A LATE HOLOCENE PALAEOFLOOD RECORD FROM SLACKWATER FLOOD DEPOSITS OF THE LLOBREGAT RIVER, NE SPAIN

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Abstract

The palaeofloods of the Llobregat River are the first to be reconstructed for any Spanish Mediterranean river basin. In total, 56 individual slackwater flood units were identified in eight valley side alcoves located along two study reaches, Pont de Vilomara and Monistrol de Montserrat. The majority of the deposits are fine sands or very fine sandy silts, with a variety of sedimentary structures identified, namely parallel laminations, climbing ripples (both in-phase and in-drift) and current ripples. The estimation of the palaeoflood discharges associated with these deposits, using the HEC-RAS one-dimensional hydraulic model, has provided long-term data regarding flood magnitude within the catchment. Palaeofloods at Pont de Vilomara, radiocarbon dated to 2640 ± 55 BP and 2580 ± 75 BP, have minimum estimated discharges of 3700-4300 m^3s^{-1}. The largest palaeoflood at Monistrol de Montserrat, dated to 305 ± 50 BP, has an estimated minimum discharge of 4700 m^3s^{-1}. The results indicate that the instrumental discharge series is of insufficient length to have witnessed the largest magnitude flood events within the Llobregat catchment and that the use of palaeoflood hydrology is a valuable means of improving the flood record of Mediterranean catchments.

Keywords

Palaeoflood hydrology, Slackwater flood deposits, Late Holocene, N.E. Spain.

Introduction

Conventional flood risk assessment is based on the statistical analysis of flood data represented by associated probabilities of occurrence, non-occurrence and/or exceedence. This approach, however, is typically based on river gauging stations that are of a very short duration for most of the world's basins. In addition, as Baker *et al.* (2002) point out, the actual measurement of large magnitude flood discharge at gauging stations is often flawed due to the complex hydraulics involved and/or flood damage to the recording devices, as was the case with the 1971 and 2000 flood events of the Llobregat River (this paper). The statistical estimation, therefore, of rare, large magnitude flood events is based on the extrapolation of potentially unrepresentative data-sets, extrapolations that are not subject to testing against the real world (Baker, 2003a). The application of palaeoflood hydrology, the reconstruction of the magnitude and frequency of large floods using geological evidence (Baker *et al*, 2002), provides information about large magnitude flooding over longer time scales than is possible for instrumental discharge series (see Baker *et al*., 2002; Baker, 2003a, 2003b for critical discussions of the methodology). As a result, flood risk assessment can be measurably improved. Furthermore, physical evidence of extreme floods that occurred in the past, as opposed to statistical probabilities such as the hundred-year flood, can improve flood risk perception for both planners and the general public alike (Baker, 2003a, 2003b; Benito *et al*., 2003a; Thorndycraft *et al*., 2003a).

The use of palaeoflood hydrology for reconstructing long-term flood magnitudes and frequencies has been applied in many regions of the world, 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), Israel (Greenbaum *et al*., 2000), India (Ely *et al*., 1996; Kale *et al*., 2000), China (Yang *et al*., 2000) and Japan (Jones *et al*., 2001). However, despite Europe's increasing susceptibility to flooding, palaeoflood studies in the region have been limited (Benito, 2003; Benito *et al*., 1998, 2003b; Ortega and Garzón, 2003; Woodward *et al*., 2001). This imbalance has been addressed by the European Commission funded SPHERE project (Systematic, Palaeoflood and Historical data for the improvEment of flood Risk Assessment) that has promoted palaeoflood research in a number of Mediterranean river basins in Spain and France (Benito *et al*., in press; Thorndycraft *et al*., 2003b; Sheffer *et al*. 2003a, 2003b). This paper presents the stratigraphy and sedimentology of slackwater flood deposits (*cf*. Kochel and Baker, 1988; Benito *et al*., 2003c) discovered along two reaches of the Llobregat River. The estimated discharges of the largest palaeofloods will be discussed in relation to those from the Llobregat gauging station data.

Study area

The Llobregat River is located in Catalonia in north east Spain (Fig. 1) and has a drainage area of 4984 km^2. The study reaches are at Pont de Vilomara and Monistrol de Montserrat, where the catchment areas are 1845 km^2 and 3370 km^2 respectively (Figs. 1 and 2). The Llobregat River has a typically Mediterranean regime with extreme seasonal variations and flood peaks around 100 times greater than the mean annual discharge of 21 m^{3}s^{-1}. Large flood events are triggered by rainfall exceeding 200 mm within a 24 hour period (Llasat, 1991). The majority of the largest floods over the last century occurred in autumn and are associated with a synoptic pattern of anti-cyclonic conditions over Europe and warm, moist, air coming from the south-east that causes intense orographic rainfall over the coastal and pre-Pyrenean mountains (Llasat, 1991).

At both study reaches the river is confined by bedrock walls, as the river cuts north-south through the Eocene Conglomerates of the Prelittoral Cordillera and the Montserrat Massif. Slackwater flood sediments have been deposited and preserved in valley side rock alcoves developed within the predominantly horizontal rock strata.

Methodology

In bedrock gorges, during high flood stages, eddies, back-flooding and water stagnation occur at marginal areas of the gorge, 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 these floods that can be preserved in stratigraphic sequences. They can provide detailed and complete records of large floods that extend back several thousands of years (Kochel and Baker, 1988). The elevations derived from these palaeo-stage indicators can then be used to determine palaeodischarges through hydraulic modelling techniques (O'Connor and Webb, 1988).

Slackwater flood deposits were found in eight rock alcoves (small caves or rock shelters formed in exposed bedrock on the valley sides), two at Pont de Vilomara and six at Monistrol de Montserrat (Fig. 2). 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 x 50 cm in size, made in the field (Thorndycraft *et al*, in press). Individual flood units were determined through a close inspection of depositional breaks and/or indicators of surface exposure. The former include clay layers at the top of a unit and erosional contacts. Surface exposure may be indicated by the presence of: bioturbation; angular clast layers, where local alcove or slope materials were deposited between flood events; or fine-grained, reddish, alcove sediments. These latter deposits probably originate from slope wash on the valley sides above the rock alcoves, the clays and silts being transported by water entering the alcoves through rock fissures. The individual flood units identified are referred to in the text by the alcove code followed by the flood unit number indicated in the stratigraphic columns (Fig. 3).

Cross-sections and flood deposit elevations (see Figs. 2 and 3) were surveyed along both study reaches using a kinematic differential Global Positioning System (GPS), with additional data using a total station where satellite visibility was poor. The river channel bottom was surveyed using an echo-sound device mounted to a small boat and connected to the rover GPS, the data collected using a navigation software.

Flood chronology was determined by radiocarbon and caesium (^{137}Cs) dating (see Table 1 for a summary). Radiocarbon dating was carried out on charcoal sampled 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 and Becker (1993), Linnick *et al.* (1986) and Stuiver and Pearson (1993). ^{137}Cs analysis was first used successfully in dating modern slackwater flood sediments of the San Francisco and Paria rivers in the USA (Ely *et al*, 1992). Sample ^{137}Cs activity was determined at the University of Exeter, using a p-type coaxial HPGe detector. Count times were typically 30,000-50,000 seconds, providing a precision of ±10% at the 95% confidence level. A detailed discussion of the ^{137}Cs results can be referred to in Thorndycraft *et al.* (submitted).

Discharge estimation by hydraulic calculation was achieved using the step-backwater method (O'Connor and Webb, 1988), currently the most commonly utilised method in palaeoflood hydrology (Webb and Jarrett, 2002). The discharge associated with the slackwater flood deposits was carried out by computing the water surface profiles for various hypothetical discharges that were routed through the river reaches. Computations were run using the HEC-RAS one-dimensional model (Hydrologic Engineering Center, 1995) run within a GIS environment. By comparing the model-generated profiles to the slackwater flood deposit elevations palaeodischarges are specified. A sensitivity test performed on the model showed that for a 25% variation in Manning's *n* roughness values, an error of 5-10% was introduced into the discharge results. A more detailed discussion of the discharge estimation for the Llobregat River palaeofloods is provided in Thorndycraft *et al.* (in press).

Results

Palaeoflood stratigraphy and chronology

In total, 56 individual flood units have been identified at the two study reaches (Fig. 3). In general, the number of flood units preserved at the different sites reflects relationships between flood magnitude and frequency, with greater numbers of modern flood events located in the lower elevation alcoves such as alcove E. The two high elevation sites, A and C (Figs. 2 and 3), are the oldest deposits preserved. Two radiocarbon dates from alcove A (Table 1 and Fig. 3) indicate that the middle flood units of this sequence were deposited around 2600 BP (853-776 cal. B.C. and 794-554 cal. B.C.). The flood unit at alcove C has been radiocarbon dated to cal. A.D. 1516-1642.

The next oldest dated sediments are from alcove F, with the basal flood unit (F1) dated to 185 ± 55 BP (cal. A.D. 1686-1913, Table 1). This date is beyond the reliable applicable age range for radiocarbon dating (Trumbore, 2000) however, it is likely the sequence dates to the nineteenth century. The best dating control for the remaining slackwater sequences is provided by ^{137}Cs analysis, as the most recent sediments could only be assigned as modern, based on the radiocarbon results alone (Table 1). The benefit of the caesium method is that is permits the modern sedimentary record to be divided between those flood units deposited before or after the mid-1950s (Ely *et al.*, 1992). Due to local hydrological conditions at the different alcoves (Thorndycraft *et al.*, submitted) the technique was not applicable for dating slackwater flood sediments at all sites (Table 1). However, at the majority of the alcoves the measured ^{137}Cs was associated with sediment mobilised from the upstream catchment by erosion and transported to the alcoves during floods, permitting the dating of post mid-1950s flood deposits. Alcove E has most modern flood units, with 10 units post-dating the mid-1950s, this reflecting its close proximity to the river channel. The ^{137}Cs data from alcoves D, G and H indicate that only the largest two, two and three post mid-50s floods reached these alcoves respectively.

The characteristics of Llobregat River slackwater flood deposits

The slackwater flood deposits of the Llobregat River are predominantly composed of very fine to fine-grained sand with parallel laminations alternating with climbing ripples in drift and climbing ripples in phase (Table 2, Fig. 3). The particle size data from all the alcoves are presented in the ternary plot of percentage clay, silt and sand (Fig. 4). The finer-grained sediments, with higher percentage silt contents, are those from alcoves A and C. The coarsest sediments are those of alcoves B, D, E, G and H. They are characterised by mean medium sand contents in excess of 10% and greater than 40% fine sand (Table 2). There are no significant differences in the mineralogy of the sediments from the different sites of deposition. The grain mineralogy is dominated by carbonates and quartz with micas and feldspars also present. The heavy mineral assemblage is dominated by tourmaline, zircon and rutile. The remaining mineral suite, including staurolite and garnet, is indicative of a source in the metamorphic rocks of the Pre-Pyrenean headwaters of the Llobregat River.

The main characteristic sedimentary structures within the flood deposits are parallel laminations alternating with climbing ripples in drift and climbing ripples in phase, indicating an upstream flow direction (see Fig. 3). This deposition is interpreted herein as having been generated in a zone with a high sediment concentration. Sand excess produced aggradation by the migration of climbing ripples that indicate variations in flow velocity and high rates of vertical sediment build-up from suspension. As the deposits have been generated in a zone of flow recirculation, drift climbing ripples migrate upstream as a consequence of the return currents generated inside the alcove (Benito *et al*., 2003c). Climbing ripples that change vertically from climbing-in-drift to climbing-in-phase are normal when there are local fluctuations in velocity and a high sediment concentration. The parallel laminations present correspond to aggradation on a planar surface produced by sediment fallout with no traction. Similar sequences were described and interpreted in slackwater flood deposits of the Tagus River in Central Spain by Benito *et al*. (2003c).

Palaeodischarge estimates

The longitudinal profile of the Monistrol study reach (Fig. 5) presents the location of each alcove and the water surface elevations associated with a range of discharges. The largest estimated minimum discharge is 6200 m^3s^{-1}, matching the slackwater deposits of the C1 unit (Fig. 3). Also shown on Fig. 5 is a lower discharge of 4700 m^3s^{-1} associated with the energy line that we consider a more accurate estimation of the minimum discharge (Thorndycraft *et al*., in press). At this site, modelled channel flow velocity was over 6 ms^{-1}, with sub-critical flow conditions (Froude Number = 0.5). This indicates a sharp velocity transition from the channel to the canyon side where sedimentation was associated with stagnant water conditions, as evident from the parallel laminations of the C1 flood deposit. The discharge of 4700 m^3s^{-1} was obtained assuming that the sedimentation at the alcove (where the velocity head equals zero) was close to the maximum flow stage and related to the total energy head for the cross-section. Therefore, the discharge associated with the C1 unit is estimated as 4700-6200 m^3s^{-1}, with a preferred value closer to 4700 m^3s^{-1}.

The ranges of estimated discharges associated with the remaining slackwater flood deposits at each alcove are indicated in Table 3. They are based on the discharge estimates required for floodwaters to reach either the base of the alcove or the top of the palaeoflood sequence. In addition to the high estimated discharge associated with unit

C1, those of alcove A were also deposited by very high magnitude floods of 3700-4300 m^3s^{-1}, as illustrated by the rating curve from cross-section 8 of the Pont de Vilomara study reach (Fig. 6). Like the discharge associated with C1, this range in the magnitude of minimum discharges is based on the energy line. Also illustrated in Fig. 6 are the minimum discharge estimates for the modern slackwater flood deposits (B2) of the 1971 flood, with a range of 2300 to 2600 m^3s^{-1}, calculated using the energy line and the water surface elevation, respectively.

There are a number of alcoves (B, D, F and G) along the study reaches that require discharges in excess of 2000 m^3s^{-1} to top the flood sediments. Only two alcoves (E and H) were covered by the 2000 flood event, with a measured peak discharge of 1200 m^3s^{-1}. The elevation of floodwater during this event at alcove H (Fig. 5) was marked by silt lines on the gorge wall and fissures in the rock filled with flood debris.

Discussion

The Llobregat River palaeoflood sequence preserves evidence of large magnitude floods that have occurred during the last few thousand years. Radiocarbon dating of palaeoflood sediments associated with discharges of 4000 m^3s^{-1} or greater indicates that at least two of these extreme events occurred around the period of the 2650 BP climatic event (van Geel *et al*., 1998) and one during the Little Ice Age (ca. A.D. 1600 to 1850). Both these periods are recognised as cold-humid phases of climatic variability. The earlier phase is thought to be the result of increased solar activity around 800 cal. BC (van Geel *et al*., 1998). Within Spain, there are few radiocarbon dated fluvial sequences from this period. In Central Spain, two radiocarbon dates (2450 ± 60 BP and 2370 ± 80 BP) have been obtained from the middle section of gravel deposits formed by the actively meandering Jarama River (Alonso and Garzón, 1996). In S.E. Spain, at the confluence of the Librilla Rambla with the Guadalentín River, an 11 m sequence of high energy fluvial deposits is bracketed by radiocarbon dates of 3885 ± 60 BP and 2505 ± 45 BP (Calmel Avila, 2000 and 2002). There is certainly more evidence of increased fluvial activity at this time elsewhere in Europe, however, the presence of a ^{14}C plateau during this period makes precise correlation between the fluvial record and the climatic event difficult to make (Macklin and Lewin, 2003; Brown, 2003).

The Little Ice Age is widely recognised as being a period of increased flooding in Europe (for example, Rumsby and Macklin, 1996; Grove, 2001; Macklin and Lewin, 2003; Benito *et al*., 2003b). Despite the single dated palaeoflood unit from the Little Ice Age (C1), there is sedimentological evidence from the alcove A slackwater flood deposits for a number of flood events with preserved sediments from this period. In the upper flood units at the Pont de Vilomara site (A6-A8, Fig. 3) there is a pronounced shift in the particle size distribution. This can be seen in Fig. 4, where there are two distinct clusters of samples from alcove A, with the units A6-A8 containing an increased silt content and, therefore, plotting closer to the silt apex of the ternary diagram. Although the particle size distribution at a site of deposition may be dependent on the flow characteristics of the flood (Benito *et al.*, 2003c) it may also be dependent on the available source material. In this case, we hypothesise that the increased silt content is caused by widespread woodland clearance, occurring since the 15th Century in the region (Schulte, 2003), that caused increased rates of soil erosion. Interestingly, the C1 deposit dated to the Little Ice Age forms a cluster with the A6-A8 samples in the ternary diagram (Fig. 4). The increase in soil erosion at this time resulted in alluviation elsewhere in Catalonia, for example in the Bisbal catchment where alluviation post-dated cal. AD 1298-1422 (Schulte, 2003).

The alternative hypothesis for the increase in percentage silt content, related to an increase in flow velocity at the site of deposition, is not supported by the sedimentological information available. The sedimentary structures are similar throughout the alcove A sequence, with parallel lamination the main structure visible (Fig. 3). As noted earlier these can be interpreted as aggradation produced by fallout with no traction (Benito *et al.*, 2003c) indicating low flow velocities throughout the alcove A sequence. It is likely that, at the valley side alcoves, away from the main flow thalweg, there were no significant differences in flow conditions between different flood events. The use of palaeoflood slackwater deposits as indicators of changing catchment stability is a theme that merits further research in the Llobregat basin.

Irrespective of the precise dating or climatic cause of these extreme flood events, the slackwater flood deposits and associated palaeodischarge estimates provide tangible evidence of flood magnitudes greater than those measured during the modern instrumental period. Fig. 7 presents the most comprehensive instrumental flood record possible for the last ca. 100 years. The majority of the data comes from the Castellvell gauging station, located 3 km upstream of the Monistrol study reach. The palaeoflood record from alcoves A and C indicates much larger flood magnitudes than that of the 1971 flood, considered the largest on record. At Monistrol, the 4700 m^3s^{-1} minimum discharge associated with the C1 flood deposits compares to a recorded discharge of 2300 m^3s^{-1} for the 1971 flood. The palaeoflood evidence, therefore, illustrates that the gauging station data is not a representative record of the largest floods that may occur in the Llobregat catchment (Fig. 7). The implication is that the hydrological series is effectively too short to make informed decisions regarding flood risk and that additional palaeoflood data provides valuable evidence of flooding over longer timescales. In fact this may be even more so with respect to other Mediterranean basins as the discharge series of the Llobregat River, despite at times being a discontinuous record, is probably one of the longest in the region.

Conclusions

The palaeoflood record of the Llobregat River is the first to be reconstructed for any Spanish Mediterranean river basin. The preserved sedimentary evidence indicates that large magnitude floods occurred around the period of the wetter and cooler 2650 BP climatic event. Two flood units were dated to 853-776 cal. B.C. and 794-554 cal. B.C. at the Pont de Vilomara study reach. The range of estimated minimum discharges associated with the Pont de Vilomara deposits is 3700-4300 m^3s^{-1}, compared to 2300-2600 m^3s^{-1} estimated for the highest modern slackwater deposits, those of the 1971 flood. At the Monistrol study reach, the minimum discharge of the largest palaeoflood, was estimated as 4700 m^3s^{-1} for a flood unit dated to cal. A.D. 1516-1642, this value being significantly larger than the recorded discharge of 2300 m^3s^{-1} for the 1971 flood. The use of palaeoflood hydrology has shown that the instrumental flood record of the Llobregat River is insufficient to make fully informed decisions regarding flood risk as it is not a representative record of the largest floods within the catchment. Indeed, with a continued increase in the development and urbanisation of Mediterranean catchments, there is a critical need for improved flood risk assessment based on real flood data rather than statistical extrapolations of short flood series. Sedimentological evidence of former flood stages is one means of achieving this goal.

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References

Alonso, A. and Garzón, G., 1996. The Jarama River. In G. Benito, A. Pérez-González, M.J. Machado and S. de Alba (Editors), Palaeohydrology in Spain: Field Excursion Guide. Second International Meeting on Global Continenal Palaeohydrology, GLOCOPH ’96, pp. 21-34.

Baker, V.R., 2003a. Palaeofloods and extended discharge records. In: K.J. Gregory and G. Benito (Editors), Palaeohydrology: Understanding Global Change. John Wiley & Sons Ltd, Chichester, UK, pp. 307-323.

Baker, V.R., 2003b. A bright future for old flows: origins, status and future of paleoflood hydrology. In: V.R. Thorndycraft, G. Benito, M. Barriendos and M.C. Llasat (Editors), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid, pp. 13-18.

Baker, V.R. and Pickup, G., 1987. Flood geomorphology of the Katherine Gorge, Northern Territory, Australia. Geological Society of America. Bulletin, 98: 635-646.

Baker, V.R., Webb, R.H. and House, P.K., 2002. The Scientific and societal value of paleoflood hydrology. In: P.K. House, R.H. Webb, V.R. Baker and D.R. Levish (Editors), Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. Water Science and Application Series, Vol. 5, AGU, Washington D.C. pp. 127-146.

Benito, G., 2003. Palaeoflood hydrology in Europe. In: V.R. Thorndycraft, G. Benito, M. Barriendos and M.C. Llasat (Editors), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid, pp. 19-24.

Benito, G., Machado, M.J., Pérez-González, A. and Sopeña, A., 1998. Palaeoflood hydrology of the Tagus River, Central Spain. In: G. Benito, V.R. Baker and K.J. Gregory (Editors), Palaeohydroloy and Environmental Change. John Wiley & Sons, Chichester, UK, pp. 317-333.

Benito, G., Thorndycraft, V.R., Llasat, M.C. and Barriendos, M., 2003a: Paleocrecidas, datos históricos y variabilidad climatica. Cuaternario y Geomorfología, 17: 5-7.

Benito, G., Sopeña, A., Sánchez-Moya, Y., Machado, M.J. and Pérez-Gonzalez, A., 2003b. Palaeoflood record of the Tagus River (Central Spain) during the Late Pleistocene and Holocene. Quaternary Science Reviews, 22: 1737-1756.

Benito, G., Sánchez-Moya, Y. and Sopeña, A., 2003c. Sedimentology of high-stage flood deposits of the Tagus River, Central Spain. Sedimentary Geology, 157: 107-132.

Benito, G., Lang, M., Barriendos, M., Llasat, M.C., Francés, F., Ouarda, T., Thorndycraft, V.R., Enzel, Y., Bardossy, A., Coeur, D. and Bobée, B., in press.

Use of systematic, palaeoflood and historical data for the improvement of flood risk estimation. Review of scientific methods. Natural Hazards.

Brown, A.G., 2003. Global environmental change and the palaeohydrology of Western Europe: a review. In: K.J. Gregory and G. Benito (Editors), Palaeohydrology: Understanding Global Change. John Wiley & Sons Ltd, Chichester, UK, pp. 105-121.

Calmel-Avila, M., 2000, Procesos hídricos holocenos en el bajo Guadalentín (Murcia, SE España). Revista de Cuaternario y Geomorfología, 14, 65-78.

Calmel-Avila, M., 2002. The Librilla "rambla", an example of morphogenetic crisis in the Holocene (Murcia, Spain). Quaternary International, 93-94, 101-108.

Ely, L.L. and Baker, V.R., 1985. Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona. Physical Geography, 6: 103-126.

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, Bulletin of the Geological Society of America, 1134-1148.

Ely, L.L., Webb, R.H. and Enzel, Y., 1992. Accuracy of post-bomb ^{137}Cs and ^{14}C in dating fluvial deposits. Quaternary Research, 38: 196-204.

Greenbaum, N., Schick, A.P. and Baker, V.R., 2000. The paleoflood record of a hyperarid catchment, Nahal Zin, Negev Desert, Israel. Earth Surface Processes and Landforms, 25: 951-971.

Grove, A.T., 2001. The "Little Ice Age" and its geomorphological consequences in Mediterranean Europe. Climatic Change, 28: 121-136.

Hydrologic Engineering Center, 1995. HEC-RAS, River Analysis System, Hydraulics Reference Manual, (CPD-69).

Jones, A.P., Shimazu, H., Oguchi, T., Okuno, M. and Tokutake, M., 2001. Late Holocene slackwater deposits on the Nakagawa River, Tochigi Prefecture, Japan. Geomorphology, 39: 39-51.

Kale, V.S., Singhvi, A.K., Mishra, P.K. and Banerjee, D., 2000. Sedimentary records and luminescence chronology of Late Holocene palaeofloods in the Luni River, Thar Desert, northwest India. Catena, 40: 337-358.

Kochel, R.C. and Baker, V.R., 1988. Paleoflood analysis using slack water deposits. In:. V.R. Baker, R.C. Kochel and P.C. Patton (Editors), Flood Geomorphology. John Wiley & Sons Ltd., U.S.A., pp. 357-376.

Kochel, R.C., Baker, V.R. and Patton, P.C., 1982. Palaeohydrology of southwest Texas. Water Resources Research, 18: 1165-1183.

Kromer, B. and Becker, B., 1993. German oak and pine C-14 calibration, 7200-9439 BC. Radiocarbon, 35: 125-135.

Linnick, T.W., Long, A., Damon, P.E. and Ferguson, C.W., 1986. High-precision radiocarbon dating of bristlecone-pine from 6554 to 5350 BC. Radiocarbon, 28: 943-953.

Llasat, M.C., 1991. Gota Fría. Boixareu Universitaria, no. 6, Barcelona, Spain, 165 pp.

Macklin, M.G. and Lewin , J., 2003. River sediments, great floods and centennial-scale Holocene climate change. Journal of Quaternary Science, 18: 101-105.

O’Connor, J.E. and Webb, R.H., 1988. Hydraulic modelling for palaeoflood analysis. In V.R. Baker, R.C. Kochel and P.C. Patton (Editors), Flood Geomorphology. John Wiley & Sons, NY, pp. 383-402.

O’Connor, J.E., Ely, L.L., Stevens, L.E., Melis, T.S., Kale, V.S. and Baker, V.R., 1994. A 4500-year record of large floods in the Colorado River in the Grand Canyon, Arizona. Journal of. Geology, 102: 1-9.

Ortega, J.A. and Garzón, G., 2003. Palaeohydrology of the Lower Guadiana River basin. In: V.R. Thorndycraft, G. Benito, M. Barriendos and M.C. Llasat (Editors), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid, pp. 33-38.

Pickup, G., Allan, G. and Baker, V.R.,, 1988. History, palaeochannels and palaeofloods of the Finke River, central Australia. In: R.F Warner (Editor), Fluvial Geomorphology of Australia. Academic Press, Sydney, pp. 177-200.

Rumsby, B.T. and Macklin, M.G., 1996. River response to the last neo-glacial (the “Little Ice Age”) in Northern, Western and Central Europe. In J. Branson, A.G. Brown and K.G. Gregory (Editors), Global Continental Changes: The Context of Palaeohydrology. Special Publication No. 115, Geological Society, London, 217-233.

Schulte, L., 2003. River-response and terrace aggradation in the Mediterranean Iberian Peninsula during historical times. In: V.R. Thorndycraft, G. Benito, M. Barriendos and M.C. Llasat (Editors), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid pp. 67-72.

Sheffer, N.A., Enzel., Y. and Benito, G., 2003a. Palaeofloods in southern France: the Ardèche River. In: V.R. Thorndycraft, G. Benito, M. Barriendos and M.C.

Llasat (Editors), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid, pp. 25-31.

Sheffer, N. A., Enzel Y., Benito G., Grodek T., Poart N., Lang M., Naulet R., Cœur D., 2003b. Historical and paleofloods of the Ardèche river, France. *Water Resources Research,* **39**, 1376.

Stuiver, M. and Pearson, G.W., 1993. High-precision bidecadal calibration of the radiocarbon timescale, AD 1950-500 BC and 2500-6000 BC. Radiocarbon, 35: 1-23.

Thorndycraft, V.R., Benito, G., Llasat, M.C. and Barriendos, M.. 2003a. Palaeofloods, historical data and climatic variability: applications in flood risk assessment. In: V.R. Thorndycraft, G. Benito, M. Barriendos and M.C. Llasat (Editors), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid pp. 3-9.

Thorndycraft, V.R., Benito, G., Walling, D.E., Sopeña, A., Sanchez, Y.. Rico, M. and Casas, A.. 2003b. Radiocarbon and Caesium-137 dating of slackwater flood deposits of the Llobregat River (NE Spain). In: V.R. Thorndycraft, G. Benito, M. Barriendos and M.C. Llasat (Editors), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid pp. 39-44.

Thorndycraft, V.R Benito G., Rico, M., Sánchez-Moya, Y., Sopeña A., and Casas, A. (in press). Palaeoflood hydrology of the Llobregat River, NE Spain: a 3000 year record of extreme flood events. Journal of Hydrology.

Thorndycraft, V.R., Benito, G., Walling, D.E., Sopeña, A., Sánchez-Moya, Y., Rico, M. and Casas, A. (submitted). Caesium-137 dating applied to slackwater flood deposits of the Llobregat River, N.E. Spain. Catena.

Trumbore, S.E., 2000. Radiocarbon Geochronology. In: J.S. Noller, J.M. Sowers and W.R. Lettis (Editors), Quaternary Geochronology: Methods and Applications, AGU, Washington D.C., pp.41-60.

Van Geel, B., Van der Plicht, J., Kilian, M.R., Klaver, E.R., Kouwenberg, J.H.M. Ressen, H., Reynaud-Farrera, I., Waterbolk, H.T., 1998. The sharp rise of $\delta^{14}C$ at ca. 800 cal. BC. Possible causes, related climatic teleconnections and the impact on human environments. Radiocarbon, 40, 335-350.

Webb, R.H. and Jarrett, R.D., 2002. One-dimensional estimation techniques for discharges of paleofloods and historical floods. In: P.K. House, R.H. Webb, V.R. Baker and D.R. Levish (Editors), Ancient Floods, Modern Hazards:

Principles and Applications of Paleoflood Hydrology. Water Science and Application Series, Vol. 5, AGU, Washington D.C, pp. 111-126.

Woodward, J.C., Hamlin, R.H.B., Macklin, M.G., Karkanas, P., Kotjabopoulou, P., 2001. Quantitative sourcing of slackwater deposits at Boila rockshelter: a record of late-glacial flooding and Palaeolithic settlements in the Pindus Mountains, Northern reece. Geoarchaeology, 16: 501-536.

Yang, H., Yu, G., Xie, Y., Zhan, D. and Li, Z., 2000. Sedimentary records of large Holocene floods from the middle reaches of the Yellow River, China. Geomorphology, 33: 73-88.

List of Tables

Table 1. Summary information regarding the radiocarbon and caesium-137 dating of the Llobregat River slackwater flood sediments.

Table 2. Summary of the mean particle size data, and the distribution of the different sedimentary structures, for the slackwater flood deposits preserved at each alcove.

Table 3. The discharge estimates calculated by the HEC-RAS one-dimensional model, indicating the minimum discharges required for the floodwaters to reach either the base or the roof of each alcove. * denotes a discharge estimated by using the energy line rather than water surface elevation (see the Results section for a more detailed explanation).

List of Figures

Figure 1. Map of the Llobregat River catchment and the Pont de Vilomara and Monistrol de Montserrat study reaches.

Figure 2. Maps of the Pont de Vilomara and Monistrol de Montserrat study reaches indicating the locations of the valley side alcoves preserving slackwater flood deposits and the surveyed topographic cross-sections.

Figure 3. The palaeoflood stratigraphy of the Pont de Vilomara and Monistrol de Montserrat study reaches (based on Thorndycraft *et al*., in press, submitted). The stratigraphy is presented in relation to elevation above the channel bed. The elevation scale is related to the upper flood unit in each alcove. In addition to the radiocarbon ages, the measureable ^{137}Cs activity in a flood unit is shown.

Figure 4. Ternary diagram for the sand, silt and clay content (%) of each individual flood unit from alcoves A-H. The flood units from alcove A are labelled.

Figure 5. Calculated water surface and energy line elevations for selected discharges related to the slackwater flood deposits at alcoves C-H along the Monistrol study reach. The elevation of debris and silt lines left above alcove H by the June 2000 flood is also indicated.

Figure 6. Rating curve for cross-section 8 of the Pont de Vilomara study reach (see Fig. 2 for location). The range of minimum discharge estimates for the alcove A slackwater flood deposits, calculated using the energy line, is illustrated along with the value obtained for the upper flood unit (A8) derived using the water surface elevation. The minimum discharge estimates for the 1971 flood, calculated using both the energy line and water surface elevation, are also shown. The elevation of this flood was derived from slackwater flood deposits at the adjacent cross-section 9 (alcove B).

Figure 7. Combined instrumental and palaeoflood discharge data for the Llobregat River. The annual series since 1942 is from Castellvell, the reference gauging station for the Monistrol de Montserrat study reach. To complete the series, the largest peak flows (>1500 m^{3}s^{-1}) from Martorell (1907-1942), are also illustrated. The instrumental data can be compared with the minimum discharge estimates associated with individual slackwater flood units (labelled).

Study reach	**Alcove**	**Caesium-137**		**Radiocarbon**			
		Caesium dating	**No. of flood units since mid-1950s**	**Laboratory No.**	**Flood Unit (Fig. 3)**	**Age (yrs BP)**	**One sigma calibrated age**
Pont de Vilomara	A	No	-	UZ-4523/ETH-23673	A4	2640 ± 55	853 BC, 776 BC
				UZ-4524/ETH-23674	A5	2580 ± 75	794 BC, 554 BC
	B	Yes	1				
Monistrol de Montserrat	C	No	-	UZ-4605/ETH-24418	C1	305 ± 50	AD 1516, AD 1642
	D	Yes	2	UZ-4738/ETH-25509	D2	modern	
				UZ-4515/ETH-23665	D2-3	modern	
	E	Yes	10	UZ-4520/ETH-23670	E2	modern	
				UZ-4521/ETH-23671	E6	modern	
				UZ-4522/ETH-23672	E11-12	modern	
	F	No	-	UZ-4517/ETH-23667	F1	185 ± 55	AD 1686, AD 1913
				UZ-4518/ETH-23668	F5	120 ± 50	AD 1712, AD 1904
				UZ-4519/ETH-23669	F11	modern	
	G	Yes	3	UZ-4516/ETH-23666	G1	modern	
	H	Yes	3	-			

Table 1

Alcove	**Mean particle size data (%)**					**Sedimentary structures (no. of flood units)**			
	Medium sand	**Fine sand**	**V. fine sand**	**Silt**	**Clay**	**Climbing – in drift**	**Climbing – in phase**	**Parallel lamination**	**Current ripples**
A	3.9	14.7	17.0	42.4	20.8	-	-	7	-
B	10.4	53.9	11.8	12.0	10.3	-		1	1
C	1.4	6.3	20.3	59.2	12.5			1	
D	18.6	45.1	12.6	12.6	9.4			1	
E	15.8	56.1	13.2	8.5	5.6	5	4	4	3
F	12.2	32.9	16.6	11.4	7.7	3		3	6
G	7.0	54.1	23.10	12.9	5.3	3	1		2
H	11.9	62.1	13.7	6.8	4.9	4		5	2

Table 2

Alcove	**Discharge Estimates (m^3s^{-1})**	
	Base of alcove	**Top of flood sediments**
A	3700*	4300*
B	2300	2600
C	-	4700*
D	1250	2500
E	200	440
F	860	2200
G	1800	2500
H	750	1000

Table 3

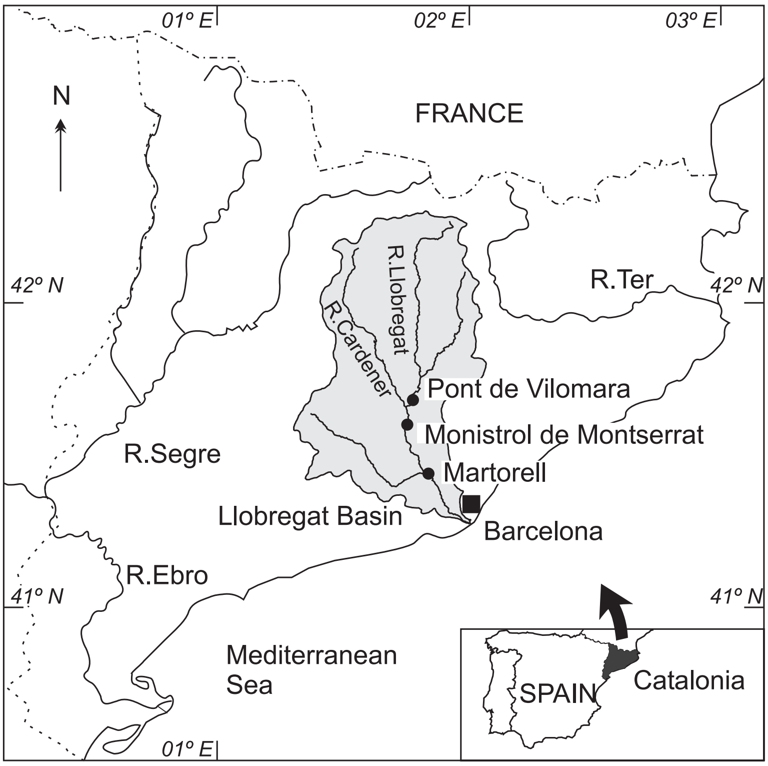

01º E
02º E
03º E
N
FRANCE
42º N
42º N
R.Llobregat
R.Cardener
R.Ter
Pont de Vilomara
Monistrol de Montserrat
Martorell
R.Segre
Llobregat Basin
Barcelona
R.Ebro
41º N
41º N
Mediterranean
Sea
SPAIN
Catalonia
01º E

Fig 1

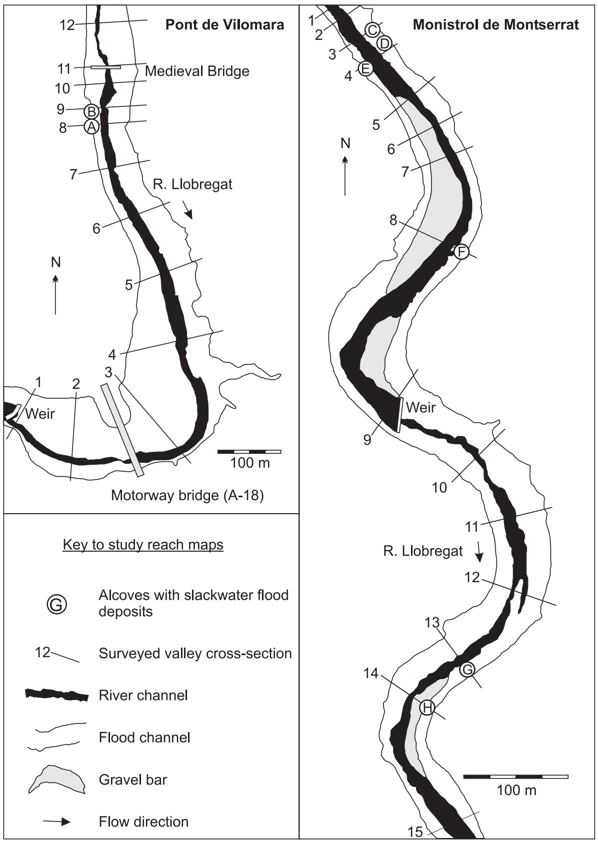
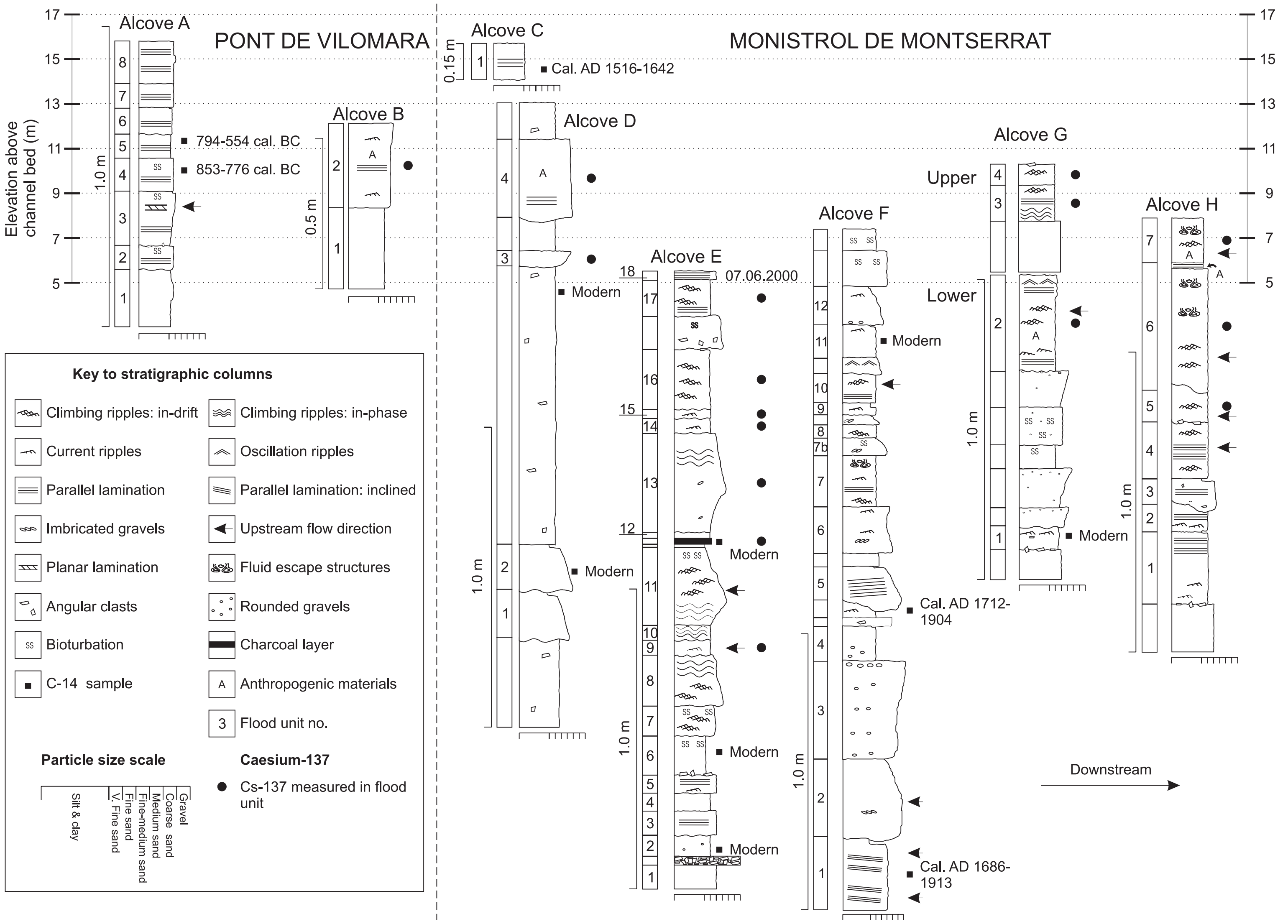

Pont de Vilomara
12
11
Medieval Bridge
10
9
B
8
A
7
R. Llobregat
6
N
5
4
1
2
3
Weir
100 m
Motorway bridge (A-18)
Monistrol de Montserrat
1
2
C
D
3
4
E
5
6
N
7
8
F
Weir
9
10
11
R. Llobregat
12
13
G
14
H
100 m
15
Key to study reach maps
G
Alcoves with slackwater flood deposits
12
Surveyed valley cross-section
River channel
Flood channel
Gravel bar
Flow direction

fig 2


PONT DE VILOMARA
MONISTROL DE MONTSERRAT
Elevation above channel bed (m)
17
15
13
11
9
7
5
Alcove A
794-554 cal. BC
853-776 cal. BC
Alcove B
Alcove C
Cal. AD 1516-1642
0.15 m
Alcove D
Modern
Alcove E
07.06.2000
Modern
Alcove F
Modern
Cal. AD 1712-1904
Cal. AD 1686-1913
Alcove G
Upper
Lower
Modern
Alcove H
1.0 m
0.5 m
Downstream
Key to stratigraphic columns
Climbing ripples: in-drift
Climbing ripples: in-phase
Current ripples
Oscillation ripples
Parallel lamination
Parallel lamination: inclined
Imbricated gravels
Upstream flow direction
Planar lamination
Fluid escape structures
Angular clasts
Rounded gravels
Bioturbation
Charcoal layer
C-14 sample
Anthropogenic materials
Flood unit no.
Particle size scale
Silt & clay
V. Fine sand
Fine sand
Fine-medium sand
Medium sand
Coarse sand
Gravel
Caesium-137
Cs-137 measured in flood unit

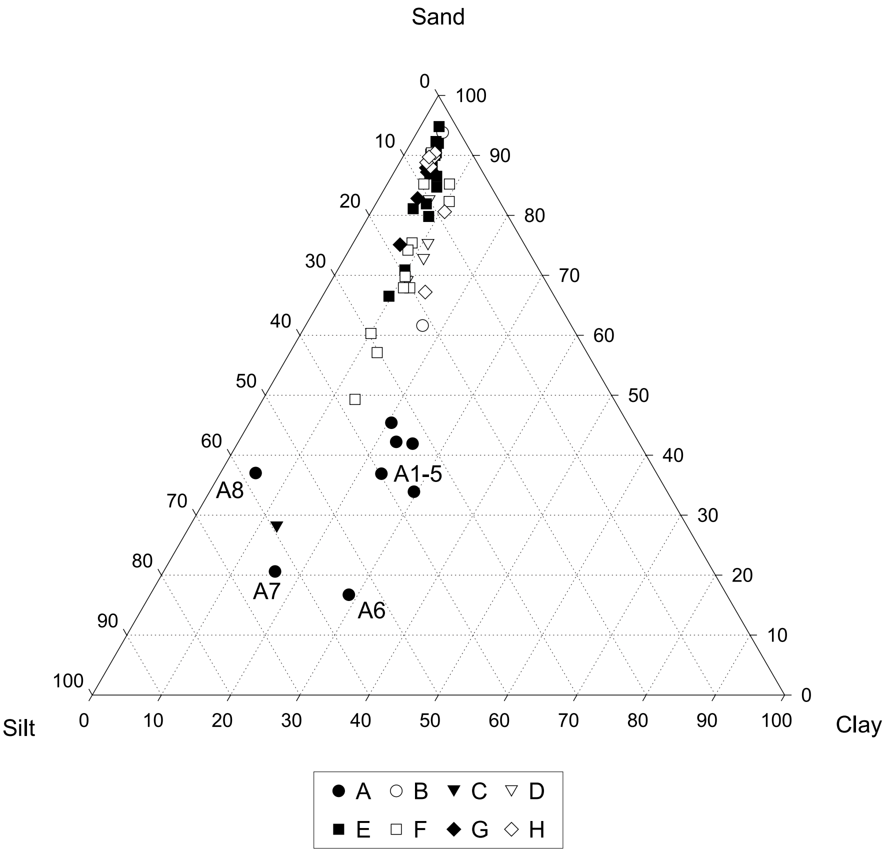

Sand
Silt
Clay
0
10
20
30
40
50
60
70
80
90
100
A8
A1-5
A7
A6
● A ○ B ▼ C ▽ D
■ E □ F ◆ G ◇ H

fig 4

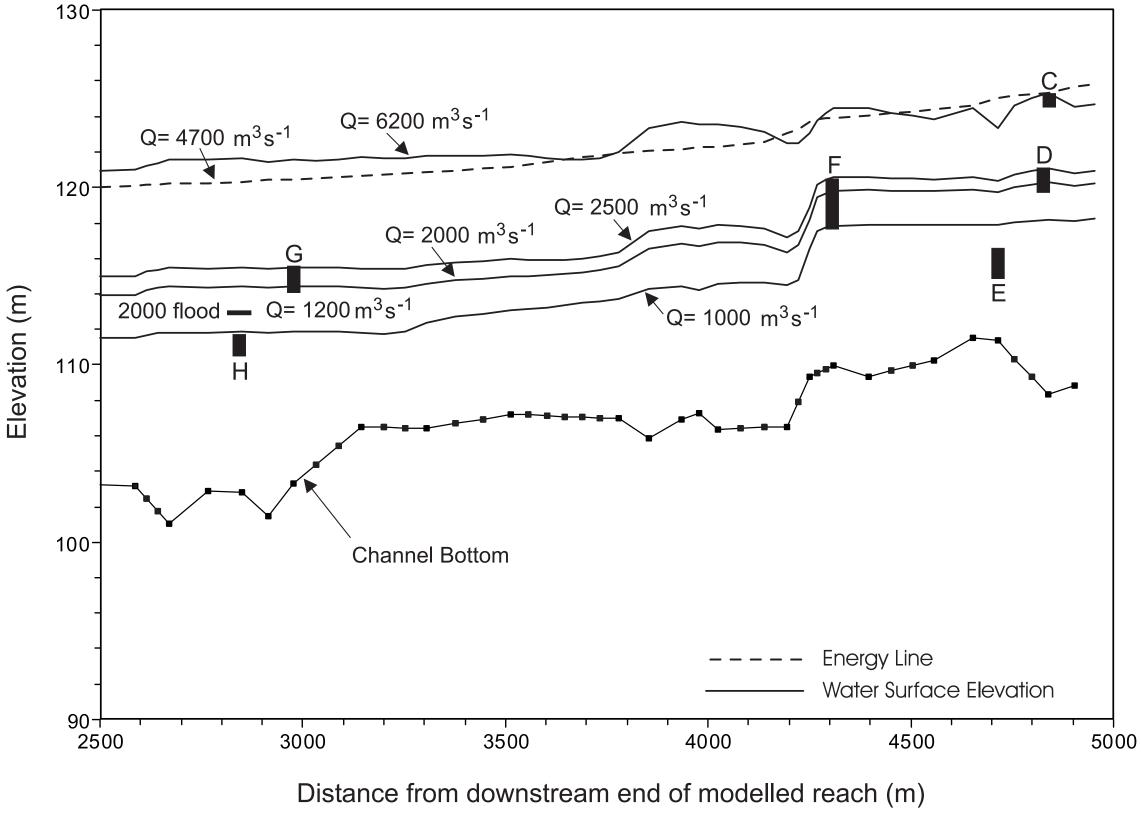

130
120
110
100
90
Elevation (m)
2500
3000
3500
4000
4500
5000
Distance from downstream end of modelled reach (m)
Q= 4700 m³s⁻¹
Q= 6200 m³s⁻¹
Q= 2500 m³s⁻¹
Q= 2000 m³s⁻¹
2000 flood
Q= 1200 m³s⁻¹
Q= 1000 m³s⁻¹
Channel Bottom
C
D
E
F
G
H
Energy Line
Water Surface Elevation

Fig 5

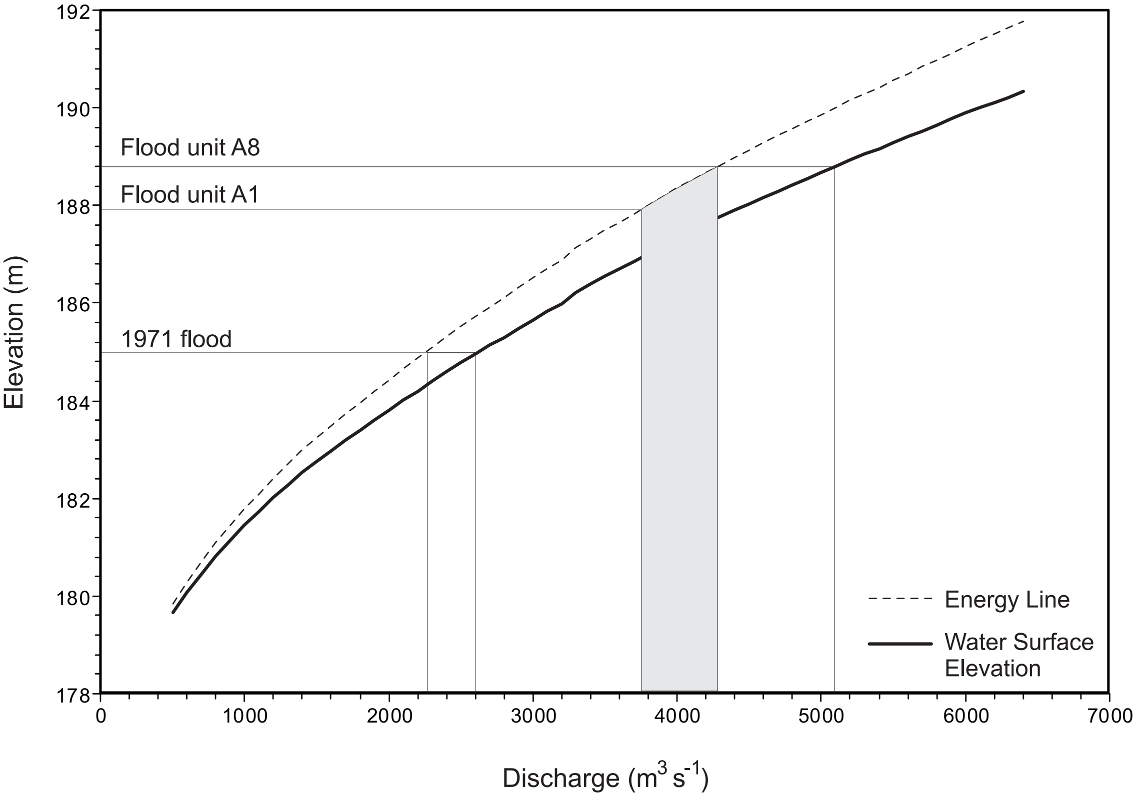

192
190
188
186
184
182
180
178
0
1000
2000
3000
4000
5000
6000
7000
Elevation (m)
Discharge (m3 s-1)
Flood unit A8
Flood unit A1
1971 flood
Energy Line
Water Surface Elevation

fig 6

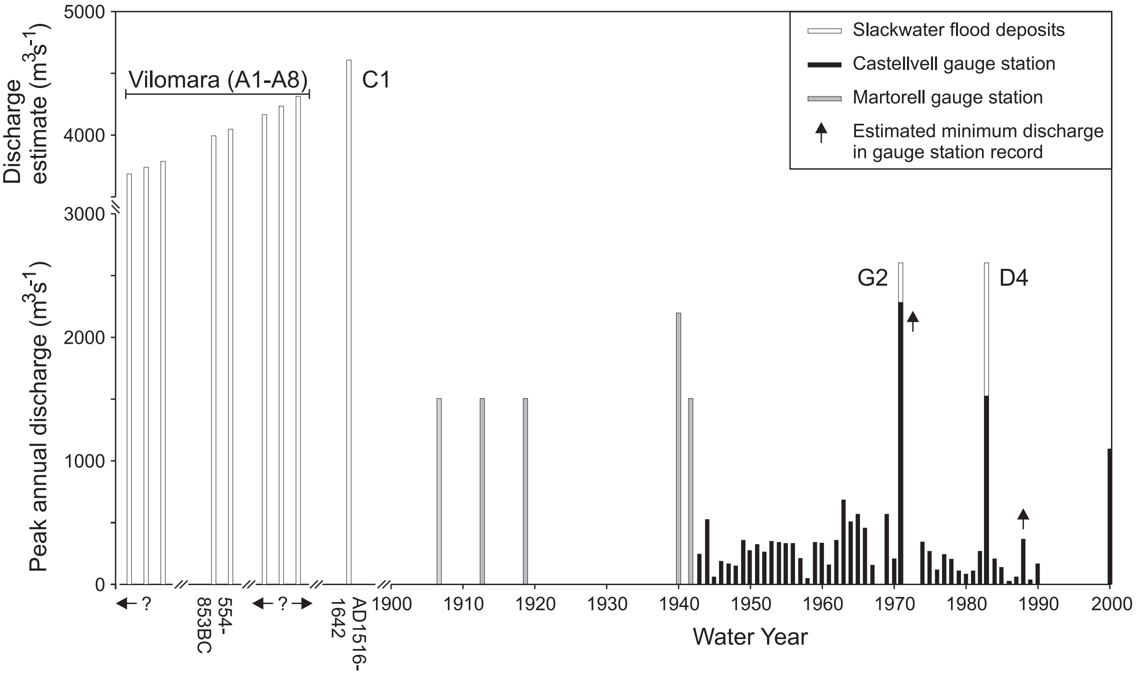

Discharge estimate (m^{3}s^{-1})
Peak annual discharge (m^{3}s^{-1})
5000
4000
3000
2000
1000
0
Vilomara (A1-A8)
C1
G2
D4
Slackwater flood deposits
Castellvell gauge station
Martorell gauge station
Estimated minimum discharge in gauge station record
?
554-853BC
?
AD1516-1642
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Water Year

Fig 7