A long-term flood discharge record derived from slackwater flood deposits of the Llobregat River, NE Spain

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Abstract

Slackwater palaeoflood deposits were identified along two bedrock gorge study reaches of the Llobregat River, at Pont de Vilomara and Monistrol de Montserrat. The compiled palaeoflood record consists of two principal flood series: a) a relatively complete record of low to high magnitude flood events from the last ca. 100 years and b) evidence of the largest palaeoflood events that have occurred over the last ca. 2700 years. The longer term extreme palaeoflood record indicates that the discharge of the 1971 flood, the largest on record, was exceeded on at least 8 occasions over the last *ca*. 3000 years, with two periods of high magnitude flooding identified: a) the Late Bronze Age (2500-2700 years ago) and b) the Little Ice Age (AD 1500-1700). At Pont de Vilomara, palaeodischarge estimates of ca. 3600 m^3/s compare to a discharge of 2300 m^3/s for the 1971 event. Downstream at Monistrol, an estimate of 4680 m^3/s for flood deposits dated as AD 1516-1642, and believed to be those of the AD 1617 event, compared to 2600 m^3/s for the 1971 flood.

Key words

Palaeoflood hydrology, Slackwater flood deposits, Hydraulic modelling, Spain

Introduction

Flooding is a major hazard in Mediterranean regions due to its extreme spatial and temporal variability. Furthermore, flood risk has been increased over recent decades as socio-economic factors have led to increasing urbanisation and development along the Mediterranean coast that has resulted in ever larger flood prone areas and societal vulnerability. With regards to flood risk prevention in the region, the estimation of rare, large magnitude floods is problematic due to short gauging station records and their limited spatial distribution. A further problem with systematic flood records is that of accurately measuring extreme flood discharges (Baker et al., 2002), which in Mediterranean regimes are often 100 times greater than the mean flow. During these large floods, gauge stations are frequently either flooded or destroyed, meaning that, in many cases, the reported floods from stream flow measurements are themselves estimated discharges using indirect methods or statistical extrapolation.

To reduce risk associated with floods there is a critical need to increase the length of the extreme flood record beyond that of the instrumental period. The flood record can be extended by hundreds to thousands of years by reconstructing past flood discharges using geomorphological indicators (palaeofloods) and documentary evidence. Palaeoflood hydrology, the reconstruction of the magnitude and frequency of large floods using geological evidence (Baker et al., 2002), has been employed in many regions of the world for compiling long term flood records for improving flood risk estimation (House et al., 2002a). In particular palaeoflood records have been reconstructed in southwest USA (Kochel et al., 1982; Ely and Baker, 1985; Partridge and Baker, 1987; O’Connor et al., 1994), Australia (Baker and Pickup, 1987; Pickup et al., 1988; Wohl et al., 1994), Israel (Greenbaum et al., 2000), India (Kale et al., 2000), Japan (Jones et al., 2001), China (Yang et al., 2000), France (Sheffer et al., 2003) and central Spain (Benito et al., 1998, 2003a).

This paper presents the results of a palaeoflood investigation of the Llobregat River, one of the study basins of the SPHERE project, a European Commission funded project that aims to improve flood risk estimation by incorporating past flood information and developing new scientific frameworks and technical tools within a European context (Benito et al., 2004). The main objectives are: (1) to reconstruct a catalogue of major flood events using the stratigraphic record of slackwater flood deposits, (2) to understand flood processes and timing of extreme events within Mediterranean regions; (3) to study the palaeoflood hydraulics associated with these flood events in order to estimate flood peak discharges; and (4) to provide relevant long term data regarding the largest magnitude floods that can be applied in flood hazard planning for the lower Llobregat River. This is of particular interest as a new flood protection channel, with a design discharge of 4000 m^3/s, is currently under construction on the Llobregat delta, an important area of economic activity to the south of Barcelona, with numerous industrial estates and the city's international airport located there.

Study location

The Llobregat River is located in Catalonia in northeast Spain (Fig. 1). The river flows north-south from the Pre-Pyrenean Cordillera to the Mediterranean Sea, immediately south of Barcelona, draining a catchment area of 4984 km^2. The study sites at Pont de Vilomara and Monistrol de Montserrat are both located in the middle reach of the

Llobregat River (Fig. 1), draining catchment areas of 1845 km^2 and 3370 km^2 respectively, with the Monistrol reach located downstream of the Cardener River tributary. The Llobregat River has a typically Mediterranean regime with a low mean annual discharge (21 m^3/s), extreme seasonal variations and flood peaks around 100 times greater than the mean discharge. Mean annual rainfall in the catchment varies from 900-1100 mm in the headwater reaches to 500-700 mm in the middle and lower reaches, however, large flood events are triggered by maximum rainfall exceeding at least 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 anticyclonic conditions over Europe and warm, moist air coming from the southeast 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. The river channel is predominantly bedrock, although on the wider gorge bends gravel bars occur (Fig. 1). Slackwater flood sediments (*cf*. Kochel and Baker, 1988; Benito et al., 2003b) have been deposited and preserved in valley side rock alcoves developed within the predominantly horizontal rock strata.

Flood hydrology of the Llobregat River

A summary of the largest floods recorded in the Llobregat catchment over the last hundred years is presented in Table 1. The most complete discharge record is from Martorell, the gauging station located furthest downstream with a drainage area of 4561 km^2 (Fig. 1). This record covers the periods 1911-1932 and 1944 onwards and records five flood events with discharges of at least 1500 m^3/s. Table 1 lists four additional floods – the 1907, 1940 and 1942 events, which occurred when the Martorell station was unoperational, and the July 2000 event that damaged it. At the Pont de Vilomara study reach discharge data has been recorded since 1915, with a gap between 1923 and 1942. The record shows three major floods over the last 60 years: 1500 m^3/s (September 1971); 950 m^3/s (November 1982); and 587 m^3/s (November 1962). The reference gauging station for the Monistrol de Montserrat study reach is located at Castellvell (3293 km^2), 3 km upstream, where records began in 1942. At Castellvell, three floods with discharges greater than 1000 m^3/s have been recorded in the last 60 years (the 1971, 1982 and 2000 events). The largest flood on record is that of 20th September 1971, with a discharge of 2300 m^3/s at Castellvell (minimum discharge) and 3080 m^3/s at Martorell. It is important to note that the largest floods at Castellvell are reported in the gauging station record as minimum discharges indicating the great difficulty in accurately recording extreme floods.

Documentary flood evidence

Historical archives record 35 catastrophic flood events on the Llobregat River since AD 1315 (Codina Vila, 1971; Llasat et al., 1999). In comparison to the rest of Catalonia, however, documentary sources regarding the Llobregat are poor (Barriendos, personal communication). For NE Spain, historical archive research has highlighted a number of periods of increased flooding: namely, the late 16th to early 17th century; the late 18th century; and the mid 19th century (Barriendos, 1996-97; Llasat et al., 1999). Like recent floods, most historical floods occurred during autumn months (Llasat et al., 1999), including the November 3rd 1617 event that registered the highest observed water level at El Prat on the Llobregat delta and caused widespread damage, and even famine, throughout the region (Barriendos, 2001).

Methodology

During high flood stages in river gorges 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 these floods that can be preserved in stratigraphic sequences (Benito et al., 2003b) providing detailed and complete records of flood events that extend back several thousand of years (Baker and Kochel, 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. 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 x 50 cm in size, made in the field (Fig. 2). Individual flood units were identified through a variety of sedimentological indicators (Baker and 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 anthropogenic indicators, such as plastics, to identify recent flood events, and 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 and Becker (1993), Linnick et al. (1986) and Stuiver and Pearson (1993). A summary of the samples submitted for dating, and their associated results, is presented in Table 2. All radiocarbon dates are quoted in the text as the one-sigma calibrated age range.

The estimation of discharges associated with the different flood units/features was accomplished by computing the water surface profiles for various hypothetical discharges that were routed through the study reaches. By comparing the model-generated profiles to the palaeostage indicators (e.g. slackwater flood deposit elevations) palaeodischarges were specified. Discharge estimation by hydraulic modelling was carried out using the step-backwater method, the most commonly utilised method in palaeoflood hydrology (Webb and Jarrett, 2002). Two discharge values were estimated for each alcove based upon the modelled water surface profile matching (1) the base of the alcove; and (2) the highest end-point of the flood sediments. Computations were run using the HEC-RAS one-dimensional model (Hydrologic Engineering Center, 1995) run within a GIS environment.

The assigned Manning's *n* values used in the HEC-RAS modelling are indicated in Table 3. A sensitivity test performed on the model indicated that for a 25% variation in roughness values, an error of 5-10% was introduced into the discharge results. Uncertainties in Manning's *n* values and energy loss coefficients had much less impact than uncertainties in cross-sectional data on discharge values estimated from hydraulic modelling (O´Connor and Webb, 1988). Model calibration is critical for the modelled discharge results. Field evidence of the June 2000 Llobregat flood at the Monistrol study reach was used in "tuning up" the model. This flood was recorded at Castellvell as 1100 m^3/s whereas in the study area the surveyed high-water marks match with a discharge estimate of 1240 m^3/s for the selected Manning's *n* and energy loss coefficients.

Cross-sections (see Fig. 1 for locations) 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. A study of morphological change in a Scottish gravel bed river allowed the accuracy of this type of GPS to be tested, with a vertical accuracy of 5 cm at the 95% confidence interval stated (Brasington et al., 2000). The river channel bottom was surveyed using an echosound device mounted in a small boat and connected to the rover GPS, the data collected using a navigation software.

At the Monistrol reach, 15 cross-sections were surveyed along a 2 km reach (Fig. 1). The geometry was completed with an additional 27 cross-sections obtained from a 1:5000 scale map and surveyed channel geometry along a 2.5 km reach downstream to the Cairat Gap. Critical flow was selected as the boundary condition at Cairat Gap, whilst it was assumed for the calculations that flow was subcritical along the rest of the modelled reach. At the Vilomara reach, 12 surveyed cross-sections and 29 additional cross-sections from a 1:5000 scale map were used in the hydraulic model. Boundary conditions were set to critical as the canyon is narrower and steeper at the lower part of the study reach. In the upper part of the reach, a Medieval bridge introduces an added complexity to the hydraulics of flood events that occurred after its construction. The first documentary reference to the bridge was in AD 1012 (Asarta et al. 1991).

Palaeoflood Stratigraphy

The stratigraphic columns described along the study reaches are presented in Figs. 3-5. Specific flood units discussed in the text are referred to by the alcove letter (see Fig. 1 for alcove locations) and the flood unit number presented in stratigraphic columns (Figs. 3-5). Table 4 presents summary information regarding each alcove, namely the elevation of the alcove above the present river channel bottom; the number of flood events preserved in each alcove; mean flood unit thickness; and mean particle size data.

Slackwater flood deposits at Monistrol de Montserrat

The palaeoflood stratigraphy for Alcoves C-E is shown in Fig. 3, alongside the valley cross-section that indicates the relative elevations of each of the alcoves. The highest elevation palaeoflood deposits, of the Monistrol reach, are located at Alcove C, 15.5 m above the channel bed. Only one flood unit is preserved here, this being a 14 cm thick, bioturbated sandy silt, composed of 59.2 % silt and 12.5 % clay. Radiocarbon dating of the unit provided an age of cal. AD 1516-1642. Alcove D records 4 flood events, separated by undifferentiated fine grained deposits (with occasional clast layers), reddish in colour, probably composing a mix of alcove and slope wash sediments and reaching up to 90 cm in thickness between units D2 and D3. The flood units can be distinguished by their greyish colour and coarser texture, containing a greater percentage of medium sand (mean 18.6%) and less clay (mean 9.4%). Charcoal from unit D2 was dated as modern, indicating an age of deposition during the last *ca.* 100-150 years for the upper three flood sediments. On the opposite bank of the river, Site E, at 5.4 m above the channel bed (Fig. 3), is the lowest elevation alcove of the study reach. Three modern radiocarbon ages from flood units E2 and E6, and a charcoal layer separating units E11 and E12, indicate that the whole sequence records 18 flood events, probably deposited over the last *ca.* 100 years. The textures of the flood units are fine sands with low silt and clay contents (8.5% and 5.6% respectively), reflecting the proximity of the alcove to the channel. The profile records both low and high magnitude flood events, the latter represented by units, E11, E13 and E16 that reach 26 cm, 33 cm and 20 cm in thickness, respectively.

The stratigraphy of the remaining three alcoves of the Monistrol reach is illustrated in Fig. 4. Profile F shows the most complex stratigraphy of the reach due to its position on the outside of a river bend creating a higher energy environment, and the proximity of slope deposits immediately upstream providing a local supply of coarse material. The stratigraphy, therefore, is dominated by distinct units of greyish sands, similar to the slackwater deposits found within the other profiles, and reddish silt-clays and clast layers, at times these clasts being incorporated within the grey sands. The ‘normal’ slackwater flood deposits, those without clasts, within profile F, have mean particle size characteristics similar to those from the other sites at Monistrol de Montserrat, with a medium sand content of 12.2%, 11.4% silt and 7.7% clay. Units F1 and F5 were radiocarbon dated to cal. AD 1686-1913 and cal. AD 1712-1904, respectively, whilst a modern age result was given for unit F11.

Alcove G contains 4 flood units that represent at least 2 distinct flood events. This is because the two highest elevation flood units (G3 and G4) are located at the back of the alcove, separated from units G1 and G2, and, therefore, may be repeated in the profile. Unit G1 was radiocarbon dated as modern. The G1 and G2 flood units are separated by layers of locally derived angular clasts, granules and clay layers. Site H is located downstream of Site G and on the inside of a river bend (Fig. 1). The alcove is at a lower elevation than Alcove G, being 7.9 m above the channel bottom. A total of 7 flood units are preserved, with 62.1 % fine sand and low mean silt and clay contents (6.8 % and 4.9 %, respectively). No radiocarbon dates were obtained, however, the deposits are likely to be modern in age, like those of Alcove G.

Sedimentary records of the 1971, 1982 and 2000 flood events

Along the Monistrol study reach, high elevation slackwater flood deposits containing plastic materials provide geomorphological evidence for the largest recent floods. At Alcove H, the uppermost two units (H6 and H7) contain plastics (Fig. 4) indicating that this alcove was inundated by both the 1971 and 1982 flood events. Fluid escape structures in these units indicate that the water surface elevation was significantly higher than the alcove, as they indicate high pressure exerted on the deposits. At Alcoves D and G, only the uppermost flood unit at each site contain plastics (D4 and G2), these deposits belonging to the 1971 event, the 1982 event not reaching these alcoves.

The June 2000 flood, the third largest in the Castellvell gauging station record, occurred during the fieldwork campaign. This flood event, with a recorded discharge of 1100 m^3/s, only covered Alcoves E and H. The flood deposited unit E18, the uppermost unit at site E. At Alcove H, evidence such as silt lines on the rock wall and plant debris within rock fissures above the alcove indicated that this alcove was covered by the floodwaters. The sediments from this flood, however, were embanked against the older deposits, with the uppermost sediments pinching out at the level of the fluid escape structures in unit H6 (Fig. 4), illustrating that the sediments in this case were deposited at least 1 m below the flood water surface.

Slackwater flood deposits at Pont de Vilomara

The highest elevation deposits at the Pont de Vilomara study reach are located at Alcove A, 15.9 m above the river channel bottom. The profile contains eight individual flood units, characterised by sandy silt textures with high clay contents (Figs. 5 and 6). The sedimentary structures, predominantly parallel laminations, and the fine grained sediments indicate a low flow velocity at the alcove. The chronology of the profile was determined by radiocarbon dates of 853-776 cal. BC and 794-554 cal. BC from units A4 and A5, respectively, indicating that the first 5 flood events recorded in the profile occurred around or prior to, *ca.* 2650 yrs BP. There is, however, no radiometric dating control for the uppermost three flood units.

The slackwater flood deposits of the Pont de Vilomara reach are completed by the two flood units of Alcove B, a small alcove located *ca.* 20 m upstream of, and approximately 3.5 m lower than, Alcove A. These sediments are characterised by a greater thickness (25 cm), an increase in sand content, with over 50% fine sand, and lower silt and clay contents. The lower unit is undated, however, the presence of plastic material in the upper flood unit dates this as modern, most probably related to the 1971 event.

Hydraulic Modelling

Discharge estimation at Monistrol de Montserrat

Fig. 6 illustrates the calculated water surface profiles of various discharges related to the slackwater flood deposits along the study reach. The step-backwater results indicate that a discharge of approximately 6200 m^3/s matches the known palaeostage evidence corresponding to the Alcove C flood deposits, the highest found along the study reach. At this cross-section (Fig. 3), channel flow velocity was over 6 ms^{-1} with subcritical flow conditions (Froude Number about 0.5). This indicates a sharp velocity transition from the channel to the canyon side where sedimentation was associated with stagnant water conditions. A lower bound discharge of 4680 m^3/s 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. In other words, this conservative discharge was obtained by matching the energy line, instead of the calculated water surface profile, to the palaeostage evidence. These two discharge estimates are illustrated in the rating curve for the Alcove C sediments (Fig. 7).

The next highest discharge estimates are for alcoves G, D and F with minimum discharge ranges of 1800-2500 m^3/s, 1250-2500 m^3/s, and 860-2200 m^3/s, respectively (Figs. 4 and 7). The uppermost flood units at both alcoves G and D, that were found to contain plastic materials, indicate that the largest recent flood, the 1971 event, reached a minimum discharge of 2500 m^3/s at this study reach. This discharge can be compared to that of 2300 m^3/s, the minimum discharge estimate from the Castellvell gauging station data. The water surface of the June 2000 event, estimated at 1240 m^3/s, covered and deposited sediments at alcoves E and H. A discharge range of 200-440 m^3/s was estimated for the low elevation Alcove E and 750-1000 m^3/s for Alcove H.

Discharge estimation at Pont de Vilomara

A peak discharge of 1650 m^3/s was estimated at the Vilomara gauging station for the 1971 flood event. About 200 m downstream of the bridge, at Alcove B, slackwater flood deposits containing plastic material are believed to have been deposited by this flood event. The step-back water calculations provide a discharge estimate associated with these deposits as between 2300 and 2630 m^3/s. A photo of the Vilomara Medieval bridge taken during the flood by a local resident also allowed calibration of the model as the water ‘ponded’ behind the bridge reached a distinct agricultural terrace identified within fields on the left bank of the river.

As indicated earlier, Alcove A contains a record of at least 8 high magnitude flood events (Fig. 5). Discharge estimation resulted in a minimum discharge of 4400 m^3/s at the base of the alcove and 5100 m^3/s related to flood unit A8. The water surface elevation of the A8 discharge is plotted relative to the Medieval bridge and the 1971 flood in Fig. 5. The channel velocity at this discharge is about 4 ms^{-1}, whereas the sedimentary structures found in the slackwater deposits filling the alcove indicate much lower velocities. A lower bound discharge matching the energy line to this palaeostage evidence, as carried out for Alcove C, resulted in a minimum discharge of 3700 m^3/s for the base of the alcove, and 4300 m^3/s for flood A8 at the uppermost part of the stratigraphic profile.

Discussion

The stratigraphic and hydraulic modelling data presented indicate that the Llobregat slackwater flood deposits primarily represent two flood series. The most complete record is that of flood events that have occurred over the last *ca.* 100 years with sediments from low, medium and high magnitude flood events all preserved. At the Monistrol study reach, Alcove E records 18 modern flood events with a range of minimum discharges from 200-440 m^3/s; Alcove H, 8 flood events with a discharge range of 750-1000 m^3/s; whilst 1250-2000 m^3/s was estimated for the 3 modern flood events of Alcove D and 1800-2500 m^3/s for the 2 events preserved at Alcove G. One modern flood event at Alcove B at Pont de Vilomara is associated with an estimated discharge of 2300-2600 m^3/s. This palaeoflood record shows a progressive self-censoring of flood stratigraphy that occurs due to the progressive elevation of the sediment banks caused by vertical depositional accretion (House et al., 2002b). The phenomenon of progressive self-censoring introduces a complexity for reconstructing a complete catalogue of palaeofloods, since some flood events are not represented throughout the studied stratigraphic profiles, depending on the elevation of the particular site of deposition. That the largest recent floods have not eroded the low elevation deposits suggest that higher magnitude events occurred that periodically flushed these alcoves of sediments from earlier low and medium magnitude floods. Evidence for such extreme flood events, with estimated discharges of 3700 m^3/s at Pont de Vilomara and 4680 m^3/s at Monistrol, comprises the second flood series, an archive that extends back *ca.* 2700 years. The Llobregat slackwater flood deposits record at least 8 flood events of this magnitude over this period. At this site, the evidence suggests that floods able to exceed this elevation are well represented within the stratigraphic record.

The palaeoflood hydrology of the Llobregat River, therefore, provides valuable geomorphological evidence for: 1) testing the accuracy of extreme flood discharge measurement at gauging stations and 2) providing a longer-term context for high magnitude flood events within the catchment. The inherent difficulty associated with accurately recording extreme flood discharges (Baker et al, 2002) can be illustrated by the Llobregat gauging station record, where the discharge of the 1971 event, the largest on record, could only be stated as a minimum discharge estimate at Castellvell. At both study reaches, high elevation slackwater flood deposits of the 1971 event (units B2, D4 and G2), identified by virtue of plastics and other anthropogenic materials within the deposits, provide a further means of discharge estimation. At the Pont de Vilomara gauging station, the recorded maximum discharge of 1650 m^3/s is lower than the 2300-2600 m^3/s discharge estimated for the Alcove B deposits containing plastic material. At the Castellvell gauging station, a minimum discharge of 2300 m^3/s was recorded. The minimum estimated discharge associated with high elevation modern flood deposits at the Monistrol study reach was 2500 m^3/s at Alcove G. The geomorphological evidence, therefore, indicates that the gauging station records at Vilomara and Monistrol underestimated the discharge of the 1971 event.

With respect to flood risk and planning in the Llobregat catchment, it is of particular interest to know how the magnitude of the 1971 flood compares with the longer term palaeoflood archive. It is evident from the palaeoflood field and hydraulic modelling evidence that the 1971 event was not the largest witnessed in the Llobregat Basin. The palaeoflood record indicates that at least 8 high magnitude events, with estimated palaeodischarges greater than that of 1971, have occurred over the last *ca.* 2700 years. In terms of palaeodischarge estimates, and assuming negligible channel bed change within the bedrock gorge study reaches, the Alcove A (Pont de Vilomara) palaeoflood events (3700 m^3/s) are up to 38% greater in magnitude than the 1971 flood, the largest on record. Downstream of the Cardener tributary junction, the estimated discharge for the Alcove C palaeoflood (4680 m^3/s), dated to *ca*. 400 yrs BP, is 46.5% larger than that of the 1971 event and is also greater than the design discharge of the flood protection channel in the delta region of the catchment (4000 m^3/s).

In terms of the chronology of these extreme palaeoflood events, the two units, A4 and A5, radiocarbon dated to 853-776 cal. BC and 794-554 cal. BC respectively, suggest a period of high magnitude flooding *ca.* 2500-2700 years ago. Climatologically, these flood events correlate with a short period of cold/wet conditions described during the Late Bronze Age (2650 ^{14}C yr BP or 800 BC; van Geel et al., 1998). In other western Mediterranean regions, general phases of aggradation associated with high river discharges (including torrential floods) and sediment loads, have been described not only during this period (ca 700-500 BC), but also in Post-Roman times (ca. AD 500-1000) and at the beginning, or during, the Little Ice Age (ca. AD 1500-1700) (Vita-Finzi, 1969; Coltorti, 1997; Provansal, 1992, 1995; Fuller et al., 1998; Benito, 2003). Within the Llobregat catchment there is no preserved evidence of large magnitude Post-Roman flooding, however, the C1 flood event, dated to cal. AD 1516-1642, is evidence of an extreme flood that occurred during the Little Ice Age. This is a known period of increased flood frequency in Spain (Benito et al., 1996, 2003c; Barriendos and Martín-Vide, 1998). Whether slackwater flood deposits from this period were also deposited in Alcove A at Vilomara is still open to speculation without further radiometric dating evidence from the upper flood units at this site. However, the severity of flooding at Vilomara during the Little Ice Age can be illustrated by historical evidence. The AD 1617 flood, believed to be the largest event in the documentary record (Barriendos, 2001), destroyed the three central arcs of the Vilomara Medieval bridge (Asarta et al., 1991). It is of particular interest to note that the date of this flood is within the one-sigma envelope of the C1 radiocarbon date (cal. AD 1516-1642) from the Monistrol reach, indicating that these deposits probably relate to this specific flood event. The main historical evidence for the elevation of the 1617 floodwaters comes from the Llobregat delta, an area too complex for accurate discharge estimation by hydraulic modelling. The value of the palaeoflood evidence is that it provides a robust discharge estimate (*ca*. 4680 m^3/s), from a stable bedrock reach, for one of the largest known floods within the catchment.

Conclusions

The palaeoflood hydrology of the Llobregat River provides evidence for extreme flood events that were of a greater magnitude than the largest floods recorded in the gauging station record. At Pont de Vilomara at least 8 extreme palaeofloods, associated with a range of minimum discharges of 3700-4300 m^3/s, occurred over the last 2700 years. The largest instrumental flood, the 1971 event, was estimated from palaeoflood evidence at this reach as 2300 m^3/s. At Monistrol, one extreme palaeoflood dated to cal. AD 1516-1642, and believed to be the AD 1617 event, had an estimated minimum discharge of 4680 m^3/s. This compares to a minimum discharge of 2500 m^3/s, estimated from slackwater deposits of the 1971 flood. The results have important implications for flood prevention and risk assessment in the catchment. In particular, a flood protection channel in the delta region of the river has been designed with a maximum discharge capacity of 4000 m^3/s, lower than the estimated discharges of the largest palaeofloods. The palaeoflood evidence provides discharge estimates of real floods that can be used to reduce reliance on statistical discharge estimations based on short instrumental flood series.

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List of tables

Table 1. Peak discharges of the major 20th Century floods. [a] Peak discharge recorded at the Martorell gauging station; [b] Peak discharge estimated by Junta d'Aigües (1994); [c] Peak discharge cited in Solé Sabarís (1958); [d] Peak discharge recorded at Castellvell as the Martorell gauging station was damaged during this event (Llasat et al., 2001).

Table 2. Radiocarbon dating samples and results, including calibrated ages calculated by the CalibETH 1.5b programme using the calibration curves of Kromer and Becker (1993), Linnick et al. (1986) and Stuiver and Pearson (1993).

Table 3. Assigned Manning's *n* values for hydraulic modelling of the study reaches.

Table 4. Summary of the slackwater flood deposits found at Pont de Vilomara (Alcoves A and B) and Monistrol de Montserrat (Alcoves C-H) illustrating the relative elevations of each alcove above the river bed, the number of flood events recorded at each alcove, mean flood unit thickness and mean particle size data.

List of Figures

Fig. 1. Location of the Llobregat Basin in NE Spain (A). The Pont de Vilomara (B) and Monistrol de Montserrat (C) study reaches, illustrating the location of rock alcoves preserving slackwater flood deposits (sites A-H) and surveyed cross sections (numbered).

Fig. 2. Sediment lacquer peel and stratigraphic column from the upper flood units of Alcove E (see Fig. 4 for complete stratigraphy and key). The photo of the peel shows the contacts between the distinct flood units and the sedimentary structures that provide information on sediment load and flow velocity. NB. flood unit 18 and the slope deposits between units 16 and 17 appear laterally in the cut trench and pinch out before reaching the back wall of the trench from where the peel was taken. (See Fig. 3 for the key to the stratigraphic column).

Fig. 3. Amalgamation of cross-sections 3 and 4 of the Monistrol study reach indicating the relative elevations of Alcoves C-E, with the respective stratigraphic columns alongside. The elevation and stratigraphy of the three profiles clearly illustrates the magnitude-frequency relationships of the three alcoves, with Alcove E representing a relatively complete record of low to high magnitude flood events over the last *ca*. 100 years, whilst Alcove C just preserves the deposits of one extreme high magnitude low frequency event that occurred in the Little Ice Age. Also indicated are the minimum discharge estimates for the upper flood units of each alcove and the Manning's *n* values used in the hydraulic model (see Table 4). Below is the key to all the stratigraphic columns (Figs. 2-5).

Fig. 4. The stratigraphies of Alcoves F-H of the Monistrol study reach. In Alcove G a small rock shelf at the back of the alcove separates the upper and lower profiles. The flood units are labelled distinctly but may be repeated in the two profiles. Also indicated are the minimum discharge estimates required for the flood waters to reach the base and roof of each alcove. (See Fig. 3 for the key to the stratigraphic columns).

Fig. 5. Cross-section 9 of the Pont de Vilomara study reach illustrating the relative elevations of Alcoves A and B. The stratigraphy of the sedimentary profiles is also shown (refer to key in Fig. 3). Note that at this site, Alcove A preserves a record of 8 extreme flood events with two flood units dated to the Late Bronze Age. The minimum discharge estimates associated with the upper flood units are also shown. Below: the water surface elevations related to the minimum discharge estimates of the 1971 flood and flood unit A8 are plotted at cross-section 11 at the Medieval bridge. A photograph of the 1971 flood passing under the bridge enabled calibration of the hydraulic model at this reach.

Fig. 6. Calculated water surface and energy line elevations for selected discharges related to the mapped palaeostage indicators (slackwater flood deposits) at alcoves C-H along the Monistrol study reach. The elevation of debris and silt lines left above Alcove H by the June 2000 flood is also indicated. This data was used to calibrate the hydraulic model at this reach.

Fig. 7. Rating curve for the C1 flood deposits, dated to cal. AD 1516-1642, at cross section 3 of the Monistrol reach illustrating the discharge estimates calculated from the

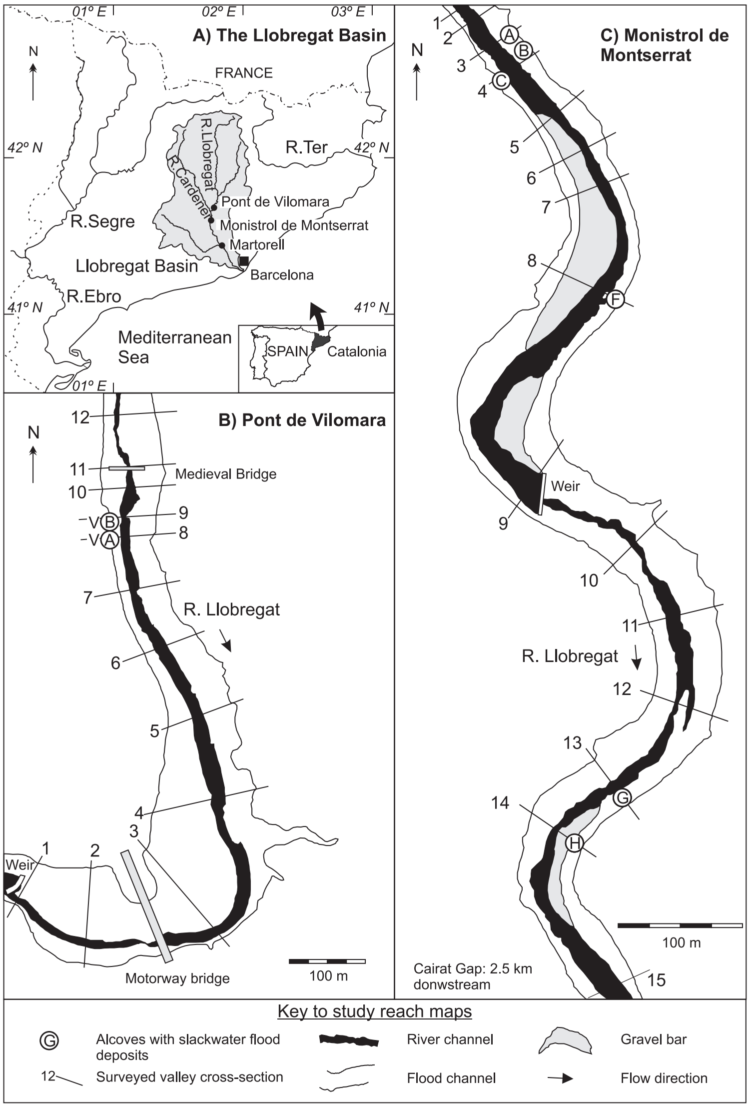
water surface elevations and the total energy head. The conservative discharge associated with the total energy head was considered more accurate as the palaeoflood sediments indicated a low flow velocity (close to zero) at the canyon side, therefore the water surface elevation would be higher than in the central flood channel where flow velocity was over 6 ms^{-1}.

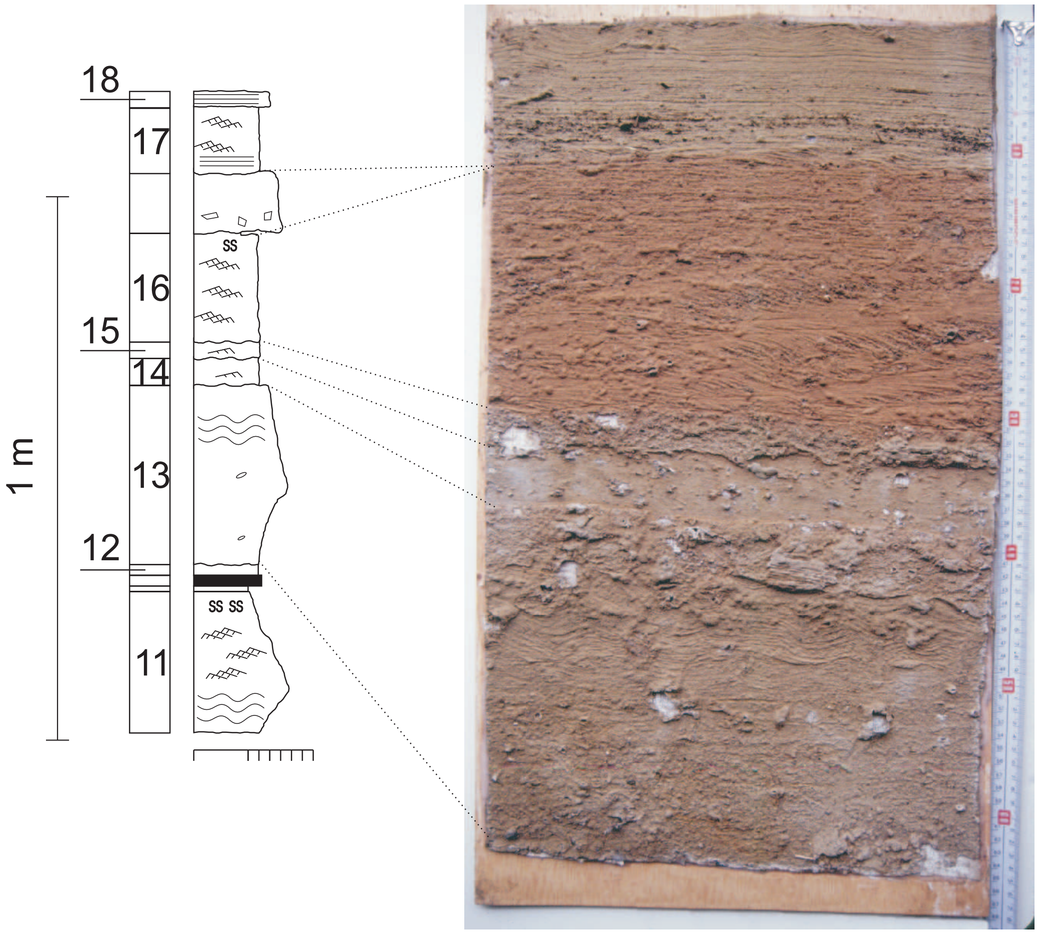
Year	**Date**	**Peak Q (m^3/s) at Martorell (4561 km^2)**	**Fatalities and economic losses (Llasat et al., 2001)**
1907	October 7th	1500[b], 2875[c]	-
1913	September 29th	1540[a]	-
1919	October 7th	1500[a]	-
1940	October 18th	2200[b]	-
1942	October 28th	1500[b]	-
1962	September 25th	1550[a]	441 deaths €15.9 m
1971	September 20th	3080[a]	9 deaths €42.1 m
1982	November 6th	1600[a]	6 deaths €270.5 m
2000	June 10th	1100[d]	5 deaths €66.1 m

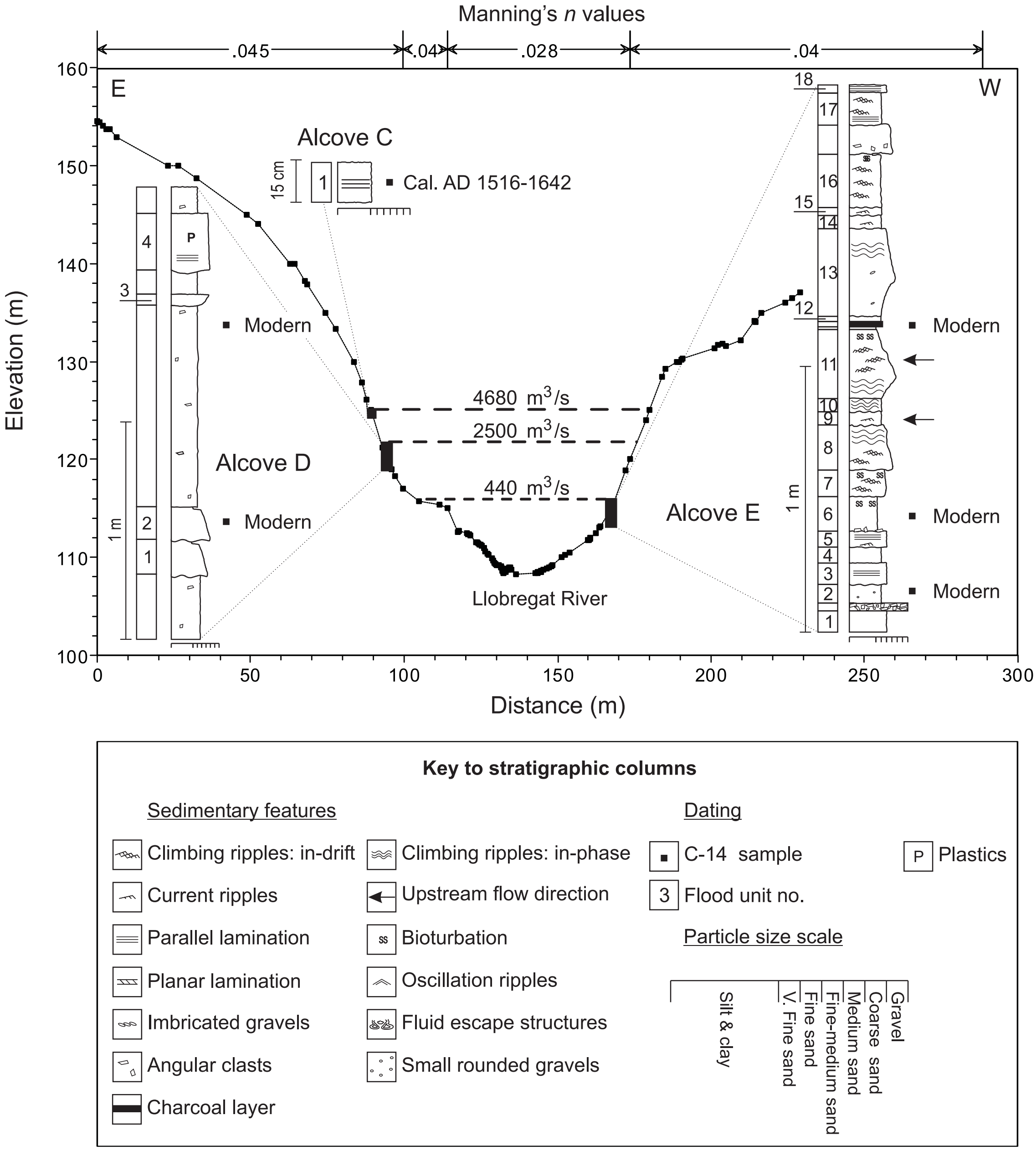
Study reach	**Flood unit no.**	**Lab code**	**Age (yrs BP)**	**Calibrated age**	**One sigma calibrated age range**
Pont de Vilomara	A4	UZ-4523/ETH-23673	2640 ± 55	798 ± 75 BC	853 BC, 776 BC
	A5	UZ-4524/ETH-23674	2580 ± 75	669 ± 114 BC	794 BC, 554 BC
Monistrol de Montserrat	C1	UZ-4605/ETH-24418	305 ± 50	AD 1585 ± 79	AD 1516, AD 1642
	D2	UZ-4738/ETH-25509	Modern	-	
	D2-3	UZ-4515/ETH-23665	Modern	-	
	E2	UZ-4520/ETH-23670	Modern	-	
	E6	UZ-4521/ETH-23671	Modern	-	
	E11-12	UZ-4522/ETH-23672	Modern	-	
	F1	UZ-4517/ETH-23667	185 ± 55	AD 1790 ± 92	AD 1686, AD 1913
	F5	UZ-4518/ETH-23668	120 ± 50	AD 1813 ± 81	AD 1712, AD 1904
	F11	UZ-4519/ETH-23669	Modern	-	
	G1	UZ-4516/ETH-23666	Modern	-	

Surface description	**Minimum Manning’s *n* value**	**Maximum Manning’s *n* value**
Channel	0.028	0.030
Exposed bedrock (rough)	0.040	0.045
Soil surface without vegetation	0.035	0.040
Vegetated surface (dense tree)	0.060	-
Vegetated surface (disperse)	0.050	-
Agricultural land	0.040	-
Gravel bars (unvegetated)	0.030	0.035

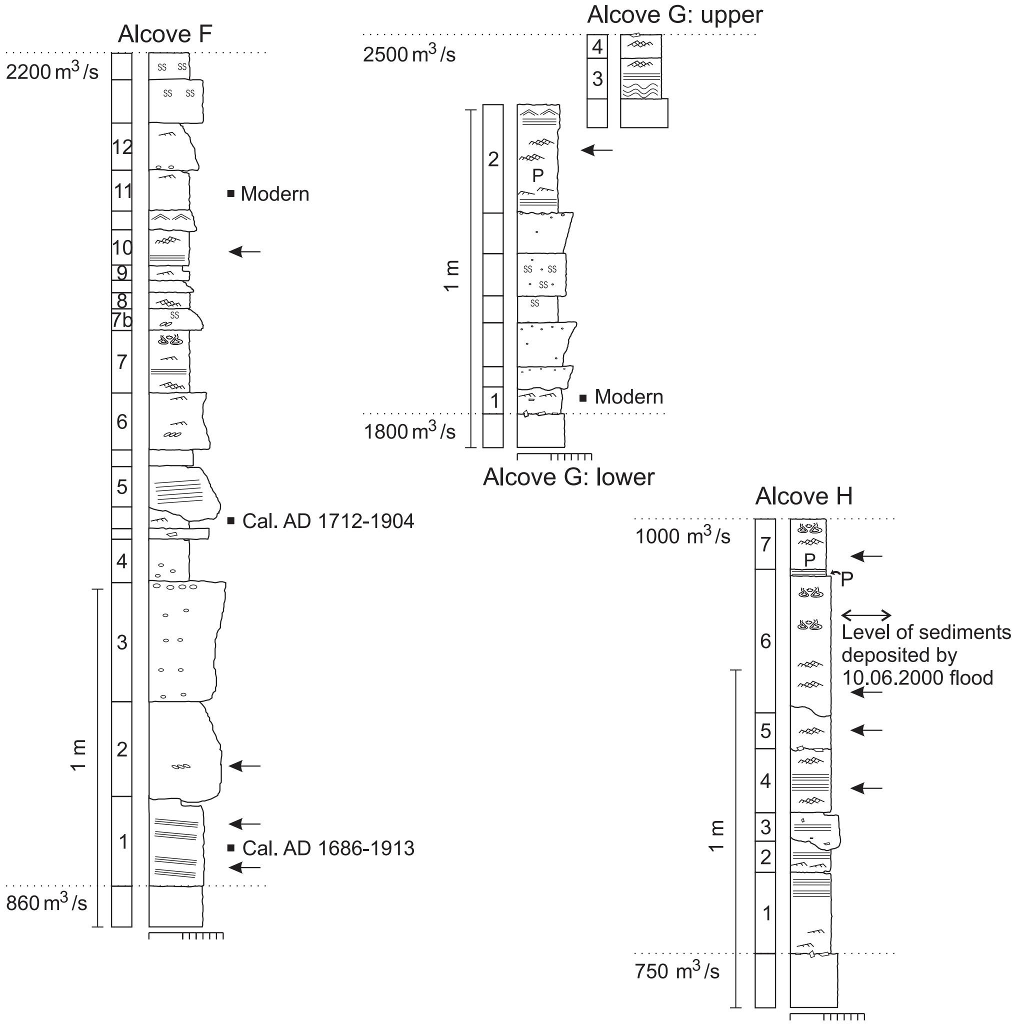
Alcove	**Elevation above channel bottom (m)**	**No. of flood events**	**Mean unit thickness (cm)**	**Mean particle size data**				
				Medium sand	**Fine sand**	**V. fine sand**	**Silt**	**Clay**
A	15.9	8	11.9	3.9	14.7	17.0	42.4	20.8
B	12.3	2	27.5	10.4	53.9	11.8	12.0	10.3
C	15.5	1	14.0	1.4	6.3	20.3	59.2	12.5
D	10.9	4	17.0	18.6	45.1	12.6	12.6	9.4
E	5.4	18	11.5	15.8	56.1	13.2	8.5	5.6
F	7.5	12	16.3	12.2	32.9	16.6	11.4	7.7
G	10.8	4	13.3	7.0	54.1	23.10	12.9	5.3
H	7.9	7	17.3	11.9	62.1	13.7	6.8	4.9

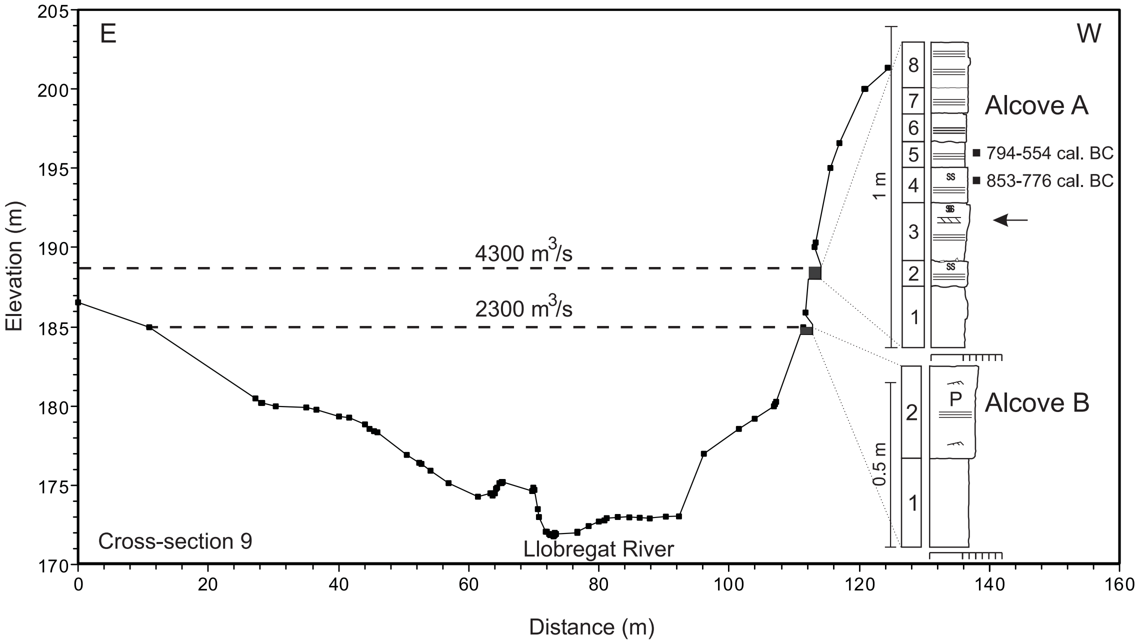

A) The Llobregat Basin
01º E
02º E
03º E
42º N
41º N
N
FRANCE
R.Llobregat
R.Cardener
R.Ter
R.Segre
Pont de Vilomara
Monistrol de Montserrat
Martorell
Llobregat Basin
Barcelona
R.Ebro
Mediterranean Sea
SPAIN
Catalonia
B) Pont de Vilomara
N
12
11
10
9
8
7
6
5
4
3
2
1
Medieval Bridge
V B
V A
R. Llobregat
Weir
Motorway bridge
100 m
C) Monistrol de Montserrat
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
A
B
C
F
G
H
Weir
R. Llobregat
100 m
Cairat Gap: 2.5 km donwstream
Key to study reach maps
G Alcoves with slackwater flood deposits
12 Surveyed valley cross-section
River channel
Flood channel
Gravel bar
Flow direction

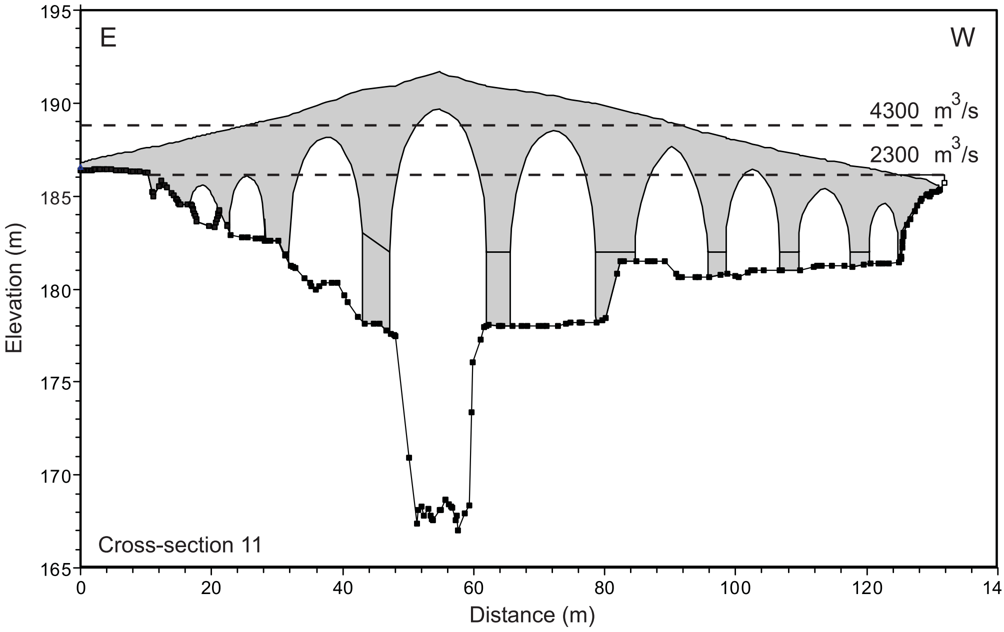

18
17
16
15
14
13
12
11
1 m
SS
SS SS

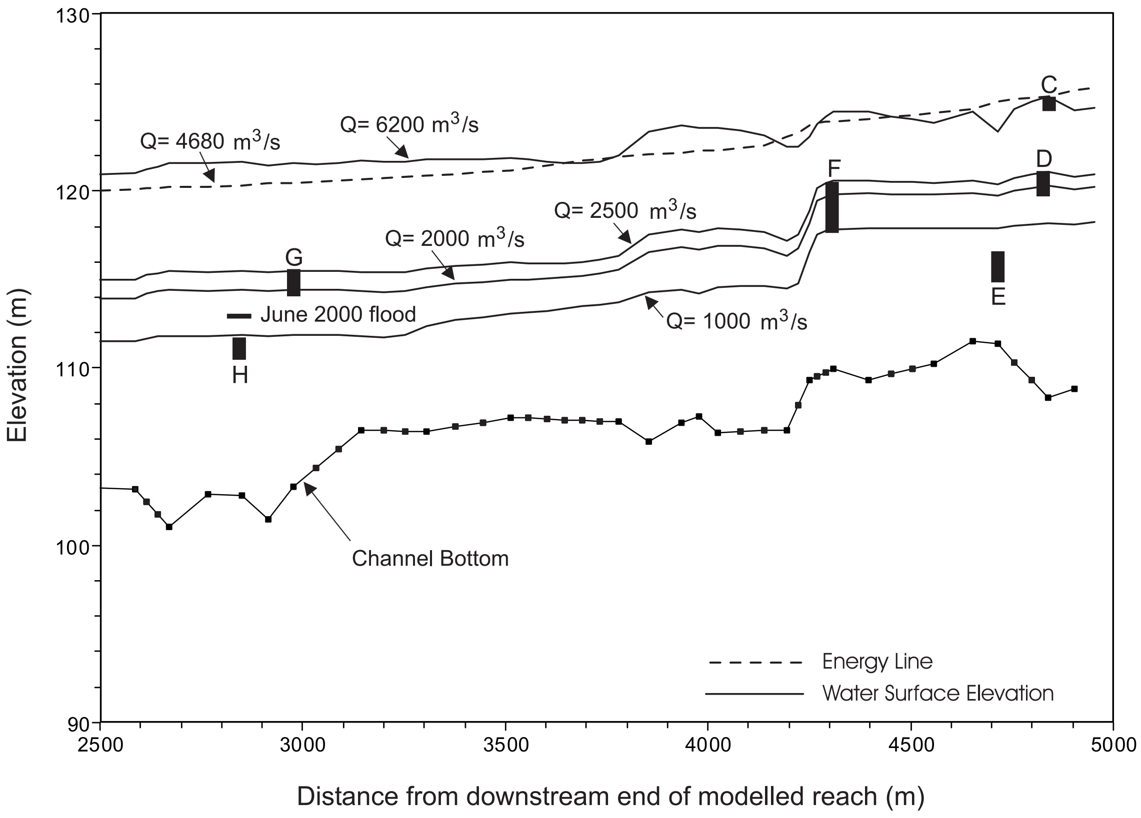


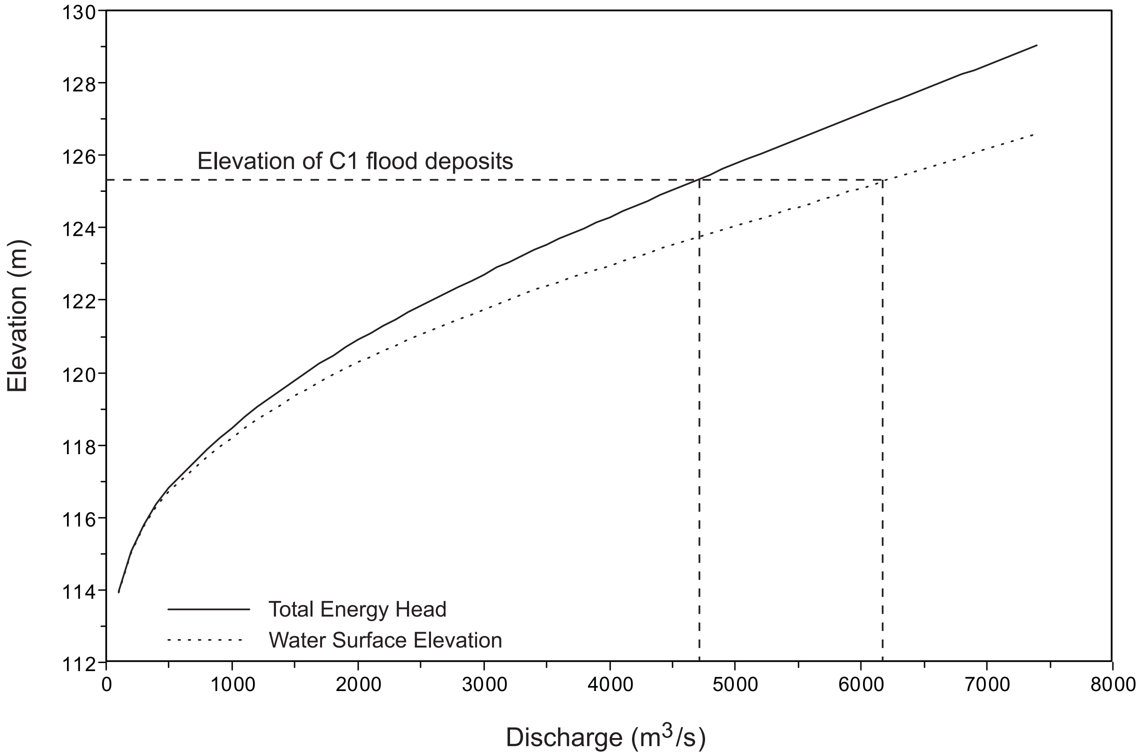
Manning's *n* values
.045
.04
.028
.04
E
W
Elevation (m)
Distance (m)
160
150
140
130
120
110
100
0
50
100
150
200
250
300
Alcove C
15 cm
1
Cal. AD 1516-1642
Alcove D
Modern
Modern
1 m
4
P
3
2
1
4680 m^3/s
2500 m^3/s
440 m^3/s
Llobregat River
Alcove E
1 m
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Modern
Modern
Modern
Key to stratigraphic columns
Sedimentary features
Climbing ripples: in-drift
Current ripples
Parallel lamination
Planar lamination
Imbricated gravels
Angular clasts
Charcoal layer
Climbing ripples: in-phase
Upstream flow direction
Bioturbation
Oscillation ripples
Fluid escape structures
Small rounded gravels
Dating
C-14 sample
3 Flood unit no.
P Plastics
Particle size scale
Silt & clay
V. Fine sand
Fine sand
Fine-medium sand
Medium sand
Coarse sand
Gravel


Alcove F
2200 m3/s
12
11
Modern
10
9
8
7b
7
6
5
Cal. AD 1712-1904
4
3
1 m
2
1
Cal. AD 1686-1913
860 m3/s
Alcove G: upper
2500 m3/s
4
3
2
P
1 m
1
Modern
1800 m3/s
Alcove G: lower
Alcove H
1000 m3/s
7
P
P
6
Level of sediments deposited by 10.06.2000 flood
5
4
3
1 m
2
1
750 m3/s


E
W
4300 m^3/s
2300 m^3/s
Alcove A
794-554 cal. BC
853-776 cal. BC
Alcove B
1 m
0.5 m
8
7
6
5
4
3
2
1
2
1
P
ss
Cross-section 9
Llobregat River
Elevation (m)
Distance (m)
205
200
195
190
185
180
175
170
0
20
40
60
80
100
120
140
160


E
W
4300 m^3/s
2300 m^3/s
Cross-section 11
Elevation (m)
Distance (m)
195
190
185
180
175
170
165
0
20
40
60
80
100
120
140


Q= 4680 m^3/s
Q= 6200 m^3/s
C
D
F
Q= 2500 m^3/s
G
Q= 2000 m^3/s
June 2000 flood
Q= 1000 m^3/s
E
H
Channel Bottom
Energy Line
Water Surface Elevation
Elevation (m)
130
120
110
100
90
2500
3000
3500
4000
4500
5000
Distance from downstream end of modelled reach (m)


Elevation of C1 flood deposits
Total Energy Head
Water Surface Elevation
Elevation (m)
Discharge (m^3/s)
130
128
126
124
122
120
118
116
114
112
0
1000
2000
3000
4000
5000
6000
7000
8000