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Palaeoflood records applied to assess dam safety in SE Spain

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ABSTRACT: Spanish dam safety regulations recommend the estimation of a return period of 1000 years for the Design Flood and of 10,000 for the Safety Check Flood, which are obtained from Flood Frequency Analysis (FFA) or on the Probable Maximum Flood (PMF). Short gauge records afford little support for the FFA or the hypothetical PMF, which in addition to the absence of an associated probability, limits the utility of these indices for risk-based dam safety decisions. Palaeoflood hydrology was applied to the Guadalentín River, upstream of the Valdeinfierno reservoir (372 km^2), which has a spillway capacity of 550 m^3s^{-1} (design flood). Palaeoflood data and gauge station records, were combined for the FFA, using the maximum likelihood estimates of the parameters for a Gumbel distribution, providing a discharge of 2350 m^3s^{-1} for the design flood (1000-yr flood) and 3450 m^3s^{-1} for the safety check flood (10,000-yr flood). The PMF discharge is 5786 m^3s^{-1}, showing an overestimation of this empirical method.

1 INTRODUCTION

Understanding the magnitude and frequency of extreme floods is critical for the design of hydraulic structures such as dams. Dams are designed, constructed and modified, when necessary, such that a catastrophic failure is prevented during a large flood. Civil engineers when designing a dam must establish the capacity of the dam and the rate at which water can be passed through the dam by means of flood gates and spillways. Dam safety components are established by two concepts: (1) the design flood and (2) the safety check flood. The design flood refers to the flood magnitude for which hydraulic design of spillways and energy dissipating structures have been designed, with a safety margin provided by the freeboard. The safety check flood represents the most extreme flood conditions that the dam structure could support without failure, including a low safety margin (worst flood scenario). Past experience indicate that overtopping represents more than 40% of dam failures, showing that extreme floods constitute an important risk for dam safety (ICOLD 1995).

According to Spanish regulations on dam safety (MOPTMA 1996), dam category depends upon the potential economic losses and human threats on downstream settlements. The Civil Protection Basic Framework on Flood Risk (MJI 1995), therefore, classifies dams into three categories: (A) High Hazard, (B) Significant Hazard, and (C) Low Hazard. A failure in a "high hazard" class of dam may cause loss of life, serious damage to residential, industrial, or commercial buildings; or damage to, or disruption of, important public utilities or transportation facilities such as major highways or railroads. The class "significant hazard" includes dam in which failure poses no threat to life but may cause significant damage to main roads, minor railroads, or cause interruption in the service of public utilities. A failure of a "low hazard" class of dam would at the most result in damage to agricultural land, farm buildings (excluding residences), or minor roads. In this flood risk Directive, the estimation of the design flood is based on probabilistic methods (statistical analysis and hydrometeorologic estimations) in which the use of historical data is highly recommended. The Spanish Committee on Large Dams (Comité Español

Table 1. Number of significant loss of life (N) according to national regulations and selection of design flood (modified from Berga 1998).

Dam hazard category	Loss of life	Impacts*	Design flood	Safety check flood
High	>N	Excessive	% PMF or 1000–5000	% PMF or 5000–10,000
Significant	0–N	Significant	% PMF or 500–1000	% PMF or 1000–5000
Low	0	Minimal	100	100–500

* Economic, social, environmental & political impacts.

de Grandes Presas 1997, Penas et al. 1997) recommends the estimation of a return period of 1000 years for the design flood and of 10,000 years for the safety check flood (Table 1). The estimation of such low frequency floods are based on either probabilistic or deterministic approaches.

The deterministic method relies on the concept of the Probable Maximum Flood (PMF) or the greatest amount of precipitation theoretically possible within a region (Maximum Probable Precipitation, PMP) subsequently maximized through "moisture maximization" and other numerical methods, finally turned into runoff or flood discharge, this depending on the characteristics of the drainage basin (Berga 1998). This methodology is complex especially in large basins due to the timing of different flood hydrographs and different land use scenarios. In addition, this deterministic approach is limited due to the lack of probability value associated to the PMF, which impedes its use on the decision support for flood risk analysis.

In most European countries, the dam design determines the probability that a storm will cause the dam to overflow and consequently destroy the structure. In Spain, most of the existing dams were designed with flood gates to handle flows upto the 500-yr flood i.e. a flood that occurs on average once in five hundred years (recurrence probability of 0.002). This statistical analysis is based either on streamflow gauge records or on hydrometeorological analysis from precipitation associated with different return periods. If the reliability of flood design and safety check flood estimation is to be improved, there is a critical need to specifically extend the record of the instrumental period (systematic period) of extreme floods. This record is usually limited to only a few dozens of years and the largest floods are therefore under-rated in the data. Information on hydrological variability and extreme floods can be completed using either or both palaeoflood hydrology and/or written chronicles of historical floods. Long records of extreme floods are then applied successfully in the design of dams and flood gates, combining palaeofloods, historical and instrumental records within the statistical analysis or testing the analysis performed in the calculation of the PMF. The statistical analysis can also contribute/benefit from regionalisation to generate statistics of extremes from combining records from several sites.

Recently, a new Dam Safety Program was launched by the Spanish Government, in which different methodological approaches to dam-safety design criteria are being revised at pilot areas. In this study, a combination of methods for the estimation of the design and safety check floods have been used in the upper Guadalentín basin, SE Spain. The specific objectives of the study are to: (1) extend the instrumental flood record to past using palaeoflood and historical data; (2) combine systematic and non-systematic information on the flood frequency analysis (FFA); (3) compare the results of the FFA using palaeoflood and historical data with those obtained from hydrometeorological methods and from the PMF; (4) estimate the design flood and the safety check flood; (5) discuss the contribution of palaeoflood hydrology to dam safety issues in Spain.

2 STUDY AREA

The Guadalentín River is located in SE Spain and is a major tributary of the Segura River which flows into the Mediterranean. The study reach is located at the upper reach of the Guadalentín, at the junction of the Rambla Mayor and Caramel River (Fig. 1), and upstream of the tail of the Valdeinfierno reservoir. The Guadalentín River has a Mediterranean regime and it is known as one of the most torrential rivers in Spain. The mean monthly discharges show two maxima: (1) in spring with a twinfold peak in February–March and May–June, a (2) in fall (September to November) during which the most catastrophic floods have been produced. The gauge station is located at the Valdeinfierno dam with a drainage area of 540 km^2. This record covers the periods 1933–1949 and 1968 onwards, the largest peak discharge recorded being 178 m^{3}s^{-1} in 1946. It is important to note that most of the gauge record corresponds to mean daily discharges.

Palaeoflood studies were conducted at the Caramel River (El Posadero site), upstream of Valdeinfierno Reservoir. At this point the drainage basin is 311 km^2, with a mean discharge of 0.6 m^{3}s^{-1} and peak discharge of 178 m^{3}s^{-1}, as recorded at the gauge station. At the El Posadero site, the Caramel River and Rambla Mayor join at the entrance of a narrow bedrock canyon carved in Cretaceous limestones. The gorge is 15–30 m wide with bedrock walls 40 m high and a gravel bed channel. During flooding, flow is hydraulically controlled by the narrow canyon entrance, producing a hydraulic damming of the flow upstream of the constriction, which favoured the accumulation of flood deposits at the entrance sides. Palaeoflood sedimentation also occurred high along the canyon

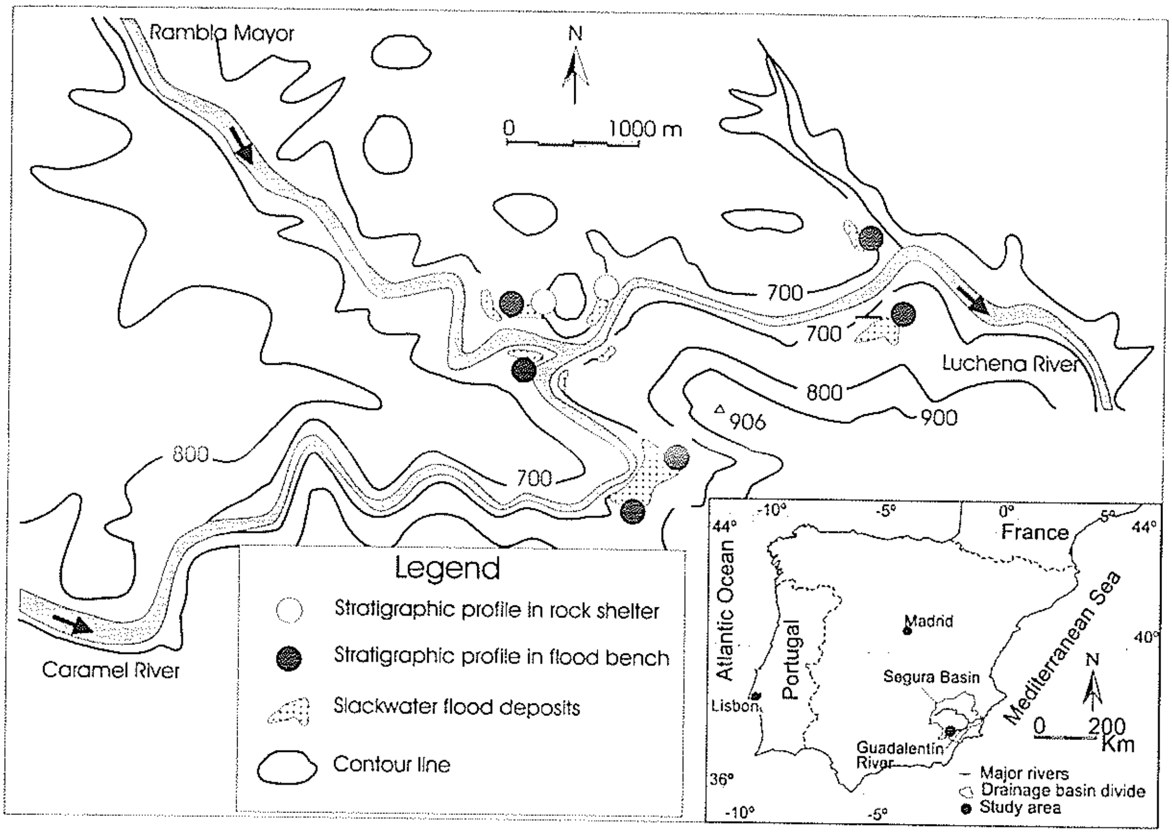

Figure 1. Location of the study area and stratigraphic profiles at the Rambla Mayor and Caramel River.

sides, bedrock caves and upstream of the canyon tributary gullies. Additional, documentary flood information of the Guadalentin at Lorca was obtained from bibliographic sources.

At the upper part of the basin, two dams where built mainly for irrigation purposes, and secondarily as flood control reservoirs. The most upstream one, Valdeinfierno, is located 5.2 km downstream of the study site, draining a catchment area of 540 km^2. The Valdeinfierno dam was built in 1806 for irrigation use and rebuilt in 1897 with a gravity structure of 51 m in height. It is 165 m in length and can hold a reservoir volume of 14 hm^3, with a spillway capacity of 673 m^{3}s^{-1} and a safety check flood of 850 m^{3}s^{-1}.

The Puentes dam drains a catchment area of 1388 km^2 and has a long history of catastrophic failures that affected the city of Lorca (13 km downstream). The Puente's dam construction started in 1647, but a year later, during the construction works, a flood caused the collapse of the structure. The dam was rebuilt in 1790 but a few years later, on April 30th 1802, the failure of the dam produced a catastrophic flood that caused 608 deaths in Lorca as well as large economic losses. In 1884 the Puentes dam was rebuilt with a spillway capacity of 945 m^{3}s^{-1}, although few years later was infilled by sediments. A new dam was built in 2000 close to the site of the former one, with a design flood of 2026 m^{3}s^{-1} and a safety check flood of 3626 m^{3}s^{-1}.

3 METHODOLOGY

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, and in this study there is a great emphasis on the last millennium. Palaeoflood hydrology is indeed defined by the fact that flood evidence is derived from lasting physical effects of floods on natural indicators, such as slackwater flood deposits, silt lines or scour lines.

During high flood stages in river canyons eddies, back-flooding and water stagnation occur at the gorge sides, producing low velocities and/or flow stagnation (slack water) that favours deposition from suspension of clay, silt and sand. These fine-grained deposits, known as slackwater flood deposits, are stage indicators of floods and can be preserved in stratigraphic sequences (Benito et al. 2003a) providing detailed and complete records of flood events that extend back several thousand of years (Baker & Kochel 1988). Slackwater flood deposits were found at three sedimentary settings: (1) forming flood benches at the sides upstream of narrow bedrock constrictions, (2) upstream of tributary valleys and (3) in rock alcoves (small caves or rock shelters formed in exposed bedrock on the valley sides) (Fig. 1). Stratigraphic and sedimentological analyses of the deposits were carried out both in the field and the laboratory, with sediment peels of the stratigraphic profiles, measuring approximately 80 cm × 50 cm in size, made in the field. Individual flood units were identified through a variety of sedimentological indicators (Baker & Kochel 1988, Benito et al. 2003b): the identification of clay layers at the top of a unit; erosion surfaces; bioturbation indicating the exposure of a sedimentary surface; angular clast layers, where local alcove or slope materials were deposited between flood events; and changes in sediment colour. As well as identifying individual flood units, sedimentary flow structures were also described in order to elucidate any changing dynamics during a particular flood event and/or infer flow velocities that can improve discharge estimation (Benito et al. 2003b).

Slackwater flood deposit chronology was determined using radiocarbon dating of charcoal collected from individual flood units. Necessary preparation and pre-treatment of the sample material for radiocarbon dating was carried out by the ^{14}C laboratory of the Department of Geography at the University of Zurich (GIUZ). The dating itself was done by AMS (accelerator mass spectrometry) with the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology, Zurich (ETH). Calibration of the radiocarbon dates was carried out using the CalibeETH 1.5b (1991) programme of the Institute for Intermediate Energy Physics ETH Zürich, Switzerland, using the calibration curves of Kromer & Becker (1993), Linnick et al. (1986) and Stuiver & Pearson (1993).

The discharge estimations associated with the slackwater flood deposits at the Luchena River were calculated using the US Army Corps of Engineers River Analysis System computer program-HECRAS (Hydrologic Engineering Center 1995). The computation procedure is based on the solution of the one-dimensional energy equation, derived from the Bernoulli equation, for steady gradually varied flow. Palaeoflood discharge reconstruction was based on the calculation of the step-backwater profile which best matches geological evidence of the flood stage.

Twenty cross-sections about 25 to 100 metres apart were obtained from field survey along a 1800 m reach where the stratigraphical sections are located. Cross-sections and flood deposit elevations, the input data for the hydraulic models, were surveyed along both study reaches using a Trimble 4700 kinematic differential GPS, with additional data using a Sokkia total station where satellite visibility was poor. The GPS comprised two GPS receivers (a fixed base station with known co-ordinates and a rover to measure the cross-sections) with a radio link between them both to allow real time data processing.

The accuracy of the discharge estimations depends on stability of the cross-section geometry through time. In stable, bedrock-confined channels, channel geometry at maximum stage is known. In this study, the gravel bed channel is susceptible for scour and fill of the channel which reduces the accuracy of the palaeodischarge modelling. Assuming recent channel bed aggradation due to the downstream reservoir construction, the resulting values would underestimate the peak flood discharges. In the modelling, it was assumed for the calculations that flow was subcritical along the modelled reach. Manning's n values of 0.03 and 0.04 over the valley floor and margins, respectively, were assigned. A sensitivity test performed on the model shows that for a 25% variation in roughness values, an error of 4% was introduced into the discharge results. Critical flow was selected as boundary conditions at the most downstream cross-section where the channel narrows into a bedrock section where a deep pool was created.

Discharge values associated with each slackwater bench were estimated upon calculated water surface profiles matching flood unit elevations at different sites along the longitudinal profile. Rating curves relating individual flood unit elevations with flood discharges were established at each site. High water marks from the largest instrumental flood that occurred in 1973 were also fitted in the model to estimate flood discharges.

Traditional methods of flood frequency analysis (FFA) assume that the distribution of the unknown magnitudes of the largest floods is well-represented by the gauged record or can be obtained by statistical extrapolation from recorded floods (usually modest floods). The value of palaeoflood data is the potential to include physical evidence of large floods, or limits on flood magnitude, over long time periods. 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 channels such as sediment deposits. It is also assumed a stationary of the long term incidence of floods. Palaeoflood data were organised in different threshold levels exceeded by flood waters over a given time period. In each threshold, individual floods are introduced as minimum, maximum, exact or range values of discharge, as well as the age dating. Data organisation on exceeded levels or thresholds reduces the potential palaeoflood discharge underestimation.

4 RESULTS

4.1 *Palaeoflood stratigraphy*

Nine stratigraphic profiles were described in a reach of 2.5 km in length. The slackwater flood deposit units varies between a few centimetres and 40 cm of fine to very fine sands and silts, with occasional clay, with gradual fining upward sequences. Massive, parallel lamination and cross-bedding are the dominant sedimentary structures.

A flood unit sequence usually culminates with climbing ripple structures overlaid by silt lamina which represents the end of the flood deposition. The oldest flood deposits were dated as 1985 ± 50 ^{14}C yrs BP (radiocarbon years before present), although the stratigraphic record contains major gaps between 2000 and 1000 BP (years before present).

The most complete section forms a flood bench on the right side of the Caramel River at the entrance of the gorge. The stratigraphic profile is ca. 7 m in thickness and provided evidence of at least 24 floods over the last 1000 years. The lower ten flood units have been dated between 1020 ± 50 and 945 ± 45 ^{14}C yrs BP, suggesting a period of frequent relatively small floods on the basis of the very fine and fine sand grain size and the thin layers. The top of this flood sequence is overlain by slope deposits which indicate a break in flood sedimentation of ca. 300 years (2-sigma age range overlaps). Overlying this are five flood layers, the lower one dated to 340 ± 45 ^{14}C yrs BP, which also have fine and very fine sand grain-size but they are generally thicker. These flood layers are capped by a 42 cm-thick colluvial layer, indicating a second break in flood sedimentation. The upper part of the section is represented by nine modern flood deposits, with a basal date of 205 ± 45 ^{14}C yrs BP, a middle date of 120 ± 45 ^{14}C yrs BP, and the upper flood layer likely left by the 1973 flood. Field evidences suggest that the 1973 flood was the largest event over the last 1000 years.

On the right side of the Rambla Mayor, also near the entrance of the gorge, a 2 m thick flood bench shows evidence of at least nine flood units with an oldest date of 190 ± 45 ^{14}C yrs BP, a middle date of 105 ± 45 ^{14}C yrs BP, and the upper deposits dated as modern. This stratigraphy is equivalent in flood unit number and chronology to the upper part of the previous stratigraphic profile.

The palaeoflood and historical flood information point out to an increase in the flood frequency and magnitude in modern times which can be attributed to climate variability accentuated by intensive deforestation and land use practices during the last 400 years.

4.2 *Discharge estimation*

Discharge values associated with each slackwater bench were estimated upon calculated water surface profiles matching the upper unit elevations at different sites along the longitudinal profile. The accuracy of the palaeodischarge estimates is reduced by the potential for scour and fill of the gravel channel bed. In the most complete stratigraphic profile, the lower 10 flood units (dated as 1020 ± 50 and 945 ± 45 ^{14}C yrs BP) are associated with minimum estimated discharges of 15 m^3s^{-1} and 580 m^3s^{-1}. The second set of flood units comprising five flood units (with a basal date of 340 ± 45 ^{14}C yrs BP) is associated with minimum discharges between 580 m^3s^{-1} and 680 m^3s^{-1} (Fig. 2). In this section the third fill set (at least nine flood units) containing a dating at the lower portion of this set of 205 ± 45 ^{14}C yrs BP matched with discharge estimates between 730 m^3s^{-1} and 1033 m^3s^{-1} (Fig. 2). These discharges are minimum estimates since the water depth above the flood units are unknown, and therefore, discharge values may be considered as conservative. However, high water marks of the 1973 flood found along the study reach provided an associated discharge of 1616 m^3s^{-1}, which shows that "exact" discharges may be 35% higher than the minimum estimates.

4.3 *Flood frequency analysis*

In the Valdeinfierno gauge station, the quality of the instrumental data is discontinuous, with most data corresponding to mean daily discharges. These mean daily discharges were transformed into peak discharges using nearby gauge data, but the degree of uncertainty was very high. Therefore, only peak discharges were used together with the palaeoflood data in the flood frequency analysis. The FFA was carried out with the MAX program (Stedinger et al. 1988), which computes the maximum likelihood estimates of the parameters of selected probability distributions. A critical assumption is that all the floods above specified discharge thresholds are recorded in the stratigraphy. In this study, only the floods postdating AD 1000 were used, since it was inferred that the stratigraphic record is complete for this time period. The exact date of each flood is not known, but the documentary flood record obtained in Lorca shows a great degree of agreement between the catastrophic historical floods and the number of floods recorded in the stratigraphy for specific time periods. Therefore, for practical purposes, each

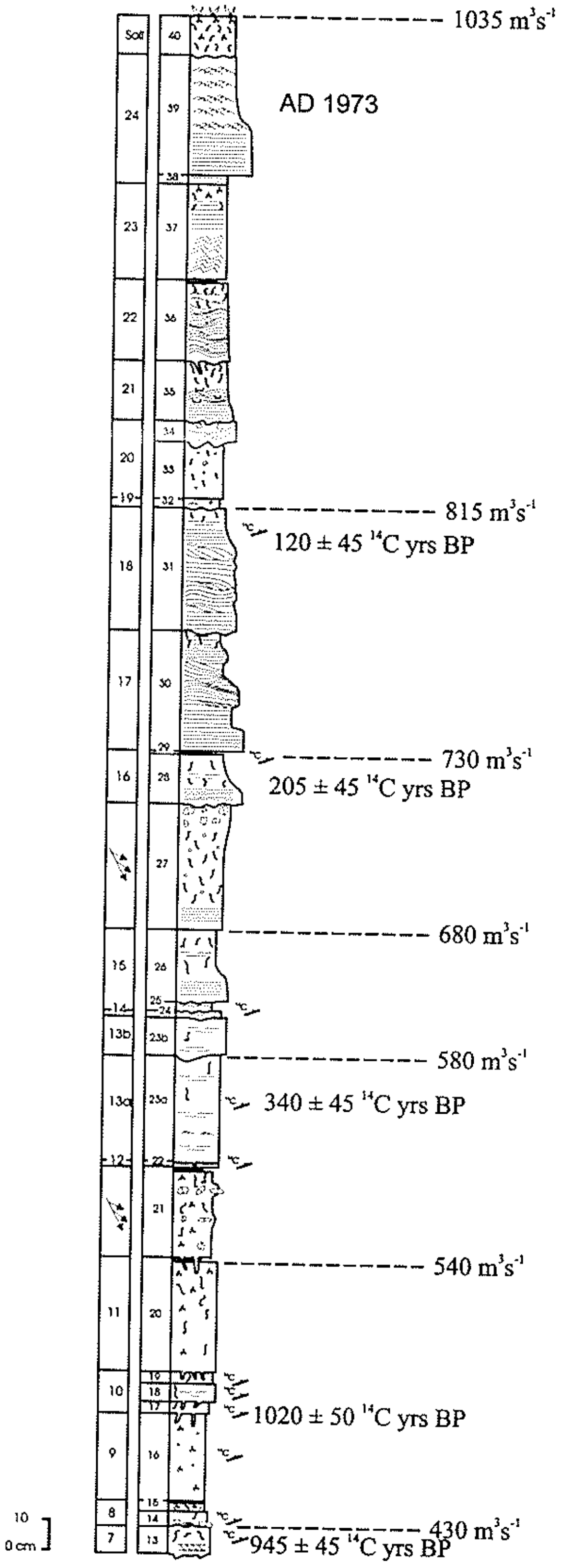

Figure 2. Stratigraphic profile, radiocarbon dates (years before present, yrs BP) and associated discharges (m^3s^{-1}).

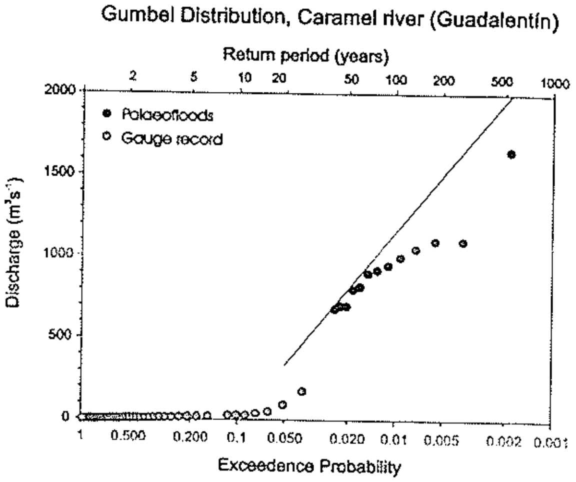

Figure 3. Gumbel distribution using gauge data (Valdeinfierno station) and palaeoflood records.

palaeoflood unit was assigned to a particular year of the historical flood record.

In this analysis, the best optimisation of the parameters was obtained using the Gumbel distribution. Plotting positions were assigned on the basis of the Weibull equation (Fig. 3). The analysis were conducted using only the last 1000 years palaeoflood record since it was noted major gaps in the previous stratigraphic record. According to this analysis the floods with return periods (T) of 100, 500, 1000, 5000 and 10,000 years correspond to discharges of 1150, 1950, 2300, 3100 and 3450 m^3s^{-1} respectively. These data are within the same order of magnitude of the rainfall-runoff analysis using a semidistributed model performed by CEDEX (Spanish Ministry of Development), in which discharges of 935, 1722, 2121, 3204 and 3727 m^3s^{-1} were calculated for the same return periods.

5 DISCUSSION

The palaeoflood data shows physical evidence of flood discharges with magnitudes almost 10 times higher than the ones recorded by the gauge station. In the studied stratigraphic profiles there is a good agreement on the number of flood units over specific time periods. A good agreement between the stratigraphic record and the documented catastrophic floods in Lorca was also found. This agreement among different data sources support the value of the palaeoflood evidence found in the study area. The potential for scour and fill of the gravely channel bed of the study reach reduces the accuracy of the palaeodischarge modelling, however, the deposits have fairly good chronological control and there is no indication of major cut and fill alluvial facies.

The FFA using palaeoflood and gauge data shows that the current design flood ($673\,m^3s^{-1}$) and the safety check flood ($850\,m^3s^{-1}$) for the Valdeinfierno dam are underestimated. The analysis using the palaeoflood data provided discharges of $2300\,m^3s^{-1}$, for the 1000-yr flood (design flood), and $3450\,m^3s^{-1}$ for the 10,000-yr flood (safety check flood). Similar conclusions can be extracted from the hydrological study performed by CEDEX in which the 1000 and 10,000-yr floods were estimated in 2121 and $3727\,m^3s^{-1}$.

Palaeoflood data can also be used for testing the analysis performed in the calculation of the PMF. The PMF has been used as a standard for hydrological analyses in dam safety for several decades (National Research Council 1985). By definition, the PMF has no return period but arbitrarily it was assigned a return period of 10,000 to 1,000,000 years at the upper and lower confidence limits for flood frequency analysis (National Research Council 1985). The PMF has been estimated for the Guadalentín River at the Valdeinfierno dam using an empirical equation based on the Meteorological World Organisation recommendations (OMM 1990), with a modification for the Spanish catchments introduced by CEDEX. According to this equation, the PMF estimated for the study reach is $5786\,m^3s^{-1}$. This value shows that the extrapolated discharges of the 10,000 year palaeoflood return period is about 60% of the calculated PMF, indicating that the calculated PMF discharges are very large overestimates. Similarly, palaeoflood studies performed for dam safety purposes by the U.S. 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). In the USA the extrapolated discharges of the 10,000 year palaeoflood return period are between 5 to 20% of the calculated PMF (Levish et al. 1996). 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 & Levish 1996).

6 CONCLUSIONS

This paper illustrates that palaeodischarge estimations can be obtained from sedimentological evidence of floodwater elevations reached by past floods. These palaeoflood data are based on "real" evidence of flood stages providing advantages over the uncertainties of other methods such as the hydrometeorological models or the deterministic (PMF) estimations. In the Guadalentín River, the 2000-yr flood record from palaeofloods indicates that floods of a larger magnitude (upto $1616\,m^3s^{-1}$) than any recorded in the instrumental record ($<180\,m^3s^{-1}$) have occurred in the past. The palaeoflood discharges can be combined with the gauge record to estimate high flood quantiles (500, 1000, 5000, 10,000 year return periods with discharges of 1150, 1950, 2300, 3100 and $3450\,m^3s^{-1}$ respectively), without relying on statistical extrapolations from short instrumental records. The current design flood ($673\,m^3s^{-1}$) and the safety check flood ($850\,m^3s^{-1}$) for the Valdeinfierno dam are underestimated, and they should be modified to $2300\,m^3s^{-1}$ for the design flood and $3450\,m^3s^{-1}$ for the safety check flood. Discharges obtained from the PMF ($5786\,m^3s^{-1}$) overestimated the discharge results, and they do not provide a realistic estimation of dam safety features (dam and spillway designs).

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