EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **35**, 707–716 (2010)

Published online 22 April 2010 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/esp.1983

Holocene flood histories in south-western USA

Tessa Harden[1], Mark G. Macklin[2]* and Victor R. Baker[3]
[1] Department of Geology, Portland State University, Portland, Oregon, USA
[2] Centre for Catchment and Coastal Research and the River Basin Dynamics and Hydrology Research Group, Institute of Geography & Earth Sciences, Aberystwyth University, UK
[3] Department of Hydrology and Water Resources, University of Arizona, USA

Received 11 June 2008; Revised 19 November 2009; Accepted 30 November 2009

*Correspondence to: Mark G. Macklin, Centre for Catchment and Coastal Research and the River Basin Dynamics and Hydrology Research Group, Institute of Geography and Earth Sciences, Aberystwyth University, Ceredigion, Wales, SY23 3DB, UK. E-mail: mvm@aber.ac.uk

ESPL
Earth Surface Processes and Landforms

ABSTRACT: River basins in south-western USA are some of the most extensively studied arid land fluvial systems in the world. Since the early 1960s their hydro-climatic histories have been reconstructed from the analysis of alluvial cut-and-fill cycles, while from the late 1970s there have been investigations of slackwater deposits and palaeostage indicators for large floods in stable-boundary bedrock reaches. However, no studies have regionally integrated Holocene fluvial histories from these two different types of fluvial environments. The current study combines the alluvial archive with flood records from bedrock reaches to generate a probability-based 12,000 year record of flooding in south-western USA. Using more than 700 ^{14}C-dated fluvial units, the analysis produces a high resolution (centennial) flood record. Seven episodes of increased flooding occurred at 11,250–10,400, 8800–8350, 8230–7600, 6700–5700, 5600–4820, 4550–3320 and 2000–0 cal. BP. Bedrock reaches are found to record more frequent floods during the middle to late Holocene, while in alluvial rivers more flood units are dated to the early and middle Holocene. These differences are primarily the result of selective preservation with alluvial reaches tending to erode during periods characterised by very large floods. Episodes of major Holocene flooding recorded in slackwater deposits within bedrock systems correspond with periods of increased precipitation in the region and lower temperatures. In contrast, within alluvial rivers above-average flooding probabilities, as well as regionally extensive channel entrenchment episodes, match with reduced annual precipitation and lower temperatures. The results of this study clearly demonstrate the value of the Holocene fluvial archive for reconstructing regional, short-term hydro-climatic change in south-western USA. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: south-western USA; Holocene flood histories; alluvial and bedrock rivers; climate change

Introduction

River basins in the south-western USA (herein south-west) are some of the most extensively studied arid land fluvial systems in the world. Since the 1960s research projects have been conducted to assess their climate history by interpreting deposits from alluvial reaches throughout the south-west (Haynes, 1968; Haynes and Huckell, 1985, 1986; Johnson *et al*., 1997; Waters and Ravesloot, 2000; Onken and Joyal, 2004). Many interpretations of the alluvial record were done for archaeological purposes and to evaluate longer-term human–river environment interactions (Walters, 1986; Homburg and Johnson, 1991; Diehl, 1997; Huckleberry, 2005), while others were conducted to better constrain Late Quaternary and historical channel and floodplain entrenchment histories (Waters and Haynes, 2001; Karlstrom 2005). Additionally, the analysis of slackwater deposits to identify and date large floods in bedrock reaches was pioneered in the south-west by Baker and co-workers, leading to a large regional inventory of Holocene palaeoflood records (Webb, 1985; Ely and Baker, 1985; Ely, 1992; O'Connor *et al.*, 1994; House, 1996). Presently, the most comprehensive Holocene palaeoflood study in the region is that compiled by Ely and her colleagues (Ely *et al*., 1993; Ely, 1997), who from the analysis of slackwater deposits identified three phases of increased flooding in the last 5000 years at 4800–3600, around 1000, and after 500 ^{14}C yrs BP.

Past researchers in the south-west have tended to focus on the investigation of either alluvial or bedrock river systems but very rarely have both been studied in a single catchment, or region, to reconstruct a record of Holocene hydrological change. However, new techniques for analyzing ^{14}C dated fluvial units have recently been developed utilizing cumulative probability density function (CPDF) plots (Lewin *et al.*, 2005; Macklin *et al.*, 2005, 2006, 2009; Thorndycraft and Benito, 2006; Hoffman *et al*., 2008) and these new approaches have prompted a re-evaluation of the Holocene flood history of the south-west and its relation to climate change, which is the subject of this paper.

This study examined 724 ^{14}C dated fluvial units from 37 locations in the arid south-west (Tables I and II, Figure 1). Bedrock reaches in this study area have river channels confined by bedrock, are located generally at higher elevations than most of the alluvial sites and occur mainly in the

Table I. Bedrock rivers in south-western USA used in this study. Reaches with multiple sets of radiocarbon dates refer to sites in close proximity to each other (<2 km).

Bedrock Reaches/ Rivers	Number of Radiocarbon Dates	References
1. Lower Virgin River, AZ	7	Enzel *et al*. 1994
2. Kanab Creek, AZ	7	Ely, 1997
3. Paria River, AZ	9, 12	Ely, 1992; Webb et al., 2002
4. Colorado River, AZ	6, 7, 10	O'Connor *et al*., 1994; Stevens NPS 1990; Ely, 1992
5. Little Colorado River, AZ	13	Ely, 1997
6. Bill Williams River, AZ	15	House, 1996
7. Maggie's Canyon, AZ	2	House, 1996
8. Verde River, AZ	19, 10, 9	House et al., 2002, Ely and Baker, 1985; O'Connor *et al*., 1986b
9. Tonto Creek, AZ	3	O'Connor *et al*., 1986a
10. Salt River, AZ	9, 9	Partridge, 1985; O'Connor *et al*., 1986a
11. Redfield Canyon, AZ	3	Wohl, 1989
12. San Francisco River, AZ	5	Ely, 1997
13. Aravaipa Creek, AZ	3	Roberts, 1987
14. East Fork Virgin River, UT	11	Ely, 1992
15. Buckskin Wash, UT	8	Ely, 1992
16. Escalante River, UT	23	Webb, 1985
17. Pecos River, TX	13, 16	Kochel, 1980; Patton and Dibble, 1982
18. Devil's River, TX	7	Kochel, 1980

Table II. Alluvial rivers in south-western USA used in the study. Reaches with multiple sets of radiocarbon dates refer to sites in close proximity to each other (<2 km).

Alluvial Reaches/Rivers	Number of Radiocarbon Dates	References
1. Gila River, AZ	9	Onken and Joyal, 2004
2. Santa Cruz River, AZ (multiple sites)	4, 43, 17, 13	Haynes and Huckell, 1985; Haynes and Huckell, 1986; Waters, 1987; Freeman, 1997
2. Santa Cruz River, AZ (multiple sites cont.)	7, 9, 55, 56, 20, 13	Stafford, 1986; Huckleberry, 2005; Mabry *et al*., 1999; Freeman, 2000, Mabry, 2006; Diehl, 1997
3. San Pedro River, AZ	20, 9	Waters and Haynes, 2001; Haynes, 1968
4. San Pedro River at Curry Draw, AZ	14	Waters and Haynes, 2001
5. Whitewater Draw, AZ	16, 4	Walters, 1986; Haynes, 1968
6. Middle Gila River, AZ	5	Onken *et al*., 2004
7. Middle Gila River at GRIR, AZ	26	Waters and Ravesloot, 2000
8. Middle Gila River, AZ	10	Huckleberry, 1993
9. Lukachukai Creek, AZ	8	Homburg and Johnson, 1991
10. Coal Mine Wash, AZ	10	Karlstrom, 2005
11. Red Peak Valley Wash, AZ	6	Karlstrom, 2005
12. Lower Verde River, AZ	8	Johnson *et al*., 1997
13. Cienega Creek, AZ	14	Haynes, 1968
14. Salt River, AZ	3	Fuller, 1987
15. Carrizo Wash, NM	21	Onken and Van West, 2005
16. Grants Area, NM	7	Haynes, 1968
17. Santa Anna, NM	6	Haynes, 1968
18. Blackwater Draw, NM	12	Haynes, 1968
19. Tule Springs, NV	12	Haynes, 1968
20. Corn Creek Dunes, NV	5	Haynes, 1968

mountainous regions of central and northern Arizona, southern Utah, and south-western Texas. Alluvial reaches are developed in unconsolidated Quaternary alluvium whose river channels experience lateral migration and periodic filling and cutting, are located in southern Nevada, New Mexico, central, southern, and south-western Arizona.

Methodology

In total, 724 ^{14}C dates was collected from published papers and reports as well as from unpublished postgraduate theses, and a database of these was compiled in the form set out by Johnstone *et al*. (2006). Information in the database included the type of material dated, geographic location, drainage area, sedimentary context, uncalibrated ^{14}C age, depositional environment and alluvial ensemble (Table III). Fluvial units that were accompanied by reliable geological cross-sections were further analyzed to determine the stratigraphic location of the dated material. If this was located at a sedimentary boundary it was then considered to be a 'change' date (cf. Macklin and Lewin, 2003) signifying a marked shift in flooding and depositional regime. The definition of a change date, however, varies slightly between bedrock and alluvial reaches. Since, the analysis of slackwater deposits in bedrock reaches has been proven to be a reliable method for identifying individual floods (Baker *et al*., 1983), all ^{14}C dated units in these type of river environments were classified as change dates. Whereas in alluvial systems within the south-west fluvial units that represent individual floods have been rarely, if ever, dated and this required using a slightly different definition of a change date in order to correlate and compare the two different fluvial environments. Only where reliable cross-sections of ^{14}C dated fluvial units were available and where a ^{14}C date came at, or close to, a boundary between two distinct fluvial units was it designated a change date. If more than one date was available

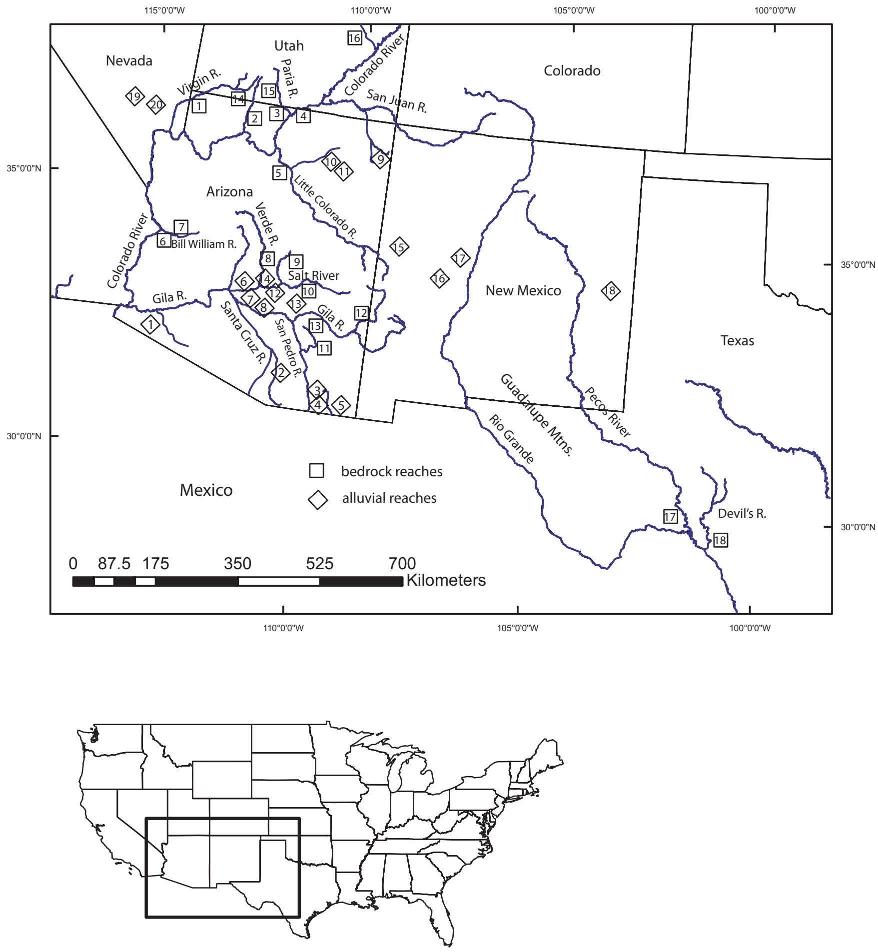

Figure 1. Bedrock and alluvial sites in the south-western United States used in this study. Refer to Tables I and II for site name and number of ^{14}C dated units. This figure is available in colour online at www.interscience.wiley.com/journal/espl

for a unit boundary the date with the smallest standard error was used. An example of a change date is shown from the Gila River, Arizona (Waters and Ravesloot, 2000) in Figure 2 where the ^{14}C date of 4485 ± 55 at the bottom of unit II marks very precisely when deposition of this unit started. This is a major change in sedimentation regime, representing in this case a switch from gravel channel deposition to finer grained overbank floodplain sedimentation. The other dates are not considered change dates because they are located towards the middle of fluvial units and not at sedimentary boundaries.

Out of the 724 fluvial ^{14}C dates, 236 came from bedrock reaches and 488 from alluvial reaches. Modern samples, samples with dating uncertainties greater than or equal to the ^{14}C age, and samples with the uncertainty age greater than or equal to 400 years were recorded in the database but not used in this analysis. A threshold value of 400 was chosen to increase the accuracy of the CPDF plots. A total of 625 ^{14}C dates were then used to create CPDF plots and of these 184 were labelled as change dates (117 from bedrock reaches and 67 from alluvial reaches). All dates were calibrated (INTCAL 98; Stuiver *et al.*, 1998) and individual probability distributions were summed using OxCal version 3·9 (Bronk Ramsey, 1995, 2001). CPDF plots were then calculated from the probability distributions. To remove peaks in the CPDF plots resulting from the ^{14}C calibration curve and preservation bias of more recent fluvial units, fluvial change dates were divided by the CPDF plot of the entire south-west USA ^{14}C database (cf. Hoffmann *et al.*, 2008). The resulting probability curves were normalized to one by dividing each date by the greatest probability in the dataset. Flooding episodes are identified in the CPDF plots by intervals where the relative probability exceeds the mean probability, which for bedrock reaches is 0·193 and for alluvial reaches is 0·211.

Holocene Flood Histories: The Influence of River Environment on Fluvial Unit Survivorship

Figure 3 plots all ^{14}C dated units in both the bedrock and alluvial reaches, and shows that the temporal distribution of ages from these two types of river environments is remarkably different. ^{14}C dates from bedrock reaches have a quasi-exponential distribution with more than 50% of the flood units dating the last 3000 years. The alluvial rivers' curve exhibits a tri-modal distribution with peaks centred around 4500, 2500, and 600 cal. BP. In contrast to the bedrock record, alluvial systems in the south-west have a far larger number of dated fluvial units from the early Holocene and the difference in distribution of dates between these different river environments can be related to preservation factors. Slackwater sequences in bedrock reaches have been found to record very large floods but during these events deposits of earlier floods are frequently removed. This is because resistant canyon walls cannot adjust to short-term changes in flow regime and sediment supply and, as a result, have more limited potential for sediment storage. The fluvial record in bedrock systems has therefore a natural bias towards the preservation of more recent Holocene flood units. In alluvial channels, however,

Table III. An example of four entries from the southwest ^{14}C database showing all information collected for each of the 724 entries. Information shown was obtained from Ely (1992), Waters and Haynes (2001), Kochel (1980) and Mabry (2006)

ID	AUTHOR	DATE	CATCHMENT	^{14}C MATERIAL	^{14}C METHOD	LAB CODE
191	Ely	1992	East Fork Virgin River at Parunaweap Canyon, AZ	wood and fine grained organics transported with flood	conventional	GX-15975
238	Waters and Haynes	2001	San Pedro River at Curry Draw, AZ	carbonized plants	conventional	SMU-15
360	Kochel	1980	Lewis Canyon, Pecos River, Texas	fine grained wood, seeds	conventional	TX-3195
693	Mabry	2006	Santa Cruz River, Tucson	Annual plant	N/A	Beta-193150

ID	LAT/LONG	ELEVATION	SAMPLE DEPTH, cm	DRAINAGE AREA, km^2	SEDIMENTARY CONTEXT	UNCAL. ^{14}C DATE	±
191	N37 10.47′, W112 51.17′	4790	N/A	840	N/A	4640	75
238	N31 27.64′, W110 6.48	4131	N/A	13.4	N/A	4000	130
360	N29 44.6′, W101 21.8′	1143	N/A	~91,000	Organic rich fine sand	1955	70
693	N32 10.16′, W110 59.39′	2400	N/A	5750	N/A	3220	40

ID	CAL. DATES (1 SD)	CAL. DATES (2 SD)	CAL.BP (2 SD) MIN
191	3623-3604BC, 3523-3348BC	3634-3550BC, 3543-3314BC, 3293-3288BC, 3274-3266BC, 3238-3107BC	5641
238	2848-2813BC, 2740-2731BC, 2693-2688BC, 2679-2336BC, 2323-2308BC	2886-2197BC, 2166-2150BC	4893
360	39BC-93AD, 97-125AD	154-138BC, 112BC-227AD	2161
693	1520-1442BC	1607-1570BC, 1561-1546BC, 1541-1417BC	3614

ID	CAL. BP (2 SD) MAX	BOUNDARY DATE	DEPOSITIONAL ENVIRONMENT	ALLUVIAL ENSEMBLE	ARCHAEO. MATERIAL	X-SECTION?
191	5114	Yes	slackwater deposit	narrow sandstone canyon	no	yes
238	4157	No	arroyo fill	entrenched ephemeral stream	no	generalized
360	1780	Yes	slackwater deposit in mouth of tributary	bedrock canyon	no	yes
693	3424	No	floodplain	wide entrenched ephemeral stream	no	no

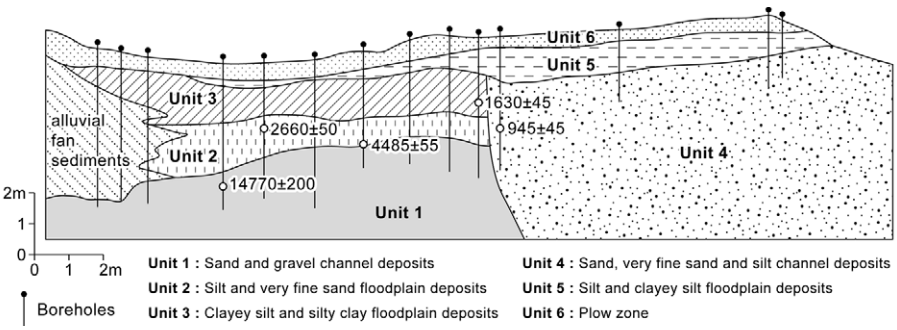

Figure 2. Schematic geological cross-section of the middle Gila River, Arizona (after Waters and Ravesloot, 2000). The ^{14}C date 4485 ± 55 is located at a unit boundary and is classified as a change date.

with more erodible banks and beds, channel migration and incision can shift flood flows away from previously deposited sediments, increasing the preservation potential of older fluvial units (cf. Lewin and Macklin, 2003).

A CPDF plot of all 117 bedrock change dates in the south-west was created (Figure 4a) and four flooding episodes, defined as having relative probabilities greater than the mean probability, are evident at 7990–7550, 6700–4930, 4500–3350, and 2050–0 cal. BP. Below-average probabilities are evident in the early Holocene (11,500–6700 cal. BP) except for a relatively short 440-year long flooding episode centred on 7800 cal. BP. This pattern suggests that there were relatively few large floods during the early Holocene in the south-west and if floods did occur in bedrock reaches they were smaller in magnitude than subsequent events and were not preserved in the fluvial record. The CPDF plot of the alluvial reaches in the south-west (Figure 4b) identifies eight flooding episodes at 11,250–10,390, 9150–7500, 6420–6290, 5360–4870, 4490–3700, 3480–3310, 1995–1600, and 1300–490 cal. BP.

When the CPDFs of bedrock and alluvial reaches are plotted together (Figure 5), many of the peaks in the bedrock CPDF plot (e.g. at 7800, 6250, 3500, 1500, 650, and 300–0 cal. BP) correspond to troughs in the alluvial CPDF plot, whereas three peaks in the alluvial reaches (8500, 6400 and 3250 cal. BP) correspond to periods with lower flood probabilities in the

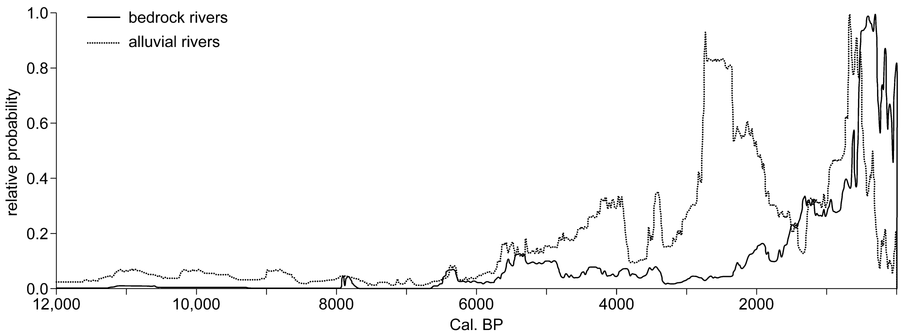

Figure 3. The summed probability distribution (normalized to one) of all dates from bedrock and alluvial reaches in this study showing the temporal distribution of ^{14}C dated units in the south-western United States. Dates from bedrock reaches exhibit a quasi- exponential curve increasing toward the late Holocene while dates from alluvial reaches exhibit a tri-modal distribution with the majority of dates between 3000 and 1500 cal. BP.

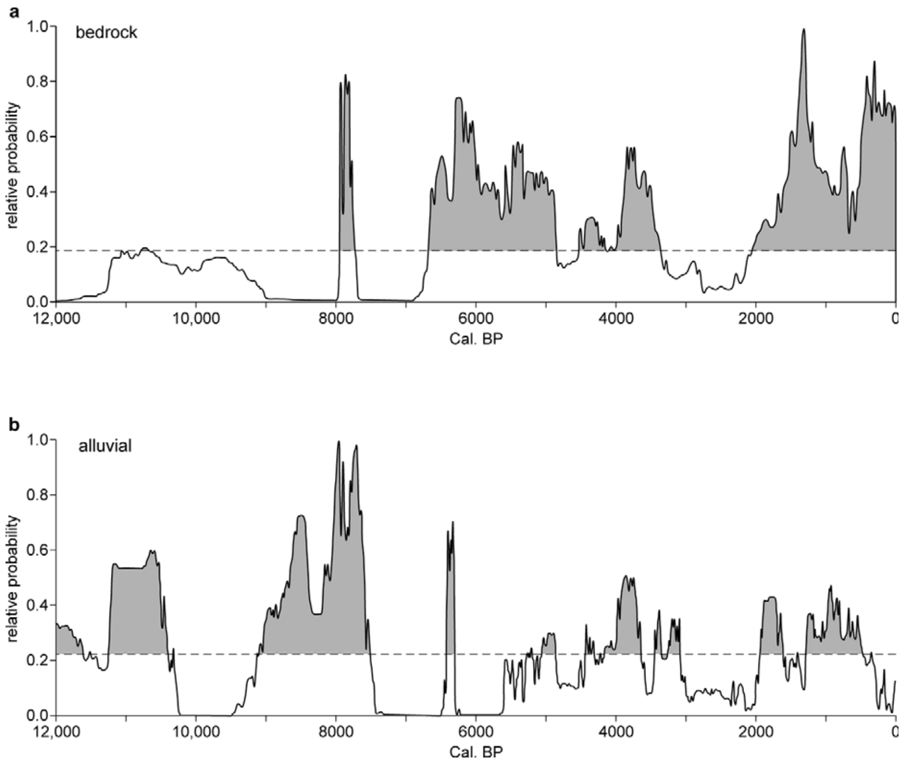

Figure 4. CPDFs of change dates in (a) bedrock and (b) alluvial reaches south-western United States. Mean probabilities are shown by dashed horizontal lines.

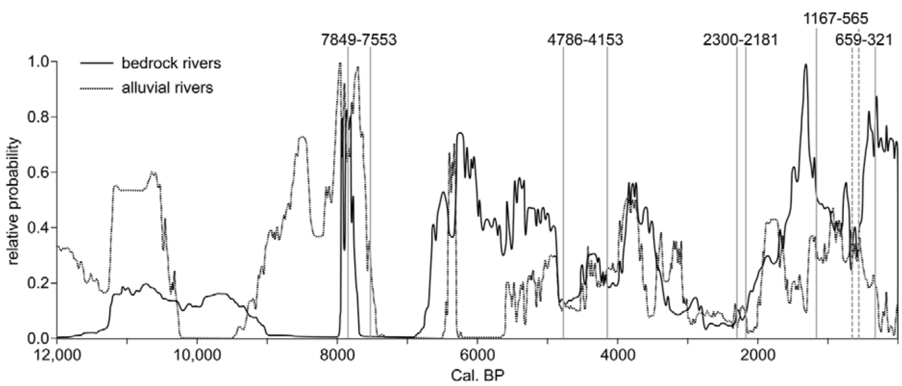

Figure 5. Alluvial and bedrock CPDF plots for south-western USA. Many of the peaks in the bedrock CPDF plot corresponds to troughs in the alluvial CPDF plot indicating periods where large floods removed some of the alluvial record. The vertical lines (solid and dashed) are region-wide channel and floodplain entrenchment episodes from Waters and Haynes (2001) and Karlstrom (2005).

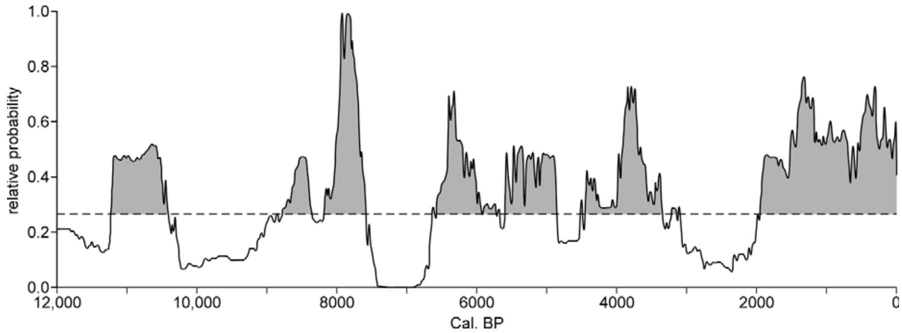

Figure 6. The combined CPDF plot of change dates from bedrock and alluvial reaches in south-western USA. Mean probability is shown by dashed horizontal line.

bedrock reaches. The pattern would appear to be primarily the result of selective preservation with alluvial reaches tending to erode during periods characterized by more frequent large floods. The relatively low number of flood units formed in the last 1000–500 years in alluvial contexts compared with bedrock systems may reflect that this was a period of more frequent large events, supporting the findings of Ely *et al.*'s (1993) earlier study.

Major channel and floodplain entrenchment in the larger south-western rivers is first documented after 8000 cal. BP (Waters and Haynes, 2001; Karlstrom, 2005). Widespread river incision occurred at about 7500, 2000, 1000, and 500–600 ^{14}C BP (Waters and Haynes, 2001; Karlstrom, 2005) and has been attributed to region-wide changes in hydroclimate. Entrenchment dates are, however, quite poorly constrained and are also reported in ^{14}C yrs BP without included uncertainty age ranges making them difficult to compare with the CPDF plots. In an attempt to make a preliminary comparison between the alluvial cut-and-fill record and our flood probability series, the maximum date for channel entrenchment was constrained by the age of the sedimentary unit that preceded incision and the age of the succeeding channel fill. Widespread entrenchment in the south-west based on studies in the Black Mesa, the San Pedro River, and the Santa Cruz River is dated (2σ age ranges) to 7849–7553, 4786–4153, 2300–2181, 1167–565, and 659–321 cal. BP (Waters and Haynes, 2001; Karlstrom, 2005).

Lastly, a CPDF plot of the combined alluvial and bedrock reach Holocene flood records (Figure 6) was created and seven episodes of increased flooding are identified at 11,250–10,400, 8800–8350, 8230–7600, 6700–5700, 5600–4820, 4550–3320 and 2000–0 cal. BP. The incidence of major floods in the region between 3000 and 2000 cal. BP appears to have been very low even though Figure 2 shows that a large number of ^{14}C dates come from alluvial river systems in the south-west during this period. These dates, however, are primarily from channel fill and floodplain deposits that formed during periods characterised by relatively small floods. Between 3000 and 2000 cal. BP the south-west experienced a wetter and cooler climate (Polyak and Asmerom, 2001) and coincided with the beginning of Early Agricultural Period in the region (Huckell, 1995). Higher water tables, possibly perennial stream flow and the lower frequency of large floods may have been a key factor for enabling agricultural societies to develop on the floodplains in central Arizona (Huckleberry, 1999).

Flooding and Holocene Climate Variability

It has long been recognised that Holocene climate variability played a central role in flooding, river behaviour and alluvial cycles in the south-west (Bryan, 1925; Haynes, 1968), as recently highlighted by Huckleberry and Duff (2008). There are, however, significant differences in opinion regarding what type of climate change is responsible for shifts in flood regime, alluviation and channel entrenchment. Rainfall and flooding in the region is generally concentrated in two periods (Asmerom *et al.*, 2007). From July through September/late October, rainfall is principally associated with North American South-west Monsoon (Adams and Comrie, 1997), with moisture derived from the Gulf of Mexico, and from infrequent dissipating tropical cyclones from the eastern Pacific that occur in the early autumn. From December through March precipitation is derived from westerly low-pressure systems that originate from the Pacific Ocean. Drier than normal winters in the south-west almost without exception follow a La Niña episode, while wet winters typically occur during El Niño years, especially when the Pacific Decadal Oscillation is positive (Cook *et al.*, 2004: Asmerom *et al.*, 2007). There is, however, no clear relationship between summer monsoon and the El Niño-Southern Oscillation (ENSO) (Redmond and Koch, 1991), but there is a potential correlation between El Niño and the incursion of east Pacific tropical storms that can cause extensive flooding in late September and early October (Webb and Betacourt, 1992). The presence of mixed populations of flood-causing atmospheric conditions in the south-west (winter cyclones, summer monsoon, autumn tropical storms) (Hirschboeck, 1988), therefore, complicates the detection of climatic effects on flood frequency in the region.

The main challenge hitherto to linking Holocene flood records and climate variability has been the lack of high-resolution (centennial or better) records that extend beyond the tree-ring chronology that in the south-west only covers the past 2000 years (Grissino-Mayer, 1996). Recently, Asmerom *et al.* (2007) produced the first complete high-resolution precipitation proxy for the south-west in the form of δ^{18}O variations in a speleothem from the Pink Panther Cave in the Guadalupe Mountains, New Mexico, covering the entire Holocene back to 12·3 ka. They interpret lower δ^{18}O values as indicating an increase in either summer or winter precipitation, or an increase in both. In Figure 7 the Holocene δ^{18}O speleothem record is plotted with the bedrock and alluvial reach CPDF flooding plots. In bedrock systems the flooding episode at *ca* 7990–7550 cal. BP begins during an interval of wetter climate and ends with a change to drier conditions. Similarly the 6700–4930 cal. BP flood episode coincides with a long-term shift towards a wetter climate in the south-west with the highest relative probabilities at *ca* 6250 corresponding with the wettest interval in the last 12,000 years. Later flood peaks at 3850–3750, 1350, 480, and 350 cal. BP all fall in wetter centuries during periods of generally drier climate.

In contrast to bedrock river systems, flooding periods on alluvial rivers in the south-west (11,250–10,390, 9150–7500,

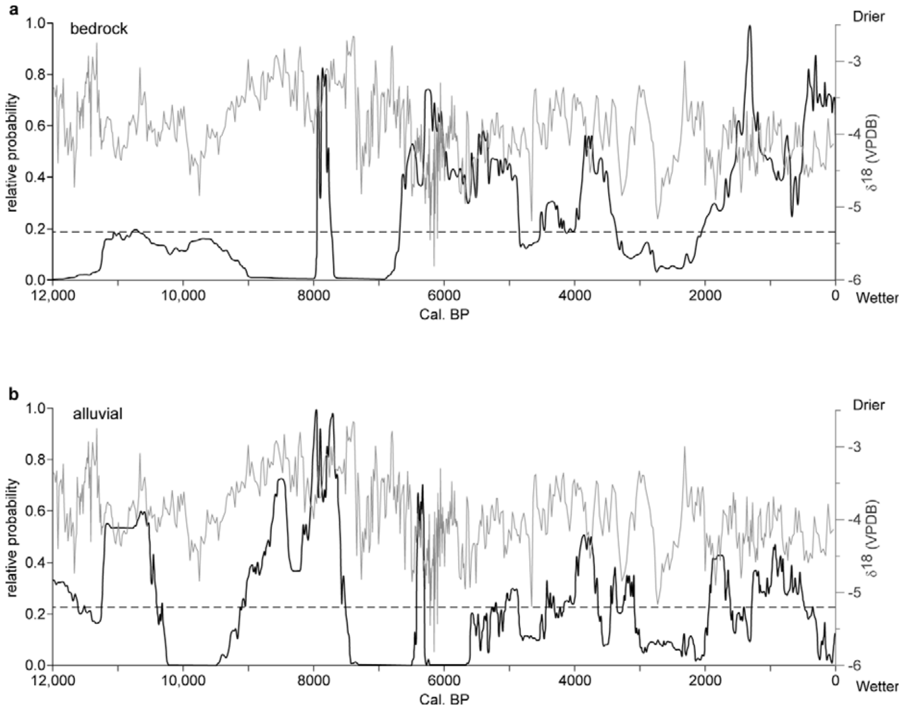

Figure 7. CPDFs of change dates in (a) bedrock and (b) alluvial reaches in south-western USA plotted with $\delta^{18}O$ variations in a speleothem from the Pink Panther Cave in the Guadalupe Mountains, New Mexico (Asmerom *et al*., 2007).

6420–6290, 5360–4870, 4490–3700, 3480–3310, 1995–1600, and 1300–490 cal. BP), with the exception of the 1995–1600 cal. BP episode, all coincide with periods of reduced precipitation with major peaks at 10,650, 8680-8320, 8000-7750, 6420-6320 and 3880 cal. BP occurring during particularly dry phases. Indeed, none of the large negative excursions of $\delta^{18}O$ in the Holocene, which correspond to unusually wet conditions in the south-west, match flood peaks evident in alluvial rivers within the region. This indicates that episodes of major flooding in alluvial river systems in the south-west are associated with 100–500 year long periods of drier climate. Furthermore, regionally extensive channel and floodplain trenching episodes at *ca* 7849, 4786, 2300, 1167 and 659 cal. BP (Figure 5) all began during periods of declining precipitation.

The influence of Holocene temperature variations on flooding regime in the south-west is more difficult to evaluate because of the lack of long and local records. However, a record of ocean oxygenation and circulation from the Santa Barbara basin in the north-east Pacific Ocean has been correlated with warm and cool conditions in the south-west during the Holocene and with North Atlantic deep water (NADW) formation (Kennett and Ingram, 1995). Comparison of the ocean circulation record for the Santa Barbara basin with the south-west Holocene flood series shows that major peaks in flooding generally occur during periods of cooling and colder climate with reduced NADW formation (Figure 8). Furthermore, all five regional episodes of channel and floodplain entrenchment in the south-west coincide with a shift to a cooler climate.

The influence of long-term changes in ENSO on Holocene flooding in the south-west has hitherto been difficult to establish because of the discontinuous nature and coarse resolution of many published ENSO proxies. A new, continuous lake sediment sequence from the Galápagos Islands provides a record of ENSO frequency and strength in the Pacific Ocean back to just before 9000 cal. BP (Conroy *et al*., 2008). What is surprising given the apparent strong relationship between historical and modern winter flooding and El Niño events is, with the exception of relatively short lived flooding episodes at *ca* 750 cal. BP in bedrock river systems and 1995–1600 cal. BP in alluvial rivers, none of the major periods and peaks in Holocene flooding in the south-west match episodes in the Galapagos lake sediment record of stronger and more frequent El Niño events (Figure 9). The lack of a strong relationship between increased flooding in the south-west and enhanced ENSO over centennial timescales during the Holocene is contrary to much recent research (Waters and Haynes, 2001; Hereford, 2002) that links Holocene alluvial cycles and changes in flooding regime to ENSO. The strong correspondence between multi-centennial long periods of increased flooding and cooler climate suggests that other meteorological causes of intense flooding aside from ENSO variability may be important. These are likely to include increased frequency of winter storms as a result of a southerly shifted jet stream linked to cooler conditions. In alluvial river systems major Holocene floods are recorded during periods of relatively low or declining annual precipitation suggesting that reduced vegetation cover could have increased runoff and flooding. However, none of the long-term climate proxies provide data on seasonal rainfall attributes and while these scenarios are plausible, at present they are speculations.

Conclusions

This is the first study to integrate Holocene flood histories in bedrock and alluvial river systems in the south-western USA. Based on a probability analysis of more than 700 ^{14}C dates, a continuous, high resolution (centennial and better) flood series has been reconstructed that allows the influence of river environment on flood unit survivorship to be evaluated, as well as comparison of an extended flood series with long-term proxy climate records. Clear differences emerge between the Holocene flood records of alluvial and bedrock river systems. Alluvial rivers tend not to preserve records of the very largest

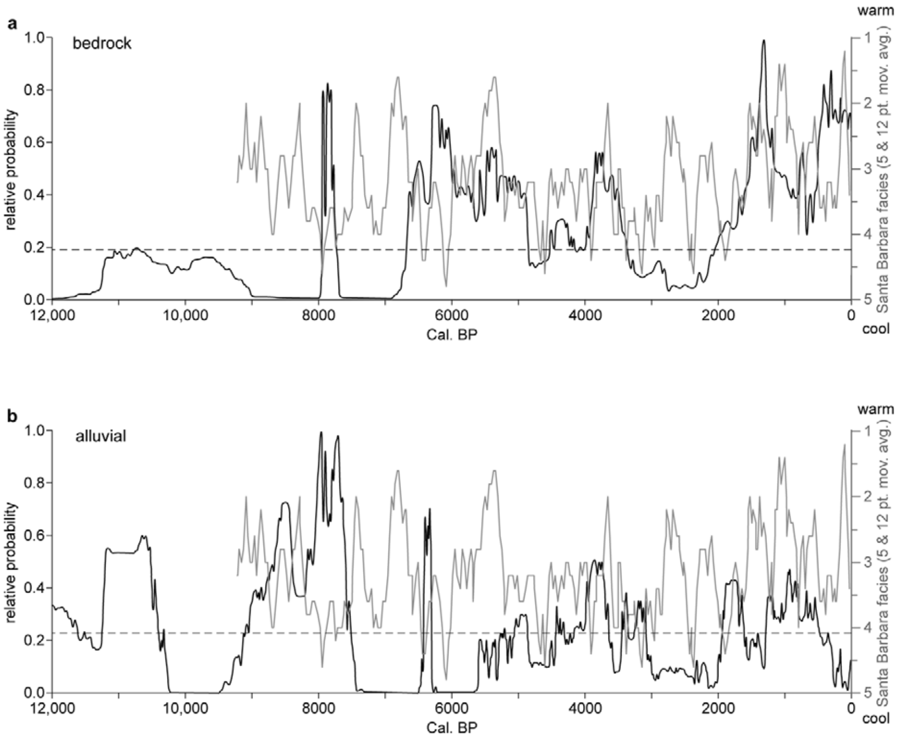

Figure 8. CPDFs of change dates in (a) bedrock and (b) alluvial reaches in south-western USA plotted with Santa Barbara basin bioturbation index (Kennett and Ingram, 1995). High scores indicate bioturbated sediments deposited under aerobic and colder conditions.

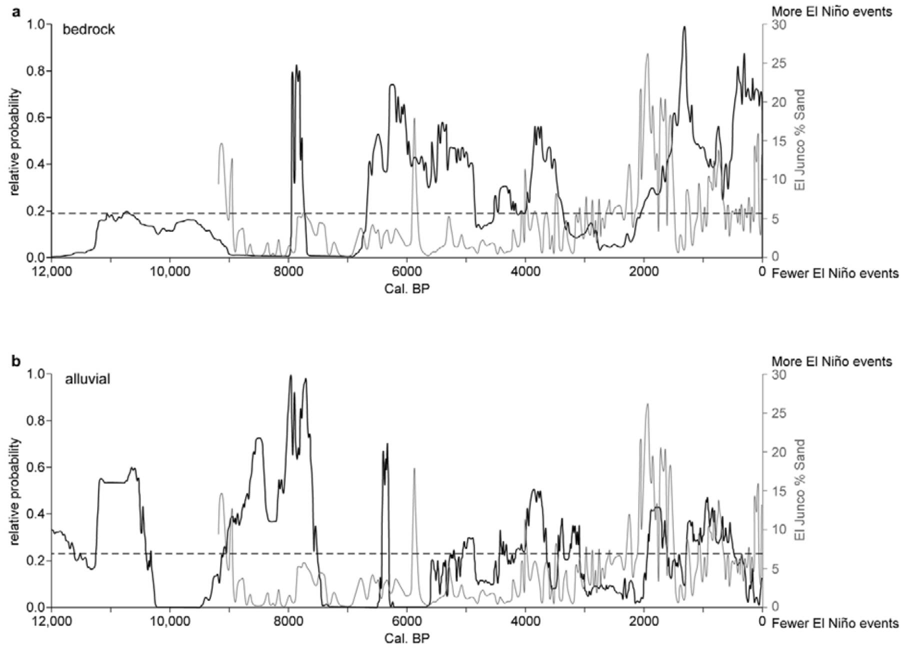

Figure 9. CPDFs of change dates in (a) bedrock and (b) alluvial reaches in the south-western United States plotted with the El Junco Lake, Galápagos Islands, ENSO record (Conroy *et al.*, 2008).

floods because these are usually lost through channel erosion and enlargement during high magnitude events. However, the deposits of large floods are more commonly preserved in bedrock reaches because of their more stable geometries. Episodes of major Holocene flooding recorded in slackwater deposits within bedrock systems in the south-west correspond with periods of increased precipitation in the region and lower temperatures. In contrast, within alluvial rivers, above average flooding probabilities, as well as regionally extensive channel and floodplain trenching episodes, correspond with reduced annual precipitation and lower temperatures. Contrary to much previous research, a strong relationship was not found between Holocene flooding in the south-west and enhanced ENSO. Alternatively, the results of this study would suggest that an increased frequency of winter storms during periods of cooler climate may have been a key factor in generating large floods in the region. Future research to improve our understanding of the longer-term controls of flood-causing atmospheric conditions will need to focus on developing seasonally resolved precipitation proxies. Last, this study demonstrates the value of meta-analysis of large ^{14}C datasets in fluvial environments, not only for the effective integration of data collected for different purposes from a wide range of contexts but also for comparing long-term flood series with continuous climate records that could not have done or envisaged previously.

Acknowledgements—This project was conceived and undertaken while Mark Macklin held a Visiting Professorship at the University of Arizona between July and December 2006. Financial support from Aberystwyth University and the University of Arizona is gratefully acknowledged. We wish also to thank the two anonymous referees for their helpful reviews that improved the clarity of the manuscript. Last but not least Mark Macklin would like to give special thanks to Vic and Pauline Baker, Tess Harden, Jeff Homburg, Jonathan Mabry and the members of the Aztec veteran football team (sorry guys it's not soccer!) for making his sabbatical at the University of Arizona such a productive and memorable 6 months.

References

Adams DK, Comrie AC. 1997. The North American Monsoon. *American Meteorological Society Bulletin* **78**: 2197–2213.

Asmerom Y, Polyak V, Burns S, Rassmussen J. 2007. Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States. *Geology* **35**(1): 1–4.

Baker VR, Kochel RC, Patton PC, Pickup G. 1983. Paleohydrologic analysis of Holocene slackwater sediments. In *Special Publication of the International Association of Sedimentologists* 6, Collinson JD, Lewin J (eds). Blackwell/University Press: Cambridge; 229–239.

Bronk Ramsey C. 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. *Radiocarbon* **37**: 425–430.

Bronk Ramsey C. 2001. Development of the radiocarbon program OxCal. *Radiocarbon* **43**: 355–363.

Bryan K. 1925. Date of channel trenching (arroyo cutting) in the arid South-west. *Science* **62**: 338–344.

Conroy JL, Overpeck JT, Cole JE, Shanahan TM, Steinitz-Kannan M. 2008. Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews* **27**(11–12): 1166–1180.

Cook ER, Woodhouse CA, Eakin CM, Meko DM, Stahle DW. 2004. Long-term aridity changes in the western United States. *Science* **306**: 1015–1018.

Diehl MW. 1997. Archaeological Investigations of the Early Agricultural Period Settlement at the Base of A-Mountain, Tucson, Arizona. Technical Report No. 96-21. Center for Desert Archaeology, Tucson.

Ely LL. 1992. Large floods in the southwestern United States in relation to late-Holocene climate variations. PhD dissertation, University of Arizona, Tucson.

Ely LL. 1997. Response of extreme floods in the south-western United Sates to climatic variations in the late Holocene. *Geomorphology* **19**: 175–201.

Ely LL, Baker VR. 1985. Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona. *Physical Geography* **6**: 103–126.

Ely LL, Enzel Y, Baker VR, Cayan D. 1993. A 5000-year record of extreme floods and climate change in the South-western United States. *Science* **262**: 410–412.

Enzel Y, Ely LL, Martinez-Goytre R, Vivian RG. 1994. Paleofloods and a dam-failure flood on the Virgin River, Utah and Arizona. *Journal of Hydrology* **153**: 291–315.

Freeman AKL. 1997. Middle to late Holocene stream dynamics of the Santa Cruz River, Tucson Arizona: Implications for human settlement, the transition to agriculture and archaeological site preservation. PhD dissertation, University of Arizona, Tucson.

Freeman AKL. 2000. Application of high-resolution alluvial stratigraphy in assessing the hunter-gatherer/ agricultural transition in the Santa Cruz River Valley, Southeastern Arizona. *Geoarchaeology: An International Journal* **15**(6): 559–589.

Fuller JE. 1987. Paleoflood hydrology of the alluvial Salt River, Tempe, Arizona. M.S. thesis, University of Arizona, Tucson.

Grissino-Mayer HD. 1996. A 2129-year reconstruction of precipitation for northwestern New Mexico, USA. In *Tree Rings, Environment and Humanity*, Dean JS *et al*. (eds). University of Arizona Press: Tucson; 191–204.

Haynes C V. 1968. Geochronology of Late-Quaternary Alluvium. In *Means of Correlation of Quaternary Successions.* Morrison RB, Wright Jr HE. (eds). Yale University Press: Salt Lake City; 267–286.

Haynes Jr CV, Huckell BB. 1985. Geological and Archaeological Investigations of Airport Wash in the Southern Tucson Basin. Institute for American Research Technical Report 85-4.

Haynes Jr CV, Huckell BB. 1986. Sedimentary successions of the prehistoric Santa Cruz River Tucson, Arizona. Arizona Geologic Survey Open File Report 86-15.

Hereford R. 2002. Valley-fill alluviation during the Little Ice Age (ca. 1400–1880), Paria River basin and Southern Colorado Plateau, United States. *Geological Society of America Bulletin* **114**(12): 1550–1563.

Hirschboeck KK. 1988. Flood hydroclimatology. In *Flood Geomorphology*, Baker VR, Kochel RC, Patton PC (eds). John Wiley and Sons: New York; 27–49.

Hoffmann T, Llang A, Dikau R. 2008. Holocene river activity: analyzing ^{14}C-dated fluvial and colluvial sediments from Germany. *Quaternary Science Reviews* **27**(21–22): 2031–2040

Homburg JA, Johnson WC. 1991. Landscape evolution in relation to Basketmaker III in the Lukachukai Valley. 56th Annual Meeting of the Society of American Archaeology paper.

House PK. 1996. Reports on applied paleoflood hydrological investigations in western and central Arizona. PhD dissertation, University of Arizona, Tucson. 355 pp.

House PK, Pearthree PA, Klawon JE. 2002. Historic and paleoflood chronology of the Lower Verde River, Arizona: stratigraphic evidence and related uncertainties. In *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology,* House PK, Webb RH, Baker VR, Levish DR (eds). Water Science and Application 5, American Geophysical Union: Washington; 267–293.

Huckell BB. 1995. *Of Marshes and Maize: Preceramic Agricultural Settlements in the Cienega Valley, Southeastern Arizona*. University of Arizona Press: Tucson.

Huckleberry GA. 1993. Late-Holocene stream dynamics on the middle Gila River, Pinal County, Arizona. PhD dissertation, University of Arizona. Tucson.

Huckleberry GA. 1999. Prehistoric flooding and its effect on indigenous agriculture in the Northern Sonoran Desert, U.S.A. *Journal of Arid Lands Studies* **9**(4): 277–284.

Huckleberry GA. 2005. Alluvial chronology for the Martinez Hill-Sentinel Peak reach of the Santa Cruz River in South-west Tucson, Arizona. In *Craft Specialization in the Southern Tucson Basin: Archaeological Excavations at the Julian Wash Site, AZ BB: 13:17 (ASM), Part 2, Synthetic Studies*. Wallace H (ed). Anthropological Paper No. 40, Center for Desert Archaeology: Tucson, AZ.

Huckleberry GA, Duff AI. 2008. Alluvial cycles, climate, and Puebloan settlement shifts near Zuni Salt Lake, New Mexico, USA. *Geoarchaeology: An International Journal* **23**(1): 107–130.

Johnson WC, Arborgast AF, Homburg JA. 1997. Alluvial geomorphology and geoarchaeology of the Lower Verde River. *Vanishing River: Landscapes and Lives of the Lower Verde Valley. The Lower Verde Archaeology Project, Vol. 2*; 17–32.

Johnstone E, Macklin MG, Lewin J. 2006. The development and application of a database of radiocarbon-based Holocene fluvial deposits in Great Britain. *Catena* **66**: 14–23.

Karlstrom ET. 2005. Late Quaternary landscape history and geoarchaeology of two drainages on Black Mesa, northeastern Arizona, USA. *Geoarchaeology: An International Journal* **20**(1): 1–28.

Kennett JP, Ingram BL. 1995. A 20,000-year record of ocean circulation and climate change from the Santa Barbara basin. *Nature* **377**: 510–514.

Kochel RC. 1980. Interpretation of flood paleohydrology using slackwater deposits, Lower Pecos and Devils Rivers, South-westernTexas. PhD dissertation, University of Texas, Austin.

Lewin J, Macklin MG. 2003. Preservation potential for Late Quaternary river alluvium. *Journal of Quaternary Science* **18**(2): 107–120.

Lewin J, Macklin MG, Johnstone E. 2005. Interpreting alluvial archives: sedimentological factors in the British Holocene fluvial record. *Quaternary Science Reviews* **24**: 1875–1889.

Mabry JB. 2006. Geomorphology and stratigraphy. Rio Nuevo Archaeology, 2000–2003: Investigations at the San Agustín Mission and Mission Gardens, Tucson Presidio, Tucson Pressed Brick Company, and Clearwater Site. (eds) Thiel JH, Mabry JB. Technical Report No. 2004-11, Desert Archaeology, Inc. Tucson, AZ; 1–24.

Mabry JB, Lindeman MW, Wocherl H. 1999. Summary and Interpretations: Prehistoric uses of a developing floodplain. Archaeological investigations on the east bank of the Santa Cruz River at A-Mountain, 88-98. Technical Report No. 98-10, Desert Archaeology Inc.

Macklin MG, Lewin J. 2003. River sediments, great floods and centennial-scale Holocene climate change. *Journal of Quaternary Science* **18**(2): 102–105.

Macklin MG, Johnstone E, Lewin J. 2005. Pervasive and long-term forcing of Holocene river instability and flooding in Great Britain by centennial-scale climate change. *The Holocene* **15**(7): 937–943.

Macklin MG, Benito G, Gregory KJ, Johnstone E, Lewin, J, Michczynska DJ, Soja R, Starkel, L, Thorndycraft VR. 2006. Past hydrological events reflected in the Holocene fluvial record of Europe. *Catena* **66**: 145–154.

Macklin MG, Jones AF, Lewin J. 2009. River response to rapid environmental change: evidence and explanation in British catchments. *Quaternary Science Reviews*. doi:10.1016/j.quascirev.2009.06.010.

O'Connor JE, Fuller JE, Baker VR. 1986a. Late Holocene flooding within the Salt River basin, central Arizona. Unpublished report to the Salt River Project, Tempe, Arizona.

O'Connor JE, Webb RH, Baker VR. 1986b. Paleohydrology of pool and riffle pattern development. *Geological Society of America Bulletin* **97**: 410–420.

O'Connor JE, Ely LL, Wohl EE, Stevens LE, Melis TS, Kale VS, Baker VR. 1994. A 4500-year record of large floods on the Colorado River in the Grand Canyon, Arizona. *Journal of Geology* **102**: 1–9.

Onken J, Van West CR. 2005. Paleoenvironmental Reconstruction. Fence Lake Project: Archaeological Data Recovery in the New Mexico Transportation Corridor and First Five-Year Permit Area, Fence Lake Coal Mine Project, Catron County, New Mexico. Vol 3, Environmental Studies; 1–31.

Onken J, Waters M R, Homburg J A. 2004. Geoarchaeological assessment for the Tres Rios Project, Maricopa County, Arizona. Technical paper prepared for the U.S. Army Corps of Engineers.

Onken J, Joyal T. 2004. Archaeological investigations for the transfer of title to facilities, works, and lands of the Gila Project, Wellton-Mohawk Division, to the Wellton-Mohawk Irrigation and Drainage District, Yuma County, AZ. Technical Report 04-64. Statistical Research, Inc. Tucson, AZ.

Partridge JB. 1985. Magnitude-frequency relationships of large floods utilizing geologic evidence on the Salt River, Arizona. MS thesis, University of Arizona. Tucson.

Patton PC, Dibble D. 1982. Archeological and geomorphic evidence for the paleohydrologic record of the Pecos River in west Texas. *American Journal of Science* **282**: 97–121.

Polyak VJ, Asmerom Y. 2001. Late Holocene climate and cultural changes in the South-western United States. *Science* **294**: 148–151.

Redmond KT, Koch RW. 1991. Surface climate and stream flow variability in the western United States and their relationship to large-scale circulation indices. *Water Resources Research* **27**: 2381–2399.

Roberts LK. 1987. Paleohydrologic reconstruction, hydraulics, and frequency-magnitude relationships of large flood events along Aravaipa Creek, Arizona. MS thesis, University of Arizona, Tucson.

Stafford TW. 1986. *Quaternary Alluvial Stratigraphy Reconnaissance of the Santa Cruz River, Tucson, Arizona*. Cultural and Environmental Systems: Tucson, AZ.

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac G, van der Plicht J, Spurk M. 1998. INTCAL98 radiocarbon age calibration, 24000-0 cal BP. *Radiocarbon* **40**: 1041–1083.

Thorndycraft VR, Benito G. 2006. Late Holocene fluvial chronology of Spain: the role of climatic variability and human impact. *Catena* **66**: 34–41.

Walters RS. 1986. The Sulphur Spring stage and its place in the New World prehistory. *Quaternary Research* **25**: 251–256.

Waters MR. 1987. Holocene alluvial geology and geoarchaeology of AZ BB:13:14 and the San Xavier Reach of the Santa Cruz River, Arizona. In *The archaeology of the San Xavier Bridge site (AZ BB: 13:14) Tucson Basin, Southern Arizona,* Ravesloot J C (ed). Arizona Department of Transportation. Project ER-19-1(97).

Waters MR, Ravesloot JC. 2000. Late Quaternary geology of the Middle Gila River, Gila River Indian Reservation, Arizona. *Quaternary Research* **54**: 49–57.

Waters MR, Haynes CV. 2001. Late Quaternary arroyo formation and climate change in the American South-west. *Geology* **29**(5): 399–402.

Webb RH. 1985. Late Holocene flooding on the Escalante River, south-central Utah. PhD dissertation, University of Arizona. Tucson. 204pp.

Webb RH, Betancourt JL. 1992. Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona. US Geological Survey Water-Supply Paper 2379.

Webb RH, Blainey JB, Hyndman DW. 2002. Paleoflood hydrology of the Paria River, southern Utah and northern Arizona, USA. In *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology,* House PK, Webb RH, Baker VR, Levish DR (eds). Water Science and Application 5, American Geophysical Union: Washington; 295–310.

Wohl EE. 1989. Large floods in Redfield Canyon. Unpublished report for contract IGA 89-6125-210-0111. Arizona Department of Water Resources.