in palaeoflood analysis

Palaeoflood hydrology is an inter-disciplinary research field, drawing on expertise, in particular, from geomorphology, sedimentology, hydrology, hydraulic modelling and statistics. The methodological steps to follow in palaeoflood studies include: (1) initial interpretation of aerial photos and topographic maps of various scales to identify suitable sites (Baker, 1987) for palaeoflood hydrological research; (2) field study and survey for the identification and selection of flood indicators (flood deposits and marks); (3) stratigraphical description with emphasis on identifying the number of flood units in a given sedimentary sequence; (4) sample collection for age dating of the flood deposits; (5) topographic survey of flood sites and river reaches; (6) hydraulic calculations and discharge estimation; (7) comparison with available historical and instrumental flood data; and (8) flood frequency analysis. In the following sections a summary is presented of the main components of palaeoflood research.

2.1. The analysis of slackwater flood deposits

The most commonly utilised PSIs in palaeoflood hydrology are slackwater flood deposits (Baker, 1987). These deposits accumulate in stable bedrock canyons at sites away from the main channel flow (Fig. 1) where during high flood stages, eddies, back-flooding and water stagnation occur. This significantly reduces flow velocities, leading to the deposition from suspension of clay, silt and sand (Baker and Kochel, 1988; Benito et al., 2003b). Palaeoflood sites are controlled by: (1) an appropriate sediment source or the presence of fine-grained sediments within the catchment area, and (2) the preservation conditions. A catchment geology dominated by granite and/or sandstones, for example, provides an abundant source of fine-grained material to be transported as suspended sediment during flood events. The deposition and preservation conditions during floods are controlled by the interplay between erosion and sedimentation processes and, afterwards, by post-flood erosion processes such as slope and tributary runoff. Preservation of slackwater palaeoflood deposits is optimised when they are deposited in valley side caves, alcoves or rock overhangs (Fig. 2), where the sediments are protected from erosion, slope movements, or excessive bioturbation by colonisation of vegetation after the flood event (e.g. Sheffer et al., 2003a; Thorndycraft et al., this issue). Tributary mouths and transitional reaches with abrupt canyon narrowing or widening are also suitable sites for flood deposits (Kochel et al., 1982; Kochel and Baker, 1988). In these environments, depositional landforms include thick, high-standing terraces or 'benches' (Fig. 1). In marginal channel zones, with the development of more energetic eddies during flood stages, flood deposits can be reworked, preserving a 'ridge' morphology more typical of eddy bars (Ely and Baker, 1985). Slackwater terraces or 'benches' are documented in a number of palaeoflood studies (e.g. Patton et al., 1979; Kochel et al., 1982; Ely and Baker, 1985; Benito et al., 2003a). They are developed by standing or slow-moving water that allows a better preservation of flood deposits through time. There are two basic assumptions explaining the formation and development of these slackwater terraces (Baker, 1989; House et al., 2002): (1) they are formed by vertical accretion of slackwater sediments, deposited by successive floods, that constitute a rising threshold or local censoring level over time, and (2) inset benches are formed when smaller floods are unable to overtop the upper terrace surface.

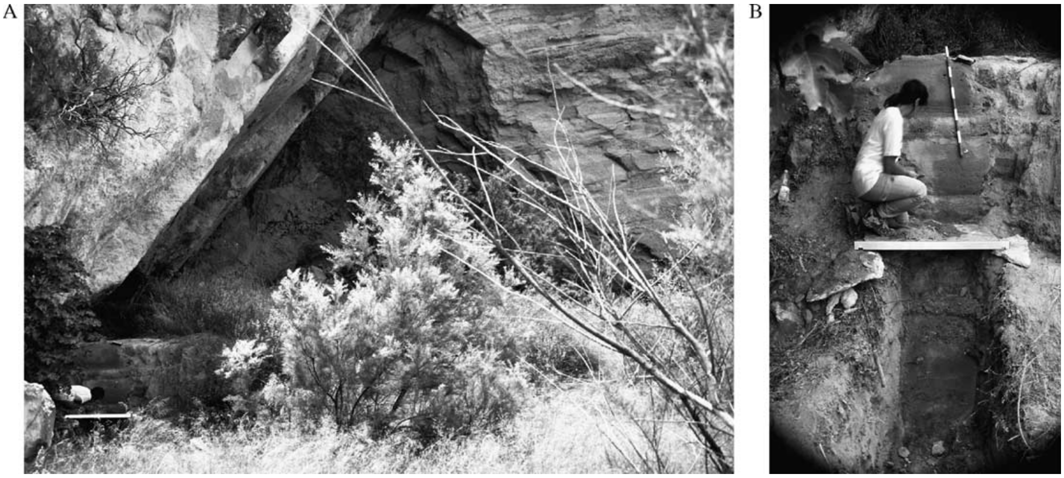

Fig. 2. A: Photo illustrating a rock shelter site of slackwater deposition in the valley of the ephemeral Guadalentín River, SE Spain. The slackwater flood deposits can be seen in the bottom left corner and in Photo B.

Successive layers, or sedimentary units, of slackwater flood sediments may be deposited by successive flood events over periods of centuries to millennia, building up a sedimentary sequence or profile (Fig. 2). If there is good preservation of the flood deposits at a particular site, the number of floods represented in the particular sedimentary profile can be identified. This task requires a detailed stratigraphical description with a major emphasis on interpreting the breaks and contacts in the sediments that are indicative of individual floods. Distinct flood units can be identified within a sedimentary profile using one, or a combination, of any of the following criteria (e.g., Kochel and Baker, 1988; Enzel et al., 1994; Benito et al., 2003b): (a) identification of a distinct clay layer at the top of a flood unit, this representing the waning stage of a flood; (b) deposition of a layer of non-flood sediments that marks a clear boundary between two successive flood units, for example colluvial sediments, clasts falling from a cave roof, or even precipitated carbonates in dripping caves (e.g. Sheffer et al., 2003a); (c) interbedded couplets at tributary junction sites where coarse-grained alluvium from the tributary alternates with fine-grained slackwater flood deposits from the main river (e.g. Greenbaum et al., 2000); (d) bioturbation (plant and animal activity) that is indicative of an exposed sedimentary surface after the flood has passed; (e) an erosional boundary where the surface of an older flood unit has been eroded by a later flood; (f) 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; (g) presence of buried soils (Ely et al., 1996; Greenbaum et al., 2000) and; (h) changes in sediment induration or mud cracks indicating surface exposure to external processes.

2.2. Age dating

Once the number of flood events within a specific sedimentary profile has been determined, to obtain an accurate understanding of flood frequency, the slackwater palaeoflood deposits must be dated. It should be highlighted that, although it is preferable to have an age for each individual flood unit, it is sufficient to bracket the flood units within an age range. Radiocarbon is a standard age dating tool employed in palaeohydrologic research (e.g. Baker et al., 1985). Sample material for radiocarbon analysis includes any organic material such as seeds, wood, charcoal, soil organics, shells and bones found within the individual flood units. Measurement errors of the radiocarbon dating technique are usually reported in the range 40–160 years (Trumbore, 2000), although those dates associated with palaeoflood deposits from recent millennia commonly have errors of 25–50 years.

These errors are acceptable for determining flood quantiles in flood frequency analysis, as new methodologies have been developed to specifically incorporate them (see Section 2.4 below). The Optically Stimulated Luminescence (OSL) method (Stokes, 1999) is another technique that has been employed in dating Holocene flood deposits (e.g. Sheffer et al., 2003a). Essentially, the method determines when sediment was last exposed to direct sunlight, before being buried in the flood deposit sequence. OSL may also contain deviations from the true age but high precision samples provide errors typically of 5–10%.

Modern sediments from recent floods can be dated using the radioactive isotope, Caesium-137 (Ely et al., 1992; Thorndycraft et al., in press). The basis of the methodology is that Caesium-137 is an artificial isotope that was first introduced into the atmosphere during nuclear bomb testing in the 1950s. Since this time Caesium-137 has been deposited on the land surface (including soils and sediments) from atmospheric fall-out. Its presence in flood sediments that are deposited within caves and protected from direct rainfall, indicates that the Caesium-137 has been derived from upstream catchment sediments, eroded and transported with the floodwaters (Thorndycraft et al., 2005). This technique is of particular relevance for dating recent sedimentary flood records and is very useful in ungauged catchments as it determines the number of floods above a certain threshold that occurred during the last 50 years.

2.3. Palaeoflood discharge estimation

The water levels associated with different palaeostages can be converted into flood discharge, which is the random variable used in the statistical analysis (e.g. Francés, 2004). Most calculated discharges from slackwater flood deposits are minimum discharge values above a known censoring threshold since the water depth above the specific flood deposits is unknown. There are a number of formulae and models to estimate past flood discharge from a known water surface elevation (O'Connor and Webb, 1988; Webb and Jarrett, 2002; Kutija, 2003). In the majority of cases they assume one-dimensional flow based on (1) slope-conveyance, (2) slope-area, (3) step-backwater, and (4) critical-depth methods, where step-backwater and critical-depth are the most commonly used. These models assume a fixed bed of the stable bedrock canyon and data required include channel slope, roughness (usually Manning's n), cross sectional geometry and, for the step-backwater method, a boundary condition upstream or downstream depending on the flow type. The two principal sources of error are: (a) an underestimate of the palaeodischarge due to the unknown level of the floodwaters above the deposited sediments and (b) changes in the valley cross-section. The first can be approached by studies of the sedimentology of the flood deposits (Benito et al., 2003b) that enable interpretations regarding flow velocities and energy conditions at the site of deposition and, therefore, inferences can be made regarding the level of the water above the deposits. A known and surveyed water surface also helps calibration of the calculations, for example in the case of the June 2000 flood of the Llobregat River (Thorndycraft et al., this issue). The second error, that of cross-sectional stability, is substantially reduced by limiting palaeoflood studies to bedrock gorge reaches. Bedrock channel geometry is significantly more stable than alluvial floodplain channels and will not have been substantially altered over past centuries to millennia. In complex reaches, multidimensional modelling may reduce some of the uncertainties associated with reconstructing flood discharge (Denlinger et al., 2002) but, generally, disharge estimates do not differ much between one- and two-dimensional models in bedrock canyon reaches, where the assumptions of one-dimensional flow are met. In bedrock gorges, therefore, one-dimensional modelling is appropriate for the estimation of palaeoflood discharges.

One often perceived criticism of palaeoflood hydrology concerns the accuracy of the estimation of extreme flood discharges (Baker et al., 2002). Our experience in Mediterranean regimes, with floods often 100 times greater than the mean flow, is that this is also a common problem with gauge station records in these regions. In fact, during large floods, gauge stations are frequently either flooded or destroyed meaning that, in many cases, the reported 'measured' discharge values of these catastrophic floods are actually discharge estimations using indirect methods or statistical extrapolation. One main concern regarding the accuracy of discharge estimation is the subsequent error that can be introduced to the flood frequency analysis, however, systematic data is not error-free either (Baker et al., 2002; Benito et al., 2004a). At a flow gauge station, measurement error increases the variability of the flood quantile estimators (Potter and Walker, 1981) but if the standard error is smaller than 10% the influence on the statistical analysis is negligible (Cong and Xu, 1987).

2.4. Statistical framework

Flood frequency analysis (FFA) with systematic data is generally developed using annual maximum series and the assumptions of inter-annual independence and stationarity of the flood population. These traditional methods also assume that the distribution of the magnitudes of the largest floods is well represented by the gauge record or that they can be obtained by statistical extrapolation from recorded floods (usually small to modest floods). The value of palaeoflood data is the potential to include physical evidence of large floods, or upper limits on flood magnitude, over long time periods. Use of palaeoflood (and/or historical flood) information gives rise to two specific problems: (a) non-systematic data (only the major floods are known) and (b) non-homogeneous data (hydroclimatically induced non-stationarity due to natural climatic variability). These problems are discussed in detail by Redmond et al. (2002), Benito et al. (2004a) and Francés (2004). The basic hypothesis in the statistical modelling of palaeoflood information is that a certain threshold of water level exists and that over a specified time interval (from one year to thousands of years), all exceedances of this level have been recorded through geological palaeoflood evidence left along the river valleys. The palaeoflood data is organised into the different threshold levels exceeded by floodwaters over a given time period. In each threshold, individual floods are introduced as minimum, maximum, exact or range values of discharge, as well as their age range. This data organisation in exceeded levels or thresholds of perception reduces the potential palaeoflood discharge underestimation. In fact, the awareness of the limitations of palaeoflood data may produce a more critical approach to flood frequency analysis, which may not necessarily be applied when using peak discharges from stream gauge records that can themselves contain uncertainties of at least 20–30% (e.g. Cook, 1987). Whatever the source of data, it is vital to incorporate explicitly the range and type of measurement errors to produce meaningful estimates of flood frequency uncertainties.

Several methods have been applied to estimate different distribution function parameters. Maximum likelihood estimators, the method of expected moments, and Bayesian methods have been shown to be efficient and to provide a practical framework for incorporating imprecise and categorical data with great benefit in various analyses of flood frequency analysis (Stedinger and Cohn, 1986; Blainey et al., 2002; O'Connell et al., 2002; O'Connell, this issue; Reis and Stedinger, this issue). A review of these various methods is presented by Ouarda et al. (1998) and by Francés (2004).

Flood record stationarity from censored samples (systematic and/or non-systematic) can be checked using Lang's test (Lang et al., 1999). This test assumes that the flood series can be described by an homogenous Poisson 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., this issue).

3. The role of palaeoflood hydrology in applied hydrological sciences

3.1. Flood risk estimation

One goal of palaeoflood studies is to gain a greater understanding of large floods that occurred before modern experience and which may, in fact, change public perception of floods. In September 2002, an extreme flood in the Gardon River (Massif Central, France) resulted in 22 fatalities and millions of Euros in damages. The flood was produced by 680 mm of rain in a 20 h period and was considered by both the media and professionals to be 'the largest flood on record'. The flood's peak discharge was estimated as 6000 m^3/s, whereas the largest historical flood, that of 1890, had an estimated discharge of 4500 m^3/s. A study of palaeofloods in the Gardon River gorge conducted by Sheffer et al. (2003b) identified, in a cave located 17 m above the level of the river's normal base flow, sedimentary evidence of at least five floods larger than the September 2002 event, which reached a stage of 14 m above base flow at the study reach. Three of these floods were radiocarbon dated to the period AD 1400–1800, during the Little Ice Age. Similarly, in the Llobregat River, NE Spain, the palaeoflood record provides physical evidence of flood magnitudes greater than those measured during the modern instrumental period (Thorndycraft et al., this issue). Fig. 3 presents the palaeodischarge data from the largest palaeofloods alongside the instrumental flood data from the Llobregat basin. The largest flood in the record is that of 1971 with a peak discharge of 2300 m^3/s, this value being an estimate as the gauge station was damaged by the flood. This is one of the longest instrumental series available for a Spanish Mediterranean basin (beginning in 1907). However, comparison with the palaeodischarge record indicates that the gauge station data is not representative of the largest floods. The palaeoflood record shows that at least eight flood events have exceeded a minimum discharge estimate of 3500 m^3/s during the last ca. 3000 years. By contrast, Ely et al. (1996) in a palaeoflood study of the Narmada River (India) recognised that a number of modern extreme floods, including the 1961 event that recorded a discharge of 55,323 m^3/s, were the largest for at least 3000 years, probably a response to 20th Century climate change.

3.2. Determining a maximum limit of flood magnitude

The rationale behind the existence of a hydroclimatic limit to the supply of moisture to river basins through storms and precipitation has led to the 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). This concept has been used for the calculation of the probable maximum flood (PMF), as well as in the determination of global and regional envelope curves. Palaeoflood data can provide a significant extension of the instrumental data series to help define the maximum limit of flooding in the analysis of envelope curves (Enzel et al., 1993). Similarly, palaeoflood data can be used for testing the analysis performed in the calculation of the PMF. The PMF has been used as a standard for hydrological analyses

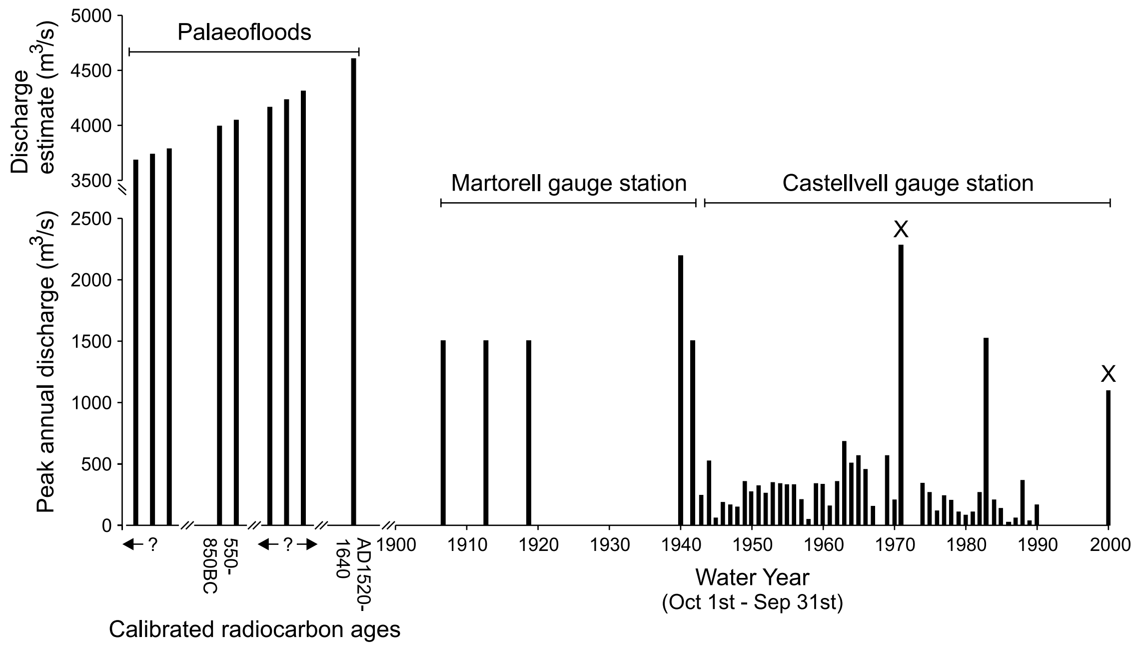

Fig. 3. Flood magnitudes of the Llobregat River illustrating the high discharges associated with the palaeofloods relative to those measured at the gauging stations.

of dam safety for several decades (NRC, 1985). By definition, the PMF has no return period but arbitrarily it was assigned a return period of 10,000–1,000,000 years at the upper and lower confidence limits for flood frequency analysis (National Research Council, 1985). Palaeoflood studies, including those performed for dam safety purposes by the US Bureau of Reclamation, show that the upper limit for palaeoflood magnitude is up to an order of magnitude smaller than the one implied by PMF calculations (Enzel et al., 1993; Levish et al., 1996; 1997). Studies performed in Spain show similar conclusions in the Llobregat and the Caramel river basins (Benito et al., 2004b). In these studies the extrapolated discharges of the 10,000 year palaeoflood return period are between 5 and 20% of the calculated PMF for the USA (Levish et al., 1996) and around 60% for the Spanish case studies (Table 1), indicating that the calculated PMF discharges are very large overestimates. The value of the PMF for dam safety studies is uncertain due to the lack of physical potential of 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 subsequently be of great value for the planning of large scale hydrological projects (e.g. Ostenaa et al., 1994; Ostenaa and Levish, 1996).

3.3. Flood–climate relationships

Quantitative estimates of the effects of climatic change on flood events are essential in flood risk planning and managing water resource issues. General circulation model (GCM) projections for the future are still too uncertain to draw anything but highly tentative conclusions on expected patterns of precipitation change, and even less on the frequency and magnitude of extreme flood events. Extreme floods are meteorological anomalies beyond the present resolution of GCMs, which mainly deal with projections of average atmospheric parameters (temperature, precipitation, pressure, density, among others). Flood magnitude and frequency shows great sensitivity to alterations in atmospheric circulation, not only in the palaeoflood record (Knox, 1993; Ely, 1997) but also during the instrumental period. A number of examples regarding non-stationarity of hydrological gauge records due to climatic forcing, and affecting flood-quantile estimates, have been published (Webb and Betancourt, 1992; Knox, 2000; Redmond et al., 2002). In one of these case studies, the gauge record (1878–1997) of the upper Mississippi river at Keokuk (Iowa) was partitioned according to climatic episodes representing shifts in the atmospheric circulation that occurred around 1895, 1920, 1950 and towards the end of the 1970s (Knox, 2000). The study illustrated that the variance in flood magnitudes was largest during the two episodes (1878–1895 and 1950–1979) when

Table 1
Instrumental, palaeoflood, the 10,000 year return period and probable maximum flood (PMF) discharges for various river basins in the USA and Spain

Location	Drainage basin area (km^2)	Largest instrumental flood (m^3/s)	Length of palaeoflood record (years)	Largest palaeo-flood discharge (m^3/s)	10,000 year palaeoflood discharge (m^3/s)	PMF discharge (m^3/s)
Santa Ynez River, California (USA)[1]	1080	2265	2900	2550	2690	13,060
Ochoco Creek, Oregon (USA)[2]	764	–	10,000–15,000	285	285	4785
Crooked River, Oregon (USA)[3]	6825	–	8000–10,000	<1100	1100	7225
South Fork Ogden River, Utah (USA)[3]	210	53	400	70	<215	3075
Llobregat River (NE Spain)[4]	3370	2500	2800	4680	–	18,985*
Caramel River (SE Spain)[4]	372	170	1985	1616	3450	5786

The 10,000 year return period discharges were estimated using the palaeoflood data in each basin. Data from: [1]Ostenaa et al., 1994 in Levish et al., 1996; [2]Ostenaa and Levish, 1996; [3]Levish et al., 1996; [4]this paper, *data from Francés (written communication, 2003).

the meridional component of the tropospheric westerly circulation was relatively strong. Flood frequency analysis, using the Log-Pearson Type III distribution, indicated that the 2-year return period floods ($Q=4900$–$5600\ m^3/s$) were only slightly influenced by these 20th Century climatic shifts. However, Knox (2000) shows that the calculated magnitudes for the 50-year return period flood varied between 7000 and 7300 m^3/s (for 1896–1919 and 1920–1949), ca. 10,000 m^3/s (for 1878–1895 and 1950–1979) and 11,200 m^3/s (for 1980–1997). These results show that climate shifts have a greater impact on the estimation of the larger flood quantiles and that they are considerably more sensitive to even minor climate change. Other studies based on gauge records have shown that hydroclimatic homogeneity may only have occurred for 30-yr intervals during the 20th Century, something that also needs to be considered in flood frequency analysis (Redmond et al., 2002; Baker et al., 2002).

A better understanding on how future climatic variations might influence flood magnitude and frequency is possible through the analysis of the palaeoflood record (Knox, 2000; Redmond et al., 2002). The aim of these studies is not necessarily to provide analogues of future flood–climate episodes but to analyse the flood response to climate shifts. Over the last three thousand years, Spanish rivers show distinct periods with clustering of flood events at 1000–600 BC, AD 900–1100, AD 1450–1500 and AD 1600–1900 (Benito et al., 2003a; Thorndycraft and Benito in press, Fig. 4). Similar flood episodes were found in Poland (Starkel, 1991) and in the S.W. United States (Ely et al., 1993; Ely, 1997). In a broad sense, these flood clusters occurred during periods of global cooling as indicated in the comparison (Fig. 4) between Spanish palaeofloods and the N. Atlantic ice-drift ice curve (Bond et al., 2001). A more detailed view of the latest cooling period, the Little Ice Age (ca. AD 1450 to ca. AD 1900), through correlation with historical flood records, shows more complex climate–flood relationships (Llasat et al., this issue). During the Little Ice Age, flood episodes with higher flood frequency coincide with changes in, for example, solar activity, periods of volcanic eruptions and glacial advances in the Alps (Starkel, 1991; Benito et al., 2003a).

3.4. Estimating the long-term sustainability of alluvial aquifers in dryland environments

In arid environments, floods are viewed not only as a natural hazard but as an important source of water, as water lost through the channel bed during floods replenishes the alluvial aquifer water supply. In recent years new methodologies have been developed, combining flood and palaeoflood records with data on modern transmission losses, to estimate shallow

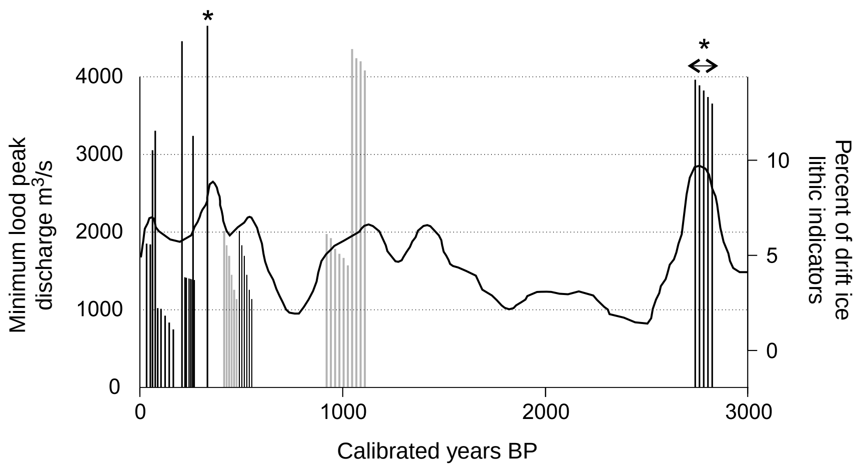

Fig. 4. The magnitude and frequency of palaeofloods during the last 3000 years in the Tagus and Llobregat river basins (Spain). The discharge scale for the Tagus floods at Alcantara (grey bars) should be multiplied by three. The Llobregat floods are indicated by an asterisk. Also shown is the N. Atlantic drift ice curve from Bond et al. (2001).

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). A newly developed flexible TDR (Time Domain Reflectometry) probe now enables more precise quantification of aquifer recharge as transmission losses can be directly monitored throughout the deep vadose zone (Dahan et al., 2003). These quantified rates of aquifer recharge from contemporary floods can be combined with long-term data on aquifer recharge through the isotopic tracing of groundwater and palaeoflood information that can estimate the frequency of recharging floods. This methodology is currently being applied in ephemeral river basins in Israel, S.E. Spain, Namibia and South Africa through the European Commission funded WADE project.

4. Conclusions

In times when recent catastrophic floods have provoked debate on the adequate measures needed to prevent and mitigate flood-associated hazards, palaeoflood hydrology provides a feasible solution for assessing and mapping flood risks and for planning issues in flood-prone zones. This review of the methodological approaches used in palaeoflood hydrology illustrates that robust palaeodischarge estimations can be obtained from sedimentological evidence of floodwater elevations reached by past floods. In many basins, for example the Gardon and Llobregat rivers, the evidence from palaeofloods indicates that floods of a larger magnitude than any recorded in the instrumental series have occurred in the past. In other basins, for example the Narmada River, palaeoflood studies show that floods recorded in the instrumental series were, in fact, the largest for many hundreds or thousands of years. Palaeoflood data can also provide physical evidence for the upper limits of flood events in a basin without relying on statistical extrapolations from short instrumental records, thus improving design discharge estimates for large scale hydrological schemes such as dams. In addition to its applications in flood risk issues, long-term palaeoflood records can be used as valuable proxies of Holocene climatic variability through the analysis of variations in the temporal distribution of floods. Palaeoflood information provides data on individual extreme hydrological events that can be compared with other proxies, such as lake levels, which respond to longer term variations in hydrological regime. Recent developments using palaeoflood data to help quantify long-term rates of shallow alluvial aquifer recharge have now seen its application to water resource issues in dryland environments, once again highlighting the important role palaeoflood hydrology can play in multidisciplinary, applied research in the hydrological sciences.

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