PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. A 2012 **370**, 2143-2172
doi: 10.1098/rsta.2011.0608

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The fluvial record of climate change

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Fluvial landforms and sediments can be used to reconstruct past hydrological conditions over different time scales once allowance has been made for tectonic, base-level and human complications. Field stratigraphic evidence is explored here at three time scales: the later Pleistocene, the Holocene, and the historical and instrumental period. New data from a range of field studies demonstrate that Croll–Milankovitch forcing, Dansgaard–Oeschger and Heinrich events, enhanced monsoon circulation, millennial- to centennial-scale climate variability within the Holocene (probably associated with solar forcing and deep ocean circulation) and flood-event variability in recent centuries can all be discerned in the fluvial record. Although very significant advances have been made in river system and climate change research in recent years, the potential of fluvial palaeohydrology has yet to be fully realized, to the detriment of climatology, public health, resource management and river engineering.

Keywords: climate change; fluvial sediments; palaeohydrology; floods; rivers

1. Introduction

The impacts of long-term and large-scale Quaternary climatic change on river system dynamics have been scientifically studied for more than 50 years. Over the last decade in particular, there have been significant empirical, methodological and technological advances. Some studies have pointed to matches between climate and the record afforded by fluvial sediments [1–3], and others to the complicated behaviour of river systems in processing climatic events [4,5], while investigations based on numerical and physical modelling have suggested that fluvial sediment transport processes can completely destroy environmental signals [6,7]. Such new and contrasted perspectives, and field evidence, make it timely to review critically the ways in which alluvial systems may in practice respond to and record climatic changes. Section 2 of this paper considers key concepts, opportunities and challenges underlying climate–fluvial system relationships. In §3; field evidence for climatic change impacts from fluvial sediments and landforms is reviewed through focusing on three time scales: the later Pleistocene, the Holocene prior to documentary records; and the historical

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One contribution of 10 to a Theme Issue 'River history'.

period, during which better dating resolution and particular sedimentary contexts in some cases allow individual flood events to be identified and related to instrumental climate records. We conclude with a consideration of future climate change impacts and why a longer-term perspective on river responses to climatic instability should be attempted in order to aid catchment management in the twenty-first century.

2. Concepts, challenges and opportunities

A change in the frequency and magnitude of floods is the main direct driver that determines the response of river systems to climatic change. This results from altered precipitation and runoff regimes, and it is coupled with variation in the input of sediments from channel-way and slope domains (figure 1). Factors that alter erodibility and sediment supply, such as riparian and catchment vegetation, frost action and permafrost melt, as well as the short- and long-term build-up and decay of glaciers and ice sheets, also play a key role in river system sediment dynamics. There is also the nature of river catchments affected by climate change to consider, because their individual hydraulic systems and morphologies may process flood-producing events differently [4]. Alluvial systems can locally both *record* the history of climate change in the form of sedimentary signals and sequences (together with biological indicators of climate) and *respond* to climatic change by adjusting gross sediment throughput and geomorphological character, including channel dimensions, change rates and patterns. This may involve net changes in the form and quantity of valley sediment storage through aggradation or lateral dispersal, or alluvial incision and bedrock erosion. In time, change may be propagated through entire fluvial systems, transforming floodplain 'fluvial style' or 'alluvial architecture ensemble', river long profiles and the extent of channel networks [3].

In practice, however, there are four things that make the effects of climate more difficult to determine in fluvial sedimentary and landform records. First, there are non-climatic factors that may also be simultaneously changing. These include human land use and river management (which can modify both sediment inputs and river flow regime), tectonic activity (which can prompt river incision or accelerated sediment input) and base-level effects related to falling or rising sea or lake levels. It is not at all easy to separate out these effects in the many situations where there is interplay between these factors but, as we argue later, considerable progress has been made over the last two decades or so.

Second, fluvial systems have hierarchical, nested components that reprocess materials [3,8]. This is part of their self-organizing capability [9,10] that allows quasi-equilibrium forms to develop and to be changed over a range of time periods. For example, river channels may accumulate sediments in periods of infrequent or smaller floods, which may then be flushed out and widely dispersed in major events. Self-organization also establishes channel sizes and shapes related to discharges and available alluvial material, during which bank erosion and complementing sedimentation may involve a change in channel location. Channel dimensions and the rate of shift may then change if sediment fluxes and river flows alter. Active rivers may migrate across braidplains and meander belts, recycling erosion products over a characteristic time scale of

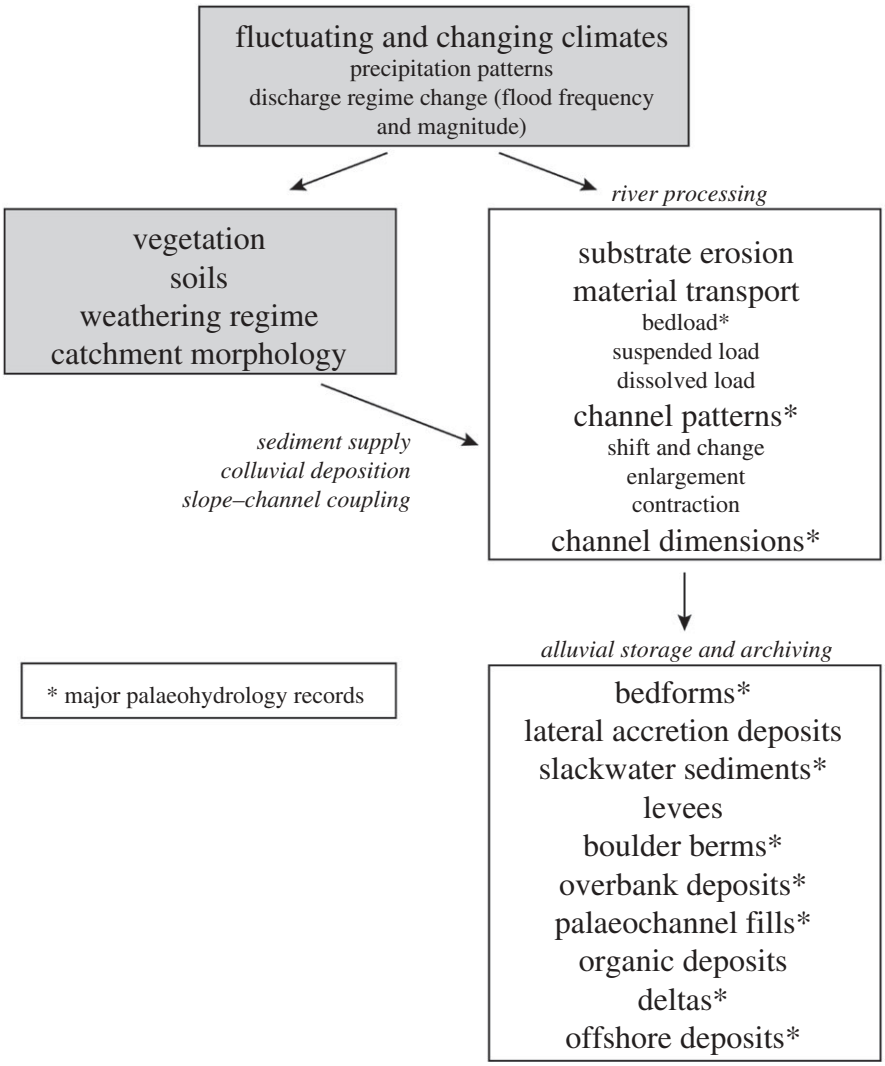

Figure 1. Diagram showing how rivers respond to and record the effects of climatic change. The key controls on sediment supply are also shown. Sediments are transported in various forms by rivers. The dimensions and dynamics of river channels may also reflect climate controls. The sedimentary signals of change are recorded in a range of sedimentary environments. See text for further discussion.

centuries or more. This allows the production and infill of cutoff channels that preserve a record both of past channel dimensions and of the history of post-cutoff sedimentation. However, migration and the cutoffs themselves are not necessarily any indication of external change; it is possible that they may have been triggered by extreme events, but it has also been shown that meander trains may be formed and destroyed autogenically to maintain a longer-term sinuousity balance [11]. Similarly, avulsions or individual cutoffs may require extended autogenic development before a triggering flood results in a channel or channel-belt shift [12].

Processing rates vary considerably within catchments. The middle reaches of smaller catchments with the highest stream powers seem to be where lateral and vertical autogenic recycling operates most effectively to provide a discontinuous sediment archive (figure 2*a*). Incision and terracing, palaeochannel fills and cut-and-fill sequences may permit the fragmentary preservation of such depositional sequences (figure 2*b*, I and V), and site data can be collated to give a more complete record. Upstream there may be boulder berms (III), and downstream and in flood basins or overbank environments there may be a more continuous record (II and IV), if only of more extreme events derived from the dispersal of fine sediments. For larger catchments and rivers, this 'small-stream' model may be less applicable. Many large catchments have low-gradient sand-bed rivers; some have low lateral mobility and extensive organic flood basins; whereas in others avulsive channel-belt relocation and floodouts across wide sedimentary/tectonic basins provide the most useful record of older sedimentary fills [14]. Furthermore, sedimentation opportunities may be restricted, and only a limited number of longer-term alluvial sequences have as yet been presented for many of the largest rivers [15]. In these circumstances, as for steepland environments, deltaic and offshore sedimentation may provide the best record of climate fluctuations currently available.

Differentiating between river behaviour related to either autogenic or allogenic controls is difficult, unless fluvial landforms or sediments are well dated, and a local climate record of appropriate temporal and spatial resolution is available. Because of chronological and proxy climatological constraints, relating short-episode feedbacks (100 years or less) to external forcing or to 'internal' river processing is especially problematic prior to the most recent instrumental period. Some autogenic changes are also directional rather than cyclical, and there may be evolutionary trends within alluvial systems that are not responses to external change (for example, overbank or channel fill flood sequences that become self-limiting as they raise sedimentation levels). This represents a change in the boundary conditions within which later phases of river activity take place. It is important to have knowledge of these within-regime nested catchment response and recovery behaviours in order to appreciate whether what is observed is simply intrinsic and ongoing activity, or is actually part of some 'reaction' and 'relaxation' sequence to be viewed as bridging different climatic regime states.

Third, the recognition of climatic change as manifested in changing river hydrology, sedimentation and morphology is not straightforward. As a consequence of climatic change, high-flow events may become larger, more frequent or last longer. Under what is regarded as a non-changing regime, well-spaced sequences of events may trigger a geomorphological response followed by periods of recovery. This can include a transformation of channel pattern from meandering to braiding, followed by many years of recovery back to the former state [16–18]. Ramped change to a new regime style may be difficult to distinguish in the short term, just as it is not possible to regard extreme rainfall or flood events as evidence of climatic change. While it may be convenient to regard climatic changes as a sequence of 'on/off' or 'active/quiescent' periods, this is not quite what happens in reality. For example, the Little Ice Age (LIA; *ca* AD 1300–1850) in northwest Europe consisted of sets of cold winters and large individual floods, particularly in the early to mid-fourteenth century

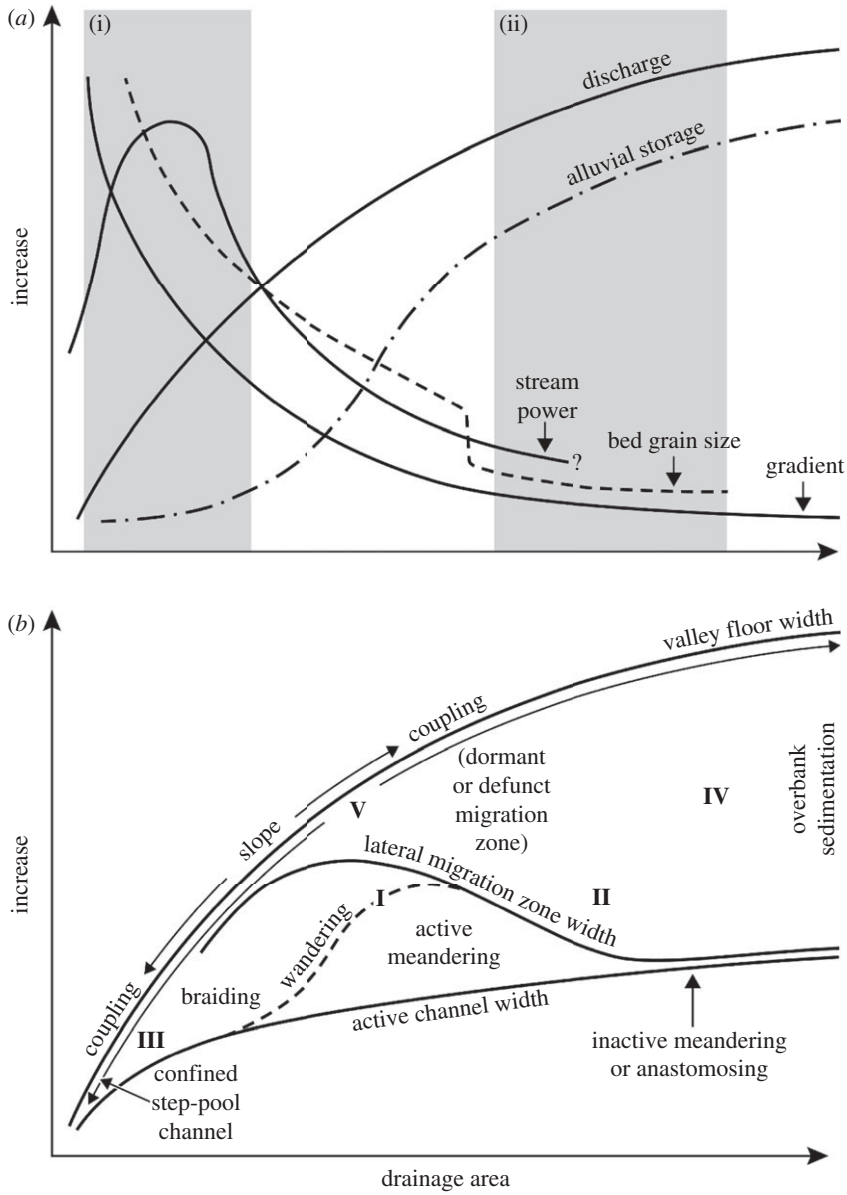

Figure 2. (*a*) River system attributes in relation to drainage area based on concepts developed by Schumm [13]. Grey-shaded columns denote reaches with higher stream powers located in piedmont areas of small catchments (i) and possibly in the lower reaches (ii) of large rivers. (*b*) River channel styles in relation to drainage area with the positioning of major depositional settings where records of climate fluctuations may be recorded (I, palaeochannel fills; II, overbank deposits; III, boulder berms; IV flood basins; V, terraces).

and late seventeenth and eighteenth centuries [19,20]. There have also been alternating periods of high and low flood frequency in switching cycles occupying a decade or more [21]. Large-scale shifts in atmospheric and ocean circulation

may lead to a clustering of flood events on a decades to century time scale [22]. Sub-epoch, stage or episode variability [23,24] is also key over longer time scales. For example, glacial–interglacial cycles were characterized by a high degree of climatic variability within individual cold and warm stages, even though the obliterating advance and retreat of ice sheets in mid-latitudes imposed periods of apparent singularity. Change or regime states are much easier to define as statistical trends and data averages than they are to observe within river systems over the short span of direct human observation. The concept of climatic 'change' in terms of river dynamics might be seen as implying prior constancy or statistical stationarity, but the reality is that river systems respond to climates in complex ways, and the present concern for global anthropogenic warming effects must be viewed in a context of event, annual, decadal, centennial and longer periods of variation.

Fourth, current knowledge uses the concepts of both linear and nonlinear behaviour in fluvial response. For example, bivariate relationships between channel dimensions (width and depth) and bankfull discharge have been established, and these have allowed a reconstruction of former discharges using dated palaeochannel dimensions [25–28]. Linear relationships between grain size and flow parameters have also been used to estimate former river discharge parameters [29]. It is, however, well recognized that these relationships involve a considerable degree of data scatter, and there are also step changes or thresholds that involve nonlinear responses. Thus, the entrainment of mixed-size river bed sediments may require bed armour to be disrupted so that a range of grain sizes moves at once. Bedforms that steer channel pattern development may be generated between lower and upper thresholds. There are process thresholds between types of channel pattern such as meandering and braiding. So, both linear responses (within limits) and thresholds have been distinguished.

All this is to underscore the fact that fluvial systems are, in the everyday sense, highly *complex* (the word has also been used, following Schumm [13], in a more limited sense to describe particular kinds of feedback in alluvial systems). It needs to be appreciated that *allogenic change* (in this case, prompted by climatic changes that can occur over decades to millennia) is *autogenically* processed by fluvial systems that have their own distinct scales and temporal hierarchies of process–landform responses. A pattern of changing flood incidence may rapidly disperse fine sediment; perhaps channel dimensions may change over a matter of years, channel patterns over decades, and entire alluvial systems in the long term. These time scales are not intrinsically absolute (many may be reproduced rapidly in laboratory flumes, or modelled numerically), but their actualities need to be observed through both field study and monitoring. It is in the nature of fluvial geomorphic systems to respond to, and to 'process', climate changes in variable and often very extended time periods. In some environments, rivers are still responding to sediment input from the last glacial retreat, which varies according to location from decades in high-altitude catchments to many millennia in mid-latitude environments affected by Late Pleistocene ice sheets. It has recently been argued that some glaciated catchments in the Mediterranean are still recycling alluvial materials that were produced by extensive upland glaciation during marine isotope stage (MIS) 12 [30]—this kind of inheritance can extend across several glacial–interglacial cycles.

At the present state of knowledge, hindcasts and forecasts of river channel and floodplain responses to climate change can use the following (figure 1):

(a) Empirical relationships between *palaeochannel dimensions* (widths, depths and meander parameters) and bankfull discharges [25–28]. These, however, have their limitations because linked adjustments in channel component measures are notoriously unpredictable in deterministic physical terms. For example, channels may either widen or deepen or both, and this may be affected by bank stability factors that cannot be later reconstructed.

(b) Observation of threshold changes in *channel patterns* and sedimentation style, including meandering to braiding transformations, and active to inactive channel mobility periods [31]. Here, despite numerous attempts to derive them, sharp hydraulic distinctions have again appeared somewhat suspect [32–34], probably because of data limitations and unmeasured factors. Also of practical interest are the lags, pathways and time scales for transformation jumps, but there is little information on these.

(c) *Sediment size* and discharge magnitudes. This includes both maximum competence-related particle size, including the formation of boulder berms, as well as more subtle fine sediment run-of-flood sequences. Sediment entrainment, flow structures and exerted forces are complex in detail and are only partly understood, but for coarse sediments broad empirical relationships have been used where a wide range of potentially transportable sediment sizes was available [20,29,35]. For finer sediments (channel fills, overbank sequences, flood basin deposits and bedrock channel slackwater deposits), a datable record of flood magnitudes and related deposits is emerging in considerable detail [36–40].

(d) *Rates of activity* may change, in terms of either lateral channel mobility or vertical flood-unit deposition. The availability of longer-term data may be a problem because lateral accretion sediments are rather poorly dated [3], although historical maps may give change rates over centuries. Only in very few instances have direct and detailed monitoring efforts over decades been attempted [41]. Furthermore, rates of sedimentation have been greatly accelerated by soil erosion and human activity.

(e) There may be fluctuations in sediment supply and local sediment transporting capacity such that rivers aggrade or become incised in their own prior alluvial deposits. This leads to *cut-and-fill terraces* [42]. In unconsolidated sediments, episodes of *headcut development* may also be documented. There may be, however, interpretation difficulties in these contexts because autogenic mechanisms (such as Schumm's 'complex response', involving feedback switching between upstream and downstream erosion and sedimentation) may become confused with allogenic ones and vice versa. Sediment discontinuities may also be used to identify external forcing [43].

(f) *Numerical and laboratory modelling* may allow the impacts of climatic change to be forecast [4,44,45]. Within the constraints of these simulations, catchment models may suggest differential within- and between-catchment response, and sensitivity to climatic forcing. Channel-system models may generate alternative morphologies depending on modelled sediment and

water throughput. The model and real worlds may not, however, prove to be closely related, and there are dangers of oversimplification and misapplication in using only landscape evolution models as predictors of river response to climatic change.

Despite their limitations at the present state of knowledge, these opportunities (a–f) allow the impacts of climatic change to be identified and reconstructed in fluvial systems in increasing detail. Some (a–c) relate primarily to local hydraulic factors; with care, others (d and e) may be aggregated site by site and collated in a meta-analytical approach to explore relationships with extended climate proxy records [43]. The time scales involved are, in general, longer than those of observing human societies, and so are extremely useful and relevant to decision-makers, who would not otherwise be able, as it were, to see over the horizon—looking either backward or forward. Geomorphology has become quite rich in conceptual models in which geomorphic changes may be set [10], but reliable and well-dated field evidence is also steadily building up, with greater global and temporal coverage.

3. Field stratigraphic evidence

(a) *Pleistocene*

Large-scale changes in climate during the Quaternary occurred in response to two principal controlling mechanisms. The first includes multi-millennial length variations in the Earth's orbit (Croll–Milankovitch forcing), the so-called pacemaker of the Quaternary Ice Age [46]. These result in glacials and interglacials, which in high- and mid-latitude regions are characterized by cold and warm climates and in low latitudes by generally dry and wetter conditions, respectively. The second mechanism involves the sub-millennial (or sub-orbital) climatic shifts in the Late Pleistocene, distinguished on the basis of pollen, ice core and marine sediment records, resulting from abrupt reorganizations of the atmosphere–ocean system associated with rapid advances or sudden melting of ice sheets in the Northern Hemisphere. In the North Atlantic, these are marked by fluctuations in ice-rafted debris and, during periods of regional cooling, by the deposition of distinctive Heinrich units on the ocean floor. These are the two dominant sets of climate drivers responsible for the formation of river terraces found worldwide in appropriate tectonic settings [47,48].

The Mediterranean region forms an excellent example in this respect and has some of the most well-developed and well-studied flights of Quaternary river terraces in the world. These were first systematically evaluated on a regional basis in Vita-Finzi's 1969 benchmark book *The Mediterranean Valleys* [49], in which he correlated major coarse sediment aggradation episodes (his so-called 'Older Fill') with the last cold stage of the Pleistocene and periods of valley floor downcutting with interglacials, principally the Holocene. This simple model of Late Pleistocene river development, which was widely used especially by the archaeological community, was not further developed until the mid–late 1980s when new dating techniques, most notably thermoluminescence (TL), infrared stimulated

luminescence (IRSL) and subsequently optically stimulated luminescence (OSL) and uranium-series techniques, were first applied, initially in Greece [50,51] and subsequently in Spain [52] and other parts of the Mediterranean. These and other studies extended field investigations of Quaternary river records into the desert margins of the Mediterranean in North Africa [53], steepland environments on the islands of the Mediterranean, including Crete [1,54] and Mallorca [55], and glaciated catchments in southern Europe, most notably in the Pindus Mountains of northwest Greece [30]. This now geographically extensive body of river development case studies, many with good dating control, allows the relationship between the Late Pleistocene climate change and the fluvial record to be explored in some detail. In figure 3, the age of fluvial units from Mediterranean river terrace and alluvial fan sequences from the last glacial cycle (*ca* 115–11 ka) are shown for the currently best-dated river catchments in the region. It should be noted, however, that sediment-based luminescence techniques give a direct age for a depositional event, while uranium-series ages on secondary carbonates provide limiting ages (older or younger) for fluvial units. In the period before *ca* 75 ka, if the full confidence intervals of the ages are considered for both luminescence and uranium-series ages, then it is not possible to assign an individual fluvial unit unequivocally to a specific marine isotope sub-stage. However, luminescence mid-point ages and sediment unit bracketing uranium-series ages indicate significant aggradation in Mediterranean Europe, including Crete, during marine isotope sub-stages 5d and 5b. These are shown by pollen and ice core records [57] to have been periods of relatively cold climate and reduced tree cover. What is, however, equally striking is an extended, nearly 10 000-year-long period characterized by pedogenic carbonate formation from *ca* 85 to 76 ka and relative river stability, valley floor downcutting and terrace development evident across the entire Mediterranean region. This is also mirrored in the long pollen record from Tenaghi Philippon (northeast Greece) by a period of high and relatively stable tree cover ending at *ca* 67 ka, with a 50 per cent drop in total arboreal pollen. The ice core record, however, indicates a much more variable climate over this period with short but pronounced cold episodes at *ca* 75 and 70 ka. To date, a fluvial response episode has only been recognized in the Sfakia region of southern Crete and Cyrenaica, Libya, in the form of small-scale sedimentation of fine gravel.

For the period from *ca* 60 to 11 ka, thanks to better dating resolution for fluvial units and the greater number of luminescence and uranium-series ages available in comparison with the earlier part of the glacial cycle, it is possible to correlate river response to sub-orbital scale climate change (figure 4). Three types of climate proxy records can be used for this purpose [58,59]: first, Greenland ice core δ^{18}O records that document change in polar temperature and atmospheric circulation patterns; second, marine sediment records of ice-rafted debris from the North Atlantic that include the Heinrich events associated with rapid ocean and land cooling in the North Atlantic region; and third, high-resolution pollen records from deep ocean cores on the Portuguese margin, which have some of the most detailed marine isotope and sea surface temperature records available for this interval. These records mirror the pattern of stadials and interstadials evident in the Greenland ice core records. What these and other records from both the western [60] and eastern [61] Mediterranean demonstrate is the *immediate* response (within the sampling resolution of approx. 200 years) of vegetation

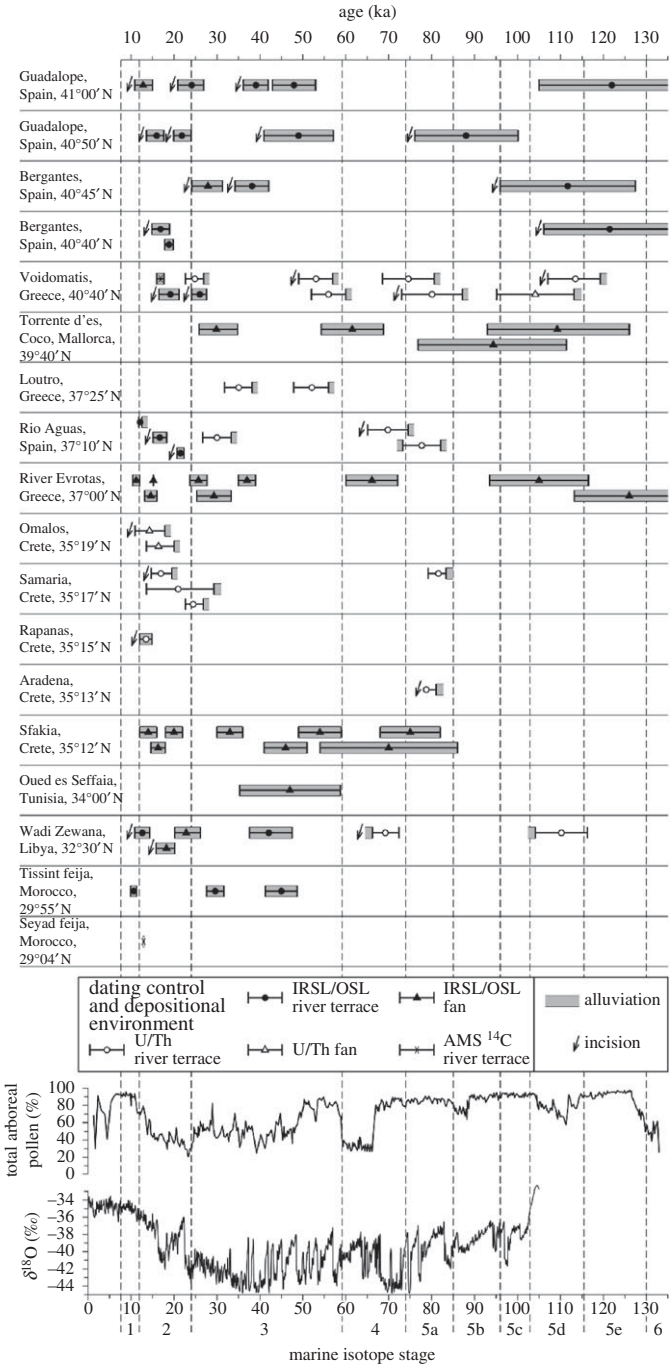

Figure 3. Dated alluvial units in river basins across the Mediterranean from the last glacial cycle (*ca* 115 to 11 ka). The various dating techniques employed are indicated and the error bars are shown for each date [56]. The proxy climate records (δ^{18}O from Greenland and arboreal pollen % from Ioannina [57]) are also shown for the same period. The catchments are shown by latitude from north to south, and all sources are given in Macklin & Woodward [56] or cited in the text.

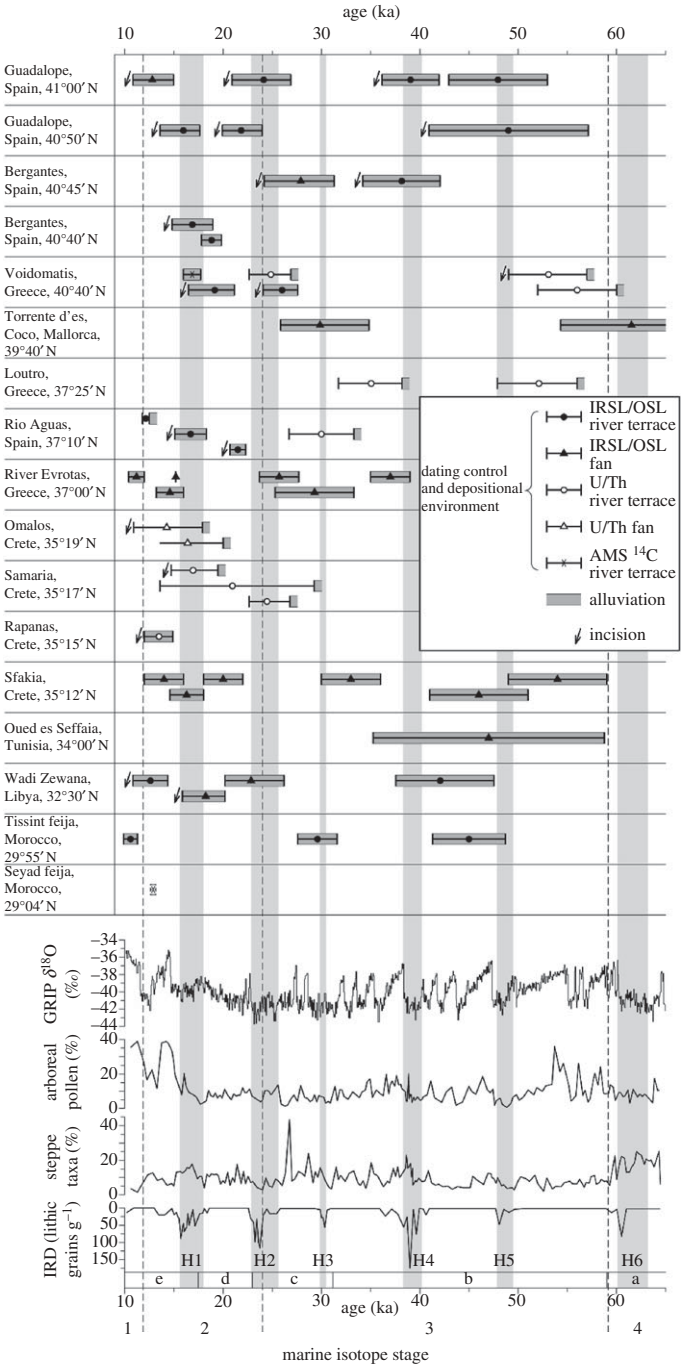

Figure 4. Dated alluvial units in river basins across the Mediterranean between *ca* 65 and 11 ka when Heinrich events took place in the North Atlantic [56]. Heinrich stadials (H1–H6) are shown [58,59]. The catchments are shown by latitude from north to south, and all sources are given in Macklin & Woodward [56] or cited in the text. Various proxy climate records from Greenland and the Portuguese margin [58] are also shown. See text for discussion.

to sub-orbital-scale climate change and how the expansion and contraction of tree populations across the Mediterranean closely tracked North Atlantic climate variability throughout the Late Pleistocene.

Many Mediterranean catchments with headwaters above 2200 m saw the development of glaciers during the cold stages of the Pleistocene; the presence of large ice masses would have exerted a strong influence on runoff and sediment delivery. Major climate shifts during Dansgaard–Oeschger and Heinrich events would have directly influenced Mediterranean river hydrology by altering precipitation and runoff patterns, although glacier growth is likely to have stalled during very cold and dry episodes. A key feature of these glaciated basins in limestone terrains is the very rapid transformation of catchment runoff and sediment sources as climate warmed at the end of the last cold stage. Late Pleistocene slackwater sediments in the lower reaches of the Voidomatis River basin of northwest Greece show a rather abrupt shift from a system dominated by meltwater floods to one dominated by rainfall-generated floods as the basin changed from glacial to interglacial mode [30,39].

In addition, climate-related effects on vegetation cover, mechanical weathering, rock breakdown, mass wasting and glacier front movements would all have resulted in significant variations in sediment supply, with river aggradation expected and found [51] during cold intervals (figure 5). Fuller *et al.* [52] first demonstrated, in a non-glacial Mediterranean context, river response to high-frequency climate oscillations, including Greenland stadials and Heinrich events, and found a strong correspondence between climate cooling (and increased aridity) evidenced by an expansion of steppe taxa and large-scale aggradation in northeast Spain (figure 4). This pattern has been confirmed by subsequent studies in Spain [55,62] and mainland [63] and island [54,56] Greece and, because of fewer dated fluvial units, to a more limited degree in North Africa.

Over the past decade, the fluvial record of the last glacial cycle (*ca* 115–11 ka) in the Mediterranean has become one of the best-studied sedimentary sequences of its kind in the world, with more than 70 fluvial units independently dated by either luminescence or uranium-series techniques. Late Pleistocene Mediterranean river evolution in terms of large-scale aggradation and incision patterns, including the formation of extensive flights of terraces, has been shown to be controlled by both orbitally driven (Milankovitch) and sub-orbital-scale climate variability. Climate–river response relationships are now much better understood because of converging and complementary developments in fluvial geochronologies and regional millennial/centennial climate records that are now available for the Mediterranean region. Yet, despite considerable recent progress, many of the issues highlighted by Macklin *et al.* [1] still remain a challenge for future Pleistocene river–climate interaction studies in the Mediterranean and more widely. They are, first, the need to develop higher-resolution (sub-millennial or better) fluvial geochronologies; second, the necessity for multiple dating assays of aggradation sequences at single sites to establish aggradation rates and the precise time intervals over which valley floor filling occurs; and finally, dating of unitary river terraces in both axial and tributary locations in order to document how and at what rate climate change signals are propagated by the fluvial system cascade, including connectivity and coupling relationships between hill slopes and river channels.

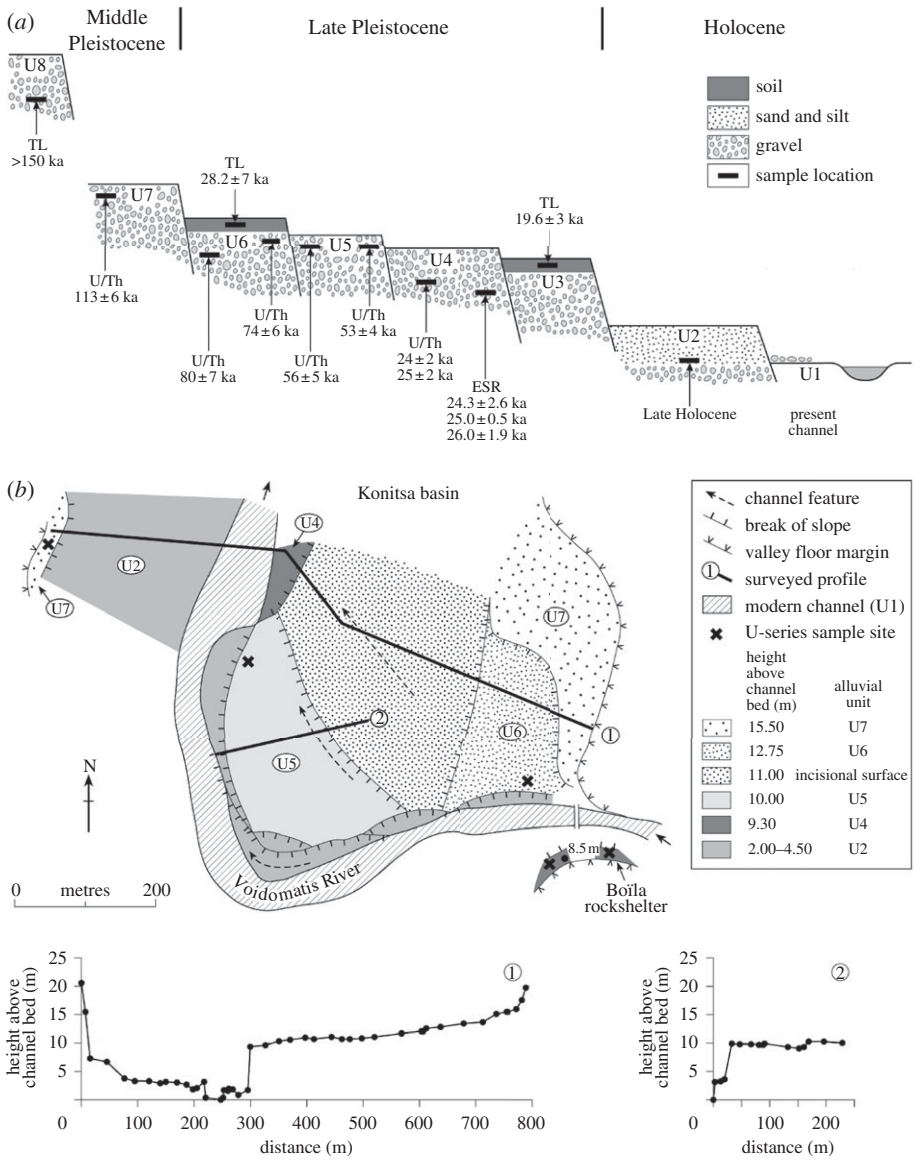

Figure 5. (*a*) Schematic showing the Pleistocene and Holocene fluvial record in the Voidomatis River basin of northwest Greece [30] and the various dating methods used to develop the geochronology. (*b*) Geomorphological map and survey profiles for the alluvial record in the Konitsa basin reach in the lower part of the Voidomatis River showing the spatial and vertical relationships between the river terraces and associated alluvial units [30]. This fluvial record has been correlated with the Middle and Late Pleistocene record of glacial activity in the Pindus Mountains [30].

One very recent and promising development has been a renewed interest in the offshore sedimentary archive in parts of the continental shelf exposed during cold stage low sea-level stands, and in deeper water turbidite systems that receive sediment from large river systems such as the Nile. Recent work on the offshore

marine sediment records in the Bay of Biscay has revealed remarkable new insights into the palaeohydrology of northwest Europe during the cold stages of the Pleistocene [64]. The 'Fleuve Manche' or Channel River was the largest river in Europe during cold stage low sea-level stands. It formed the major conduit for the transfer of meltwater and fine sediment to the marine realm during the cold stages of the Pleistocene, as it connected the southern North Sea and many of the large rivers of western Europe directly to the continental margin of the North Atlantic. Marine cores in the Bay of Biscay provide a quasi-continuous record of changes in Northern Hemisphere climate, ice sheet and runoff dynamics for at least the last 1.2 million years [64]. A complementary sedimentary record from the Nile margin showing detailed variations in the fluvial response to changing monsoon intensity over the last 100 000 years or so has recently been published by Revel *et al.* [65]. Strontium and neodymium records obtained from the terrigenous sediment fraction show sediment source variations throughout the last cold stage. This archive records a series of abrupt changes in climate and runoff in the Nile basin, with phases of dominantly Nile fluvial suspended sediment delivery during wetter periods alternating with periods of greater aeolian sediment input from the Sahara during arid intervals [65].

(*b*) *Holocene*

The long-held assumption of the constancy and relative stability of climate during the Holocene is now widely considered to be unsatisfactory [23]. Over multi-millennial time scales, the main factors that have effected Holocene climate change are related to orbital forcing [66]. In the early Holocene, precessional changes resulted in higher summer insolation at all latitudes of the Northern Hemisphere, the principal climatological effect of which was an enhanced monsoon circulation over large parts of the northern continents, leading to increased precipitation and greater runoff—most notably in river systems of sub-Saharan Africa [67]. Millennial- to centennial-scale climate variability is now generally believed to be associated with solar forcing, and the deep oceans would appear to be driving and sustaining a long-term climate change over these time scales [66,68]. Quasi-periodic (approximately 1500 year) cycles referred to as Bond events, similar to the glacial Dansgaard–Oeschger cycles discussed earlier, have been identified in records of drift ice deposition in the North Atlantic and correlated with radionuclide records from Greenland ice cores [69]. Bond *et al.* [69] suggest that amplification of the relatively weak solar signal is due to the sensitivity of the Arctic Ocean and Nordic Sea to changes in surface water salinity. Hence, increased freshening of the region would reduce North Atlantic deep water formation and thus transmit the solar influence globally. However, while the millennial-scale solar output theory remains contentious, the effects of changes in solar irradiance over century to decadal time scales on global temperatures and large-scale atmospheric circulation patterns, such as the positions of the tropospheric westerly jet and the Hadley circulation, are better documented and understood [66]. Long-term changes in solar activity can be estimated from changes in cosmogenic isotopes present in tree rings (^{14}C) or in ice cores (^{10}Be). Prolonged periods of reduced activity are associated with Holocene neoglacials, such as the Maunder Minimum of the late seventeenth century, characterized by overall cooler conditions and a shift in the Northern

Hemisphere of the North Atlantic Oscillation (NAO) and Arctic Oscillation towards lower index conditions [66,68]. Variations in these supposed internal modes of climatic variability, which also include the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation and the Arctic Oscillation, over long (multi-centennial) and short (decadal) time scales provide a direct link to Holocene river behaviour, as they have been shown to be the major control on flooding over decadal–century and longer time scales [70].

Up until the early 1990s, longer-term Holocene river development in many Old World catchments was seen solely as a response to prehistoric and historical farming practices, which through their presumed large-scale, ubiquitous and early impact on catchment erosion and runoff were believed to be responsible for major Holocene river cut-and-fill episodes [71,72]. Although this oversimplistic view was challenged by Starkel and his co-workers in a series of benchmark studies of Holocene river development in Poland [73], it is only in the last decade or so, prompted by a number of interdisciplinary and technological advances in the fluvial sciences, that the evidence for the effects of short-term (100 years or less) climate change on river behaviour has begun to emerge in a global framework [3]. The distance of travel of our current understanding of river responses to Holocene climate change can be usefully measured by reference to Blum & Tornqvist's [74] and Knox's [75] benchmark reviews on this topic. In the context of these papers, two developments stand out over this period: first, the marked increase in the number and geographical range of catchment-scale studies in which radiometrically dated alluvial deposits have been compared with regional climate records [76]; and second, the growing worldwide use of meta-analysis of large databases of ^{14}C-dated fluvial units that now allow statistically robust correlations between Holocene river behaviour and external environmental controls, including climate [2,77,78]. Moreover, the meta-analysis approach, which in the majority of cases is underpinned by regionally derived databases of many hundreds of ^{14}C ages, can produce probability-based records of river flooding in a form that can be matched with other biological, chemical and isotopic records of climate change in a way that was not believed possible by the Holocene climate research community perhaps even five years ago. This can be illustrated by three recent applications in both Northern and Southern Hemisphere catchments from dryland and humid river systems in the American Southwest, New Zealand and the UK.

Arroyos and other presently entrenched alluvial river systems of the American Southwest were the subject of some of the very first studies of long-term Holocene river development anywhere in the world. But, as highlighted by Knox [79] in his seminal analysis of Holocene river histories of the conterminous USA for nearly 100 years, there has been a contentious debate, prompted by the early research of Huntington [80] and Bryan [81], centred on whether periods of river aggradation and incision in the arid lands of the Southwest reflected periods of long- or short-term climate change. This discussion has not been restricted to the USA—it has taken place in many dryland catchments around the world, including Australia [82], the Mediterranean [83] and South Africa [84]. In the Southwest, difficulties in resolving this issue arose not from the lack of case studies and local information on Holocene fluvial dynamics and chronologies, but through the problem of trying to correlate multiple flood records preserved as slackwater deposits in bedrock canyons (studied since the 1970s by Baker and

co-workers [85]) with flood sediments recorded in alluvial rivers in the region characterized by episodes of filling and cutting over the Holocene [86,87]. Harden *et al.* [88] have, for the first time, achieved an integration of the Holocene flood records in the American Southwest through the compilation and regional analysis of more than 700 ^{14}C-dated fluvial units from both bedrock and alluvial rivers, and the correlation of probability-based flood records with high-resolution hydroclimate proxies.

One of the new and very striking findings of Harden *et al.*'s [88] analysis was that probability peaks of flooding in the American Southwest bedrock river record at *ca* 7800, 6200, 1500 and 300 cal. BP (calibrated years before present) agree precisely with low probabilities of fluvial units that mark major flood events at alluvial river sites in the region (figure 6). Conversely, probability peaks at *ca* 8500 and 6400 cal. BP in alluvial reaches correspond with significantly reduced flood probabilities at bedrock sites. In terms of geomorphological process–form relationships, this can be explained by the erosion of alluvial reaches during periods characterized by exceptionally large floods that are recorded by slackwater sediments in bedrock rivers. In contrast, smaller floods preserved in alluvial rivers are 'censored' in canyon rivers because they cannot overtop the deposits of larger and topographically higher events. However, previously identified episodes of regional river entrenchment and arroyo formation in the American Southwest do not correspond with flooding phases recorded in either bedrock or alluvial reaches, and in the latter river environment they coincide with probability minima of ^{14}C-dated fluvial units deposited by major floods (figure 6). By their nature, erosion events are usually less well constrained chronologically than periods of deposition whose unit boundaries are most often used to bracket phases of river incision. Poor chronological precision of the dating of the initiation and ending of river erosion is one explanation for this apparent mismatch between arroyo cutting and major Holocene flooding episodes in the American Southwest. Alternatively, it could be that river entrenchment tends to be more localized and does not scale to the same size of floods as picked out by the meta-analysis approach.

The main challenge hitherto of linking Holocene flood records and climate variability in the American Southwest has been the lack of high-resolution (centennial or better) records that extend beyond the regional tree ring chronology, which covers the past 2000 years [90]. Recently, Asmerom *et al.* [89] produced the first complete high-resolution climate proxy for the Southwest in the form of δ^{18}O variations in a speleothem from the Pink Panther Cave in the Guadalupe Mountains, New Mexico. This can be compared with the regionally aggregated Holocene flood records for bedrock and alluvial rivers in the Southwest (figure 6). In bedrock systems, the flooding episode at *ca* 7800 cal. BP begins during an interval of wetter climate and ends with a change to drier conditions. Similarly, the period of flooding at *ca* 6700–4900 cal. BP also coincides with a long-term shift towards a wetter climate in the Southwest, with the highest probabilities at *ca* 6250 cal. BP corresponding with the wettest interval in the last 12 000 years. Later flooding episodes centred on 3800, 1350 and 500 cal. BP all fall within wetter centuries during periods of generally drier climate. In contrast to bedrock river systems, major flooding periods in alluvial rivers of the Southwest (11 250–10 400, 9150–7500, 6400–6300, 4500–3700, 2000–1600 and 1300–500 cal. BP)—with the exception of the 2000–1600 episode—all

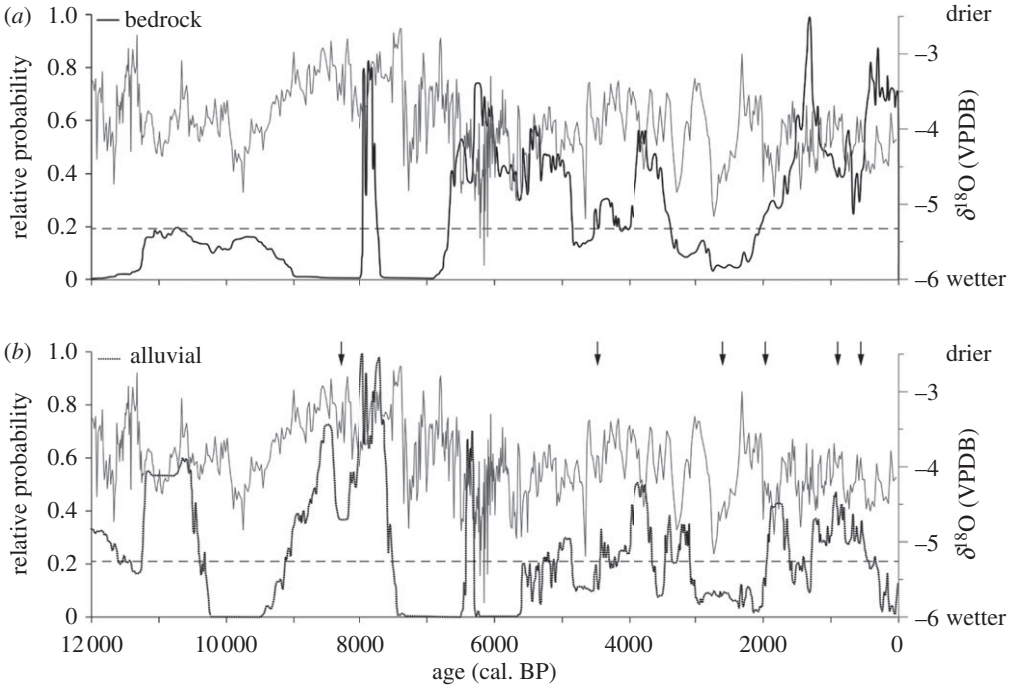

Figure 6. Holocene flood records for (*a*) bedrock and (*b*) alluvial rivers in the southwestern USA [88] when compared with speleothem δ^{18}O variations from the Pink Panther Cave in the Guadalupe Mountains, New Mexico [89]. Episodes of regional river entrenchment and arroyo formation are marked by black arrows.

coincide with multi-centennial length periods of reduced precipitation. Indeed, none of the large negative excursions of δ^{18}O in the Holocene, which correspond to unusually wet conditions in the American Southwest, match flood peaks evident in alluvial rivers in the region. This indicates that episodes of major flooding at alluvial sites in the Southwest are associated with 100–500 year long periods of drier climate. However, what also emerges from this study, which is presently the largest of its kind for any arid land area in the world, is that not all multi-centennial length periods of reduced precipitation, such as those centred on 7000 and 2400 cal. BP, are associated with flooding. This suggests that geomorphic thresholds (influenced by such factors as catchment geology, vegetation type and cover), historical contingency and changes over time of fluvial unit survivorship are all likely to play an important role in the creation of the fluvial record of environmental change. Where the meta-analysis of large ^{14}C-dated fluvial databases is most useful is for evaluating whether or not specific climatic events prompted a geomorphic catchment response, as well as quantifying 'gearing' relationships between climatic perturbations of varying size and the production of fluvial sedimentary records.

One of the major challenges of palaeoclimate research that meta-analysis of large ^{14}C-dated fluvial databases is presently addressing is whether short-term Holocene climate change has been in phase between the Northern and

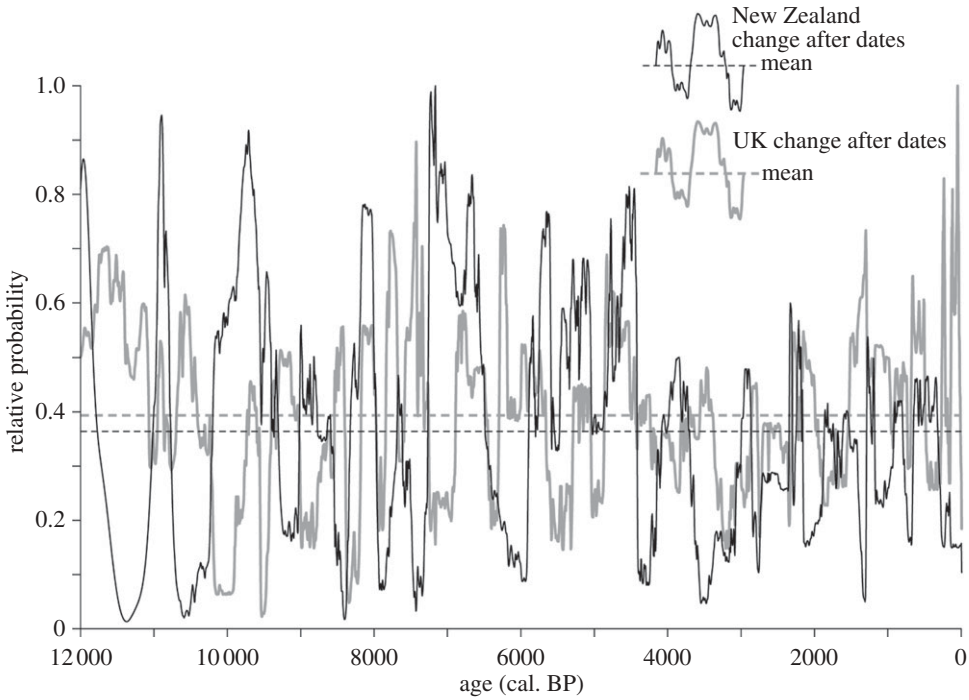

Figure 7. Probability-based Holocene hydroclimate series constructed from New Zealand and UK [22] fluvial sedimentary archives [93]. The horizontal lines indicate the mean probability above which a period of major flooding is inferred. See text for discussion.

Southern Hemispheres [91]. On the basis of studies such as those by Knox [26] and Rumsby & Macklin [92], which show that rivers respond immediately to climatic variations through changes in flooding regime linked to abrupt shifts in atmospheric circulation, a probability-based hydroclimate series has been generated using two recently compiled large (over 1000 ages) ^{14}C databases constructed from New Zealand and UK [22] fluvial sedimentary archives [93] (figure 7). These reveal statistically significant out-of-phase centennial and multi-centennial length hydrological periods in New Zealand and in the UK, which indicate asynchrony of inter-hemispheric climate changes over this time scale during the Holocene. These long-term flood series bridge the geographical and temporal gap identified by Denton & Broecker [91] that existing marine and glacial records cannot presently close. This is the first independent regional confirmation that centennial and longer oscillations in deep water production in the Northern Atlantic and Southern Ocean have directly affected hydroclimates in mid-latitude regions of both hemispheres. It also supports Denton & Broecker's [91] model of a 'wobbly' ocean conveyor during the Holocene.

Another aspect of Holocene regional-scale river behaviour that has not been systematically studied over the last decade is the timing and spatial patterning of river incision episodes, which in both alluvial and bedrock rivers commonly result in the formation of terraces. As alluded to earlier, the dating of incision episodes in river catchments is often imprecise because their timing (initiation

and cessation) and duration are usually constrained by the ages of associated bounding alluvial units. Nevertheless, for the UK we have begun to explore river entrenchment episodes using the same meta-analysis approach that has been used to evaluate the depositional record of Holocene flooding. Figure 8*a* shows all the river reaches in the UK where Holocene age river terraces have been mapped and dated using ^{14}C. What immediately emerges from this map is that the southern boundary of Holocene river incision and development of terrace flights in the UK is circumscribed exactly by the last (Devensian) glacial limit. Holocene river terraces are not, however, delineated by the supposed 'hinge point' of post-glacial uplift that runs north of a line located approximately between the Mersey and the Tees estuaries. This might be expected if glacio-isostatic uplift was the primary control of Holocene river development in Wales and the northern UK, as suggested by some workers, notably Bridgland *et al.* [94]. The overwhelming majority of river reaches in the UK that show evidence of repeated and large-scale Holocene incision are located in the piedmont zone of catchments that fringe the UK uplands. This removal of Pleistocene sediments would suggest that relatively high stream powers in these areas (figure 2), together with long-term variations in sediment supply controlled by paraglacial processes [95] and hillslope–channel coupling [96], have governed terrace formation in catchments of western and northern Britain. To judge from both historical [20,97] and observational [98] records, single exceptional floods and clusters of large events appear to produce large-scale incision in piedmont and upland rivers in both alluvial and bedrock reaches by channel entrenchment. This occurs through simultaneous river bed and bank erosion, and by the creation of multiple cutoffs that significantly shorten and steepen channels, thereby promoting incision.

In figure 8*b* are plotted the ^{14}C ages providing maximum and minimum ages for both single and multiple episodes of all dated Holocene river incision phases in the UK. Compared with the river depositional record in the UK, where the number of ^{14}C-dated fluvial units used in the meta-analysis is nearly 800 [22], only 24 Holocene incision (terrace-forming) events in 13 catchments have both their beginning and termination radiometrically constrained. A temporal phasing of river terrace formation for the UK Holocene with this limited dataset is difficult to discern at present. However, if all the ages (83 in total) that mark the onset of incision are used, there do appear to be significant variations in the occurrence of entrenchment events over the last 4500 years (figure 9). Using the same criteria as in Macklin *et al.* [22] for assessing the hydrological significance of peaks in the relative probability curve in the very much larger UK sedimentary-based dataset, episodes of river incision were identified where the relative probability exceeded the mean and where at least three ^{14}C ages marking the onset of incision occurred within two centuries in the corresponding part of the age–frequency plot. This gives centennial-scale resolution and shows that, in broad terms, the periods 4200–3700, 3000–2900, 2100–1900, 1800–1500 and particularly the last 1000 years (with the most prominent peaks at 900–800 and 700–600 cal. BP) were times of accelerated incision in northern and western UK rivers (figure 9). On the grounds that changes in catchment runoff and the associated incidence of flood events capable of eroding and transporting gravel size material (which comprise the majority of the bed, bar and bank material in northern and western UK rivers) are the major hydrological drivers over the past 4500 years, the frequency of ^{14}C ages that mark incision and their relative probability are plotted with peat-derived

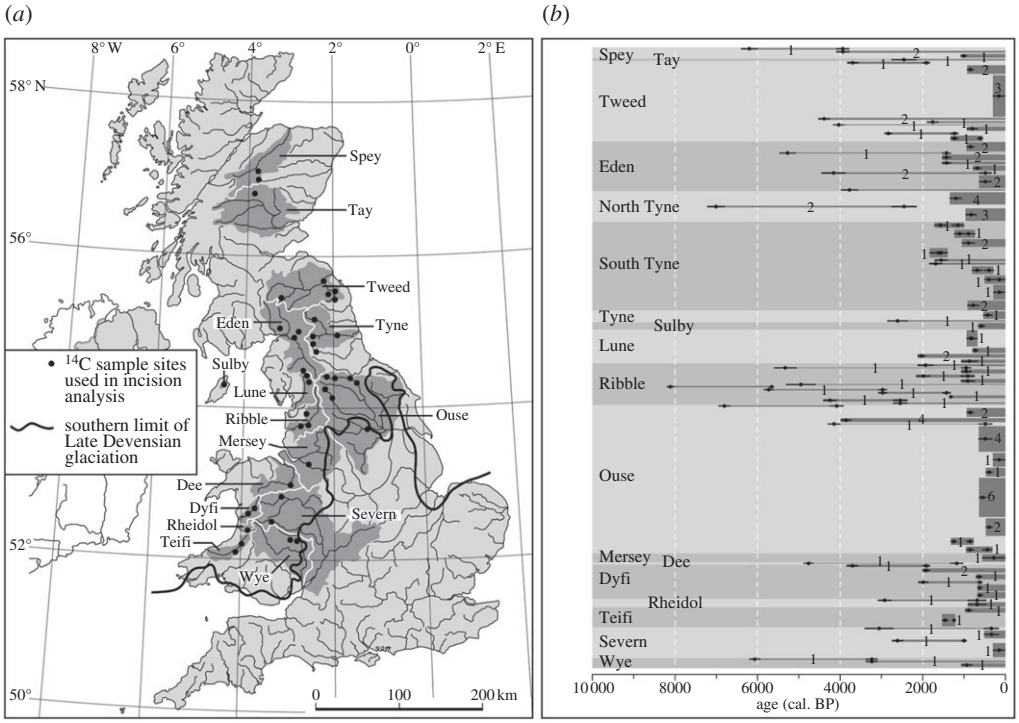

Figure 8. Episodes of Holocene river entrenchment in the UK as indicated by river terraces dated using ^{14}C: (*a*) site locations and (*b*) maximum and minimum ages for both single and multiple episodes of all dated Holocene river incision episodes in the catchments shown.

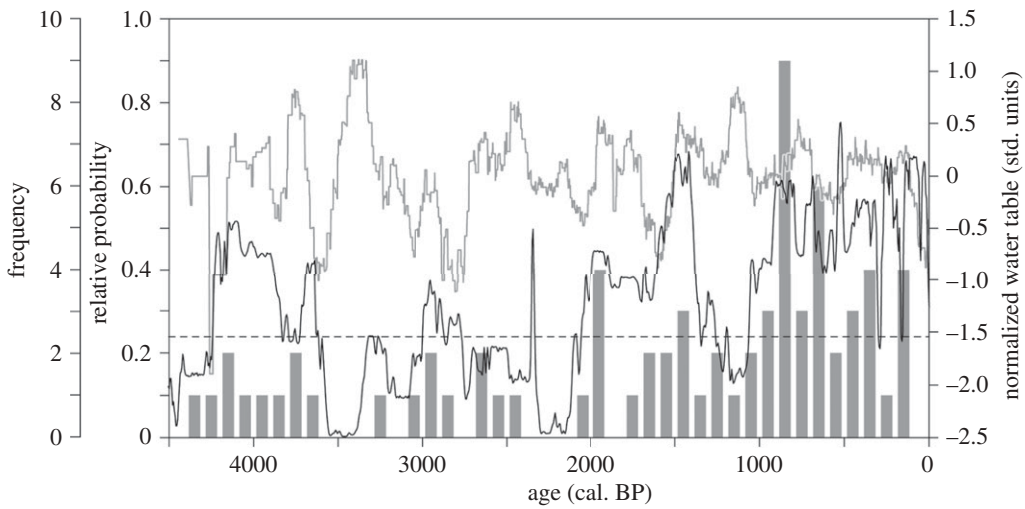

Figure 9. Relative probability for ^{14}C-dated episodes of incision in relation to the northern British water table record [99]. Grey bars represent the frequency of dated samples in 100-year age classes. Black curves represent the onset of incision, whereas grey curves represent the northern British water table record.

water table records [99] over the same period. Multi-centennial length episodes of channel entrenchment match phases of high water table in northern British peatlands, but not all wet periods (e.g. those centred on 3400 and 1200 cal. BP) are characterized by accelerated river incision. After the rise in 1600 cal. BP, peat bog water tables remain consistently high until the last 100 years. This mirrors the probability curve and frequency plot of ^{14}C ages associated with river incision and indicates that at 900–600 cal. BP both the frequency (figure 8*b*) and scale of channel entrenchment increased markedly across northern and western Britain. Other factors contributing to accelerated river incision at this time include large-scale channelization to improve navigation and the construction of many thousands of water mills used for grinding grain from the rapid expansion of arable crop cultivation during the Mediaeval period [100]. Increasing runoff through the conversion of land from woodland to farmland at a time of wetter climate would, in combination, have resulted in more frequent floods capable of entraining coarser bed and bank material. The timing and controls of Quaternary river incision—especially in self-formed alluvial systems—is clearly an important and presently under-researched topic, which may, through the further interrogation of existing large ^{14}C-dated fluvial databases now available worldwide, yield valuable information on environmental factors, including climate change, that push river systems across geomorphic thresholds.

(*c*) *Historical and instrumental*

Detecting climate-related signals in the gauged flood record has proved to be far from simple as a consequence of the relatively short average length of daily flow records, ranging from as little as 8 years in Belarus up to 75 years in Germany—the longest in the world [40]. Exceptions to this are Knox's [75] analysis of the annual maximum flood series for the upper Mississippi River since 1878 that showed significant variability of the 50 year probability flood, which tracked shifts in patterns of large-scale atmospheric circulation. However, most studies, notably a global review by Kundzewicz *et al.* [101] of river flow series of a record length of at least 40 years, do not demonstrate a worldwide increase in high flows, with 67 per cent showing no significant changes and 16 per cent showing decreases in annual maximum flows. A similar result was found very recently by Hirsch & Ryberg [102], who, from an analysis of 200 long-term (85–127 years of record) stream gauges in the conterminous USA, found no strong statistical evidence for flood magnitudes increasing with rising global mean carbon dioxide ($GMCO_2$) concentrations. However, the American Southwest region did show a statistically significant negative relationship between $GMCO_2$ concentrations and flood magnitude.

Prior to modern gauged records, historical flood levels have been recorded for the River Nile at Cairo back to AD 662 [103], while documentary evidence provides continuous information for the severity of floods (duration, extent, loss of life and damage to buildings and infrastructure) from *ca* AD 1500 in both China [104] and Europe [105]. These observation-based records show clear relationships to short-term climate variability, including the NAO and ENSO, as well as to longer climate episodes, such as the Mediaeval Climatic Anomaly (MCA) and the LIA. However, identifying high-resolution climate signals from event-based flood sequences from the fluvial sedimentary record during the

historical period is presently only possible in a relatively restricted range of depositional environments. These include, in mountain and upland areas, high-energy flood deposits comprising boulders and large cobbles—termed 'boulder berms' [20]. In Andean catchments of South America [35], in steepland Crete [106] and in the British uplands [20], lichen-dated flood records that cover all major events over the past 200–300 years have been compiled. Using these changes in the occurrence of floods, the synoptic conditions that generate extreme events have been related to the index of the NAO in the Northern Hemisphere catchments and to ENSO phase in Southern Hemisphere mountain river systems. The other depositional environment where event-resolved, continuous and extended sedimentary flood records are being developed, which can be related to short- and longer-term climate variations, are low-energy flood basins particularly in former or presently anastomosing river systems [107]. Here, a combination of very low rates of channel movement and long-term aggradation result in the near-continuous preservation of major overbank floods [40]. For example, in the upper Severn catchment, Wales, a continuous record of out-of-channel flooding has been reconstructed for the last 3700 years [107], which shows abrupt changes in flood frequency over a matter of decades that correspond to centennial- and multi-centennial-scale wet and dry phases (figure 10*a*). Extended periods of drier climate are reflected in an increased mean age of ancient oak trees preserved in Irish peat bogs (figure 10*a*), and are also characterized by a marked decrease in the occurrence of large floods with a present-day return frequency of *ca* 30 years or longer. A similar pattern emerges when the floodplain sedimentary archive is compared with long-term proxy NAO records [108], which shows a marked reduction in the occurrence of large floods during the MCA, a time of generally warmer temperatures and a more positive NAO, compared with the period before AD 1000 and particularly after AD 1550 during the cooler LIA (figure 10*b*). These studies demonstrate repeated and significant changes in flooding regime in the last 500–1000 years, which were very much greater than those that have been observed in recent instrumental flow records. This should be of concern for flood risk estimates based only on the analysis and extrapolation of relatively short gauged flood series of 50 years or less.

4. Conclusions

We have demonstrated that climatic signals can, with careful analysis and appropriate dating control, be identified within the fluvial sedimentary record. During the Pleistocene, larger-dimension landforms such as fluvial terrace sequences and their sediment bodies relate to particular climate stages and episodes, while flood units in the historical period may be related to hydrological episodes on much smaller temporal and spatial scales. We do not agree that environmental signals are entirely 'shredded' by what has been called 'morphodynamic turbulence' [6] but suggest rather that morphodynamic systems do supply archival niches from which a more extended record of climate/fluvial system signals may be aggregated. Results from what are still, in process terms, relatively simple numerical and physical models cannot be scaled up in space and time to simulate river system response to multiple past and present environmental perturbations as recorded in the resultant sedimentary

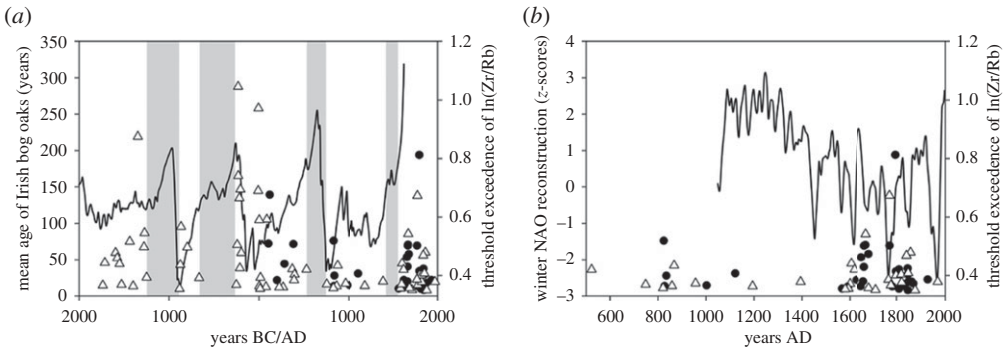

Figure 10. Holocene flood sediment units in the upper Severn catchment, Wales [107]. (*a*) Flood events were identified from two separate cores (denoted by white triangles and black circles) and are believed to correspond to the modern-day 30-year probability flood [107]. Periods with no major flood events are picked out by grey-shaded columns. (*b*) Comparison of upper Severn sedimentary flood archive since AD 550 with long-term proxy NAO records [108].

archive in catchments worldwide. Indeed, recent field-based research that uses an increasing range of sophisticated mapping, sediment analysis and dating techniques is revealing an ever more detailed record of climate change over both orbital and sub-orbital time scales. These show evidence of highly nonlinear, complex (*sensu lato*) behaviour, which indicates that during the Quaternary river systems were rarely, if ever, in equilibrium, however defined. Yet environmental signals of climate change are preserved and can be read with increasingly clarity, especially using recently compiled large databases of radiometrically dated fluvial records from a growing range of geomorphic settings around the world. Critically, even with an increase in the frequency of external forcing by climate change, over all of the time scales evaluated in this paper, there is not the loss of signal resolution that some modelling would seem to suggest. Perhaps not surprisingly, laboratory experiments using sand trays or rice piles, or numerical models of virtual 1×2 km catchments consisting of two valley slopes and a thalweg, cannot be used as precise analogues of the fluvial sediment cascade and as a guide to the sedimentary record. This is not to suggest that under steady boundary conditions sediment transport rates do not undergo autogenic, large-scale fluctuations and exhibit self-organization, as field [17] and physical modelling [109] studies showed more than 20 years ago. While noting the cautionary messages to be derived from numerical and physical modelling, we observe that they should be better coupled with an appreciation of the growing and now geographically extensive literature on Quaternary stratigraphic actualities before an unduly negative approach is accepted. It is also revealing in this context that Jeromack & Paola [6] and Van De Wiel & Coulthard [7] cite only one field-based paper [43] that discusses the relationship between climate change over Holocene and historical time scales as documented by well-dated fluvial sedimentary archives.

Intriguingly, there is a similar and in many ways parallel debate regarding the credibility of current global climate models [110], which often exhibit strong bias, particularly with respect to precipitation estimates. These have been shown to be inadequate predictors of the normal control period (1961–1990) [111] and,

of most concern, assume stationarity of the hydrological system for predicting the impacts of near-future climate change. This is despite the fact that the idea that natural systems fluctuate within an unchanging envelope of variability was shown not to be true by palaeohydrological studies more than 25 years ago [36]. Indeed, it is only very recently acknowledged and understood by water resource engineers [112].

We would contend that there is a once-in-a-generation opportunity for fluvial geoscientists to play a leading role in global water resource and flood risk management through, for example, flood-series extension and validating climate and hydrological models that are used worldwide for the protection of life, property and infrastructure. It is at the regional and especially at the local scale where the fluvial landform and sedimentary archive of past flood events and hydrological change are likely to be most useful for climate impact studies. In both the developed and developing world, fluvial geoscientists can play a central role in identifying catchments and river reaches most susceptible to an altered flooding regime and associated channel instability. This might involve a 'no regrets' flood risk policy of relocation of housing and critical infrastructure out of floodplain areas. In subtropical and tropical catchments, it could also include assessment of water-borne diseases and of malaria, where a diverse set of hydrological and geomorphological processes govern surface water body formation and persistence that form vector breeding sites (see Wasson [113] and Whitcombe [114]). It is clear that huge advances have been made in river system and climate change research in recent years but arguably the key remaining challenge to this rapidly maturing discipline will be realizing the potential of applied fluvial palaeohydrology for mitigating water-related problems that threaten people worldwide.

We thank RCUK, ARC and the Leverhulme Trust for facilitating our joint research over the last three decades. We are particularly grateful to Ian Gulley and Antony Smith for drafting the figures and to Paul Brewer, Ian Fuller and Anna Jones for their much valued and continuing collaboration. M.G.M. acknowledges and thanks HEFCW and the Welsh Government's support of the Centre for Catchment and Coastal Research at Aberystwyth University.

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