Accepted Manuscript

Palaeoflood and floodplain records from Spain: Evidence for long-term climate variability and environmental changes

G. Benito, V.R. Thorndycraft, M. Rico, Y. Sánchez-Moya, A. Sopena

PII: S0169-555X(08)00217-1
DOI: doi: [10.1016/j.geomorph.2008.05.020](https://doi.org/10.1016/j.geomorph.2008.05.020)
Reference: GEOMOR 2661

To appear in: *Geomorphology*

Please cite this article as: Benito, G., Thorndycraft, V.R., Rico, M., Sánchez-Moya, Y., Sopena, A., Palaeoflood and floodplain records from Spain: Evidence for long-term climate variability and environmental changes, *Geomorphology* (2008), doi: [10.1016/j.geomorph.2008.05.020](https://doi.org/10.1016/j.geomorph.2008.05.020)

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Palaeoflood and floodplain records from Spain: evidence for long-term climate variability and environmental changes.

G. Benito¹, V.R. Thorndycraft², M. Rico³, Y. Sánchez-Moya⁴, and A. Sopeña⁴

¹Institute of Natural Resources, CSIC, Serrano 115 bis, 28006 Madrid, Spain.

²Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, U.K.

³Instituto Pirenaico de Ecología, CSIC, Zaragoza, Spain

⁴Instituto de Geología Económica, CSIC-Universidad Complutense, 28040 Madrid, Spain

Abstract: Palaeoflood chronologies from seven Spanish river basins and floodplain aggradation chronologies from thirteen rivers are analysed. These fluvial records were divided in to two sub-sets, namely Atlantic (10 ka record) and Mediterranean (3 ka record) river basins, which represent distinct modern hydroclimatic conditions. In Atlantic basins floods result from intense, widespread rainfalls associated with Atlantic frontal systems transported by westerly airflow. Mediterranean river flooding is related to heavy rainfall induced by mesoscale convective systems (MCSs) during autumn months. Evidence from radiocarbon dates in slackwater flood deposits shows six periods of flood clusters at 10,750-10,240; 9550-9130; 4820-4440; 2865-2350; 960-790; and 520-290 cal BP. Despite the different flood-producing weather conditions in Atlantic and Mediterranean rivers, the radiocarbon sample clusters overlap, and indicates changes in large-scale atmospheric circulation and climatic conditions in the Iberian Peninsula. Comparison with proxy records of mean temperature for the Northern Hemisphere demonstrates a relation of the period of slackwater flood deposition with cold climatic phases (e.g. the 2650 yr BP climatic event or AD 1590-1650 period of the Little Ice Age). Radiocarbon dates from aggraded floodplain sediments were clustered at 2710-2320, 2000-1830, and 910-500 cal BP. The first cluster period is in phase with the timing of slackwater deposition, whereas the third (910-500 cal BP) occurs in between two periods of increased flood frequency as indicated by the palaeoflood and documentary flood records. It is argued that the 910-500 cal BP floodplain aggradation period reflects the first post-Roman evidence of environmental change related to generalised land-use changes at the catchment scale, which produced high sediment load transported to overbank areas during high flows.

Key words: Palaeofloods, Slackwater flood deposits, Floodplain alluviation, Fluvial Geomorphology, Holocene, Spain

1. Introduction

The geographic location of the Iberian Peninsula, at the southern limit of influence of the polar front in the subtropical-sensitive Mediterranean zone, provides great potential for elucidating short-term climatic or environmental changes from sedimentary archives (Vita-Finzi, 1969; Butzer, 1974, 1975, 2005; Lewin et al., 1995). The sensitivity of the region is shown in the temporal and spatial variability of natural indicators, such as

desertification, floods, droughts and biodiversity, which are closely related to the global change drivers, climate and human activity.

The hydrological history of the Iberian Peninsula appears to have been a complex alternation of wet and dry episodes with abrupt transitions related to the impact of changes in atmospheric circulation and oceanic currents (Luterbacher et al., 2006). Interpretation of palaeohydrological changes from alluvial sequences is a complex task because of problems in the identification of successive phases of local cyclic events, the internal dating and external correlation, and uncertainties about the causation (e.g. climate vs. land-use change) in a region with a long history of human intervention (Butzer, 1980 p. 133-134; Macklin et al., 1995). Furthermore, the perception of “rapid” environmental changes from fluvial sedimentary records is time-dependent and even site specific (Thomas, 2004), with an uneven temporal resolution of potential hydrological reconstruction that depends upon sedimentary environments.

Fluvial records in Spain fall within five types of depositional environments: alluvial overbank, flood basin, alluvial channel gravels, fluvio-torrential deposits and slackwater flood deposits (Thorndycraft and Benito, 2006a). Sediments from alluvial channel gravels and fluvio-torrential environments are related to highly erosive fluvial dynamics and the interpretation in terms of regional climate or environmental changes may be ambiguous. Such changes are likely to be recorded in fine-grained fluvial sediments deposited by high flows. Of particular relevance are: 1) the cut and fill sequences of alluvial floodplain and flood-basin environments (Sancho et al., 2007), which may record changes in the discharge-sediment load relationships over long-time periods (0.1-1 ka temporal resolution); or 2) sedimentary records of individual floods (0.01-0.1 ka resolution) (Baker 1987, Benito and Thorndycraft, 2005). The imprint of environmental and climate changes on floodplain cut and fill sequences is often nonlinear and subject to delayed responses and time lags (Schumm, 1977, Ashley, 1999). By contrast, sedimentary sequences of individual events may provide high resolution records occurring over short time periods (hours to days), mostly related to extreme hydrological events. In combination, the two types of fluvial archives have great potential in terms of determining key drivers and rates of change in fluvial systems. Indeed it has been shown that the magnitude and frequency of geomorphologically “effective” floods respond more rapidly, and perhaps more

sensitively, to short-term, external climate forcing than do pollen and lake records in the region (Benito et al., 2003a, Macklin et al., 2006). A major limitation, however, in establishing the spatial and temporal occurrence of these palaeohydrological changes are the uncertainties and errors inherent in the dating methods. In this respect, the combination of palaeoflood and historical records for obtaining data on floods that occurred during the last thousand years has been demonstrated to reduce the uncertainties associated with radiocarbon dating, and has even allowed the identification of individual events in the sedimentary record (Benito et al., 2004a, Thorndycraft et al., 2006).

This paper aims to (1) define the temporal and spatial patterns in the occurrence of large floods on rivers throughout Spain during the Holocene; (2) to explain these patterns in the context of the regional variability of climate fluctuations (100s to 1000s years), and land-use changes; and (3) to understand and compare the sensitivity of different fluvial environments to record palaeohydroclimatic and environmental changes.

2. Hydrology and flood hydroclimatology in Spain

The Iberian Peninsula is surrounded by the Atlantic Ocean to the west and by the Mediterranean Sea to the east (Figure 1). The influence of these large water masses, together with the orographic characteristics of the peninsula, result in a distinct division between basins draining towards the Atlantic and those to the Mediterranean. These contrasting hydroclimatic regions are, therefore, affected by different air masses which, because of distinctive characteristics, are responsible for different types of rainfall in terms of spatial distribution, seasonality and duration.

2.1 Atlantic river basins

Flood generation, duration and magnitude in Atlantic basins, are closely related to changes in winter rainfall (Capel, 1981; Benito et al, 1996; Rodrigo et al., 1999). Although the relationships between mean discharge, rainfall and peak discharge are not straightforward in these basins, the extremely wet years correspond to years with high peak discharges. The heaviest rainfall in the Atlantic basins occurs when the zonal circulation is displaced towards lower latitudes (35-45° N) and the western Iberian Peninsula is affected by the entry of successive frontal systems, thus generating heavy and persistent rainfall in the basins of the Duero, Tagus, Guadiana and Guadalquivir

rivers. A southerly wet air flow associated with an undulating flow circulation pattern is often responsible for intense rainfall over the Guadiana and Guadalquivir basins.

The position of zonal circulation in Western Europe can be characterized by the North Atlantic Oscillation index (NAO), measured by pressure differences between Iceland and the subtropical Atlantic from the Azores across the Iberian Peninsula (Walker and Bliss, 1932; van Loon and Rogers, 1978). Associations have been observed between these pressure differences and the distribution of winter rainfall and discharge in the Atlantic basins of the Iberian Peninsula (Trigo et al., 2004), and floods particularly in the Guadiana and Guadalquivir rivers (Ortega and Garzon, 2003, Benito 2006). Periods with the NAO in a negative phase are associated with humid/wet conditions in the western Mediterranean and northern Africa (Wanner et al., 1994) and cold air in northern Europe. A study of the wintertime (DJF) correlation between the NAO index and stream flow of Iberian Atlantic rivers (Trigo et al., 2004) shows that the basins most sensitive to the NAO are the more southerly basins (correlation value of -0.79 for Guadiana) followed by the Tagus (-0.77) and Duero (-0.76) basins. Recent studies have shown that the NAO index decreases during secular maxima of solar activity and increases during periods of decreased solar activity (Kirov and Georgieva, 2002). Because NAO is a natural mode of atmospheric variability, it is uncertain how anthropogenic climate change might influence modes of NAO (Corti et al. 1999; Hurrell et al., 2003), and subsequently winter rainfall excess and flooding over NAO sensitive areas of the Iberian Peninsula. Past analogues of climate variability, NAO mode and flood response may provide some light on potential future scenarios for flood impacts over Iberia in a climate change context.

2.2 Mediterranean river basins

In the east of the peninsula during autumn months, a general increase occurs in westerly, northwesterly and southwesterly circulation types. Synoptic situations with a southeasterly direction at low atmospheric levels and southwesterly at high altitude (associated with the presence of a high altitude trough or cold pool), and with advection of hot and humid air at low levels, are favourable for the development of organised mesoscale convective systems (MCSs), which generate floods (Llasat and Puigcerver, 1990). These systems affect mainly the Mediterranean coast and lead to events that generate floods in rivers of the Eastern Pyrenees and Ebro, the Júcar and Segura basins,

as well as southern coast rivers (Fig. 1). In the case of the Mediterranean rivers that drain the Iberian Range (Júcar, Segura and Turia), the highest peak discharges are recorded during this period and reach values up to 11,000 times greater than mean discharge during the largest floods (Masachs, 1950).

In Mediterranean basins, where the mechanisms established between climate and floods are more complex, no valid indices have been established, or models developed, to enable predictions to be made within a scenario of climate change. Climate conditions with strong seasonal temperature variations that augment the temperature differences between the Mediterranean Sea and the continent may favour convective rainfall over mountainous areas leading to flash floods, especially in autumn (Llasat and Puigcerver, 1990).

3. Methodology

Given the difficulties inherent in determining complete flood chronologies from individual sites, for example because of the lack of datable material within each flood unit, regional chronologies may provide long-term patterns of extreme flood frequency over thousands of years, patterns which are likely to be related to changing climatic factors that influence regional flood-generating weather conditions (e.g. Ely et al., 1993). Under this premise, a database of radiocarbon samples, collected from fluvial depositional environments, was compiled. The details of the full database are summarised in Thorndycraft and Benito (2006a). In this paper we analyse only those dates from slackwater flood deposits (*sensu* Baker, 1987) and floodplain sediments. In total this accounted for 79 radiocarbon dates from 13 river basins. Of the 79 dates, 51 were sampled from slackwater flood sediments (18 from Mediterranean rivers and 33 from Atlantic basins). The remaining 28 radiocarbon dates were from overbank fines of alluvial floodplains. In terms of the regional distribution of dates, the database includes information from three (Duero, Tagus, and Guadiana) of the four main Atlantic river basins. The Mediterranean region is represented by the Llobregat, Segre, Guadalentín, and Guadalquivir rivers.

All the radiocarbon dates were calibrated using the OXCAL calibration program (Bronk Ramsey, 2000, version 3.5, September 2003) to standardise the data-set. Analysis of the compiled data-set was performed using the sum probability command within

OXCAL following Johnstone et al. (2006) and Thorndycraft and Benito (2006a). This results in cumulative probability density function (CPDF) plots (where the y-axis is probability per year and the x-axis is the calibrated radiocarbon age) that illustrate the temporal distribution of all the dates entered into the analysis. This summed probability-based analysis provides a standardised tool to compare palaeohydrological records that may be linked to major climatic and environmental changes at the regional scale (Macklin et al., 2006). Combining radiocarbon chronologies at the regional scale may overcome some of the problems related to the palaeoflood archive in terms of the potential sampling or preservation bias of long-term flood histories (Lewin et al., 2005; Macklin et al., 2006). Probability plots were produced for Atlantic and Mediterranean river sub-sets of radiocarbon dates, as well as for slackwater and floodplain environments. The resultant chronologies were interpreted with respect to palaeoclimatic and environmental (land-use) variability within the region.

In addition to the analysis of radiocarbon dates, during the historical period the sedimentary records have been combined with documentary flood information collated from archives of public and ecclesiastical administrations (Benito et al., 1996; Barriendos and Martín Vide, 1998). Three types of records were obtained from these documentary sources: i) complete and continuous series from the 16th Century until the present; ii) discontinuous series between the 14th and the 15th Century, and iii) occasional events since classical times through the use of Greco-Roman and scattered Christian medieval and Arabic documents (Barriendos and Martín Vide, 1998). Most of the documentary flood evidence in Spain provide a high resolution temporal flood record (Benito et al., 1996; Barriendos and Martín Vide, 1998), and occasionally flood magnitudes (e.g. for the Tagus river) using step-backwater hydraulic modelling (Benito et al., 2003b; Brázdil et al., 2006).

4. Spanish palaeoflood chronology: Links to palaeoclimate and environmental changes

Figure 2 shows the sum probability plot based on the 51 radiocarbon dates from the slackwater flood deposits. The black line illustrates the record from Atlantic basins studied, whilst the grey shaded area represents Mediterranean rivers. Also presented are the midpoint ages (in calibrated years BP) and the two sigma age range (95%) of each date. Some of the probability distribution peaks during the mid Holocene are

represented by a single radiocarbon sample, however, in our analysis only clustering of dates were considered. The slackwater flood deposits can be divided into six date clusters occurring at 10,750-10,240; 9550-9130; 4820-4440; 2865-2350; 960-790; and 520-290 cal BP. The Mediterranean record covers the last 3000 years, which may relate to lower preservation potential because of the torrential and high slope gradient nature of most Mediterranean rivers in contrast to those of Atlantic basins. The palaeoflood record of the Llobregat River does contain three extreme events pre-dating 2800 BP, though a lack of dateable material has prevented the ages of these events to be constrained (Thorndycraft et al., 2005). Despite the different flood-producing weather conditions in the Atlantic and Mediterranean regions, the radiocarbon sample clusters overlap. This suggests that changes in large-scale atmospheric circulation and climatic conditions occurred that increased the likelihood of major flood producing events over the Iberian Peninsula as a whole. For example, during the Little Ice Age (LIA), increased periods of blocking over central Europe may be associated with increased frequency of westerly frontal systems pushing further south, whilst also contributing to occurrence of intense Mediterranean events, such as the 1617 floods in NE Spain (Thorndycraft et al., 2006). The record from floodplain environments is illustrated in Fig. 3, highlighting three main periods of alluviation, over the last 3000 years, at 2710-2320, 2000-1830, and 910-500 cal BP. The first period is in phase with the timing of slackwater deposition, whereas the third one (910-500 cal BP) occurs between two main slackwater deposition phases dating to 960-790 and 520-290 cal BP (Fig. 3).

In the Iberian Peninsula wet winters with flood generation can be explained in terms of a relatively small number of large-scale circulation modes at the monthly time scale (Capel, 1981; Benito et al., 1996; Trigo and Palutikof, 2001). In this respect, slackwater-based palaeoflood records provide real evidence for the occurrence of an individual extreme hydrological event that can potentially be linked to regional and global climatic variation during the Holocene. In contrast, floodplain deposition depends on the occurrence of overbank exceeding discharges and a sufficiently high sediment yield within the catchment (Thomas, 2004). Therefore, floodplain deposition is controlled by a combination of hydrological changes (principally controlled by climate) and sediment delivery from slopes and tributary streams which may be linked to either climate (runoff generation and vegetation cover) or human (land-use) perturbation within the catchment. Chronological comparison of radiocarbon

chronologies in these two fluvial environments (in-phase or out-of-phase) will provide further insight into the roles of climate and environmental change within the Iberian Peninsula.

The early Holocene flood cluster from slackwater flood deposits (Fig. 2) at 10,750-10,240 cal BP, with all samples coming from the Tagus River (Benito et al., 2003a), reflects a period with an anomalous number of floods (at least 12 events in ca. 400 yr) of very high magnitude (100-1000-yr return period events). This flood period occurred immediately after the Younger Dryas period (12,700 to 11,500 yrs BP), and it can be interpreted as being related to a return to westerly-dominated hemispheric circulation with the Azores High at lower latitudes and a low index zonal circulation over the Atlantic (Benito et al., 2003a). Modern flood analogues reaching such a large peak discharge (e.g. the 1947 flood event) resulted from a combination of persistent rainfall combined with a high proportion of snowmelt discharge from mountainous areas.

The 9550-9130 cal BP cluster coincides with evidence for a short climatic cooling event (Thorndycraft and Benito, 2006a) from proxy records, namely an increase in hebeaceous taxa in NE Spain (Laguna Lucenza; Leira and Santos, 2002) and central Spain (Tablas de Daimiel; Dorado et al., 2002). Thorndycraft and Benito (2006a) noted that this period also coincides with a peak (cold phase) in the North Atlantic drift ice index, dated to ca 9400 cal BP (Bond et al., 2001), believed to be related to solar forcing because of an increase in the production rate of cosmogenic nuclides at this time. According to Benito et al., (2003a), flood magnitudes of the Tagus River during the 9550-9130 cal BP phase were estimated at about half the peak discharge of the previous period (10,750-10,240 cal BP). The lower peak flow discharge may be interpreted as being related to two different flood-producing conditions such as a lower discharge from snowmelt or rainfall sources during the 9550-9130 cal BP period.

Between 9000 and 4800 yr BP, palaeoflood records are represented by a few single-dated slackwater flood dates mostly recorded in Atlantic Basins (Fig. 2). This discontinuous record may be interpreted as a result of a decline in average winter rainfall over the Iberian Peninsula, or alternatively as a response to changes in catchment characteristics associated with the Holocene climatic optimum (9000 to 5000 yr BP). This latter hypothesis is yet to be explored fully; however, it is likely that

increased vegetation cover across the landscape, including floodplains, during the early to mid Holocene would have had a profound impact on the hydrology and sediment delivery of rivers, thus, potentially influencing peak flood discharge and the supply and deposition of sediment within early Holocene and middle Holocene fluvial systems. The changing inter-relationships between discharge regime, floodplain and catchment vegetation, sediment supply and channel pattern have been elucidated for lowland Holocene floodplains of UK rivers such as the Nene and Soar (Brown et al., 1994). In their proposed stable beds aggrading banks (SBAB) model of floodplain development, Brown et al. (1994) hypothesised that the early Holocene floodplains of these rivers metamorphosed from the braided gravel floodplains of the Younger Dryas into stable anastomosing rivers, initially through a reduction in discharge and the abandonment and infilling of the smaller channels of the braided system during the early Holocene. The multiple channels of the anastomosing system were maintained by the subsequent colonisation of floodplain woodland and the continued reduction in sediment size so that river banks were composed of fine grained cohesive bank material (Brown and Keough, 1992). It is only during the late Holocene (last 3000 years) that these floodplains developed a single meandering pattern with significant floodplain alluviation i.e. post-dating the impact of deforestation and agricultural development (Brown et al., 1994).

In the Tagus River a series of floods with poor chronological control (one single date) were placed at 7690- 7480 cal BP, with magnitudes corresponding to a 25 to 50-yr flood return period (Benito et al., 2003a). In the Huebra river (Duero Basin) the slackwater flood record shows physical evidence of at least two small size floods (10-yr return period) during 4820-4440 cal BP (unpublished data). Similarly, few dates exist from alluvial floodplains prior to 4000 yr BP. An increase of floodplain activity was found during the interval 3890-3060 cal BP with four radiocarbon dates recorded in the Tagus and Guadalquivir basins (Atlantic regime) (Fig. 3). This period seems to correspond to a marked increase of aridity, indicated for example by an increase in xerophytic vegetation from ca 3600 cal BP at Villaverde (central Spain) on the edge of La Mancha plain (Carrión et al., 2001). These dry climate conditions seem to prevail throughout the late Holocene in the Ebro valley (Davis, 1994; Valero-Garcés et al., 2000). The decrease of arboreal vegetation, related to the drier climate, could have led to increased sediment yields from slopes and tributary streams favouring floodplain aggradation.

It is generally considered that in the last 3,000 years the general atmospheric circulation has presented similar characteristics to the present (Knox, 1983), and it is, therefore, during this period that analysis of climate–flood relationships is of greatest interest. The Spanish record contains more dates from this time in both Mediterranean and Atlantic basins, with clusters of slackwater flood dates at 2865-2350 yr BP (6 dates), and on floodplains at 2710-2320 yr BP (Fig. 3). This time interval is probably associated with the 2650 yr BP climatic event, though precise correlation is problematic because of the calibration curve plateau during this period. This event is believed to relate to variations in the emission of solar radiation (van Geel et al., 1998) and is characterised by widespread cooling in the North Atlantic region (Risebrobakken et al., 2003), relatively wet conditions in Western Europe (e.g., Magny, 1993; van Geel et al., 1996; 1998; Holzhauser et al., 2005), and flooding in different regions of western and central Europe (Macklin et al., 2003; 2006; Starkel et al., 2006 and Thorndycraft and Benito, 2006b). In the Llobregat River, the magnitude of the floods generated in this period is almost double those recorded in the 20th Century and can only be compared to some events observed in the 17th Century (Thorndycraft et al., 2005). High discharges were associated with high rates of sediment production enhancing floodplain aggradation in several Iberian rivers such as the Guadalquivir (Uribelarrea and Benito, in press), Jarama (Alonso and Garzón, 1996) and Guadalentín rivers (Calmel-Avila, 2000). A period of slackwater sedimentation was also identified between 2330-2000 yr BP, although it was only recorded in a single river (3 dates) of the Duero Basin (unpublished data) so has not been included as a separate cluster.

A major issue relates to the role of human activity as a key driver of fluvial activity. The establishment of agricultural societies that set in motion widespread deforestation and the subsequent working of the land resulted in an increase in sediment delivery to stream channels (Trimble, 1983). Analysis of pollen from different Spanish locations indicate that widespread changes of vegetation cover from human intervention did not occur until the last 2000 years (Allen et al., 1998) and since 2000-1700 BP in south-central Spain (e.g. Burjachs et al., 1997; Santos et al., 2000 and Carrión et al., 2001). As shown elsewhere in Europe (e.g. the Rhine basin, Hoffmann et al., in press) floodplain aggradation is sensitive to human impact because of the increased sediment supply associated with progressive erosion of soils and higher sediment delivery to river

systems. In the Spanish record, only few radiocarbon dates from lateral gravel aggradation facies of the Guadalquivir river provided ages between 2000-1830 cal yr BP during the first millennium AD, a period which seems to be characterised by low river channel migration and relative stability (Uribelarrea and Benito, in press). According to the floodplain chronology of the Guadalquivir river, Uribelarrea and Benito (in press) argue that: (1) deforestation or its impacts were not significant at the basin scale until late medieval times; or that (2) the hydroclimatic conditions were not optimal in terms of river transport capacity and river mobility until approximately 1000 AD. The available geoarchaeological and bioarchaeological data in Spain supports this picture of Roman-era stability extended until AD 1000 with associated soil formation on floodplains and forest regeneration (Butzer, 2005).

Sediment records of palaeofloods covering the last millennium indicate an abnormally high frequency of large floods in the Atlantic and Mediterranean basins during 960-790 cal BP and 520-290 cal BP (Figs. 2, 3 & 4). The flood timing can be improved by considering only those slackwater flood deposit sequences with multiple radiocarbon dates precisely bracketing periods of increased flood frequency. The flood clusters can then be redefined to AD 1000-1200 and AD 1430-1660, with a probable later period at AD 1730-1810, though the resolution of radiocarbon dating during the last 300 years is poor. The first palaeoflood period (AD 1000-1200) broadly corresponds to the late Medieval Warm Period (MWP; probably AD 900-1200, after Flohn, 1993), though some authors doubt that the MWP can be clearly defined at the global and continental scale (Hughes and Diaz, 1994). The second and third phases coincide with the Little Ice Age (LIA, ca 1500-1850), generally believed to be a more widespread event at the global scale.

The concentration of floods from AD 1000 and 1200 is also apparent in documentary evidence from Atlantic basins of the Iberian Peninsula (Benito et al., 1996), these events probably associated with unusually wet winters. Flooding of the Tagus River from AD 1100 to 1200 was frequent as well as exceptional, and water stage data indicate that these floods were the greatest of the available documentary record (Benito et al., 2003b). Of particularly large magnitude were the floods of AD 1168 (also recorded for the rivers Duero and Guadalquivir; Benito et al., 1996), 1178, 1181 and 1207. These floods attained peak discharges in Toledo of $3600 \text{ m}^3 \text{ s}^{-1}$, exceeding the catastrophic floods of

the Tagus in AD 1876 and 1947, the largest events of modern times (Benito et al., 2003b).

In contrast to the periods showing a high flood frequency, the lack of slackwater deposits between AD 1200 and 1430 should also be highlighted as a period of reduced flood frequency. This period is also evident in the documentary record (Benito et al., 2003b). This period 800-500 cal. BP (Fig. 3), however, comprises one of the main phases of floodplain aggradation of Iberian Rivers as has been described by other researchers (Vita-Finzi, 1976; Butzer et al., 1985). The onset of this phase of alluviation may vary as a consequence of land-use change on a local scale (Butzer, 1980), although this period of accelerated alluviation during the late Medieval period is almost ubiquitous in most Spanish rivers (Butzer et al., 1983, Uribealarea and Benito, in press), even causing burial of irrigation structures (Butzer et al., 1985). For instance, average channel lateral migration of the Guadalquivir River between AD 1000-1500 was estimated at 1.2 m yr^{-1} , which is three times higher than the previous and following periods (Uribealarea and Benito, in press). Floodplain aggradation of Iberian rivers is likely to be related to high sediment load as a consequence of land use change, including deforestation and expansion of agricultural land into marginal areas, as well as to scattered flood events until the 1500s (Butzer et al., 1983, Benito et al. 1996; Butzer, 2005).

Over the last 500 years, the palaeoflood record shows a phase of slackwater deposition during 520-290 cal BP with peaks between AD 1430-1660 and AD 1730-1810 (Figs. 3 & 4). Similar timing on the flood clusters were obtained for the Atlantic and Mediterranean rivers despite the different flood-producing weather situations. Historical climatology research indicates that the first palaeoflood period overlaps one of the main phases (AD 1590-1650) of the LIA in southern Spain when the prevailing anomalies were wet, with the wettest years centred around the AD 1590s and 1630s and 1640s (Rodrigo et al., 1999). During the interval AD 1750-1810, rainfall anomalies were fluctuating with a generally positive rainfall anomaly over the period (Rodrigo et al., 1999). These palaeofloods can also be compared to the documentary flood record, including information allowing meteorological reconstructions of individual past floods. Documentary records show an increase in the frequency of floods of large magnitude in the Atlantic basins of the Iberian Peninsula during the periods AD 1150-1290, 1590-

1610, 1730-1760, 1780-1810, 1870-1900, 1930-1950 and 1960-1980 (Benito et al., 1996; 2003b). In Mediterranean river basins, documentary sources indicate highest flood severity during AD 1580-1620 and AD 1840-1870 (Barriendos and Martín Vide, 1998; Llasat et al., 2005). A further period (AD 1760-1800) was noteworthy for its strong climatic variability with floods and droughts occurring (Barriendos and Llasat, 2003). The effects of these events spread throughout much of Western and Central Europe, with a clear impact on agricultural production elsewhere in Europe (Barriendos and Llasat, 2003). The palaeoflood and documentary flood evidence suggest that the catastrophic floods of AD1617, affecting the Ter, Llobregat and Segre rivers, were the most extreme during the last ca.700 years in NE Spain. An estimated minimum peak discharge of $4680 \text{ m}^3\text{s}^{-1}$ was calculated for the Llobregat River (Thorndycraft et al., 2006), twice the largest instrumental flood of 1971, measured at $2300 \text{ m}^3\text{s}^{-1}$ at the Monistrol gauge station within the palaeoflood study reach.

6. Palaeofloods, floods and long-term variations in NAO index

In the Atlantic basins, large inter-annual variability of river flow is predominantly modulated by North Atlantic circulation, indicated by the NAO (Trigo et al., 2004). In these basins floods are highly related to persistent rainfall (several weeks) caused by the successive passage of Atlantic cold fronts over the Iberian Peninsula in winter months. It is, therefore, natural to expect a strong impact of the NAO on flooding in large Atlantic river catchments. Figure 5 shows the relationship between the average winter (DJF) NAO index reconstructed by Luterbacher et al. (2002) since AD 1500 and the maximum discharges recorded during those months from instrumental (gauge stations) and documentary sources (Benito et al., 2003b) for the Tagus River at Talavera (near the Puente del Arzobispo palaeoflood site) and Alcantara. A strong correlation is generally observed between negative DJF NAO index and flood discharges above $1500 \text{ m}^3\text{s}^{-1}$ for Talavera and $4000 \text{ m}^3\text{s}^{-1}$ at Alcantara, as expected, given the correlation between rainy years and years with large floods in the Atlantic basins. Despite this correlation, however, it is important to note that negative DJF NAO index values are not always related to the occurrence of extraordinary floods. The link between the NAO index and extreme floods can also be detected in certain episodes obtained through historic documents for the basins of the Guadalquivir (Benito 2006) and Guadiana (Ortega and Garzón, 2004), as well as a correlation between some flood periods and moments of maximum solar activity (Vaquero, 2004; Benito et al., 2004b).

In terms of the palaeoflood records, periods with high flood frequency (4820-4440; 2865-2350; 960-790; and 520-290 cal BP.) should be associated with a prevailing negative winter NAO mode, at least over the last 3000 years, when present-day atmospheric circulation was probably in existence (Knox, 1983). Some studies have shown, however, that the association between the NAO circulation mode (NAO index) and local or regional climate variables (rainfall and temperature) has changed over time (Rodó et al., 1997; Goodess and Jones, 2002). The influence of the NAO on temperature variability in southern Europe is extremely sensitive to the position of the NAO action centres (Castro-Díez et al., 2002), which changes from year to year (Mächel et al., 1998; Davis et al., 1997). Whatever the relationships, palaeoflood records have revealed connections between floods and major climate shifts in the past (Ely et al., 1993; Ely 1997), and may provide clues for the response of future flood frequency.

Scenarios and predictions of future variations in the NAO index are currently being generated with the use of climate simulation models (GCMs), which can be used to establish the patterns of future flood response in the Iberian Atlantic river basins. The projection of this index in relation to global warming is unclear and it is not agreed whether a positive NAO phase in the 1980s and 1990s will be maintained or will intensify during the first half of the 21st Century. Presently half of the models predict a positive intensification of the index associated with climate change, whereas the other half predict that the NAO index will remain at levels comparable to those of the last few decades (Osborn, 2004). In both scenarios we can expect a clear downward tendency of extraordinary floods in the Atlantic basins of the Iberian Peninsula in relation to the frequency patterns existing during the second half of the last century (Benito et al., 2005).

Regarding the Mediterranean basins, where the mechanisms established between climate and floods are more complex, no valid indices have yet been established, nor models developed, to enable predictions to be made within climate change scenarios. Palaeoflood and historical flood series indicate that extreme floods have occurred during episodes of irregular rainfall, at seasonal and annual scales (droughts followed by floods; e.g. 2700 B.P., and at the start of the LIA). In recent times, such as during the

1980s, an increase has been observed in the generation of intense rainfall in the Mediterranean area of the Iberian Peninsula, an increase interpreted as a response to climate change. This tendency was reversed in the 1990s, however, which reveals the complexities involved in the generation of extreme events. In a global warming scenario, an increase in summer temperatures and temperature gradients between the Mediterranean Sea and the continent are likely to favour the generation of storms and flash floods, especially in autumn.

7. Conclusions

A palaeoflood chronology, based on radiocarbon dates from slackwater flood deposits investigated in seven Spanish river basins has been presented. Slackwater flood records represent real evidence for individual, extreme floods which can be unequivocally related to anomalous weather (rainfall) conditions. Currently, flooding of Iberian Atlantic rivers is sensitive to persistent rainfall caused by Atlantic fronts crossing the region from west to east during winter months, which are controlled by the North Atlantic Oscillation (NAO). Current flooding in Mediterranean river basins mainly results from southwest flow at altitude producing cyclonic cells or mesoscale convective systems (Capel, 1981). Radiocarbon flood chronologies are clustered in time periods occurring at 10,750-10,240, 9550-9130, 4820-4440, 2865-2350, 960-790, and 520-290 cal BP. Despite the different flood-producing weather conditions in the Atlantic and Mediterranean hydroclimatic regions, the radiocarbon date clusters coincide, at least during the last 3000 years, since the time of the oldest dated slackwater flood deposit from a Mediterranean basin. The occurrence of these flood clusters has enabled the determination of decadal to centennial changes in atmospheric circulation and possible variations in climatic conditions over the Iberian Peninsula. The direction of the climatic shift, however, is not unequivocal with some flood episodes clearly related to cold (wet) conditions at the hemispheric scale (e.g. 10,750-10,240, 2865-2340, and 520-290 cal BP) whereas other flood episodes were produced at times with a high hydroclimatic variance (warming-dry periods; e.g. 9550-9130, 4820-4440, 960-790 cal BP).

Radiocarbon samples from overbank alluvial deposits from the last 3000 years show clusters at 2710-2320, 2000-1830, and 910-500 cal BP. Floodplain aggradation requires high sediment production from the catchment (climatically or human induced) and

overbank (moderate or extreme) flows to inundate the floodplain. The aggradation phase at 2710-2320 cal BP is in phase with the timing of slackwater deposition and indicates a climatic driven aggradation phase. The aggradation dated to 910-500 cal BP, however, is not in phase with the palaeoflood record, and occurred between two periods of slackwater deposition at 960-790 and 520-290 cal BP. This period of reduced flood frequency, at least of high magnitude events, is also indicated in the documentary flood record. This alluviation phase is interpreted as a diachronous response to periods of environmental change related to an increase of agriculture and deforestation (changing land-use) and its impact on runoff and sediment supply.

Over the last millennium, the palaeoflood chronology is in accord with the documentary record of flooding periods in Atlantic basins at AD 1150-1290, 1590-1610, 1730-1760, 1780-1810, 1870-1900, 1930-1950 and 1960-1980 (Benito et al., 1996; 2003b), and in the Mediterranean basins at AD 1580-1620, 1760-1800 and 1840-1870 (Barriendos and Martín Vide, 1998; Llasat et al., 2005). The reconstructed winter (DJF) North Atlantic Oscillation index since AD 1500 (Luterbacher et al., 2002) was compared with peak discharges of the Tagus River from instrumental and documentary sources. A strong correlation was observed between negative winter (DJF) NAO index and flood discharges above $1500 \text{ m}^3 \text{ s}^{-1}$ for Talavera and $4000 \text{ m}^3 \text{ s}^{-1}$ in Alcantara. It may be concluded that palaeoflood clusters represent periods of a dominant negative mode in the NAO index at least over the last 3000 years, when general features of the present-day atmospheric circulation were probably in existence (Knox, 1983). This information may be used for a better understanding of potential impacts of future climate change (Gregory et al., 2006).

Acknowledgements

This palaeoflood research has been funded by the European Commission through the projects “Systematic, Palaeoflood and Historical data for the improvEment of flood Risk Estimation – SPHERE” (contract no. EVG1-CT-1999-00010) and “FloodWater recharge of alluvial Aquifers in Dryland Environments – WADE (contract no. GOCE-CT-2003-506680). The Spanish Commission of Science and Technology funded the project “Incorporation of palaeoflood and historical flood data in the calculation of dam safety –PALEOCAP” (CICYT project no. REN2001-1633-RIES), and the project “Infiltration on channel beds and recharge of aquifers related to floods and palaeofloods

in ephemeral rivers- PALEOREC” (CICYT project no.CGL2005-01977/HID). We would also like to thank David W. May (University of Northern Iowa) and Ellen Wohl (Colorado State University) for their comments, which helped improve the original manuscript.

References

- Allen, J.R.M., Huntley, B., Watts, W.A., 1998. The vegetation and climate of northwest Iberia over the last 14,000 years. *Journal of Quaternary Science* 11, 125-147.
- Alonso, A., Garzón, G., 1996. The Jarama River. In: Benito, G., Pérez-González, A., Machado, M.J., de Alba, S. (Eds.), *Palaeohydrology in Spain: Field Excursion Guide. Second International Meeting on Global Continental Palaeohydrology, GLOCOPH '96*, CSIC, Madrid, pp. 21-34.
- Ashley, G.M., 1999. Methods, potential and limitations for tracing abrupt climatic changes in elastic environments. *GFF* 121, 162-165.
- Baker, V.R., 1987. Paleoflood hydrology and extraordinary flood events. *Journal of Hydrology* 96, 79-99.
- Barriendos, M., Llasat, M.C., 2003. The Case of the 'Maldá' Anomaly in the Western Mediterranean Basin (AD 1760–1800): An Example of a Strong Climatic Variability. *Climatic Change* 61, 191-216.
- Barriendos, M., Martín Vide, J., 1998. Secular Climatic Oscillations as Indicated by Catastrophic Floods in the Spanish Mediterranean Coastal Area (14th-19th Centuries). *Climatic Change* 38, 473-491.
- Benito, G., 2006. Riesgos de inundaciones: Tendencias históricas y perspectivas de acuerdo con el Cambio Climático. *Cuaternario y Geomorfología* 20 (3-4), 29-44.
- Benito, G., Barriendos, M., Llasat, C., Machado, M., Thorndycraft, V. R., 2005. Impactos sobre los riesgos naturales de origen climático. In: Moreno, J.M. (Coord.), *Evaluación preliminar de los impactos en España por efecto del Cambio Climático*. Ministerio de Medioambiente, Madrid, pp. 527-548.
- Benito, G., Sopeña, A., Sánchez-Moya, Y., Machado, M.J., Pérez-Gonzalez, A., 2003a. Palaeoflood record of the Tagus River (Central Spain) during the Late Pleistocene and Holocene. *Quaternary Science Reviews* 22, 1737-1756.
- Benito, G., Díez-Herrero, A., de Villalta, M.F., 2003b. Magnitude and frequency of flooding in the Tagus basin (Central Spain) over the last millennium. *Climatic Change* 58, 171-192.

- Benito, G., Lang, M., Barriendos, M., Llasat, M.C., Frances, F., Ouarda, T., Thorndycraft, V., Enzel, Y., Bardossy, A., Cœur, D., Bobée, B., 2004a. Use of Systematic Paleoflood and Historical Data for the Improvement of Flood Risk Estimation. Review of Scientific Methods. *Natural Hazards* 31, 623-643.
- Benito, G., Díez-Herrero, A., de Villalta, M.F., 2004b. Flood response to solar activity in the Tagus basin (Central Spain) over the last millennium. *Climatic Change* 66, 27-28.
- Benito, G., Machado, M.J., Pérez-González, A., 1996. Climate change and flood sensitivity in Spain. In: Branson, J., Brown, A.G., Gregory, K.J. (Eds.), *Global continental changes: The context of palaeohydrology*. Geological Society Special Publication 115, London, pp. 95-98.
- Benito, G., Rico, M., Thorndycraft, V.R., Sánchez-Moya, Y., Sopeña, A., Díez Herrero, A., Jiménez, A., 2006. Palaeoflood records applied to assess dam safety in SE Spain. In: Ferreira, R., Alves, E., Leal, J., Cardoso, A. (Eds.), *River flow 2006*. Taylor & Francis Group, London, pp. 2113-2120.
- Benito, G., Thorndycraft, V.R., 2005. Palaeoflood hydrology and its role in applied hydrological sciences. *Journal of Hydrology* 313 (1-2), 3-15.
- Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294, 2130-2136.
- Brázdil, R., Kundzewicz, Z.W., Benito, G., 2006. Historical hydrology for studying flood risk in Europe. *Hydrological Sciences Journal* 51 (5), 739-764.
- Bronk Ramsey, C., 2000. *OxCal Program v3.5: the manual*. Oxford.
- Brown, A.G., Keough, M.K., 1992. Holocene floodplain metamorphosis in the East Midlands, United Kingdom. *Geomorphology* 4, 433-445.
- Brown, A.G., Keough, M.K., Rice, R.J., 1994. Floodplain evolution in the East Midlands, United Kingdom: the lateglacial and Flandrian alluvial record from the Soar and Nene valleys. *Philosophical Transactions of the Royal Society of London, Series A* 348, 261-293.
- Burjachs, F., Giralt, S., Roca, J.R., Seret, G., Juliá, R., 1997. Palinología Holocénica y desertización en el mediterráneo occidental. In: Ibáñez, J.J., Valero Garcés, B.L., Machado, C. (Eds.), *El paisaje mediterráneo a través del espacio y del tiempo. Implicaciones en la desertificación*. Geoforma ediciones, Logroño, pp. 379-394.

- Butzer, K.W., 1974. Accelerated soil erosion. In: Manners, I., Mikesell, M.W. (Eds.), *Perspectives on Environment*. Association of American Geographers, Washington D.C., pp. 57-78.
- Butzer, K.W., 1975. Pleistocene littoral-sedimentary cycles of the Mediterranean Basin: a Mallorquin view. In: Butzer, K.W., Isaac, G.L. (Eds.), *After the Australopithecines*. Mouton, The Hague, pp. 25-71.
- Butzer, K.W., 1980. Holocene alluvial sequences: Problems of dating and correlation. In: Cullingford, R.A., Davidson, D.A., Lewin, J. (Eds.), *Timescales in Geomorphology*. John Wiley, Chichester, pp. 131-142.
- Butzer, K.W., 2005. Environmental history in the Mediterranean world: cross-disciplinary investigation of cause-and-effect for degradation and soil erosion. *Journal of Archaeological Science* 32, 1773-1800.
- Butzer, K.W., Butzer, E.K., Mateu, J.F., Kraus, P., 1985. Irrigation agrosystems in Eastern Spain: Roman or Islamic origins?. *Annals, Association of American Geographers* 75, 495-522.
- Butzer, K.W., Miralles, I., Mateu, J.F., 1983. Urban geo-archaeology in Medieval Alzira (Prov. Valencia, Spain). *Journal of Archaeological Science* 10, 333-349.
- Calmel-Avila, M., 2000. Procesos hídricos holocenos en el bajo Guadalentín (Murcia, SE España). *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.
- Capel, J., 1981. *Los Climas de España*. Col. Ciencias Geográficas. Oikos-Tau, Barcelona.
- Carrión, J.S., Andrade, A., Bennet, K.D., Navarro, C., Munuera, M., 2001. Crossing forest thresholds: inertia and collapse in a Holocene sequence from south-central Spain. *The Holocene* 11, 635-653.
- Castro-Díez, Y., Pozo-Vazquez, D., Rodrigo, F.S., Esteban-Parra, M.J., 2002. NAO and winter temperature variability in southern Europe. *Geophysical Research Letters* 29, 8, 1-4.
- Corti, S., Molteni, F., Palmer, T.N., 1999. Signature of recent climate change in frequencies of natural atmospheric circulation regimes. *Nature* 398, 799-802.
- Cuenca Paya, A., Walker, M.J., 1977. Nuevas fechas 14C para el sector de Alicante y Murcia. *Trabajos sobre Neógeno y Cuaternario* 6, 309-317.

- Davis, B.A.S., 1994. Paleolimnology and Holocene environmental change from endorheic lakes in the Ebro Basin, north-east Spain. Ph.D. Thesis, University of Newcastle Upon Tyne, UK.
- Davis, R.E., Hayden, B.P., Gay, D.A., Phillips, W.L., Jones, G.V., 1997. The North Atlantic subtropical anticyclone. *J. Climate* 10, 728-744.
- Dorado, M., Valdeolmillos, A., Ruiz, M.B., Gil, M.J., Bustamente, I., 2002. Climatic changes since the Late-glacial/Holocene transition in La Mancha Plain (South-central Iberian Peninsula, Spain) and their incidence on Las Tablas de Daimiel marshlands. *Quaternary International* 93-94, 73-84.
- Ely, L.L., 1997. Response of extreme floods in the southwestern United States to climatic variations in the late Holocene. *Geomorphology* 19, 175-201.
- Ely, L.L., Enzel, Y., Baker, V.R., Cayan, D.R., 1993. A 5000-year record of extreme floods and climate change in the southwestern United States. *Science* 262, 410-412.
- Faust, D., Díaz del Olmo, F., Baena Escudero, R., 2000. Soils in the Holocene alluvial sediments of the Río Fraja valley, Spain: in situ or soil-sediments?. *Catena* 41, 133-142.
- Flohn, H., 1993. Climatic Evolution During the Last Millennium: What Can We Learn from It?. In: Eddy, J.A., Oeschger, H. (Eds.), *Global Changes in the Perspective of the Past*. John Wiley and Sons Ltd., Chichester, pp. 295-316.
- French, C., Passmore, D.G., 1998. Detailed geomorphological and micromorphological analysis of the Barranco de Gatas, the Rambla Ancha and Gatas settlement. In: Castro, P.V. et al. (Eds.), *Aguas Project; palaeoclimatic reconstruction and the dynamics of human settlement and land-use in the area of the middle Aguas (Almeria), in the south-east of the Iberian Peninsula*. Report to the European Commission; Environment and Climate Programme, Luxembourg, pp. 45-49.
- Goodess, C.M., Jones, P.D., 2002. Links between circulation and changes in the characteristics of Iberian rainfall. *International Journal of Climatology* 22, 1593-1615.
- Gregory, K.J., Benito, G., Dikau, R., Golosov, V., Jones, A.J.J., Macklin, M.G., Parsons, A.J., Passmore, D.G., Poesen, J., Starkel, L., Walling, D.E., 2006. Past hydrological events related to understanding global change: An ICSU research project. *Catena* 66, 2-13.

- Hoffmann, T., Lang, A., Dikau, R., in press. Holocene river activity: analysing 14C-dated fluvial and colluvial sediments from Germany. *Quaternary Science Reviews*, in press.
- Holzhauser, H., Magny, M., Zumbühl, H.J., 2005. Glacier and lake-level variations in west-central Europe over the last 3500 years. *Holocene* 15, 789-801.
- Hughes, K.M., Diaz, H.F., 1994. Was There a 'Medieval Warm Period', and if so, Where and When?. In: Hughes, M.K., Diaz, H.F. (Eds.), *The Medieval Warm Period*. Kluwer Academic Publishers, Dordrecht (The Netherlands), pp. 109-142.
- Hurrell, J.W., Kushnir, Y., Visbeck, M., Ottersen, G., 2003. An Overview of the North Atlantic Oscillation. In: Hurrell, J.W., Kushnir, Y., Ottersen, G., Visbeck, M., (Eds.), *The North Atlantic Oscillation: Climate Significance and Environmental Impact*. Geophysical Monograph Series 134, Washington DC, pp. 1-35.
- Johnstone, E., Macklin, M.G., Lewin, J., 2006. Holocene river dynamics and flooding in Great Britain: Evaluating regional responses to climate and land-use change. *Catena* 66, 14-23.
- Kirov, B., Georgieva, K., 2002. Long term variations and interrelations of ENSO, NAO and solar activity. *Physics and Chemistry of the Earth* 27, 441-448.
- Knox, J.C., 1983. Responses of river systems to Holocene climates. In: Wright, H.E. Jr. (Ed.), *Late-Quaternary Environments of the United States*, V.2. University of Minnesota Press, Minneapolis, pp. 26-41.
- Leira, M., Santos, L., 2002. An early Holocene short climatic event in the northwest Iberian Peninsula inferred from pollen and diatoms. *Quaternary International* 93-94, 3-12.
- Lewin, J., Macklin, M.G., Johnstone, E., 2005. Interpreting alluvial archives: sedimentological factors in the British Holocene fluvial record. *Quaternary Science Reviews* 24, 1873-1889.
- Lewin, J., Macklin, M.G., Woodward, J.C., 1995. Mediterranean Quaternary River Environments- Some future research needs. In: Lewin, J., Macklin, M.G., Woodward, J.C. (Eds.), *Mediterranean Quaternary River Environments*. Balkema, Rotterdam, pp. 283-284.
- Llasat, M.C., Barriendos, M., Barrera, A., Rigo, T., 2005. Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documentary sources and old instrumental records. *Journal of Hydrology* 313, 32-47.

- Llasat, M.C., Puigcerver, M., 1990. Cold air pools over Europe. *Meteorology and Atmospheric Physics* 42, 171-177.
- Luterbacher, J., and 48 coauthors, 2006. Mediterranean climate variability over the last centuries: A review. In: Lionello, P., Malanotte-Rizzoli, P., Boscolo, R. (Eds.), *The Mediterranean Climate: an overview of the main characteristics and issues*. Elsevier, Amsterdam, pp. 27-148.
- Luterbacher, J., Xoplaki, E., Dietrich, D., Jones, P.D., Davies, T.D., Portis, D., Gonzalez-Rouco, J.F., von Storch, H., Gyalistras, D., Casty, C., Wanner, H., 2002. Extending North Atlantic Oscillation Reconstructions Back to 1500. *Atmos. Sci. Lett.*, 2, 114-124 (doi:10.1006/asle.2001.0044).
- Mächel, H., Kapala, A., Flohn, H., 1998. Behavior of the centers of action above the Atlantic since 1881. Part I: Characteristics of seasonal and interannual variability. *Int. J. Climatol.* 18, 1-22.
- Macklin, M.G., Benito, G., Gregory, K.J., Johnstone, E., Lewin, J., Soja, R., Starkel, L., Thorndycraft, V.R., 2006. Past hydrological events reflected in the Holocene fluvial history of Europe. *Catena* 66, 145-154.
- Macklin, M.G., Johnstone, E., Lewin, J., 2003. Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change. *Holocene* 15, 937-943.
- Macklin, M.G., Lewin, J., Woodward, J.C., 1995. Quaternary fluvial systems in the Mediterranean basin. In: Lewin, J., Macklin, M.G., Woodward, J.C. (Eds.), *Mediterranean Quaternary River Environments*. Balkema, Rotterdam, pp. 1-25.
- Macklin, M.G., Passmore, D.G., Stevenson, A.C., Davis, B.A., Benavente, J.A., 1994. Response of rivers and lakes to Holocene environmental changes in the Alcañiz region, Teruel, North-East Spain. In: Millington A.C., Pye, K. (Eds.), *Environmental change in drylands: Biogeographic and geomorphological perspectives*. John Wiley & Sons Ltd., Chichester, pp. 113-130.
- Magny, M., 1993. Solar influences on Holocene climatic changes illustrated by correlations between past lake-level fluctuations and the atmospheric ^{14}C record. *Quaternary Research* 40, 1-9.
- Masachs, V., 1950. Aportación al conocimiento del régimen fluvial mediterráneo. *Comptes Rendus du Congrès International de Géographie*. UGI, Lisbonne 1949, Vol. II, pp. 358-390.

- Ortega, J.A., Garzón, G., 2003. Palaeohydrology of the Lower Guadiana River basin. In: Thorndycraft, V.R., Benito, G., Barriendos, M., Llasat, M.C. (Eds.), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid, pp. 33-38.
- Ortega, J.A., Garzón, G., 2004. Influencia de la oscilación del Atlántico norte en las inundaciones del Río Guadiana. In: Benito, G., Díez Herrero, A. (Eds.), Riesgos naturales y antrópicos en Geomorfología. CSIC, Madrid, pp.117-126.
- Osborn, T.J., 2004. Simulating the winter North Atlantic Oscillation: the roles of internal variability and greenhouse gas forcing. *Climate Dynamics* 22, 605-623.
- Rico, M., 2004. Las paleocrecidas en la cuenca media del Río Segre durante el Pleistoceno superior-Holoceno: registros morfosedimentarios y análisis hidrológico. PhD thesis, University of Zaragoza, Spain.
- Risebrobakken, B., Jansen, E., Andersson, C., Mjelde, E., Hevrøy, K., 2003. A high-resolution study of Holocene paleoclimatic and paleoceanographic changes in the Nordic Seas. *Paleoceanography* 18, 1017. doi:10.1029/2002PA000764.
- Rodó, X., Baert, E., Comin, F.A., 1997. Variations in seasonal rainfall in southern Europe during the present century: Relationships with the North Atlantic oscillation and the El Niño–Southern Oscillation. *Climate Dynamics* 13, 275-284.
- Rodrigo, F.S., Esteban-Parra, M.J., Pozo-Vázquez, D., Castro-Díez, Y., 1999. A 500-year precipitation record in southern Spain. *Internacional Journal of Climatology* 19, 1233-1253.
- Sancho, C., Peña, J.L., Muñoz, A., Benito, G., McDonald, E., Rhodes, E.J. and Longares, L.A. (2007). Holocene alluvial morphopedosedimentary record and environmental changes in the Bardenas Reales Natural Park (NE Spain), *Catena*, doi:10.1016/j.catena.2007.09.011
- Santos, L., Vidal Ramoni, J.R., Jalut, G., 2000. History of vegetation during the Holocene in the Courel and Queixa Sierras, Galicia, northwest Iberian Peninsula. *Journal of Quaternary Science* 15, 621-632.
- Schulte, L., 2003. River-response and terrace aggradation in the Mediterranean Iberian Peninsula during historical times. In: Thorndycraft, V.R., Benito, G., Barriendos, M., Llasat M.C. (Eds.), Palaeofloods, historical data and climatic variability: applications in flood risk assessment. CSIC, Madrid pp. 67-72.
- Schumm, S.A. 1977. The fluvial system. Wiley, New York.

- Starkel, L., Soja, R., Michczynska, D.J., 2006. Past hydrological events reflected in the Holocene history of Polish rivers. *Catena* 66, 24-33.
- Thomas, M. F., 2004. Landscape Sensitivity to Rapid Environmental Change – A Quaternary Perspective with Examples from Tropical Areas. *Catena* 55, 107-124.
- Thorndycraft, V.R Benito G., Rico, M., Sánchez-Moya, Y., Sopeña A., Casas, A., 2005. A long-term flood discharge record derived from slackwater flood deposits of the Llobregat River, NE Spain. *Journal of Hydrology* 313, 16-31.
- Thorndycraft, V.R, Barriendos, M., Benito G., Rico, M., Casas, A., 2006. The catastrophic floods of AD 1617 in Catalonia (northeast Spain) and their climatic control. *Hydrological Sciences Journal* 51 (5), 899-912.
- Thorndycraft, V.R, Benito G., Rico, M., Sánchez-Moya, Y., Sopeña A., Casas, A., 2004. A Late Holocene palaeoflood record from slackwater flood deposits of the Llobregat River, NE Spain. *Journal of the Geological Society of India* 64, 549-559.
- Thorndycraft, V.R., Benito, G., 2006a. The Holocene fluvial chronology of Spain: Evidence from a newly compiled radiocarbon database. *Quaternary Science Reviews* 25, 223-234.
- Thorndycraft, V.R., Benito, G., 2006b. Late Holocene fluvial chronology of Spain: The role of climatic variability and human impact. *Catena*, 66, 34-41.
- Trigo R.M., Palutikof, J.P., 2001. Precipitation scenarios over Iberia: a comparison between direct GCM output and different downscaling techniques. *Journal of Climate* 14, 4422-4446.
- Trigo, R.M., Pozo-Vázquez, D., Osborne, T., Castro-Díez, Y., Gámiz-Fortis, S., Esteban-Parra, M.J., 2004. North Atlantic Oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *International Journal of Climatology* 24, 925-944.
- Trimble, S. W., 1983. A sediment budget for Coon Creek basin in the Driftless Area, Wisconsin, 1853-1977. *American Journal of Science* 283, 454-474.
- Uribe-larrea, D. and Benito, G., in press. Fluvial changes of the Guadalquivir river during the Holocene in Córdoba (S. Spain). *Geomorphology*, in press.
- Valero-Garcés, B.L., González-Sampériz, P., Delgado-Huertas, A., Navas, A., Machín, J., Kelts, K., 2000. Lateglacial and Late Holocene environmental and vegetational change in Salada Mediana, central Ebro Basin, Spain. *Quaternary International* 73/74, 29-46.

- van Geel, B., Buurman, J., Waterbolk, H. T., 1996. Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP, *J. Quat. Sci.*, 11, 451–460.
- van Geel, B., van der Plicht, J., Kilian, M. R., Klaver, E. R., Kouwenberg, J. H. M., Renssen, H., Reynaud-Farrera, I., and Waterbolk, H. T., 1998. The sharp rise of ^{14}C around 800 cal BC: possible causes, related climatic teleconnections and the impact on human environments, *Radiocarbon* 40, 535–550.
- van Loon, H., Rogers J.C., 1978. The Seesaw in Winter Temperatures Between Greenland and Northern Europe. Part I: General Description. *Mon. Wea. Rev.* 106, 296-310.
- Vaquero, J.M., 2004. Solar signal in the number of floods recorded for the Tagus river basin over the last millennium. *Climatic Change* 66, 23-26.
- Vita-Finzi, F., 1969. *The Mediterranean valleys: Geological changes in historical times.* Cambridge University Press, Cambridge.
- Vita-Finzi, F., 1976. Diachronism in Old World alluvial sequences. *Nature* 263, 218-219.
- Walker, G.T., Bliss, E.W., 1932. World Weather V. *Mem. Roy. Meteor. Soc.* 44, 53-84.
- Wanner, H., Brázdil, R., Frich, P., Frydendahl, K., Jonsson, T., Kington, J.A., Pfister, C., Rosenorn and Wishman, E., 1994. Synoptic interpretation of monthly weather maps for the late Maunder Minimum (1675-1704). In: Frenzel, B., Pfister, C., Glaser, B. (Eds.), *Climatic Trends and Anomalies in Europe.* Gustav Fischer Verlag, Stuttgart, 401-424

Figures

Figure 1: Location of the studied rivers, sites described in the text, and boundary of the Atlantic and Mediterranean river catchments. Numbers refer to Table 1

Figure 2: Summed probability for the radiocarbon dating from slackwater flood deposit sequences on Atlantic and Mediterranean Iberian rivers, and periods (upper numbers) of main dating clusters. 1:10,750-10,240; 2: 9550-9130; 3: 4820-4440; 4: 2865-2350; 5: 960-790; and 6: 520-290 cal BP. Temperature anomaly data (°C) over the Holocene is plotted "(grey solid line)" as reference (elaborated by Rohde from different proxy records, http://www.globalwarmingart.com/wiki/Image:Holocene_Temperature_Variations.png Sept. 12, 2007). Also shown are the radiocarbon dates (black dots) indicating the two sigma (95.4%) age range (horizontal error bar) of each date entered into the analysis.

Figure 3: Summed probability plots of radiocarbon samples from slackwater flood deposits and floodplain deposits. On the bottom bar are show overlapping periods of slackwater and floodplain deposition (dark grey), only slackwater flood date clusters (black) and only floodplain deposition (light grey).

Figure 4: Photo illustrating a site of slackwater deposition of the Tagus River, near Alcantara, Spain. On the left side, the stratigraphic profile and dating results in radiocarbon years BP are shown.

Figure 5: Relationship between winter (DJF) NAO index values reconstructed by Luterbacher et al., (2002) and reconstructed discharge of historical floods in the Tagus River in Alcantara (top) and Talavera de la Reina (bottom) since 1500 AD.

List of Tables

Table 1. Radiocarbon sampling location and pollen sites referred to in the text (numbers refer to Fig. 1), and original bibliographic references with the number of dates obtained from each reference indicated (fluvial sites only) and the main type of sediment. (SWD = slackwater flood deposits).

Site location (Fig. 1)	Reference	Main sediment type	Number of ^{14}C dates
<i>Fluvial sites in Atlantic catchments</i>			
1 R. Tagus (Puente de Arzobispo)	Benito et al., 2003a	SWD	14
2 R. Tagus (Alcantará)	Benito et al., 2003a	SWD	4
3 R. Guadalquivir	Uribelarrea & Benito, in press	Alluvial fines	6
4 R. Guadiana	Dorado et al., 2002	Alluvial fines	2
5 R. Fraja (Barbate basin)	Faust et al., 2000	Overbank	2
6 R. Regallo	Macklin et al., 1994	Alluvial fines	1
7 R. Guadiana (Portugal)	Ortega & Garzón, 2003	SWD	11
8 R. Jarama	Alonso & Garzón, 1996	Alluvial gravels	5
9 R. Huebra	Benito, unpublished	SWD	15
<i>Fluvial sites Mediterranean catchments</i>			
10 R. Guadalhorce	Benito, unpublished	SWD	3
11 R. Guadalentín (upper)	Benito et al., 2006	SWD	15
12 R. Guadalentín	Calmel-Avila, 2000 & 2002 & Cuenca Paya & Walker, 1977	Alluvial fines	6
13 R. Segre	Rico, 2004	SWD	3
14 Rambla Bisbal	Schulte, 2003	Alluvial fines	2
15 R. Llobregat	Thorndycraft et al. 2004	SWD	5
16 various rivers (R. Segura)	Vita Finzi, 1976	Alluvial fines	3
17 Rambla Ancha (R. Aguas)	French & Passmore, 1998	Overbank	1
<i>Pollen sites</i>			
18 Villaverde	Carrión et al., 2001	-	-
19 Las Tablas de Daimiel	Dorado et al., 2002	-	-
20 Laguna Lucenza	Leira & Santos, 2002	-	-
21 Padul	Pons & Reille, 1988	-	-