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Past hydrological events reflected in the Holocene fluvial record of Europe

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Abstract

A comprehensive database of radiocarbon dated fluvial units in Great Britain, Poland and Spain has been compiled to investigate the relationship between environmental change, flooding and Holocene river dynamics. Following the methodology recently developed by Macklin and Lewin [Macklin, M.G., Lewin, J., 2003. River sediments, great floods and centennial-scale Holocene climate change. Journal of Quaternary Science 18, 101 – 105], radiocarbon dates in fluvial sequences that coincide with a modification in sedimentation rate, or style, have been highlighted, allowing geomorphologically significant changes in Holocene river activity to be identified. Data analysis has been undertaken at both national and sub-national scales, and on catchments of different size, type and land-use history. Multiple phases of higher flood frequency, characterized by accelerated erosion and sediment deposition on floodplains, are recognized and compared with a range of climate proxies. The relative and varying roles of climate and land-use on river dynamics are considered and the value of the database for reconstructing past hydrological events, as well as for predicting river response to future environmental change, is assessed.

Keywords: River floods; ^{14}C dating; Fluvial sediments; Environmental change; Europe

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1. Introduction

Since the end of the 1950s, the number of investigations in Europe of river system response to Holocene environmental change has grown considerably. Presently, Holocene fluvial sedimentary sequences and river terraces of most major European river basins have been studied, to some degree, although the resolution of dating control and environmental reconstruction varies considerably between catchments. From this research, the influence of both human activity (primarily in terms of changes in land-use and cover, and its impact on runoff and sediment supply) and climate change (reflected principally by variations in the occurrence of extreme hydrological events, notably major floods and droughts) on Holocene river behaviour have been documented. These factors have been found to vary significantly both over time and geographically, and have given rise to highly diverse and complex fluvial sedimentary records. However, outside of a few relatively well studied regions (e.g. Great Britain– Macklin and Lewin, 1993, 2003; the Netherlands– Berendsen and Stouthamer, 2001; Poland– Starkel, 1991; Spain– Benito et al., 2003), Holocene river sequences in Europe have not been analysed and compared systematically in a manner likely to reveal an underlying structure, or pattern, within the fluvial record. The International Council for Science funded project "Past hydrological events related to understanding global change" provided a timely collaboratory framework to consider these important issues, and to critically evaluate Holocene fluvial records across selected

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parts of Europe and, from this, highlight gaps in our understanding of longer term river dynamics and identify future research priorities.

In this paper, recently compiled databases of ^{14}C dated Holocene fluvial units from Great Britain (Macklin and Lewin, 2003; Lewin et al., 2005; Johnstone et al., 2006-this volume; Macklin et al., 2005), Poland (Starkel et al., 2006-this volume) and Spain (Thorndycraft and Benito, 2006-this volume), in catchments unaffected by sea-level change, are compared (Fig. 1). In order to identify possible large-scale hydroclimatic teleconnections, correlations are also made between Holocene riverine flooding episodes, the North Atlantic ice rafting debris (IRD) record (Bond et al., 2001) and phases of higher and lower lake levels in middle (Magny et al., 2003) and southern Europe (Carrión, 2002). However, one of the primary aims of adopting what might be termed a 'metadata' approach in reviewing the three data sets was to try and draw out some observations of more general relevance, which would not have emerged from considering each of the databases in isolation. This is certainly the first time in Europe and, to the authors' knowledge, probably anywhere in the world that such a procedure has been used to investigate Holocene river dynamics at approaching a continental scale. The value of assembling and interrogating large radiometrically dated fluvial databases for reconstructing past hydrological events and for forecasting possible river basin response to future environmental change is also considered.

Fig. 1. Map of Europe showing the locations of Great Britain, Poland and Spain where databases of ^{14}C dated Holocene fluvial units have recently been compiled.

2. Study regions and methodology

The history, nature and focus of Holocene river system research over the past 30 to 40 years have differed markedly in Great Britain, Poland and Spain. Research started in Poland in the late 1950s with Starkel (1960) and his colleagues, most notably Klimek and Starkel (1974), and Kozarski and Rotnicki (1977), who pioneered the study of late glacial and Holocene palaeohydrology in Europe, particularly through the widespread use of ^{14}C dating of peat and sub-fossil wood incorporated within fluvial deposits. Much of the work during the 1980s and 1990s centred on detailed investigations of longer-term river channel planform development, especially palaeomeander stratigraphies (e.g. Kozarski, 1983; Rotnicki, 1983). From these studies, Starkel and his co-workers identified a large number of relatively brief (c. 200–500 years) episodes during the Holocene that were characterized by the more frequent occurrence of major floods and linked to periods of wetter and cooler climate (Starkel et al., 1996).

In Spain, research on Holocene river sequences began somewhat later, principally through the studies of Vita-Finzi (1969, 1976) who relied primarily on dating fluvial sediments using incorporated or associated, archaeological material and sites. He identified a unitary, pan-Mediterranean post-Roman fluvial unit which he termed the "Younger Fill", the deposition of which was dated to the late Roman and medieval periods and attributed to climate change. During the 1970s and 1980s, this view was challenged by the findings of several archaeologically focused river valley surveys, most notably in Greece (Pope and van Andel, 1984), that identified multiple phases of river erosion and sedimentation and demonstrated what they believed to be a better temporal correspondence between anthropogenically induced land-cover change and longer term river behaviour in the Mediterranean. Nevertheless, the number of catchments in the region where Holocene fluvial sedimentary sequences are well constrained by multiple radiometric dates remains surprisingly few. Since the middle of the 1990s, however, there has been an increase in the number of published fluvial ^{14}C dates in non-archaeological contexts, especially through the work of Benito and co-workers' investigations of slackwater sediments in bedrock gorges resulting from very large flood events (Benito et al., 2003; Thorndycraft et al., 2005).

Research on Holocene river development in Great Britain was both by European and North American standards initiated relatively recently. In the late 1970s and early 1980s, the first studies tended to be focused either in small, formerly glaciated upland catchments of northern (Harvey et al., 1981) and western (Macklin and Lewin, 1986) Britain or in larger lowland basins in the southern and eastern part of the country, at the margin (Brown and Barber, 1985) or beyond the last ice sheet (Robinson and Lambrick, 1984). Throughout the 1980s and up to the early 1990s, opinions on the primary controls of Holocene river dynamics in Great Britain tended to be somewhat caricatured either into 'cultural' or 'climatic' schools of thought (e.g. Ballantyne, 1991). The consensus today favours the views of Macklin and Lewin (as first set out by Macklin et al., 1992; Macklin and Lewin, 1993) who consider river response to environmental change over the Holocene in terms of a continuum between the two forcing factors, each of which can vary in importance over time and space both within a single drainage basin and between catchments.

All published (up to the end of 2003) and unpublished (available to the authors) ^{14}C dated Holocene fluvial units in Great Britain (506), Poland (589) and Spain (99) have been assembled into a database that for each ^{14}C date includes information on drainage basin area, depositional environment and type of material used for dating. Following the methodology recently outlined by Macklin and Lewin (2003), ^{14}C dates which coincided with an abrupt modification in sedimentation style or rate (termed 'change' dates), and attributed to major floods, were also identified. Long-term records of flooding in the three areas were reconstructed using the frequency distributions of all 'change' dates (263, 335 and 51 in Great Britain, Poland and Spain, respectively). Dates were calibrated and then for each region plotted as cumulative probability density functions (CPDFs) in OxCal (version 3.9; Bronk Ramsey, 1995, 2001). The calibration curve (INTCAL98; Stuiver et al., 1998), however, exerts an influence on the CPDFs so that a date coinciding with a plateau in the calibration curve may produce a smaller, less well-defined peak than a date which occurs at a steep section of the curve. Macklin et al. (2005) have developed a correction to account for this by generating a second CPDF plot using a simulated data set of evenly distributed ^{14}C dates and subtracting this from the CPDF plot of observed ^{14}C dates. The resulting probability difference curves (PDCs; Fig. 2) show the difference between the two CPDFs where peaks and troughs relate to apportioned and dispersed probabilities of several dated units. Changes in the height of the PDCs over the Holocene are interpreted to reflect variations in the occurrence of major floods. Multi-centennial deviations above, or below, the zero point on the PDCs represent extended periods during which flood units are more common (indicative of major flooding episodes), or when they are rare or absent (phases when large floods occurred very infrequently or when conditions did not favour the preservation of flood sediments).

Finally, we anticipated that by comparing the results of identical PDC-based analyses we could also evaluate the degree to which the palaeohydrological records of the three regions may be contingent upon the choice of investigative theme, and/or study catchment. Major issues such as the representativeness of the fluvial archive as a record of environmental change, and the effects of sampling or preservation bias on long-term flood histories, have very rarely been addressed empirically (but see recent papers by Lewin and Macklin, 2003; Lewin et al., 2005 on this topic).

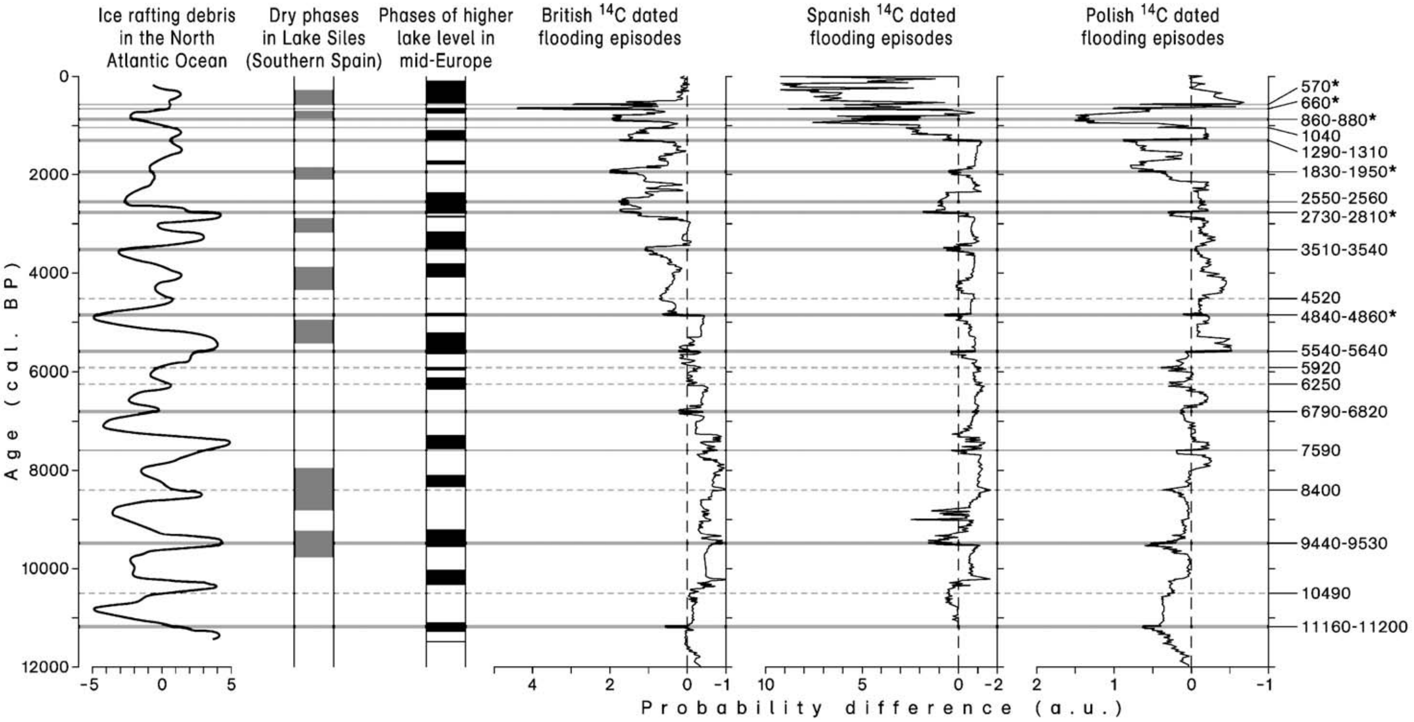

Fig. 2. PDCs of ^{14}C dates associated with major flooding episodes in Great Britain, Spain and Poland plotted alongside the North Atlantic IRD record (Bond et al., 2001) and hydrological records from lakes in southern Spain (Carrión, 2002) and mid-Europe (Magny et al., 2003). Episodes of European flooding are listed on the right-hand axis and episodes occurring in all three study regions are denoted with an asterisk.

Table 1
Number of Holocene fluvial ^{14}C dates in Great Britain, Poland and Spain, and those which are associated with geomorphic change

	All ^{14}C dates	'Change' ^{14}C dates
Great Britain	506	263 (52%)
Poland	589	335 (57%)
Spain	99	51 (52%)
Total	1194	649 (54%)

Understanding these factors is, however, critically important if the alluvial record is going to be used, for instance, to better inform and improve present and future flood risk estimates.

3. The influence of drainage basin characteristics, depositional environment and sedimentological factors on the Holocene fluvial record

A total of nearly 1200 Holocene fluvial ^{14}C dates are included within the British, Polish and Spanish databases with Britain and Poland together contributing more than 90% of the radiometrically dated fluvial units (Table 1). The proportion of ^{14}C dates that mark major changes in river behaviour (coinciding with a modification in sedimentation style or rate) is similar in all three areas, and generally just exceeds 50%. Considering this from the reverse viewpoint, nearly half of the ^{14}C dates obtained from fluvial sedimentary sequences in Britain, Poland and Spain would appear to relate to autogenic activity and, therefore, are of relatively little value in interpreting external environmental influence, or for reconstructing past hydrological events.

In Table 2, ^{14}C dates (and the proportion of these that coincide with geomorphic change) are classified on the basis of the size of drainage basin upstream from where ^{14}C dating was undertaken, and significant differences are evident between the three areas. In Great Britain, 44% of the ^{14}C dates have come from relatively small river basins with drainage areas of less than 100 km^2, compared to 22% and 18% in similarly sized basins in Poland and Spain, respectively. The majority of fluvial ^{14}C dates in Great Britain come from catchments with drainage areas between 100 and 1000 km^2, whereas in Poland and particularly Spain most reported ^{14}C dates come from the largest river basins in both countries. These regional variations arise partly because of physiographic differences between the three areas, with river basins in continental Europe generally being larger than those in Great Britain, but also because of different research strategies adopted by local investigators. This is also shown by the relationship between the proportion of ^{14}C dates that mark geomorphic change and catchment size. The proportions of so-called 'change' dates in Great Britain systematically decrease with increasing drainage basin area, while in both Poland and Spain the reverse relationship is evident. Thus, in Great Britain, catchments with drainage areas less than 10 km^2 would appear to be particularly sensitive to environmental changes and/or favour the preservation of extreme flood events. By contrast in Poland and Spain larger river basins with drainage areas exceeding 10,000 km^2 that have been investigated produce a better record of allogenic forcing over the Holocene. The relatively small number of ^{14}C dates presently available from Spain makes it difficult to attribute this pattern to any specific cause, and the relationship between ^{14}C dates that mark geomorphic change and drainage area may well be an artefact of the fact that the Holocene fluvial histories of small catchments in Spain (particularly those with drainage areas less than 10 km^2) have been under-researched. However, the much larger British and Polish databases appear to have been influenced less by the deliberate or inadvertent selection of river basins of a certain size for study. Therefore, variability in the manner in which environmental change and flooding episodes are recorded in the basins of varying size is likely to reflect long-term differences in catchment hydrology, river sediment transport processes and supply between the two areas.

In Great Britain, for instance, examination of historical channel change over the last 200 years in western and northern catchments (Lewin, 1983, 1987) has shown a tendency for average rates of geomorphic change to be greatest in the middle reaches of rivers, or in the 'piedmont zone' (Newson, 1981) where valleys open out from upland areas but river gradients and stream power are still relatively high. This may be one factor that accounts for the progressive decrease in the percentage of change dates as drainage area increases, particularly the abrupt fall off when catchments exceed 1000 km^2 that in the major easterly draining rivers in northern Britain marks the downstream limit of the piedmont zone. In larger British catchments, although flood discharges are relatively high, river channel gradients decrease to a point where stream powers are generally too low to transport gravel-size sediment overbank into long-term storage, thereby incorporating material of this type into the alluvial 'archive'. Similarly, in small British basins (≤ 10 km^2), the apparently high proportion of ^{14}C dates that appear to reflect external forcing by environmental change is likely to result partly from better slope-channel coupling and higher rates of sediment supply but also because of the greater geomorphological impact that

Table 2
Number of fluvial ^{14}C dates classified by drainage area

Drainage area (km^2)	Great Britain	Poland	Spain
<1	79 (60, 76%)	12 (0, 0%)	0 (0, 0%)
1 to ≤10	77 (59, 77%)	24 (0, 0%)	3 (1, 33%)
10 to ≤100	65 (32, 49%)	96 (54, 56%)	15 (5, 33%)
100 to ≤1000	214 (98, 46%)	95 (60, 63%)	22 (12, 55%)
1000 to ≤10,000	71 (14, 20%)	249 (150, 60%)	22 (12, 55%)
>10,000	0 (0, 0%)	113 (71, 63%)	28 (21, 75%)
Unclassified	0 (0, 0%)	0 (0, 0%)	9 (0, 0%)

The number and proportion (expressed as a percentage) of 'change' dates are shown in brackets.

Table 3
Number of fluvial ^{14}C dates classified by depositional environment

Depositional environment	Great Britain	Poland	Spain
Channel bed and bar sediments	61 (22, 36%)	82 (48, 58%)	11 (1, 9%)
Palaeochannel fills	147 (59, 40%)	241 (152, 63%)	0 (0, 0%)
Overbank sediments	177 (99, 55%)	183 (114, 62%)	64 (44, 69%)
Flood basin sediments	112 (78, 70%)	46 (21, 46%)	10 (2, 20%)
Debris flow/colluvial sediments	9 (5, 55%)	15 (0, 0%)	8 (4, 50%)
Unclassified	0 (0, 0%)	22 (0, 0%)	6 (0, 0%)

The number and proportion (expressed as a percentage) of ‘change’ dates are shown in brackets.

localized extreme rainfall events have on small catchments. However, in Poland, given the extensive mountain headwaters of the upper Vistula, the apparently low number of ^{14}C dates (especially those marking geomorphic change) in catchments with drainage areas of less than 10 km^2 must, to a large degree, reflect the lack of research in river basins of this size. The greater proportion of ‘change’ ^{14}C dates in Poland’s larger river basins arises because of higher stream powers particularly in the steeper gradient river systems (e.g. upper Vistula, Raba and Wisloka) draining the foreland of the Carpathian Mountains, which are also affected by major ice-jam floods.

Depositional environment, as well as river activity rates (both in the lateral and vertical sense) and style, has been shown to have a major effect on the length and completeness of the Holocene fluvial archive (Lewin and Macklin, 2003; Lewin et al., 2005), particularly the record of extreme flood events (Macklin and Lewin, 2003). In order to explore these relationships in more detail, each ^{14}C date has been classified according to the depositional environment from which it was collected. The majority of ^{14}C dates in all three areas come from either palaeochannel fills or overbank sediments, with the former providing the largest number of ^{14}C dates in Poland and the latter depositional environment accounting for most ^{14}C dates in both Great Britain and Spain (Table 3). However, with respect to ^{14}C dates that pick out geomorphologically significant change in river activity over the Holocene, flood basin sediments in Great Britain, palaeochannel fills in Poland and overbank (slackwater) sediments in Spain are the most important as recorders of environmental change. Factors likely to favour the recording and preservation of an environmental signal in these depositional contexts are firstly, that major flood events are commonly registered by abrupt changes in sediment size and secondly, flood sediments are preferentially incorporated into depositional niches located some distance away from the main river channel or channel belt. In Spain the absence of ^{14}C dates from palaeochannel fills is an anomaly, especially as dateable material has been recovered from channel bed and bar sediments (Table 3), and must be attributed (assuming that ^{14}C dates have been correctly classified) to researcher bias in the selection of study sites for investigation.

Finally, to evaluate whether sampling strategies adopted for dating varied between the three areas, and whether this may have affected the fluvial record, ^{14}C dates were classified by type of organic material used for dating (Table 4). A considerable range of material has been used and some quite major differences are evident in the three regions. In Spain, with its Mediterranean climate and a higher incidence of natural fires in the landscape, charcoal is the most common material that has been recovered and used for ^{14}C dating. By contrast, within cooler and generally wetter British and Polish catchments, samples from peat and wood have together provided the largest number of ^{14}C dates. In Poland, organic muds formed either in standing water within cutoffs or in flood basins have also been used frequently in dating. Similar dateable material, however, is rare within British and Spanish alluvial sequences, probably as a consequence of longer histories of land drainage resulting in the loss of river wetlands (containing seasonal or more permanent open water bodies) suitable for the deposition of organic-rich muds.

4. The relationship between large-scale Holocene hydro-climatic teleconnections in Europe and episodes of major riverine flooding

One of the principal aims of this multi-national project was to improve our understanding of the impact of climate change on the spatial and temporal occurrence of extreme hydrological events during the Holocene. The construction of PDCs of ^{14}C dated flood units in Great Britain, Poland and Spain provide, for the first time in Europe, probability-based records of riverine flooding that extend over the entire Holocene. Periods of more frequent flooding are recognised by peaks (above zero) in the PDCs and are listed in Table 5. From these, where PDC peaks in two or more areas fall within a 100-year range, major flood episodes (possibly of pan-European extent) have been identified. In Fig. 2, the Holocene flood series for Great Britain, Poland and Spain

Table 4
Number of fluvial ^{14}C dates classified by type of organic material used for ^{14}C dating

Organic material used for ^{14}C dating	Great Britain	Poland	Spain
Bone	17 (7, 41%)	0 (0, 0%)	2 (0, 0%)
Calcified roots	0 (0, 0%)	0 (0, 0%)	2 (0, 0%)
Charcoal	35 (10, 29%)	0 (0, 0%)	50 (36, 72%)
Organic mud	15 (10, 67%)	139 (90, 65%)	3 (1, 33%)
Peat	173 (120, 69%)	269 (144, 53%)	0 (0, 0%)
Plant macrofossils	19 (11, 58%)	48 (18, 38%)	0 (0, 0%)
Pollen	0 (0, 0%)	0 (0, 0%)	3 (1, 33%)
Shell	0 (0, 0%)	0 (0, 0%)	7 (6, 86%)
Soil	40 (32, 80%)	0 (0, 0%)	0 (0, 0%)
Wood	181 (65, 36%)	110 (75, 68%)	2 (0, 0%)
Unclassified	26 (8, 31%)	23 (8, 35%)	30 (7, 23%)

The number and proportion (expressed as a percentage) of ‘change’ dates are shown in brackets.

Table 5
Periods of major flooding in Great Britain, Spain and Poland

Great Britain	Spain	Poland
570	**570**	**570**
660	**660**	**660**
860	**865**	**880**
	1040	**1040**
1290		**1310**
1650		
1950	**1930**	**1830**
2280		
2550	**2560**	
2730	**2750**	**2810**
3540	**3510**	
4520		
4840	**4860**	**4840**
5540	**5640**	
5730		
		5920
		6250
6820		**6790**
	7260	
	7590	**7590**
		8400
	8820	
	8870	
	9010	
	9330	
	9440	**9530**
	10490	
11160		**11200**

Flooding episodes recorded in two or more areas are shown in bold (ages cal. BP).

are compared with hydrological records from lakes in southern Spain and mid-Europe, and the North Atlantic IRD record. Major flooding episodes in Europe (PDC peak in two or more regions) are shown by solid horizontal grey lines, while PDC peaks that are evident only in one of the three flood records are denoted by broken horizontal grey lines. Fifteen major periods of flooding are discernible, six of which (at c. 570, 660, 860–880, 1930–1950, 2370–2810 and 4840–4860 cal. BP) are recorded in river basins across Europe. Comparison with the similarly well dated, lake-level record of mid-Europe shows that 11 out of 15 peaks of flooding coincide with phases of higher lake level. It is also noteworthy that the majority (7 out of 11) of PDC peaks occur either at the very beginning or during the early part of the higher lake-level phases. This would indicate not only a common underlying control but also that river basins in Europe (through changes in the frequency and magnitude of geomorphologically ‘effective’ floods) respond more rapidly, and perhaps more sensitively, to short-term, external climate forcing than do lake systems in the region. This is a significant finding particularly in the context of the current research on detection and attribution of climate change signals associated with global warming, based on hydrological indicators.

Out of the four major riverine flooding episodes (at c. 860–880, 1040, 1830–1950 and 6790–6820 cal. BP) that do not coincide with phases of higher lake level in mid-Europe, three are recorded within the last 2000 years. The most prominent of these are those at c. 860–880 and 1830–1950 cal. BP, which occur at the same time as significant agricultural expansion, deforestation and land-use change in the Roman period (Great Britain and Poland) and during the Middle Ages (all three regions). As has been demonstrated by many earlier studies (Butzer, 1980; Macklin et al., 1992; Macklin and Lewin, 1993; Kalicki, 1996; Coulthard and Macklin, 2001; Benito, 2003; Macklin and Lewin, 2003), although large-scale forest removal and agricultural development augmented both runoff and sediment supply, the geographically widespread nature of these sedimentation events suggests that climate-related changes in flood frequency and magnitude played a role as well. Indeed, documentary records of flooding in both Great Britain (Brown, 1998) and Spain (Benito et al., 1996) show that the early part of the Middle Ages was characterized by an increased frequency of large floods, which corresponded to changes of prevailing atmospheric circulation patterns affecting western Europe at that time. This period of marked climatic variability is not, however, manifested in the lake record of middle Europe. This is possibly due to its short duration but also may reflect the relative insensitivity in this part of Europe of lake systems to hydroclimatic changes except those of an extreme nature lasting several centuries.

Before 5000 cal. BP most of the major flood periods match Holocene cooling phases marked by IRD events in the North Atlantic Ocean (Fig. 2). However, the widespread so-called 8.2 ka cold event (Alley et al., 1997), coincides with prominent troughs in all three flood records, indicating a very low incidence (or preservation) of major floods. Indeed, in both Great Britain and Spain the period c. 7600–8400 cal. BP appears from the fluvial record to have been particularly dry, an interpretation also supported by very low lake levels documented in southern Spain (Carrión, 2002) at this time. After 5000 cal. BP, the association between marine ice-drift indices and riverine flooding becomes much weaker with only four (at c. 570, 660, 1040, 2730–2810 cal. BP) out of the nine post 5000 cal. BP major flood episodes corresponding with IRD peaks in the North Atlantic sector. This weaker coupling between cooling in the North Atlantic Ocean and hydrological change since c. 5000 cal. BP is also apparent in the mid-European lake record (Magny et al., 2003). A similar mid-Holocene hydroclimate ‘system switch’ (Steig, 1999) has been shown recently in many other European terrestrial (Leuschner et al., 2002; Magny and Haas, 2004) and marine (Hall et al., 2004) proxy-climate records, and would suggest external forcing of hydroclimate during this period not only by changes in ocean circulation but also increasingly by variations in solar activity as well (Macklin et al., 2005).

Over both the instrumental and documentary record, the most severe and widespread floods in Europe have generally occurred during cooler periods of climate, when the lateral temperature gradient is steeper and circumpolar air masses

Table 6
Periods characterized by significantly fewer ^{14}C dated flood units in Great Britain, Spain and Poland

Great Britain	Spain	Poland
		260–560
690–760	690–760	
950–1040		1060–1260
1420–1550	**1300–1870**	**1540–1690**
2180–2340	**2000–2350**	**2150–2750**
2950–3400	**2830–3440**	**2870–4830**
	3560–4170	
	4350–4830	
4870–5320	**5960–5590**	**4860–5600**
6270–6690	5660–7220	6000–6150
		6400–6670
6860–10440	7300–7530	7420–7570
	7610–8780	7680–7980
	9020–9270	8630–9000
	9530–10280	9710–10180

Episodes in the late and middle Holocene recorded in all three areas are shown in bold (ages cal. BP).

are shifted southwards favouring more frequent and enhanced occurrence of meridional wind patterns in mid latitudes (Benito et al., 1996; Rumsby and Macklin, 1996). Comparing the timing of widespread flooding episodes identified in this paper with climate reconstructions from lake and marine records also suggests that a similar relationship between climate and flooding in Europe existed during much of the Holocene (i.e. flood frequency and magnitude were higher during relatively cool, wetter periods). Furthermore, our data generally supports Magny et al.'s (2003) hydrological reconstruction for the 8.2 ka cold event and other Holocene climate cooling phases, although the flood record indicates that cyclonic activity during these later periods extended further southwards in Europe, to around 36°N in southern Spain. This would indicate that the timing of hydrological change in the mid-latitudes of Europe from between 59° and 36°N, and at least as far east as 24°E (eastern Poland), was broadly synchronous during the Holocene, especially with respect to the incidence of extreme hydrological events.

Identification of periods during the Holocene characterized by significantly fewer ^{14}C dated fluvial units in Great Britain, Poland and Spain is fairly straightforward (Table 6), although attributing these to either a lower frequency of large floods or local preservation factors is more problematic. Since c. 6000 cal. BP, four episodes of apparently reduced river activity at c. 1420–1690, 2180–2350, 2950–3400 and 4870–5400 cal. BP are recorded in all three regions, which suggest that these were actually times when large floods were relatively uncommon in Europe. There are, however, major differences in the overall temporal distribution of Holocene fluvial units between Great Britain, Poland and Spain, shown clearly by the contrasting shapes of the three PDCs (Fig. 2). In Great Britain and Spain, the probability of flood unit preservation progressively decreases with age until c. 8000 cal. BP, indicating the generally eroding nature of British and Spanish river systems until this time (at least those which have been studied) and the resulting loss of older units. Alluvial units deposited before c. 8400 cal. BP, however, are better preserved in both areas. In the case of Great Britain, this has been partly attributed to downcutting in many river valleys during the early Holocene (Lewin and Macklin, 2003), but it may also reflect the size of the forcing events between c. 11,200 and 9000 cal. BP, which in Spain was a period characterized by a series of very large floods (Benito et al., 2003). The form of the age–frequency plot for dated flood sediments in Poland indicates a rather different set of preservation factors have operated to produce the temporal bias observed in the fluvial record. The broadly negative exponential relationship between age and the number of flood units found in the larger alluvial river systems of Poland back to c. 5500 cal. BP is a pattern that would be expected to be associated with long-term lateral migration of river channels, and limited channel incision or aggradation (Lewin and Macklin, 2003). Immediately prior to c. 5500 cal. BP the higher frequency of flood units suggests a different river activity style in the early Holocene of episodic valley floor aggradation followed by incision that favoured alluvial preservation. Thus, while the timing of many of the high-frequency 'spikes' (related to climatically controlled change in flood occurrence and magnitude) in the PDCs are very similar in Great Britain, Poland and Spain, the primary determinant on preservation potential, as reflected by the overall form of the PDC in each area, is the regional context and local river system behaviour.

5. Conclusions and future research priorities

This paper provides a probability-based record of riverine flooding in Europe during the Holocene and has been constructed using a new, large database of nearly 1200 ^{14}C dated fluvial deposits from Great Britain, Poland and Spain. Employing a novel, sedimentologically based methodology recently developed by Macklin and Lewin (2003) and Macklin et al. (2005), phases of significantly higher, and lower, flood occurrence have been identified during the Holocene and dated. Fifteen major periods of flooding are evident (Table 5; Fig. 2), eleven of which coincide with phases of lake level rise in mid-Europe. This demonstrates a common underlying climatic control but also somewhat surprisingly indicates that river basins can respond, through variations in the frequency and magnitude of major floods, more rapidly to climate change than lake systems. Indeed, punctuated instability appears to be an inherent, and natural, characteristic of many rivers in Europe over the last 11,500 years. We have also addressed, using one of the largest Holocene river databases so far constructed in Europe, major issues such as the 'representativeness' of the fluvial archive as a record of environmental change (cf. Richards, 2002), as well as the effect of sampling and preservation bias on reconstructing longer-term flood histories.

Although recent developments in the numerical modelling of Holocene drainage basin and alluvial valley floor evolution are showing considerable promise (e.g. Coulthard and Macklin, 2001; Coulthard et al., 2005), scale and process representation (for instance, lateral channel movement), as well as the availability of suitable data to drive models (climate and flood series), remain as significant constraints in their wider use. The empirical database approach outlined in this paper offers a complementary data analysis tool to numerical modelling. In interpretation terms, it is similarly process-based but it presently has the significant advantage of being able to readily utilise the many thousands of ^{14}C dates that have already been obtained from fluvial contexts in Europe, and elsewhere in the world, over the last 30 or so years. However, answering some research questions may need a more purposive sampling and study strategy than has hitherto been adopted. The Holocene alluvial archive currently consists of a somewhat disparate set of site studies conducted for a variety of purposes. Although the metadata analysis procedure we have adopted has facilitated the reconstruction of major hydrological events from the European Holocene fluvial record, it has also identified certain periods (e.g. the early Holocene in Great Britain), regions (e.g. small river basins in Spain and Poland) and depositional settings (e.g. palaeochannels in Spain) in each of the three study areas for which there is currently very little information. These need to be targeted in future investigations. Key research questions that have emerged from this present study are: 1. How did Holocene river dynamics and flooding impact on human settlement and exploitation of river valleys in the prehistoric and early historic periods? 2. To what degree does land cover in a river basin have to change in order to either amplify or reduce the climate signal recorded in fluvial sediments? 3. Is the location of land-use change within a catchment important in this respect? Further interrogation and development of the Holocene fluvial database is required to address these topics, as well as to try and evaluate differential response of contiguous catchments to identical and/or simultaneous climate/land-use forcing. Such information could be invaluable for improving forecasts of possible river system response to present and future environmental change. Finally, the data analysis methodology outlined here is generic and could readily form the basis for compiling and extending records of extreme flood events worldwide, particularly in ungauged catchments and regions where documentary records of flooding do not exist.

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