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Use of Systematic, Palaeoflood and Historical Data for the Improvement of Flood Risk Estimation. Review of Scientific Methods

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Abstract. The catastrophic floods recently occurring in Europe warn of the critical need for hydrologic data on floods over long-time scales. Palaeoflood techniques provide information on hydrologic variability and extreme floods over long-time intervals (100 to 10,000 yr) and may be used in combination with historical flood data (last 1,000 yr) and the gauge record (last 30–50 yr). In this paper, advantages and uncertainties related to the reconstruction of palaeofloods in different geomorphological settings and historical floods using different documentary sources are described. Systematic and non-systematic data can be combined in the flood frequency analysis using different methods for the adjustment of distribution functions. Technical tools integrating multidisciplinary approaches (geologic, historical, hydraulic and statistical) on extreme flood risk assessment are discussed. A discussion on the potential theoretical bases for solving the problem of dealing with non-systematic and non-stationary data is presented. This methodology is being developed using new methodological approaches applied to European countries as a part of a European Commission funded project (SPHERE).

Key words: Palaeofloods, historical floods, hydrometeorological hazards, flood frequency analysis, Europe

1. Introduction

Over recent years Europe has witnessed severe flooding with immense social impact, including loss of human life and major damage to property and infrastructure. Of particular importance, recently, were the floods of 1993, at the time the worst

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for 60 years in central and north-western Europe, that resulted in 14 fatalities and €2100 million in insurance losses (Munich Re Group, 2000). The Rhineland in Germany was severely affected, as were the Oise, Moselle and Meuse rivers in France, the latter, in Belgium, reaching the highest flood levels recorded since 1926 and cutting off the city of Dinant. This widespread scene of devastation was repeated in January 1995, with similar flood levels in both the Rhine and Meuse rivers causing 28 fatalities and €3677 million losses. In both years the events were reported as "the flooding of the century". However, these floods were surpassed even further, in terms of casualties and damages, by the floods of August 2002, affecting rivers such as the Danube, Vltava and Elbe causing economic losses in the region of €55 billion and 230 fatalities.

Recent catastrophic flash floods in smaller drainage basins (<500 km^2), predominantly in Spain, France, Switzerland and Italy, also resulted in large numbers of fatalities and economic losses. Most recent examples include the Spanish floods of Biescas in the Pyrenees (1996; 87 deaths) and Badajoz (1997; 24 deaths and €300 million losses), floods in south-eastern part of France such as in Vaison-La-Romaine (1992, 42 deaths), Nîmes (1988, <500 million losses) and Languedoc (1999, 37 deaths and €500 million losses), among others.

Throughout Europe, national legislation on flood risk assessment is based on flood-frequency analysis to estimate discharges associated with different return periods (50, 100, 500 yrs). The usual procedure involves extrapolation from gauged hydrological records documenting 30–40 year records of observed (normally small) floods to the estimation of the quantiles of very large, rare floods. This conventional method of addressing flood risk assessment can be improved by including information on past floods, which should be accomplished using clear systematic procedures and methodologies.

Past flood information can be obtained from palaeoflood hydrology (a new and developing branch of hydrology and geomorphology based on geologic indicators) and from historical information (based on documents and chronicles). Both sources are types of non-systematic information and use the same statistical analysis approach (Stedinger and Baker, 1987; Francés *et al.*, 1994, Francés, 1998). Documentary records provide a catalogue of the largest flood events that occurred during periods of settlement, while palaeoflood investigations using palaeostage geological indicators can document the magnitudes of the largest floods over well defined periods of time (usually from decades to millennia), and provide evidence of all other events below or above specified flow stages or thresholds (Stedinger and Baker, 1987). Long records of extreme floods are then applied successfully in risk analysis together with the more traditional empirical, statistical and deterministic methods to estimate the largest floods. These extreme floods are the ones the planners and engineers are most interested in but are very rare in the observational record (Enzel *et al.*, 1993).

This paper reviews the scientific approach for reconstructing past flood events and its use in flood frequency analysis, as well as the theoretical difficulties re-

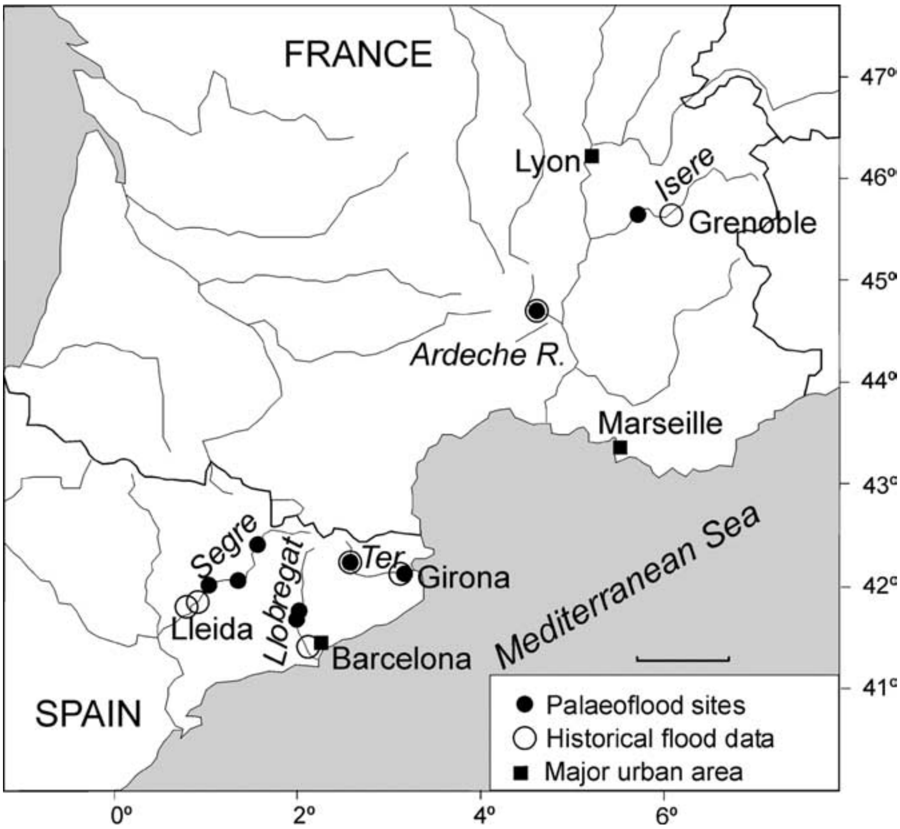

Figure 1. Location of palaeoflood sites and documentary archives studied in the SPHERE Project.

lated to the use of palaeoflood and historical data. Flood discharge estimates from systematic, palaeoflood and historical data will be compared and the incorporation of non-systematic and non-homogeneous data in flood frequency analysis will be discussed. The conclusion presents the approach of the European SPHERE project which aims to promote the use of non-systematic data in flood risk mitigation, using case studies in different European rivers (Figure 1).

2. Discharge Estimate of Floods

2.1. DISCHARGE ESTIMATES USING SYSTEMATIC DATA FROM HYDROLOGICAL NETWORKS

Each European country manages its own hydrological gauge station network, which provides information on flood stage and the relationship between the stage and flood discharge (the rating curve). Continuous gauged stage and/or discharge data is usually available for the last 30–40 years. The quality of instantaneous flood data is generally lower than measurements on average flow because direct measurement of the largest floods is an unusual situation due to logistic constraints on its measurement: high flow velocities, danger for personnel and field gear; operational delay for someone to be present during the peak flood etc. In addition, during large floods conventional stream gauge stations have great difficulty in accurately recording extreme floods – they may be inundated, damaged by floodwaters or even totally destroyed producing gaps in the gauged flood record of the largest floods. Therefore, in many cases, data of the largest floods within systematic gauge records are actually post-flood indirect estimates. Extrapolation of the rating curve, from low stage-discharge to high stage-discharge, is then a fundamental step for discharge estimation and can add substantial errors. It could be improved by including hydraulic considerations, for example taking into account the river topography and specific roughness conditions during floods. Errors on flood discharge estimate are generally considered to be in the range of 10% to 100%, depending on the quality of the rating curve and its extrapolation to large floods.

2.2. FLOOD LEVEL DERIVED FROM PALAEOFLOOD DATA USING GEOLOGICAL INDICATORS

Techniques to estimate peak discharge based on palaeostage indicators have been successfully employed in several regions of the USA (see latest works in House *et al.*, 2002) such as Texas (Kochel *et al.*, 1982), Arizona (Partridge and Baker, 1987; Ely *et al.*, 1993, O'Connor *et al.*, 1994) Utah (Webb *et al.*, 1988), Colorado (Jarret, 1990, 1991) Wisconsin (Knox, 1985), Washington (Chatters and Hoover, 1986) and Southern California (Enzel, 1992) as well as in other countries including India (Ely *et al.*, 1996, Kale *et al.*, 1994), South Africa (Boshoff *et al.*, 1993; Zawada, 1997), Israel (Greenbaum *et al.*, 2000), Peru (Wells, 1990) and Australia (Pickup *et al.*, 1988). In Europe, studies using palaeoflood hydrology in combination with historical flood information data showed an improvement in estimating flood hazards (Benito *et al.*, 1998, 2003; Thorndycraft *et al.*, 2003).

A palaeoflood record is obtained from interdisciplinary techniques that combine different sources of past flood information from geomorphological settings and stratigraphic criteria separating and correlating flood units. Sources of palaeoflood data are geological indicators such as flood deposits, silt lines and/or erosion lines found along a river's channel, valley walls and/or terraces etc. Palaeoflood data and its meaning as minimum, maximum or exact flow stage value depend upon the mark type (see review in Section 2.4), although most of them represent minimum flood stage indicators. It is relatively easy to reconstruct the size of the largest palaeoflood(s) in a given time period, and frequently most efforts are directed at reconstructing the complete record (number and size) of large-intermediate palaeofloods. Two different geomorphologic settings can be considered: (a) bedrock river reaches and (b) alluvial river reaches. Different methodological procedures are applied in each case for reconstructing the palaeoflood record, or stage constraints

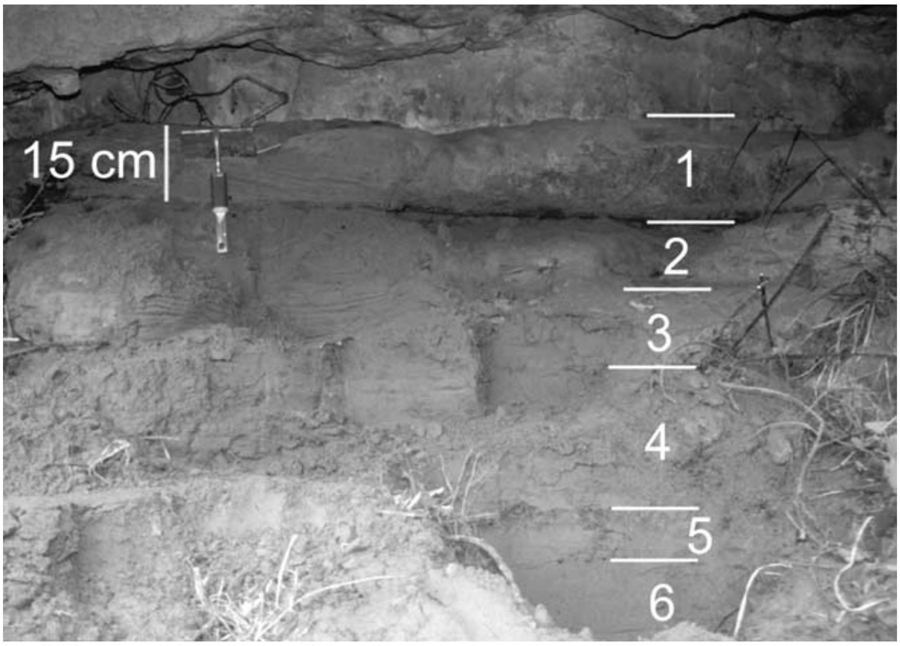

Figure 2. Alcove filled with slack-water flood deposits of the Llobregat river. Numbers indicate distinct flood units or flood events.

(minimum or maximum bounds) applicable to the discharge calculations, and in the flood frequency analysis.

River channels cutting through hard bedrock or other resistant boundary materials (e.g., cemented terraces) provide the most suitable settings for reconstructing the palaeoflood record (Baker *et al.*, 1983) as they are the most conducive to the accumulation and preservation of flood deposits and palaeostage indicators (PSI's). PSI's include slackwater flood deposits (eddy bars, flood deposit benches and deposits at tributary months), and bedrock scour features. During flood stages, eddies, back-flooding and water stagnation occur at marginal areas of the channel, producing low velocities and/or flow stagnation (slack water) which favours deposition from suspension of clay, silt and sand. These fine-grained deposits can be preserved in stratigraphic sequences (Figure 2), providing detailed and complete records of flood events that extend back several thousands of years (Patton *et al.*, 1979; Baker *et al.*, 1983).

In palaeoflood studies, detailed maps of erosional and depositional features are compiled within each of the specific study reaches. In the slackwater sedimentation sites, a detailed stratigraphy of the fine-grained flood sediments is described (Benito *et al.*, 2003), and individual flood units (representing single events) are separated (Figure 2). Sediment samples for physical and chemical analysis of the flood deposits (texture, $CaCO_3$, organic matter, etc.) are taken. Numerical dating using radiocarbon (C-14) and luminescence methods (thermo- (TL) and optically stimulated- (OSL), for example) is obtained, through collection of organic (seeds, charcoal, wood debris, etc.) and sand samples, respectively.

Common dating techniques such as C-14, TL and OSL may contain deviations from the true age. In the case of radiocarbon this depends upon the age (years BP) and the amount of carbon in the sample. For samples with an age ranging from 0 to 5000 years BP, standard deviations are between ±9 to ±12 years for samples containing 25 g of C, and between ±80 to ±110 years for <0.005 g of C in the sample (Mook and Waterbolk, 1985). Due to atmospheric C-14 fluctuations during the last 450 years, multiple calendar dates, or a much broader spectrum of calendar years, may be derived from a single radiocarbon date (Stuiver, 1978). However, the main problem of numerical dating is not the error of the measurement but the scarcity of organic remains within the flood deposits and the residence time of the organic material in the environment prior to its deposition within the flood deposit sequence (Ely *et al.*, 1992). New C-14 dating techniques based on accelerated mass spectrometry (AMS) have helped resolve the problem since it permits the dating of minute remnants such as seeds or small fragments of charcoal. For young floods (last 200 years) dating can be completed using distinctive archaeological materials (Benito *et al.*, 1998) and/or radio-isotopes, for example ^{137}Cs which is derived from atmospheric nuclear testing (Baker *et al.*, 1985; Ely *et al.*, 1992).

The final palaeoflood record is completed using available stratigraphical and geomorphological criteria and correlation at multiple sites. The palaeoflood results comprise the stratigraphy with the number of the palaeofloods, sedimentological analysis, and their minimum palaeostages and the chronology (absolute or relative) of each palaeoflood record. To address the evaluation of the magnitude and frequency of flooding, over a long time span (decades to millennia), the construction of a complete catalogue of palaeodischarges, exceeding or not exceeding various censoring levels or threshold discharges (Figure 3B), over specific time periods, is required. A censoring level is a threshold of discharge or stage above which the palaeoflood record can be assumed to be complete over a specific time interval (Baker, 1989), i.e., all discharges exceeding the censoring level (threshold), during this time period, have left evidence in the palaeoflood record.

In *alluvial valleys*, an approach using floodplain terraces as palaeohydrologic bounds can be applied. The palaeohydrologic bound methodology is based on the statement that if ages can be derived for preserved and/or flood-modified surfaces, then the surfaces can become conservative datum for the magnitude of large floods (Levish *et al.*, 1997; Levish, 2002). The absence of features indicative of significant inundation is positive evidence of non-exceedence of a specific, limiting flood stage over the time spanned by the surface. This palaeohydrologic bound approach is less sensitive to record a complete catalogue of floods over distinct periods of time, but the potential for identifying non-exceedence bounds in most rivers provide this technique with a near universal applicability. Within the study reaches, floodplains and lower terraces are mapped. Their altitudes are determined by accurately plotting their positions by surveying with theodolites or GPS. Erosional

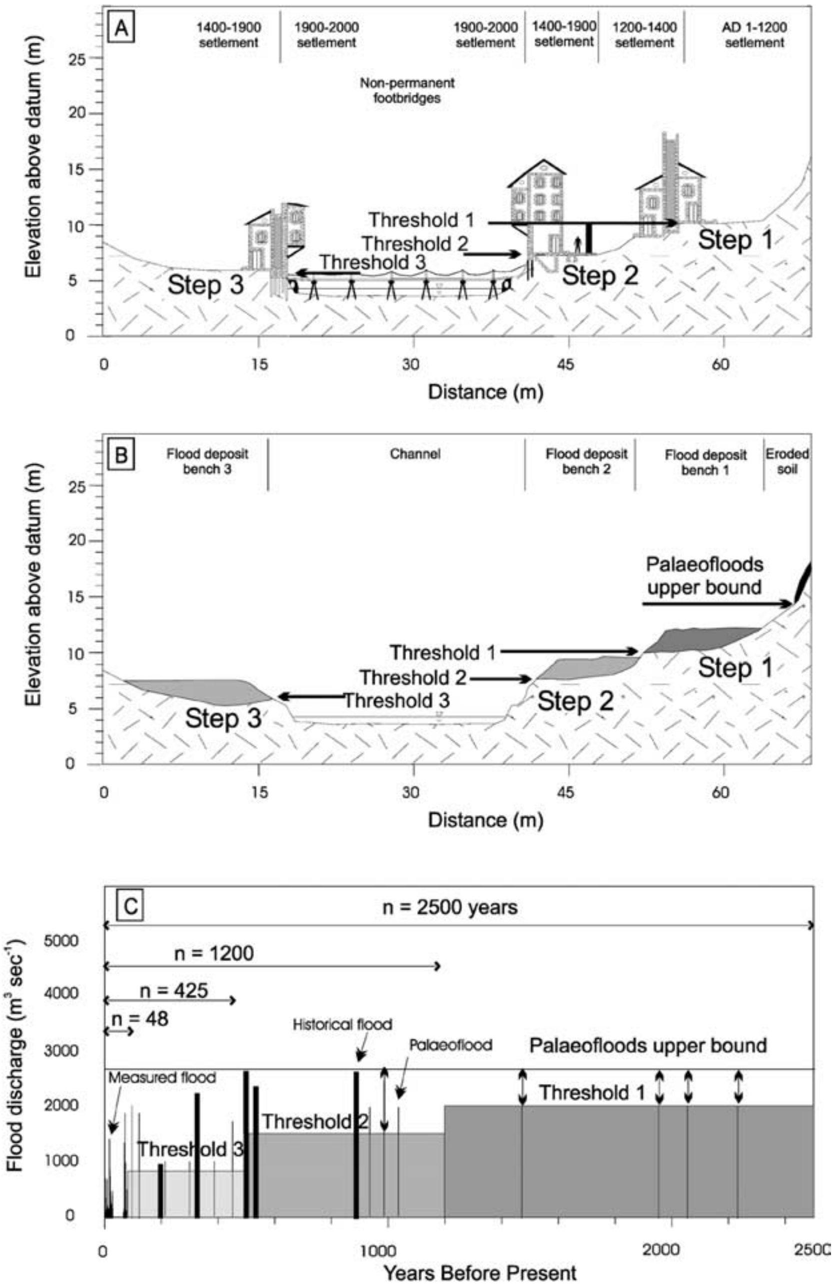

Figure 3. (A) Schematic diagram illustrating the changing level of flood perception through time according to progressive human settlement towards the river. This means that the threshold of flood discharges recorded in the historical documents decreases with time. (B) Geomorphic surfaces covered with slack-water flood deposits showing different thresholds of flood discharges. (C) Organisation of historical, palaeoflood and systematic data, using the described discharge thresholds, for flood frequency analysis.

and depositional flood-related features are located, as well as non-flooded surfaces (non-exceedence bounds). Detailed stratigraphic description of the late Holocene flood deposits overlying different geomorphological units and their numerical dating together with dating of non-flooded terraces will provide a suite of hydrologic bounds exceeded and non-exceeded during different time spans.

Three major uncertainties are associated with palaeoflood analysis: (1) water depth above the flood deposits during flood stage, (2) uncertainties related with numerical dating of the flood deposits, (3) continuity and completeness of the palaeoflood record. Palaeostage indicators can be in a range of between 0.3 and 2 m lower than water stage during peak discharge. New criteria such as the highest end-point of the flood unit at the contact with the canyon slope used by Yang *et al.* (2000) provide a better approximation to the flood stage during peak discharge.

Regarding the continuity in the palaeoflood record, erosion of the flood benches near the main channel may lead to record gaps. However, for time spans recorded within a stratigraphic sequence or site, periods with no sediment deposition result from a lack of major flood events at this time. In some cases this can be corroborated where there is the opportunity to correlate palaeoflood deposits with the historical record. For example, in the Ter Basin at Girona (NE Spain; Figure 1), an alcove located approximately 15 m above the river contains a record of three extreme flood events. A coin preserved within the oldest flood unit dates from 1650–52. Comparison with the historical flood record from this area (Barriendos 1996–97) indicates four extreme events post-dating the age of this coin: September 1678, October 1919, October, 1940 and October 1970. This site, therefore, indicates a continuous record of the extreme events occurring since the mid 17th century.

2.3. FLOOD LEVEL DERIVED FROM HISTORICAL DATA USING DOCUMENTARY SOURCES

Documentary evidence not only provides historical facts about a society at a particular time but can also provide information on environmental themes. Using such records it is possible to analyse different environmental phenomena in terms of their temporal dimension or extreme expression.

The recovery of environmental information is not devoid of certain shortcomings. Firstly, there is the large volume and variety of documents in which information may sporadically or systematically appear. Further, this information does not always directly describe a particular phenomenon but rather may expose its effects or impact (proxy-data). And lastly, not all information is of optimum reliability and necessitates the critical analysis of its sources (Glaser, 1996). This problem arises from the tradition of making successive copies, reinterpretations, selections or *résumés* of original texts and is aggravated by the printing and transcription of documents.

Information regarding past floods documented in Western Europe comes from riverside societies where flooding can lead to damage of the infrastructure of the particular locality. In pre-industrial societies, dependence on hydraulic energy and the inability to construct large flood control systems resulted in a high degree of vulnerability. It may be possible to compile a chronology of events dating from the 13–15th centuries to the present day for societies with a well documented past.

Data acquisition should be undertaken from original document sources to ensure their quality. This may involve consulting hundreds of manuscript volumes. The best information on floods and their effects is generally found in local administration records and in the more personal diaries and bibliographies. The need for auxiliary techniques also arises, e.g., chronology for calendar adjustments or metrology for the conversion of units of measure or palaeography for the correct interpretation of writing styles.

According to present experience, the minimum information that may be obtained from historical archives would be the precise dating of past flood events, damages incurred, some reference to peak flood levels (Figure 4) and certain information on the prevailing meteorological situation. This allows a straightforward but standardised classification of simple flood events, extreme floods causing discrete damage and floods that cause the total destruction of different infrastructures (Figure 3A). Most historical floods provide information on the water stage during peak discharge which can be precisely marked on buildings and landmarks or it can be related to a datum (bridges, houses, gates, walls, and so on) exceeded or non-exceeded by the flood waters. In the specific case of the River Ter in Girona (NE-Spain), 170 flood events for the period 1322–1987 have been identified (Barriendos, 1996–97, Barriendos and Martin-Vide, 1998), 77 contain exact information on the flood stage, 89 are associated with levels exceeded or not exceeded by the flood water and only 4 events do not provide any information on the flood stage.

2.4. SPECIFIC ERRORS IN FLOOD DISCHARGE ESTIMATES USING NON-SYSTEMATIC DATA

Non-systematic data provides information related to water levels during flood episodes (Figure 3A, B). Information regarding water stage associated with historical flooding are: (1) sites or landmarks reached by the flood (e.g., churches, bridges, etc.), (2) flooded areas (e.g., orchards, floodplain areas), and (3) non-flooded areas or landmarks. Similarly, palaeostage indicators provide water stage information on (1) elevations reached by the flood (e.g., erosion lines or silt and clay lines), (2) flooded areas (flood deposits and erosion landforms), and (3) non-flooded areas (unmodified geomorphic surface or soil profiles or areas lacking any allochthonous material). This historical and palaeoflood information can be interpreted as different flood stage indicators: (1) exact discharge level (equal to the flood stage), (2) minimum flood stage, (3) maximum flood stage (Figure 3).

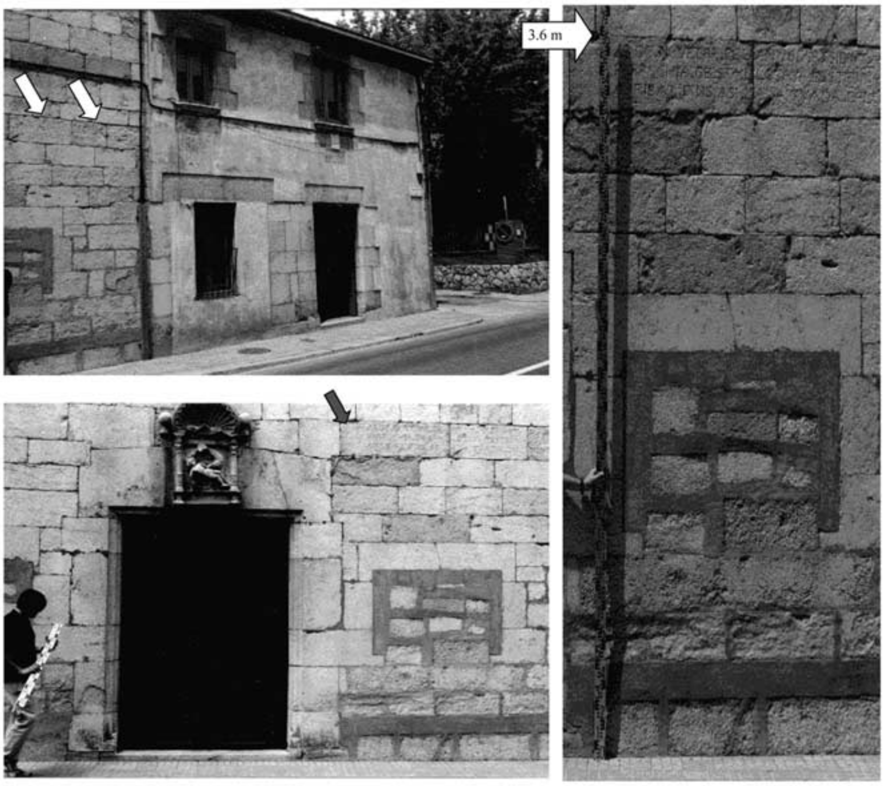

Figure 4. Different views of the Pont Major Church (Girona) illustrating the level of the November 3rd 1617 flood event of the Ter river. Arrows indicate the flood elevation which is approximately 3.6 m above street level.

These water levels must be converted into discharge values which is the variable used in statistical analysis. In reality this conversion is an inverse problem, where the maximum discharge is obtained by trial and error using the appropriate hydraulic model by matching the calculated water levels to observed water levels. Hydraulic modelling requires the estimation of some of the hydraulic characteristics of the river reaches (slope, roughness and cross sections) as well as the boundary conditions upstream or downstream depending on the flow type. In the case of a mobile bed, or alluvial channel, it is also necessary to know the sediment characteristics. It should be pointed out that the precision of a mobile bed model is lower than for a fixed bed, mainly due to the complexity of the transport and sediment processes. Also in a mobile bed, and especially in alluvial channels, the current topography can be completely different to that at the time of the hydraulic reconstruction.

For these reasons, in the case of palaeoflood data, it is preferable for the information to be located in bedrock canyons, because the past hydraulic characteristics can be assumed similar to the present ones, as bed movements are minimal. In the case of historical data, it will be critical to have information regarding the topography of the river and on the settlement evolution of its surroundings, contemporaneously with the historical information (Figure 3A). This available historical cartography has to be used to determine the range of possible flow conditions. If for the first step (compilation of the flood events) lengthy work is needed, for this second step the research is more difficult still, and for this reason it is only applied to certain selected rivers and cities.

One main concern regarding non-systematic information is the error that can be introduced in the flood frequency analysis, although systematic information is not free of errors either. At a flow gauge station, measurement error increases the variability of flood quantile estimators (Potter and Walker, 1981), but if the standard error is smaller than 10% the influence is negligible (Cong and Xu, 987). This standard error is typical for the interpolation of rating curves at a gauge station. For a large flood, however, the discharge must be obtained by extrapolation of the rating curve resulting in a greater error due to the change in hydraulic characteristics when the floodplain is flooded. In these cases it is advisable to obtain the maximum discharge by following the methods described above for the non-systematic information, especially if the gauge station was destroyed, as the uncertainty of this information will be similar to that of the largest floods in the systematic record. Even with a standard error of 60%, additional information regarding large floods is always valuable (Cong and Xu, 1987).

3. Flood Frequency Analysis Using Non-systematic and Non-stationary Data

3.1. CLIMATIC NATURE OF EXTREME FLOODS

Advances in this topic are mainly devoted to improving knowledge of the atmospheric factors involved in heavy rain events and their forecasting, using deterministic and statistical approaches. Climatic analysis of the flood-producing events include the classification, characterisation and variability analysis of these flood events (Hirschboeck, 1991; Webb and Betancourt, 1990; Enzel *et al.*, 1989; Ely *et al.*, 1993, 1994; Llasat, 1997; Redmond *et al.*, 2002). This analysis can be made from a local and/or regional point of view. However, regarding the temporal variability of the floods, it is necessary to consider that it can be related both to changes in meteorological factors (connected with climatic fluctuations) and changes in environmental factors (mainly connected with human activity). In this case, the main problem is the lack of long term quantitative and instrumental information that forces the use of palaeoflood and documentary flood sources to establish links between flood occurrence and climate variability.

A basic question dealing with a long temporal flood series is whether the flood-producing mechanisms in the past have been similar to those of the present (Hirschboeck, 1991). The analysis of the monthly distribution of historical floods in the Iberian Peninsula for the last millennium shows a similar pattern to the present monthly flood distribution (Barriendos, 1996–97, Benito *et al.*, 1996, Barriendos and Martín-Vide, 1998), indicating that flood-producing mechanisms in the past have been similar to those operating at present. It is thought that general features of present-day atmospheric circulation were probably in existence by the mid- to late Holocene (Knox, 1993). However, flood distributions in the Iberian Peninsula have changed through time as indicated by the clusters of flood events at specific periods both in the historical record (Sánchez Rodrigo *et al.*, 1995, Barriendos, 1996–97, Benito *et al.*, 1996, Barriendos and Martín-Vide, 1998) and in the palaeoflood record (Benito *et al.*, 2003). It has been established that floods are highly sensitive to even modest changes in climate (Enzel *et al.*, 1989; Knox, 1993, 2000; Ely, 1997; Barriendos, 1996–97, Redmond *et al.*, 2002). Historical flood and palaeoflood analysis permits the identification of periods showing a greater frequency of a particular behaviour, or pattern, related to changes in the atmospheric global circulation and, in some way, allows the estimation of the size of these anomalies over time. The linkages between past floods and climate is critical to address the complexity of the non-stationarity problem in flood frequency analysis.

For the north east of Spain, the historical flood record, with more than 248 flood events, shows clusters of floods during specific time periods: AD 1588–1610, AD 1760–1800 and AD 1840–1859 with an additional minor phase between AD 1660–1700 (Barriendos, 1996–97). A climatic characterisation of these periods was possible using historical documentary sources. The period AD 1588–1610 was characterised by a flood frequency twice the mean, and included the great flood of AD 1617 that affected several basins of the Mediterranean coast. By contrast the period AD 1760–1800 was characterised by high climatic irregularity accompanied by both hydrologic extremes, catastrophic floods and drought. The final period AD 1840–1859 was characteristically similar to the AD 1588–1610 cluster, including a sharp increase in the number of floods and a decrease in periods of drought. This phase represented the end of the Neoboreal episode in Mediterranean latitudes. These marked clusters of historical floods are associated with changes in the climatic pattern at both the regional and global scales (Barriendos and Martín Vide, 1998; Brázdil *et al.*, 1999). Any realistic analysis of flood frequency projected over time spans greater than a 100 years must consider these types of changes in temporal flood distribution.

In order to evaluate the size of these anomalies through time a detailed meteorological analysis of each historical flood event is required. The problem in this case is the lack of the instrumental data (pressure, temperature and humidity at different atmospheric levels) that prevents the reconstruction of the synoptic framework of each event. One possibility is to use a public pressure database (e.g., those of the Climate Research Unit or of the NOAA), but in this case daily data are only available for less than 100 years and monthly data can be obtained only for one or two centuries. Another possibility is to use daily temperature and pressure series for a longer period obtained within the framework of other international projects. For instance, the daily series of Padua, Milan, San Fernando/Cádiz, Belgium, Uppsala and Stockolm, from the 18th century to the present, are available in European data-bases (Camuffo and Jones, 2002). The third possibility is to reconstruct each event on the basis of meteorological information included in the flood event description found in the manuscripts and other contemporaneous information. This technique has already been applied for the analysis of catastrophic naval events based on logbooks (García *et al.*, 2000). This kind of analysis can be improved by the introduction of conceptual models based on the complete meteorological analysis of recent flood events. Here, collaboration between meteorologists, climatologists and historians is needed.

3.2. STATISTICAL FRAMEWORK

Flood frequency analysis (FFA) with systematic data is generally developed using annual maximum values and the assumptions of interannual independence and stationarity of the flood population. Use of historical and palaeoflood information gives rise to two specific problems dealing with: (a) non-systematic data (only the major floods remain known) and (b) non-homogeneous data (hydroclimatically induced non-stationarity due to natural climatic variability within the last 1000–10000 years).

Non-Systematic Data

The basic hypothesis in the statistical modelling of historical and palaeoflood information is that a certain perception of water level exists and that over a specified time interval (historical or prehistorical), all exceedances of this level have been recorded, either in newspapers, in people's memory, or through geological palaeoflood evidence left along the river channels such as sediment deposits (Figure 3).

In the United States, the U.S. Water Resources Council (1982) recommended the use of *the method of adjusted moments* for fitting the log Pearson type III distribution. A weighting factor is applied to the data below the threshold observed during the gauged period to account for the missing data below the threshold in the historical period. Several studies have pointed out that the method of adjusted moments is inefficient. *Maximum likelihood estimators* (Condie and Lee, 1982) based on partially censored data have been shown to be much more efficient and to provide a practical framework for incorporating imprecise and categorical data. Unfortunately, for most of the 3-parameter distributions commonly used in hydrology, the maximum likelihood method poses numerical problems. More recently, Lane and Cohn (1996) proposed use of *the method of expected moments*, a variant of the method of adjusted moments, which gives less weight to observations below the threshold (Figure 3C). According to preliminary studies, estimators based on expected moments are almost as efficient as maximum likelihood estimators, but have the advantage of avoiding the numerical problems related to the maximisation of likelihood functions.

Bayesian methods have been used with a great success to solve various problems of statistical and stochastic hydrology. Van Gelder (1996) proposed a *bayesian framework* for the inclusion of historical information in flood frequency analysis. Bayesian approaches can also be used to improve the performance of existing methods. For instance, in the method of expected moments, a bayesian methodology can be developed to estimate the weight of observations below the detection threshold for the historical period (previous to systematic gauging). The Bayesian method is being used by the U.S. Bureau of Reclamation for the evaluation of dam safety, for guiding hydrologic dam safety decisions and management of reservoirs in the western United States (Levish *et al.*, 1997; O'Connell *et al.*, 1997).

Other methods include the *partial probability weighted moments method* (PPWM) proposed by Wang (1990) for the General Extreme Value Distribution; and the *non-parametric approach* (NP) proposed by Bardsley (1989). PPWM, in fact, represents a variation of the method of adjusted moments, while the main problem with NP is that it separates the treatment of systematic and historical events. Furthermore, several problems remain with NP, mainly in relation with the practical choice of the kernel and bandwidth values. A review of these various methods is presented by Ouarda *et al.* (1998).

Non-Homogeneous Data

The annual flood series used in FFA are assumed to be stationary in time (all floods were randomly generated from a single probability distribution with stable moments). Climatic fluctuations, however, are a source of uncertainty and can lead to misjudgement and misuse of flood-frequency analyses (Dunne and Leopold, 1978). As described before, non-stationarity in hydrological series using non-systematic information must be considered. The temporal changes in the trajectory and statistics of a state variable may correspond to natural, low-frequency variations of the climate hydrological system or to non-stationary dynamics related to anthropogenic changes in key parameters such as land use and atmospheric composition (Baldwin and Lall, 1999). In fact, global warming will lead to a change in hydrological variables (IPCC, 2001). The consequences of possible non-stationarities on the estimation of exceedance probability have been investigated by Porporato and Ridolfi (1997). They have studied the hypothetical case of a trend superimposed on a random stationary variable, and they highlighted the strong dependence of exceedance probability on possible non-stationarity, with special reference to the simplified case of linear trends.

3.3. DIFFICULTIES OF A JOINT USE OF SYSTEMATIC, PALAEOFLOOD AND HISTORICAL DATA

Theoretical difficulties to be solved in the combined use of systematic and non-systematic information stem from: (1) methodological complexity and uncertainties associated with the reconstruction of the catalogue of past flood events (historical and/or palaeoflood data); (2) data processing of non-systematic information – setting the appropriate censuring levels (threshold discharge) and non-exceeded levels through different time spans – in such a way that increasing the amount of information produces an increase in the flood quantile estimate reliability, and (3) the influence and evidence of non-stationarity in long timescale flood records.

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

A major effort must be focused on flood frequency analysis for managing this non-systematic and, even more importantly, non-stationary information. Different statistical tools, such as the maximum likelihood and Bayesian methodologies, have been successful in managing non-systematic data, even data with a high degree of uncertainty regarding peak discharge values which has been solved using censuring levels and thresholds. In the analysis of non-stationary flood series it is also critical to reach a better understanding of flood producing mechanisms and flood-climate links during different time periods. A change in flood generating mechanisms, or in flood frequency patterns, can be related to climatic variations, and therefore, a study of these variations, quantifying the frequency of climatic patterns responsible for flooding, is required.

Interest in past flood information will increase proportionally to the availability and knowledge of methodological guides for reconstructing discharges and tools (such as software) for flood frequency analysis using non-systematic and non-stationary data. To this end a new synergetic approach is being undertaken within the European Commission funded SPHERE project (Figure 5), based on a multidisciplinary combination of pure and applied research, using palaeoflood, historical flood and systematic data, combined with new statistical tools, for addressing flood risk assessment.

4. Conclusions and Future Perspectives

In times when catastrophic floods have provoked European debate on the adequate structural and non-structural measures needed to prevent and mitigate flood-

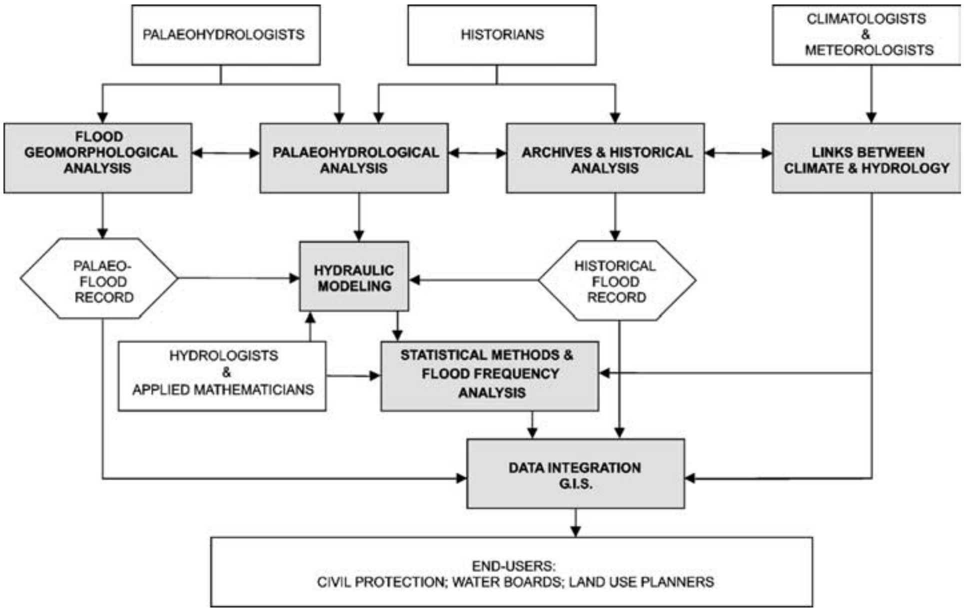

Figure 5. Flow diagram illustrating the SPHERE methodology.

associated hazards, palaeoflood and historical flood data provide a feasible solution for assessing and mapping flood risks, and planning flood-prone zones. These improved flood-potential estimates using palaeoflood and historical flood data also have significant beneficial economic and environmental implications, related to floodplain planning, management design of hydraulic structures, management of critical water-resources and environmental conservation issues.

The European Commission funded SPHERE project (2000–2003) represents the European effort in creating new approaches in the joint use of palaeoflood and documentary flood data as widely integrated long-term records in conventional hydrology and engineering flood studies. From this point of view the SPHERE project aims to address the standardisation of methodological procedures of reconstructing past floods and to develop tools (methodologies and software) for its efficient integration into flood frequency analysis for flood design and planning. Palaeoflood and documentary flood information is ideally suited for hydrological design of structures at risk from extreme floods (e.g., dam design) and for the delineation of flood prone areas with high levels of desired and/or tolerated protection against floods.

There are several ways in which future research in other disciplines, and the search for solutions to various practical problems, might benefit from the application of the results of this project to other disciplines and to practical problems. The SPHERE project will contribute to the improvement of methods directed towards the reconstruction of past flood peak discharges, extending the hydrological records of extreme floods to include the last several millennia. In Europe, palaeoflood hydrology is still a developing field with a great potential for being complemented for the last thousand years with detailed documentary records. Inundation levels identified in the palaeoflood and documentary data analysis can be transformed into flood magnitude and frequency through conventional hydraulic modelling.

An added value of documentary records is obtained from description and quantification of flood impacts on past societies, including economic losses, recovery strategies and flood management at different periods. The history of past floods, such as the one that occurred in 1617 in NE-Spain ("year of the dilluvium"), provide a unique opportunity to understand the flood hydrology and the social impact of "catastrophic floods" with magnitudes far beyond the ones recorded in gauge stations. This, in turn, means gaining an understanding of individual extreme events not available and perhaps not predicted by the instrumental record, as well as to gain a new dimension on socio-economic impacts and perception of extreme events, which needs to be evaluated according to different historical contexts. Flood damage exerted on riverside societies during centuries is very valuable information to be used in risk education tasks directed to Civil Protection technicians, volunteer bodies and in schools.

Hydrologic design of high risk structures, such as dams, or floodplain delineation for nuclear power plants, currently obtained using the probable maximum flood (PMF), can also benefit from palaeoflood hydrology. So far, the PMF is obtained from a combination of meteorological and physical assumptions producing a valuable but uncertain result. In some cases, the PMF appears to be unreasonably large in comparison to the palaeoflood record (Levish *et al.*, 1997). Here, we propose the development of methodologies to obtain extreme flood data through direct measurements (past inundation levels) of the river systems, to be used for the selection of appropriate hydrological model parameters, and for improving flood frequency analysis. Many researchers have emphasised the potential gain of the statistical methods for estimating flood quantiles by the use of palaeoflood and documentary information. Because palaeoflood and documentary floods are large by definition, their introduction into a flood frequency analysis improves the estimates of the probabilities of rare floods. This is particularly true when 3-parameter distributions are considered. Moreover, historical information increases and tests the representation of outliers in the systematic data.

In terms of the hydrological effects of climate change, future global circulation model projections incorporate too much uncertainty to accurately specify expected patterns of precipitation change, and even less the frequency and magnitude of extreme storm and flood events. Predictions can be improved by incorporating long-term flood records (several millennia) in climatic modelling and statistical analysis. The study of temporal variability of past climate-flood links can establish short- and long-term relationships at regional levels and in areas within different climatic zones. Regional studies of long-term climate-flood links involve calibrating the relationships, detecting trends (where they exist) and revising estimates of return periods. This integration will greatly advance our understanding of flood frequency and magnitude in the context of changing climates where the assumption of stationarity (implicit in most current flood risk models) is being questioned.

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References

Baker, V. R., Kochel, R. C., Patton, P. C., and Pickup, G.: 1983, Paleohydrologic analysis of Holocene flood slack-water sediments, *Internat. Assoc. of Sedimentologists Special Publ.* **6**, 229–239.

Baker, V. R., Pickup, G., and Polach, H. A.: 1985, Radiocarbon dating of flood events, Katherine Gorge, Northern Territory, Australia, *Geology* **13**, 344–347.

Baker, V. R.: 1989, Magnitude and frequency of palaeofloods, In: K. Beven and P. Carling (eds), *Floods*, *Their Hydrological*, *Sedimentological and Geomorphological Implications*, John Wiley, Chichester, pp. 171–183.

Baldwin, C. K. and Lall, U.: 1999, Seasonality of streamflow: the Upper Mississippi River, *Water Resour. Res.* **35**, 1143–1151.

Bardsley, W. E.: 1989, Using historical data in nonparametric flood estimation, *J. Hydrol.* **108**, 249–255.

Barriendos, M.: 1996–97, El clima histórico de Catalunya (siglos XIV–XIX). Fuentes, métodos y primeros resultados, *Revista de Geografía* **30–31**, 69–96.

Barriendos, M. and Martín Vide, J.: 1998, Secular climatic oscillations as indicated by catastrophic floods in the Spanish Mediterranean Coastal Area (14th–19th Centuries), *Climatic Change* **38**, 473–491.

Benito, G., Machado, M^{a}.J. and Pérez-González, A.: 1996, Climate change and flood sensitivity in Spain, In: J. Branson, A. G. Brown and K. J. Gregory (eds), *Global Continental Changes: The context of Palaeohydrology*, Geological Society of London Special Publication No. 115, pp. 85–98.

Benito, G., Machado, M^{a}. J., Pérez-González, A., and Sopeña, A.: 1998, Palaeoflood hydrology of the Tagus river, Central Spain, In: G. Benito, V. R. Baker and K. G. Gregory (eds), *Palaeohydrology and Environmental Change*, John Wiley, Chichester, pp. 317–333.

Benito, G., Sánchez-Moya, Y., Sopeña, A.: 2003, Sedimentology of high-stage flood deposits of the Tagus River, Central Spain, *Sediment. Geol*. **157**, 107–132.

Boshoff, P., Kovacs, Z., Van Bladeren, D., and Zawada, P. K.: 1993, Potential benefits from palaeoflood investigation in South Africa, *South African Civil Engineer* **35**, 25–26.

Brázdil, R., Glaser, R., Pfister, C., Antoine, J. M., Barriendos, M., Camuffo, D., Deutsch, M., Enzi, S., Guidoboni, E., and Rodrigo, F. S.: 1999, Flood events of selected rivers of Europe in the Sixteenth Century, *Climatic Change* **43**, 239–285.

Camuffo, D. and Jones, P. (eds): 2002, Improved understanding of past climatic variability from early daily European instrumental sources, *Climatic Change* **53**, 1–392.

Chatters, J. C. and Hoover, K.A.: 1986, Changing later Holocene flooding frequencies on the Columbia River, Washington, *Quaternary Res.* **26**, 309–320.

Condie, R. and Lee, K. A.: 1982, Flood frequency analysis with historic information, *J. Hydrol.* **58**, 47–61.

Cong, A. and Xu, Y.: 1987, Effect of discharge measurement errors on flood frequency analysis, In: V. P. Singh (ed.), *Application of Frequency and Risk in Water Resources*, Reidel Publishing Company, pp. 175–190.

Dunne, T. and Leopold, L. B.: 1978, *Water in Environmental Planning*, W. H. Freeman, San Francisco, 818 pp.

Ely, L. L.: 1997, Response of extreme floods in the southwestern United States to climatic variations in the late Holocene, *Geomorphology* **19**, 175–201.

Ely, L. L., Webb, R. H., and Enzel, Y.: 1992, Dating Historic flood deposits using post-bomb ^{14}C and ^{137}Cs, *Quaternary Res.* **38**, 196–204.

Ely, L. L., Enzel, Y., and Cayan, D. R.: 1994, Anomalous North Pacific atmospheric circulation and large winter floods in the southwestern United States, *J. Climate* **7**, 977–987.

Ely, L. L., Enzel, Y., Baker, V. R., and Cayan, D. R.: 1993, A 5000-year record of extreme floods and climate change in the southwestern United States, *Science* **262**, 410–412.

Ely, L. L., Enzel, Y., Baker, V. R., Kale, V. S., and Mishra, S.: 1996, Changes in the magnitude and frequency of Holocene monsoon floods on the Narmada River, *Central India, Geol. Soc. Am. Bull.* **108**, 1134–1148.

Enzel, Y.: 1992, Flood frequency of the Mojave River and the formation of the late Holocene playa lakes, southern California USA, *Holocene* **2**, 11–18.

Enzel, Y., Cayan, D. R., Anderson, R. Y., Wells, S. G.: 1989, Atmospheric circulation during Holocene lake stands in the Mojave Desert: evidence of regional climate change, *Nature* **341**, 44–47.

Enzel, Y., Ely, L. L., House, P. K., Baker, V. R., and Webb, R. H.: 1993, Paleoflood evidence for a natural upper bound to flood magnitudes in the Colorado River basin, *Water Resour. Res*. **29**, 2287–2297.

Francés, F.: 1998, Using the TCEV distribution function with systematic and non-systematic data in a regional flood frequency analysis, *Stoch. Hydrol. Hydraul.* **12**, 267–283.

Francés, F., Salas, J. D., and Boes, D. C.: 1994, Flood frequency analysis with systematic, historical and paleoflood data based on the GEV model, *Water Resour. Res.* **30**, 1653–1664.

García, R., Gimeno, L., Hernández, E., Prieto, R., and Ribera, P.: 2000, Reconstructing the North Atlantic atmospheric circulation in the 16th, 17th and 18th centuries from historical sources, *Climate Res.* **14**, 147–151.

Glaser, R.: 1996, Data and methods of climatological evaluation in historical climatology, *Historical Social Research* **21**, 56–88.

Greenbaum, N., Schick, A. P., and Baker, V. R.: 2000, The palaeoflood record of a hyperarid catchment, Nahal Zin, Negev Desert, Israel, *Earth Surf. Proc. Land.* **25**, 951–971.

Hirschboeck, K. K.: 1991, Climate and floods, In: *National Water Summary 1988–1989*, *Floods and Droughts: Hydrologic Perspectives on Water Issues*, US Geol. Surv. Water-Sup. Paper 2375, pp. 67–88.

House, P. K., Webb, R. H., Baker, V. R., and Levish, D. R. (eds): 2002, *Ancient Floods*, *Modern Hazards: Principles and Applications of Palaeoflood Hydrology*, Water Science and Application, Vol. 5, American Geophysical Union, 385 pp.

IPCC: 2001, In: R. T. Watson and the Core Writing Team (eds), *Climate Change 2001: Synthesis Report.* A contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge UK, 398 pp.

Jarret, R. D.: 1990, Paleohydrologic techniques used to define the spatial occurrence of floods, *Geomorphology* **3**, 181–195.

Jarret, R. D.: 1991, Paleohydrology and its value in analyzing floods and droughts, *US Geol. Surv. Water-Sup. Paper* 2375, 105–116.

Kale, V. S., Ely, L. L., Enzel, Y., and Baker, V. R.: 1994, Geomorphic and hydrologic aspects of monsoon floods in the Narmada and Tapi rivers in central India, *Geomorphology* **10**, 157–168.
Knox, J. C.: 1985, Responses of floods to Holocene climatic change in the upper Mississippi Valley, *Quaternary Res.* **23**, 287–300.
Knox, J. C.: 1993, Large increases in flood magnitude in response to modest changes in climate, *Nature* **361**, 430–432.
Knox, J. C.: 2000, Sensitivity of modern and Holocene floods to climate change, *Quaternary Sci. Rev.* **19**, 439–457.
Kochel, R. C., Baker, V. R., Patton, P. C.: 1982, Paleohydrology of Southwestern Texas, *Water Resour. Res.* **18**, 1165-1183.
Lane, W. L. and Cohn, T. A.: 1996, Expected moments algorithm for flood frequency analysis, *North American Water and Environment Congress '96*, June 22–28, Anaheim, Ca, USA, 6 pp.
Levish, D. R., Ostenaa, D. A., and O'Connel, D. R. H.: 1997, Paleoflood Hydrology and dam safety, In: *Proceedings of the International Conference on Hydropower*, *Waterpower '97*, August 5–8, 1997, Atlanta, GA, pp. 2205–2214.
Levish, D. R.: 2002, Palaeohydrologic bounds – non-exceedance information for flood hazard assessment, In: P. K. House, R. H. Webb, V. R. Baker and D. Levish (eds), *Ancient Floods, Modern Hazards: Principles and Applications of Palaeoflood Hydrology*, *Water Science and Application*, Vol. 5, American Geophysical Union, pp. 175–190.
Llasat, M. C.: 1997, Meteorological conditions of heavy rains, *UNESCO: FRIEND Flow Regimes from International Experimental and Network Data. Third report: 1994–1997*, pp. 269–276.
Mook, W. G. and Waterbolk, H. T.: 1985, *Radiocarbon Dating*, Handbooks for Archaeologists No. 3, European Science Foundation, Strasbourg, 65 pp.
Munich Re Group: 2000, Welt der Naturgefahren/World of Natural Hazards, Münchener Rückversicherungs-Gesellschaft, Munich, CD-ROM.
O'Connell, D. O., Levish, D. R., and Ostenaa, D.: 1997, Bayesian flood frequency analysis with paleohydrologic bounds for late Holecene paleofloods, Santa Ynez River, California, In: E. C. Gruntfest (ed.), *Twenty Years Later: What We Have Learned Since the Big Thompson Flood*, Special Publication 33, Natural Hazards Research and Applications Information Center, University of Colorado, pp. 183–196.
O'Connor, J. E., Ely, L. L., Wohl, E. E., Stevens, L. E., Meli, T. S., Kale, V. S., Baker, V. R.: 1994, 4000-year record of large floods on the Colorado River in the Grand Canyon, *J. Geol.* **102**, 1–9.
Ouarda, T. B. M. J., Rasmussen, P. F., Bobée, B., and Bernier, J.: 1998, Use of historical information in hydrologic frequency analysis, *Water Sciences Journal/Revue des Sciences de l'Eau* **11**, 41–49.
Partridge, J. and Baker, V. R.: 1987, Palaeoflood hydrology of the Salt River, Arizona, *Earth Surf. Proc. Land.* **12**, 109–125.
Patton, P. C., Baker, V. R., and Kochel, R. C.: 1979, Slackwater deposits: a geomorphic technique for the interpretation of fluvial palaeohydrology, In: D. D. Rhodes and G. P. Williams (eds), *Adjustments of the Fluvial System*, Kendall-Hunt, Dubuque, IO, USA, pp. 225–252.
Pickup, G., Allan, G., and Baker, V. R.: 1988, History, paleochannels and paleofloods of the Finke river, Central Australia, In: Warner, R.F. (ed.), *Fluvial Geomorphology of Australia*, Academic Press, Sydney, pp. 177–200.
Porporato, A. and Ridolfi, L.: 1998, Influence of weak trends on exceedance probability, *Stoch. Hydrol. Hydraul.* **12**, 1–14.
Potter, K. W. and Walker, J. F.: 1981, A model of discontinuous measurement error and its effects on the probability distribution of flood discharge measurements, *Water Resour. Res.* **17**, 1505–1509.
Redmond, K. T., Enzel, Y., House, P. K., and Biondi, F.: 2002, Climate impact on flood frequency at the decadal to millennial time scales, In: P. K. House, R. H. Webb, V. R. Baker and D. Levish (eds), *Ancient Floods*, *Modern Hazards: Principles and Applications of Palaeoflood Hydrology*, Water Science and Application, Vol. 5, American Geophysical Union, pp. 21–45.

Sánchez Rodrigo, F., Esteban-Parra, M.J. and Castro-Díez, Y.: 1995, The onset of the Little Ice Age in Andalusia (Southern Spain): Detection and characterisation from documentary sources, *Annales Geophysicae* **13**, 330–338.

Stedinger, J. R. and Baker, V. R.: 1987, Surface water hydrology: historical and paleoflood information, *Rev. Geophys.* **25**, 119–124.

Stuiver, M.: 1978, Radiocarbon timescale tested against magnetic and other dating methods, *Nature* **273**, 271–274.

Thorndycraft, V. R., Benito, G., Barriendos, M., and Llasat, M. C. (eds.): 2003, *Palaeofloods, Historical Data and Climatic Variability: Applications in Flood Risk Assessment*, CSIC, Madrid, 372 pp.

U.S. Water Resources Council: 1982, *Guidelines for Determining Flood Flow Frequency*, U.S. Interagency Advisory Committee on Water Data, Hydrology Subcommittee, Bulletin 17B, Washington D.C., 28 pp.

Van Gelder, P. H. A. J. M.: 1996, A new statistical model for extreme water levels along the Dutch coast, In: K. S. Tickle, I. C. Goulter, C. Xu, S. A. Wasimi, and F. Bouchart (eds), *Stochastic Hydraulics '96*, Balkema, Rotterdam, pp. 243–249.

Wang, Q. J.: 1990, Unbiased estimation of probability weighted moments and partial probability weighted moments from systematic and historical flood information and their application to estimating the GEV distribution, *J. Hydrol.* **120**, 115–124.

Webb, R. H. and Betancourt, J. L.: 1990, *Climatic Variability and Flood Frequency of the Santa Cruz River*, *Pima County*, *Arizona*, US Geological Survey, Open-File Report 90-553, 69 pp.

Webb, R. H., O'Connor, J. E., and Baker, V. R.: 1988, Paleohydrologic reconstruction of flood frequency on the Escalante River, South-Central Utah, In: R. V. Baker, R. C. Kochel and P. C. Patton (eds), *Flood Geomorphology*, Wiley, New York, pp. 403–418.

Wells, L. E.: 1990, Holocene history of the El Niño phenomenon as recorded in flood sediments of the northern coastal Peru, *Geology* **18**, 1134–1137.

Yang, D., Yu, G., Xie, Y., Zhan, D., and Zhijia, L.: 2000, Sedimentary records of large Holocene floods from the middle reaches of the Yellow River, China, *Geomorphology* **33**, 73–88.

Zawada, P. K.: 1997, Paleoflood hydrology: method and application in flood-prone southern Africa, *South Africa Journal of Science* **93**, 111–132.