THE PALAEOFLOOD RECORD OF THE GARDON RIVER, FRANCE: A COMPARISON WITH THE EXTREME 2002 FLOOD EVENT

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ABSTRACT

A paleoflood study in the Gardon River gorge in southern France identified extreme floods larger than any modern or historically gauged flood. During the course of our study, an extreme flood on the 8-9th of September 2002 claimed the lives of 21 people and caused millions of Euros worth of damage to the towns and villages along the river. The magnitude of this flood was larger than any known historical flood on record,. However, there is evidence of greater magnitude flood events in the form of slack-water flood deposits preserved in caves elevated 17-19 m above the normal base flow, and up to 3 m above the level reached by the 2002 floodwaters. The stratigraphy and radiocarbon dating show that at least five extreme events occurred during the past 500 years. The discharge estimation associated with these flood units, achieved using the HEC-RAS one dimensional model, indicates that at least three floods were bracketed by discharges between 6850 and 7100 m³s⁻¹, and at least two floods reached a magnitude above 8000 m³s⁻¹. Therefore, the extraordinary flood of 2002 was not the largest in the basin.

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1. INTRODUCTION

During the past few years, Europe has experienced extraordinary flooding, which has caused billions of Euros worth of damage. Many of these extreme floods were larger than expected or predicted. During the summer and autumn of 2002, rivers in France, Italy, Germany, Hungary, the Czech Republic and Russia flooded killing 230 people and rendering thousands homeless. The economic damage of this flooding in central Europe alone was estimated at €18.5 billion, of which only €3.1 billion was insured (Munich Re, 2003). Knowledge of prior floods of similar or larger magnitude in these catchments might have served in flood hazard estimation and in the prevention and preparation towards such floods.

In southern France, the Gardon River (Fig. 1) experienced an extreme flood during the 8th-9th of September 2002 (e.g. Sheffer et al., 2003a), which claimed the lives of 23 people, and caused €1.2 billion worth of damage to towns and villages along the river. Seven thousand houses were damaged, 100 of which were completely destroyed and 1500 submerged under 2 meters of water (Huet et al., 2003). The magnitude of this flood is larger than any known historical flood on record in this catchment.

The 2002 event occurred during our study of the paleoflood hydrology of the Gardon River. This study was a part of the EU-SPHERE project, one of the aims of which was to identify regional flood patterns using systematic, historical and paleoflood data (Benito et al., 2004). The SPHERE project led to paleoflood studies in a number of basins in Europe: the Llobregat, Segre and Ter rivers of northeast Spain (Thorndycraft et al., 2005, 2006 and Benito et al., 2004); and the Ardèche and Gardon rivers in France (Sheffer et al., 2003a, 2003b). Paleoflood hydrology is a method of studying past floods directly from the physical environment. The method is based on geomorphic, sedimentologic and hydrologic analysis of historical and late Holocene floods and provides a long-term perspective on extreme floods. The chronology of flooding is determined through the stratigraphy and radiometric dating of slack-water deposits accumulated along a river reach (Kochel and Baker, 1982; Baker, 1987,

2003). Peak discharge reconstruction of past floods can be achieved by running hydraulic models through surveyed study reaches.

The main objectives of this paper are: (1) to provide an accurate and reliable discharge estimation of the 2002 flood at the study reach, (2) to reconstruct a record of major flood events using paleoflood hydrology, and (3) to improve the understanding of the 2002-flood magnitude and considering the long-term perspective of rare events and extreme flood discharges provided by the paleoflood record.

2. STUDY SITE

2.1 The Gardon River basin

The Gardon River (~2000 km²), located in the southeast Massif Central (Cévennes Region) is approximately 135 km long from its headwaters at 1500 m above sea level to its confluence with the Rhône River at 6 m above sea level (Fig. 1). The Gardon is the most southern tributary of the Rhône River. In its lower eastern reaches the Gardon River flows in a gorge incised into hard carbonate rocks. These rocks are separated by faults from the metamorphic and granitic rocks of the upper Gardon basin.

The study site is a gorge (Fig. 2), 1600 m long, with steep banks of flood terraces and exposed rocky cliffs. The base flow width is approximately 40-60 m wide with a depth varying from <1 m at the rapids, to >5 m at pools along the river bed. The paleoflood sites are in caves and alcoves in the gorge walls along both river banks.

The mean annual rainfall in the Cévennes region averages 1000-1100 mm distributed throughout the year with the largest amounts in September and October (>100 mm/month; Meteo-France - URL). The altitude of the mountain range varies from practically sea level (6 m asl at the Rhône confluence) up to 1600 m in roughly 30 km producing a pronounced orographic effect. Like other Mediterranean mountain ranges in northeast Spain and southern France, the Cévennes region experiences heavy autumn storms that are able to produce catastrophic floods (e.g. Llasat, 1997; Miniscloux et al., 2001). Storm may last 1-2 days of almost continuous rain. The warm moist air coming from the Mediterranean supports the continuous precipitation.

This flux is associated with an eastward-moving, upper-level trough reaching the French Atlantic coast (e.g. Minisclox *et al.*, 2001).

2.2 Historical data

The systematic daily water level in the Gardon River exists since 1890, at the Nîmes Flood Warning Office (FWO). The observations are from Remoulins (Fig. 1) which is ~13 km downstream of our study reach. Fig. 3 shows the maximum stages during extreme floods recorded at the Remoulins gauging station (Fig. 4). Historical data of the Gardon River dates back to the XIth century (six floods between 1295 and 1470), although the most continuous record of floods started since the XVth century with 58 floods between 1600 and 1900 (Anton and Cellier, 1993; Davy, 1956; www.gard.equipement.gouv.fr 27/10/2006). These floods cluster at 1740-1750 1765-1786, 1820-1846, 1860-1880, 1890-1900. The magnitude of these floods is unknown, although following the damage and the descriptions showed in the DDE (2004) database file probably the AD 1403, 1604, 1741, 1768, 1846, and 1958 were the most catastrophic ones (DDE, 2004). Lescure (2004) indicated that the AD 1403 flood reached a discharge of 8000 m³s⁻¹ at Pont du Gard, this value determined according to historical references to destruction of villages in the Gardon basin by floods.

2.3 Meteorological settings on 8-9 September 2002

The 2002 flood was caused by an autumn storm, typical of this region, which struck with immense force. Rain gauges and rain radar show that in some areas the rain measured was more than 600 mm in 20 hours (Delrieu *et al.*, 2004). Following the detailed description and analysis of this rainfall event carried out by Delrieu *et al.*, 2004, the first convective cells formed around 04 UTC on September 8 2002 over the Mediterranean. The convection progressed northward to form over the Gard region a V-shape Meso-scale Convective System (MCS). The quasi-stationary MCS stayed over the same region until approximately 08 UTC the next morning and then evolved eastward with the surface front. Convection formed well ahead of the surface cold front, in the warm sector, where low-level southeasterly flows prevailed. During the afternoon and night of the 8 to 9th September 2002, the surface cold front slowly progressed eastward and the low-level flow over the Gulf of Lion accelerated. During the same time, the upper main deep trough swung into a NW/SE orientation leading to

an upper south-southwesterly flow over Southeastern France. As the surface front passed over the Gard region, it contributed to the heavy precipitation, but also swept the convective activity with it (Delrieu et al., 2004).

3. METHODS

3.1 Paleoflood analysis

During large floods in canyons, slackwater deposits (SWD), usually fine sands and silts, accumulate relatively rapidly from suspension in sites of abrupt drop in flow velocity (Ely and Baker, 1985; Kochel and Baker, 1988; Benito et al., 2003a). As a result, a layer of these deposits is formed. This sediment may be preserved in protected sites, such as: caves and alcoves in the canyon walls; and channel expansions upstream of channel contractions (Kochel and Baker, 1982; Ely and Baker, 1985; Baker, 1987; Baker and Kochel, 1988; Enzel et al., 1994; Greenbaum et al., 2000; Springer, 2002; Webb et al., 2002; Benito et al., 2003a; Benito and Thorndycraft, 2005). Subsequent flood deposits may accumulate above this layer by floods with stages higher than the top of the depositional sequence (Baker, 1987). In humid regions exposed deposits are not readily preserved however, caves may record this information (e.g. Kite and Linton, 1993; Springer and Kite, 1997; Sheffer, 2003, Sheffer et al., 2003b). In the case of the Gardon River the protected sites mainly include caves and alcoves in the canyon walls. Four main flood deposit sites were studied along this reach: GZ, GL, GU and GH (Fig. 2). The bedrock canyon allows the assumption that little to no change in the shape of the canyon throughout the late Holocene occurred.

3.2 Radiocarbon dating

Radiocarbon dating is a standard absolute dating tool employed in paleohydrologic work (e.g. Baker et al., 1985). The importance of dating the flood deposits is to allow the incorporation of their associated floods into the flood record in a correct sequence. Dating the events also enables the identification of historical events in cases of historical and paleofloods overlapping. In this study the conventional and AMS methods were used to date radiocarbon samples found in the SWD sequence. The paleoflood methods of separating slack water deposits and dating by radiocarbon used

in this study is thoroughly discussed by Sheffer (2003) and Sheffer *et al.*, (2003b). The important distinction is between flood deposits and other cave deposits. Flood SWD usually exhibit some sort of flow structure as opposed to the cave deposits which have no apparent structures. Any unit with these flow structures is therefore considered a flood deposit.

3.3 Hydraulic modeling

The discharge estimation was calculated using the US Army Corps of Engineers River Analysis System computer program-HEC RAS (Hydraulic 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 (O'Connor and Webb, 1988). Water surfaces of diverse discharges are calculated along the study reach based on step-backwater calculations and these are matched to the elevations of the flood deposits. The best correlation with direct field observations of low flow stage was used to test the calculation. Furthermore, flood discharges were estimated for the 2002 flood using a field survey of high water marks (HWM), and for slackwater flood sediments in caves left by previous floods along the study reach.

The accuracy of the discharge estimations depends on the cross-section stability through time. In stable, bedrock-confined channels, such as in the studied reach, channel geometry at maximum stage is known or can be approximated as no major changes can be assumed to have occurred over the last hundreds of years. Here, the step-backwater calculations, together with the geologic references of flow stages, provide good discharge estimates. In the calculations it is assumed that flow was subcritical along the modeled reach. Additional cross-sections for a 2 km reach downstream were obtained from a 1:5000 scale map to set up a normal depth boundary condition ($s=0.0005$ m/m) at the starting cross-section.

Field survey was performed along a 1600 m long river reach using a kinematic differential GPS Trimble 4700 combined with a Sokkia Total Station. In total, 26 cross-sections were surveyed at distances between 30 and 90 m apart. River channel topography was obtained by direct measurements of water depth, using a graduated rod operated from a boat, and taking as reference position a rope fixed at both sides of the river. In addition, the survey included reliable HWM associated with the 2002

flood and position of the paleostage indicators of previous floods, including erosion lines, caves containing slackwater flood deposits and flood bench deposits.

4. RESULTS

4.1 Paleoflood sites

4.1.1 Site GZ

This site is a cave (110.10 m asl), approximately 17 m above the normal base flow of the Gardon. Six units were found at this site (Fig. 5), five of which are flood deposits. These flood deposit units consist of silt-clay sediments featuring mainly diffused lamination flow structures. The contacts usually consist of angular gravel and ash residue. These units were all dated to the past 500 years (Table 1). The maximum water level during the 2002 flood according to high water marks (HWM) is 1.5 m below the site.

4.1.2 Site GL

This site is an alcove (110.80 m asl), approximately 19 m above the normal base flow of the Gardon. Three depositional units were found at this site, two of which corresponds to flood deposits. The flood deposits consist of fine sand to silt, featuring diffused lamination, with many charcoal pieces. The maximum water level during the 2002 flood according to HWM is 0.95 m below the site.

4.1.3 Site GU

This site is an alcove (112.95 m asl), and 2.15 m above site GL. Four depositional units were found at this site, two of which corresponds to flood deposits. The flood units consist of coarse sand to silt, featuring diffused lamination and bio-turbation. The maximum water level during the 2002 flood according to HWM is 3.1 m below the site.

4.1.4 Site GH

This site is a cave 12 m above the river thalweg (104.8 m asl). Twelve units were found in this cave (Fig. 6). Ten of which are flood deposits. These flood deposits consist of medium to very fine sand, featuring parallel lamination and diffused lamination. In some of the contacts ash residue was found. Units 4, 5 and 11 were dated to 2850 ± 45 BP, 2260 ± 40 BP and 260 ± 35 BP respectively (Table 1). This site was submerged during the 2002 flood, with at least 6.6 m of water between the SWD and the HWM.

4.2 Discharge estimation

Assigned Manning's n values varied between 0.027 and 0.1, which were selected from field observations and photographs of the study reach taken prior to the 2002 flood, and following the recommendation criteria provided by the U.S. Geological Survey (Arcement and Schneider, 1989). A sensitivity test performed on the hydraulic calculations show that for a 25% variation in roughness values ($0.75n$ and $1.25n$), an error of 4-18% was introduced into the discharge results at the cross-sections with HWM and paleostage indicators (Fig. 7), although at the downstream cross-sections this error may reach up to 40% (Table 2). Uncertainties in Manning- n values and energy loss coefficients had much less impact than uncertainties in cross-sectional data on discharge values estimated from hydraulic modeling (O'Connor and Webb, 1988; Enzel et al., 1994). Nevertheless, uncertainties introduced by Manning's coefficients were reduced by selecting the discharge associated with the 2002 flood at cross-sections that showed the lower sensitivity to roughness changes (cross-section 4 to 26, Table 2).

The discharge estimated for the 2002 flood using surveyed HWM matches many of the HWM associated with discharges that vary between 6400 and $6700 \text{ m}^3 \text{ s}^{-1}$ (Fig. 8). Paleoflood evidence at sites GZ, GL and GU indicate higher discharges than those of the 2002 floods. At site GZ (Fig. 2), field inspection showed that the 2002 flood HWM evidence was 1.5 m lower than the flood deposits. In this site at least five floods occurred over the last 500 years with a discharge larger than the 2002 flood.

The GL and GU (Fig. 2) alcoves are located at 0.95 m and 3.10 m higher than the 2002 flood HWM. Both caves comprise two flood units which are associated with an estimated minimum discharge of $7100 \text{ m}^3 \text{ s}^{-1}$ for the GL and $>8000 \text{ m}^3 \text{ s}^{-1}$ for the GU

providing the largest paleoflood evidence in the Gardon River. The stratigraphy suggests that the two flood units at GL and GU sites were left by an equal number of flood events. Unfortunately, no radiocarbon dates have been obtained for these flood deposits, however, the lack of indurations and the upper cultural layer (ashes and charcoal) suggest a similar age to the deposits described at the GZ site.

Cave GH (Fig. 2) is located at an elevation below the 2002 flood water level representing low magnitude floods, and contains a record of 10 low magnitude events, of which at least 7 units were deposited in the last 2000 years. Discharge estimation resulted in a minimum discharge of $2600 \text{ m}^3\text{s}^{-1}$ at the base of the alcove.

5. DISCUSSION

On the 8 and 9th of September 2002, a *typical* storm struck the Gard region with an *atypical* immense force producing 680 mm of rain in 21 hours, giving rise to the so claimed "largest flood on record". In this study, a detailed field survey of the HWM left by the 2002 flood at a bedrock canyon near La Baume provided a reliable map of the flood water surface elevation along the reach. On the basis of calculated water-surface profiles, a range of discharges that produces a best match with those high-water evidences estimated the flood peak to be 6400 to $6700 \text{ m}^3\text{s}^{-1}$. These values are similar to the discharge estimated by the Service d'Annonce des Crues (2003) of the Direction Départementale de l'Équipement du Gard which reported a discharge between 6500 - $7200 \text{ m}^3\text{s}^{-1}$, in Remoulins, 13 km downstream of the study reach, and 6000 - $6800 \text{ m}^3\text{s}^{-1}$ in Russan, 16 km upstream of the study site (Table 3).

The stratigraphic and hydraulic modeling data presented indicates that at least five floods of a larger magnitude ($\geq 6850 \text{ m}^3\text{s}^{-1}$) than the 2002 flood occurred over the last 500 years. The slackwater flood deposits indicate that at least three floods were bracketed by discharges between 6850 and $7100 \text{ m}^3\text{s}^{-1}$, and at least two floods reached a magnitude above $7100 \text{ m}^3\text{s}^{-1}$. This paleoflood evidence provides a robust discharge estimate from a stable bedrock reach for the largest floods within the Gardon River that must be accounted for in risk estimates along the river.

At the lower elevation caves (e.g. Site GH), the number of flood units preserved is much larger accounting up to 10 flood units at Site GH. At site GH, slackwater

deposits matched a minimum associated discharge of $2600 \text{ m}^3\text{s}^{-1}$. At low elevation alcoves, frequent flooding may erode the slackwater flood sediments (e.g. site GC). In contrast, deposits in high elevation caves (largest floods) may have a larger preservation potential, since only extreme events are able to flush away the sediments accumulated at these higher sites. For example, in the Llobregat River (NE Spain), Thorndycraft et al., (2005) have also described flood deposits representing two flood series, one related to a recent low elevation flood record and a second to high alcoves providing evidence of a complete record for the high magnitude floods. The paleoflood hydrology of the Gardon River, therefore, provides a reliable record of the largest floods over the last 400 years. Despite susceptibility to erosion because of its low position, site GH actually preserves evidence of much older floods. In addition to the recent floods, unit 11 dated to the Little Ice Age (LIA), units 4 and 6 were dated to $2850 \pm 45 \text{ BP}$ and $2260 \pm 40 \text{ BP}$ respectively. The adjacent Ardèche basin also witnessed paleofloods in these periods (Sheffer, 2003; Sheffer et al., 2003b), with paleoflood clustering dated to 2170 BP and 2705 BP, as well as during the LIA. Similar records were found in other Mediterranean basins, for example in north east Spain (Thorndycraft et al., 2004). This period is close in time to a cold and wet phase around 2,850 years ago, which is associated with variations in the emission of solar radiation (van Geel et al., 1999).

In alcove GZ, the radiocarbon dates indicated that at least five flood events occurred between AD 1625-1840, perhaps associated with the secular climate episode of the LIA (around AD 1550-1850, after Flohn, 1993). Documentary flood evidence records 64 flood events of the Gardon River since AD 1295, of which 58 occurred between AD 1600 and AD 1900 (Anton and Cellier, 1993; Davy, 1956; DDE, 2003b in www.gard.equipement.gouv.fr 27/10/2006). In terms of flood frequency, the historical flood database compiled by the Direction Départementale de l'Équipement du Gard in the (DDE, 2003b) show flood clusters between 1740-1750 1765-1786, 1820-1846, 1860-1880, 1890-1900. The magnitude of these floods is unknown, although following the documented damage and the descriptions in the DDE database (DDE, 2003b) it is possible to point out that five to six floods in AD 1403, 1604, 1741, 1768, 1846, and 1958 were probably the most catastrophic ones. Lescure (2004) describes that the AD 1403 flood would reach a discharge of ca. $8000 \text{ m}^3\text{s}^{-1}$ at Pont du Gard, whereas the 2002 flood at this site reached a magnitude of $6800 \text{ m}^3\text{s}^{-1}$. In general

terms, the number and timing of the historical flood events matches with the paleoflood stratigraphy described in this study. The highest historical discharge value ($8000 \text{ m}^3\text{s}^{-1}$) was assigned to a single event – the AD 1403 flood (Lescure, 2004). Similar values are calculated for the highest SWD site found at GU ($>8000 \text{ m}^3\text{s}^{-1}$), with at least two flood event recorded at this site.

The Little Ice Age has been related to increased flood frequency in France (Guilbert, 1994; Coeur, 2003; Sheffer, 2005; Sheffer, 2003; Sheffer et al., 2003a, b), and in Spain (Benito et al., 1996, 2003b; Barriendos and Martín-Vide, 1998; Thorndycraft and Benito, 2006a, b). In the Llobregat and Ter Rivers (NE Spain), within a similar hydroclimatic context, the magnitude of the floods generated during this period practically doubles those recorded in the 20th Century (Thorndycraft et al., 2004, 2005, 2006). During the last 1,700-2,000 years, hydrological response was affected both by climatic variability and human activities, the latter related to the establishment of agricultural societies that set in motion intense deforestation processes (Jorda et al., 1991; Jorda and Provansal, 1996). It is evident, however, that the generation of floods in medium-sized to large-size basins are always associated with extreme rainfall in these basins, with a moderate or less important role played by human activity in terms of the infiltration capacity of soils.

In Spain, sediment records of paleofloods covering the last 2,000 years indicate an abnormally high frequency of large floods during AD 1000-1200, AD 1430-1685 and AD 1730-1810 periods (Thorndycraft and Benito, 2006 a, b). The resolution of the radiocarbon dating technique for the last 300 years is poor, and this last period could, therefore, reflect dating errors. During the most recent period, a precise chronological constraint can be obtained from historical records. In the Isère River (Grenoble Valley, France), the historical flood record shows that the highest flooding severity was registered at 1620-1670, 1730-1780 and 1840-1860, (Coeur, 2003), whereas in Mediterranean Spain the highest flood severity was reached during 1580-1620 and 1840-1870 (Barriendos and Martín Vide, 1998). The climatic conditions prevailing in these periods with a high frequency of floods are difficult to estimate. The LIA average temperature in southern France (Marseille) reconstructed from proxy evidence (grape-harvest dates and tree-ring data) indicated a cooling of 0.5°C with maxima of 1.5°C (Guiot et al., 2005) However, in terms of extreme hydrological

events, the LIA in south-western Europe was indeed characterized by extreme variability, with periods of increased frequency of torrential rains, reflected in catastrophic flooding, as well as by an increased frequency of prolonged droughts (Benito et al., 1996, 2003b; Barriendos and Martín Vide, 1998).

A previous time interval with increased flood occurrences similar to the LIA is 2860-2690 years BP. In this period, the paleoflood records show an abnormal concentration of extreme events in different basins in the Mediterranean environment (Thorndycraft et al., 2004, Sheffer et al., 2003b). This period precedes or is close in time, to a cold and wet phase around 2,650 years ago (van Geel et al., 1999), which is associated with variations in the emission of solar radiation. Site GH records evidence of floods dated to this period – 2850 BP.

6. CONCLUSIONS

The paleoflood hydrology of the Gardon River proved an effective method for reconstructing the much needed past flood record. Although the gauged record is quite impressive (1890-present) and the historical record goes as far back as the 13th century, the physical evidence preserved in caves and alcoves on the frequency and magnitude of the largest floods add crucial information and can change the perception of flood risk. The historical record stores information on flood occurrence, without having data on the magnitude. Combining the historical with paleoflood data provides a much better understanding of the river's flood history. According to SWD found at sites GZ, GL and GU at least five extreme events occurred during the Little Ice Age. Each was larger than the 2002 flood. If this research had been conducted prior to the 2002 flood, the consequences of that flood could have been different due to better risk assessment and management. Therefore, expanding paleoflood hydrology research to adjacent basins may significantly improve the safety of those areas in future events.

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Figures and tables:

Table 1: Stratigraphic units and radiocarbon dating results. All calibrated ages were calculated within 1σ . Calibration was carried out using the OXCAL 3.5 software (C. Bronk Ramsey, OxCal program, version 3.5, 2000, <http://www.rlaha.ox.ac.uk/orau/index.htm>).

Table 2: Elevation and discharges associated to the HWM's and PSI's surveyed along the study reach. Note the percentage of variation in the discharge estimation resulted of a 25% changes in the Manning's n values.

Table 3: Flood discharge for 100 year flood and discharge estimated for the September 2002 along different locations of the Gardon River (Data after Direction Départementale de l'Équipement du Gard, DDE, 2003a; ISL, 2005; and SOGREAH, 2001 in Delgado, 2006).

Fig. 1: The Gardon River drains the Cévennes Region of the Massif Central (Southern France) into the Rhône River. The upper reaches of the catchment are incised in granitic metamorphic and basaltic bedrock and are separated by a fault from the lower reaches, which are incised in carbonates. The catchment area of the Gardon is $\sim 2000 \text{ km}^2$.

Fig. 2: A map showing the study sites in the Gardon Gorge. SWD were found in sites GU, GL, GH and GZ.

Fig. 3: The peak water surface elevation data series from the Remoulins gauging station (Fig. 4) 13 km downstream of La Baume (Fig. 4). On the top right corner are the estimated values of the 2002 flood ($6600 \text{ m}^3/\text{s}$) and the paleoflood estimates at GL ($7100 \text{ m}^3/\text{s}$) and GU ($>8000 \text{ m}^3/\text{s}$).

Fig. 4: a. The Remoulins bridge, 13 km downstream of La Baume. The gauging station that produced the record of Fig. 3 is at this bridge. b. The same bridge during the 2002 flood.

Fig. 5: a. Site GZ in relation to the 2002 flood erosion line. b. A picture of the SWD found at GZ. c. The stratigraphy at site GZ, 5 flood units were found at this site (units 2-6).

Fig. 6: a. A picture of the SWD found at GH. b. SWD stratigraphy at site GH. 12 depositional units were found at this site, 10 of which are flood deposits.

Fig. 7: Calculated water-surface profiles and HWM for the 2002 flood (triangles) along the study reach. The location of the caves containing geological evidences is shown in circles. The dotted line represents the 2002 flood energy line (computed with HEC-RAS).

Fig. 8: Rating curves of cross-section 24 for the assigned Manning-n values and for the one resulting for the 25% variation of this value. This sensitivity test shows that an error of up to 10% may be introduced into the discharge results due to roughness coefficient uncertainties

Site	Unit	Lab Reference	Age B.P.	Calibrated Age
GZ	2	RTT-4467	270±35	1520-1570 1630-1670 1780-1800
GZ	2	BA-170960	420±40	1430-1500 1600-1620
GZ	3	BA-170961	190±40	1660-1690 1730-1810 1930-1960
GZ	4	RTT-4469	150±30	1670-1700 1720-1780 1790-1820 1910-1950
GZ	5	BA-170962	250±40	1520-1560 1630-1670 1770-1800 1940-1960
GZ	6	RTT-4470	50±30	1690-1720 1810-1840 1880-1920 1950-1960
GH	4	RTT-4460	2850±45	BC 1110 – 920
GH	6	RTT-4461	2260±40	BC 400 – 350 BC 300 – 210
GH	11	RTT-4465	260±35	1520 – 1560 1630 – 1670 1780 – 1800

Table 1.

Cross-section	HWM/PSI	Altitude	Q (m ³ s ⁻¹)			VARIATION	
number		(m a.s.l.)	n*1.25	n*1	n*0.75	-% (n*1.25)	+% (n*0.75)
26	HWM1	111.38	5030	5520	5760	8.88	4.35
25	HWM1	111.42	5340	5920	6200	9.80	4.73
24	Cave GH	104.82	2320	2610	2720	11.11	4.21
	HWM1	111.42	5420	6040	6320	10.26	4.64
	HWM2	112.24	5880	6540	6840	10.09	4.59
21	Cave GC	112.46	6000	6670	6980	10.04	4.65
	HWM1	110.77	5520	6340	6840	12.93	7.89
	15	HWM1	109.85	5400	6460	7450	16.41
15	HWM2	109.48	5180	6200	7180	16.45	15.81
	Cave GU	112.96	7300	8760	10050	16.67	14.73
	Cave GL	110.81	5960	7140	8250	16.53	15.55
13	HWM1	106.90	4260	4460	5120	4.48	14.80
12	Mx erosion line	109.43	5060	5980	6800	15.38	13.71
10	HWM1	111.46	6220	7320	8300	15.03	13.39
8	Cave	106.60	4060	4240	4850	4.25	14.39
	HWM1	108.50	4820	5830	6820	17.32	16.98
6	HWM2	106.50	4350	4540	5320	4.19	17.18
	HWM1	102.96	2140	2560	3000	16.41	17.19
5	HWM2	105.50	3210	3840	4460	16.41	16.15
	HWM1	102.10	1840	2200	2540	16.36	15.45
4	Cave GZ	110.20	5720	6850	7920	16.50	15.62
	HWM1	108.83	5030	6060	7060	17.00	16.50
3	HWM1	108.70	5520	7220	-	23.55	-
2	HWM1	108.37	5140	6480	8820	20.68	36.11
1	HWM2	108.21	5050	6360	8660	20.60	36.16
	HWM1	107.80	4800	6040	8140	20.53	34.77
	HWM2	108.30	5110	6410	8640	20.28	34.79
	HWM3	109.90	6100	7660	10300	20.37	34.46

Table 2.

Source	Flood	Discharge ($\text{m}^3 \text{s}^{-1}$)				
		Alés (307 km^2)	Anduze (539 km^2)	Ners (1088 km^2)	Dions- Russan (1515 km^2)	Comps (2029 km^2)
SOGREAH 2001	100-yr	--	--	4500	--	4500
SIEE 1999	100-yr	1500	--	4500	4200	4800
DDE, 2003a	Sept.1958			5250	3500	
ISL2005	Sept.2002	2500	3400	6600	6800	5800
DDE, 2003a	Sept.2002	--	3000- 3400	6500-7200	6000-6800	--
This study	Sept.2002	--	--	--	6400-6700	--
This study	Largest paleoflood	--	--	--	>8000	--

Table 3.

Fig 1.

Fig 2.

Fig 3.

Fig 4.

Fig 5.

Fig. 6.

Fig 7.

Fig 8.