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Abstract

The CAESAR (Cellular Automaton Evolutionary Slope And River) model is used to demonstrate significant differences in coarse sediment transfer and alluviation in medium sized catchments when responding to identical Holocene environmental changes. Simulations for four U.K. basins (the Rivers Swale, Ure, Nidd and Wharfe) shows that catchment response, driven by climate and conditioned by land cover changes, is synchronous but varies in magnitude. There are bursts of sediment transfer activity, generally of rapid removal but with some sediment accumulation 'spikes', with longer periods of slow removal or accumulation of sediment in different valley reaches. Within catchments, reach sensitivity to environmental change varies considerably: some periods are only recorded in some reaches, whilst higher potential sensitivity typically occurs in the piedmont areas of the catchments modelled here. These differential responses appear to be highly non-linear and may relate to the passage of sediment waves, by variable local sediment storage and availability, and by large- and small-scale thresholds for sediment transfer within each catchment. Differential response has major implications for modelling fluvial systems and the interpretation of field data. Model results are compared with the record of dated alluvial deposits in the modelled catchments.
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1. Introduction

Catchment complex response, broadly interpreted to mean differential internal catchment processing of sediment transfer in response to uniform external forcing stimuli, has been noted in a variety of studies. Initial support came especially from experimental physical modelling of network development

and sediment transfer (see Schumm, 1979, pp. 493–497). In these experiments, incision in the lower part of an experimental catchment led to rejuvenation of upstream tributaries and their enhanced sediment delivery then led to aggradation in the lower incised reaches. Later experiments on terrace formation in small catchments similarly indicated that physically continuous terraces could be asynchronous, whilst lower surfaces upstream could be temporally equivalent to higher surfaces downstream in relation to longitudinal profiles (Germanoski and Harvey, 1993).

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Field conditions, particularly in medium sized and large river basins may be more difficult to interpret, given a requirement to date alluvial bodies over an extended time period, and the likelihood that forcing stimuli such as climate change and human activity may themselves have varied in a complex manner. Nevertheless, a number of studies have pointed to the differential behaviour of catchments and sub-catchments, with periods of aggradation and incision being contrasted in what may be nearby reaches of trunk and tributary streams (Boison and Patton, 1985; Rains and Welch, 1988). Considerations related to network topology and storage basins within catchments have recently been emphasised in a review by Richards (2002), who concludes that catchment modelling is required in order to examine the linkage between 'external' change (for example climate and land-use) and responding alluviation which may be delayed and differentiated within and between catchments. Paola also describes how the timing of the sedimentological record can be 'finicky', being sensitive to external controls as well as "*the internal dynamics of the sediment–deposition system*" (Paola, 2003, p. 459).

For fluvial modellers, this makes any general forecasting of fluvial system response especially difficult, as relationships established for one river system can rarely be applied to others. Collecting site specific data to calibrate and validate geomorphic models renders them costly and time-consuming. An ideal solution would be to develop a generic modelling approach that could be applied with a minimum of alteration to any river system. However, in order to reach such a goal, it is first necessary to establish whether catchments do actually respond in a similar fashion to imposed environmental changes.

Investigating causes of catchment change, previous authors have established three main groups of factors (e.g. Schumm, 1979).

1. Changes to the *external* environment, as in tectonic activity, sea level change or climate fluctuations. Some of these may be rapid as in the case of local response to faulting, but for the most part changes occur over timescales of centuries to millennia.
2. Anthropogenic factors, as in land-use changes, sediment extraction or river channel engineering. These are also imposed on or are *external* to the

geomorphological system in their origin. Again, immediate effects on catchments may be evident, as in the case of impacts on sediment yields, but broadly speaking such factors relate to periods of human occupation which vary from decades to millennia in different parts of the world.
3. Geomorphological factors, which include catchment morphology and *internal* sediment transfer, storage and availability as conditioned also by prior erosional and depositional history. These can be rapid but local, but extending over long time-scales where bedrock exposure and catchment transformation are involved.

It should be noted that sediment transfer processes within any catchment may be affected by all of these factors simultaneously.

Computer modelling would appear to be an ideal tool for exploring the impact of these factors, as modellers have total control over their simulated environments, and thus the capability to compare how landscape development is altered. Adopting a reach based modelling approach would at first seem logical, as a reach may exhibit an immediate response to a forcing event such as an extreme flood, and produce deposits recording its occurrence. However, it is the differential triggering of sediment movement and different rates of sediment routing down the length of the fluvial system that is likely to effect large scale deposition or removal of alluvial units over extended time periods. Therefore, fluvial processes operating throughout the catchment have to be considered. To allow this, some workers have used models that simulate the development of long profiles (e.g. Tebbens and Veldkamp, 2001) and landscape evolution models have been developed that model whole drainage basins with a grid of square cells (e.g. Willgoose et al., 1991; Howard, 1994; Tucker and Slingerland, 1994) or with an irregular mesh of nodes and links (Tucker et al., 2001; Braun and Sambridge, 1997). These studies have explored the impacts of the first two groups of factors, including tectonics (Willgoose et al., 1991; Braun and Sambridge, 1997; Howard, 1994) and the effects of climate and land cover changes (Tucker and Slingerland, 1997; Coulthard and Macklin, 2001; Coulthard et al., 2002). Some models have also partially addressed the third group of geomorphological factors, reproducing internal

instabilities and generating non-linear sediment discharges from an early application of the CAESAR model (Coulthard et al., 1998), and from a braided river model (Murray and Paola, 1994). These have been attributed to the irregular input of material from mass movement and slope processes (Coulthard et al., 1998) and to the passage of mobile bar structures (Murray and Paola, 1994).

Here we aim to investigate these geomorphological factors in greater detail by using a cellular model to examine differences in behaviour between river catchments. Instead of focussing on how external factors affect catchment evolution and sediment delivery as considered in a previous paper (Coulthard and Macklin, 2001), we explore how subtle changes in catchment morphology and internal instabilities may combine to produce a variable erosion/sedimentation response and thus a variable long-term simulated environmental history as revealed by site alluviation and erosion. For this purpose, the CAESAR model is applied to four similar catchments from the Yorkshire Dales, northern England to simulate their evolution over the last 9000 years (Figs. 1–4). To exclude the influence of other factors, these simulations were carried out using identical initial conditions (aside

Table 1
Characteristics of study catchments

River	Swale	Ure	Nidd	Wharfe
Modelled drainage area (km^2)	383	646	281	697
Max. relief of modelled area (m)	514	564	560	546
Main channel length (km)	62	82	49	97

from catchment morphology), climate, and land cover drivers.

2. Methods

A brief description of the CAESAR model is provided here, but for more detailed information, readers are referred to Coulthard et al. (2002). CAESAR is a cellular model that uses a regular mesh of grid cells to represent the river catchment studied. Every cell has properties of elevation, water discharge and depth, vegetation cover, depth to bedrock and grain size. The model uses an hourly rainfall record as the input for a hydrological model (based upon TOPMODEL, Beven and Kirkby, 1979), which may be altered to represent the hydrological effects of different vegetation covers. The output
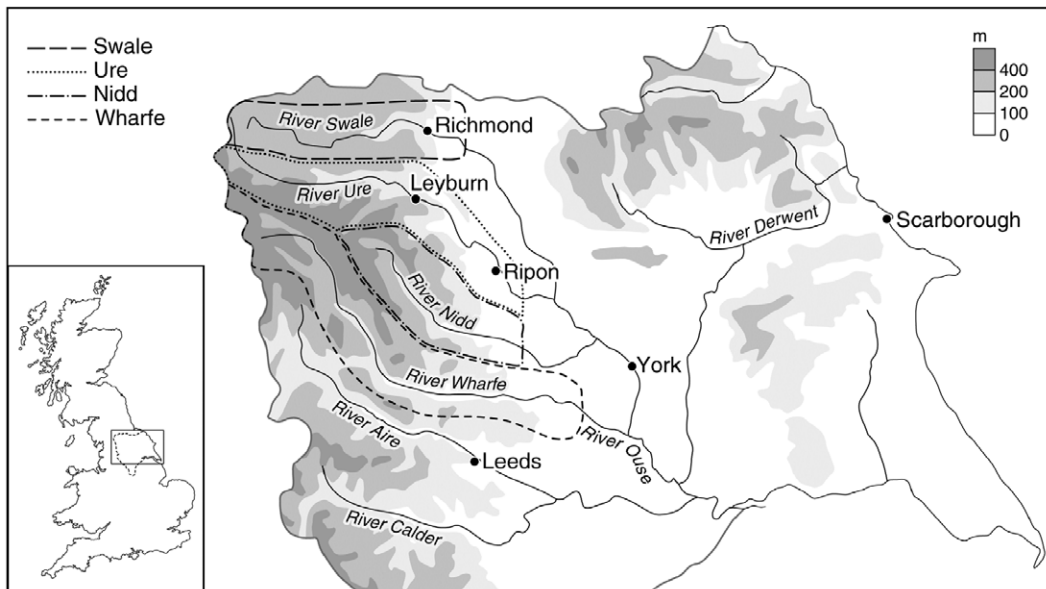

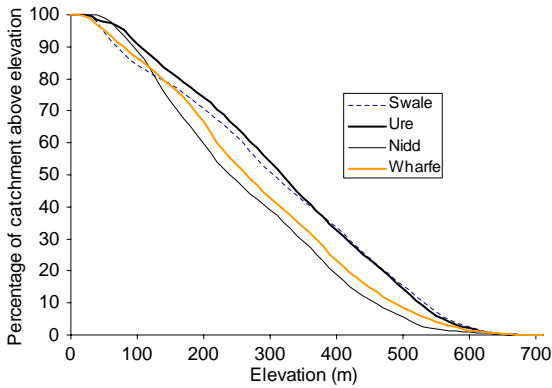Fig. 1. The study area, indicating the four catchments modelled.

Fig. 2. Hyposmetric curves for the modelled sections of the Rivers Swale, Ure, Nidd, and Wharfe.

from the hydrological model is then routed through the catchment using a scanning multiple flow algorithm that sweeps across the catchment in four directions (from north to south, east to west, west to east, and south to north). In each scan, flow is routed to the three downslope neighbours (as per Murray

and Paola, 1994), but if the total flow is greater than the subsurface flow, the excess is treated as surface runoff and a flow depth is calculated using an adaptation of Manning's equation. The maximum depth calculated for the cells over all four scans is then recorded. Any flow that is not removed from the basin remains for the following iteration, allowing hollows to fill up and also any flow 'trapped' in meanders remains, enabling complex channel patterns (such as braids and meanders) to be simulated. For all cells with a flow depth, fluvial erosion and deposition are calculated using the Einstein Brown equation (Einstein, 1950). This is applied to 11 grain size fractions (from 1 to 256 mm) that are integrated within a series of active layers (Hoey and Ferguson, 1994) that allows surface armouring to develop as well as a limited stratigraphy. Over the course of long simulations, this importantly allows previously deposited finer sediment (as on a floodplain) to become future erosion sources. Limited slope processes are also included, with mass movement when a critical slope threshold is exceeded, together with
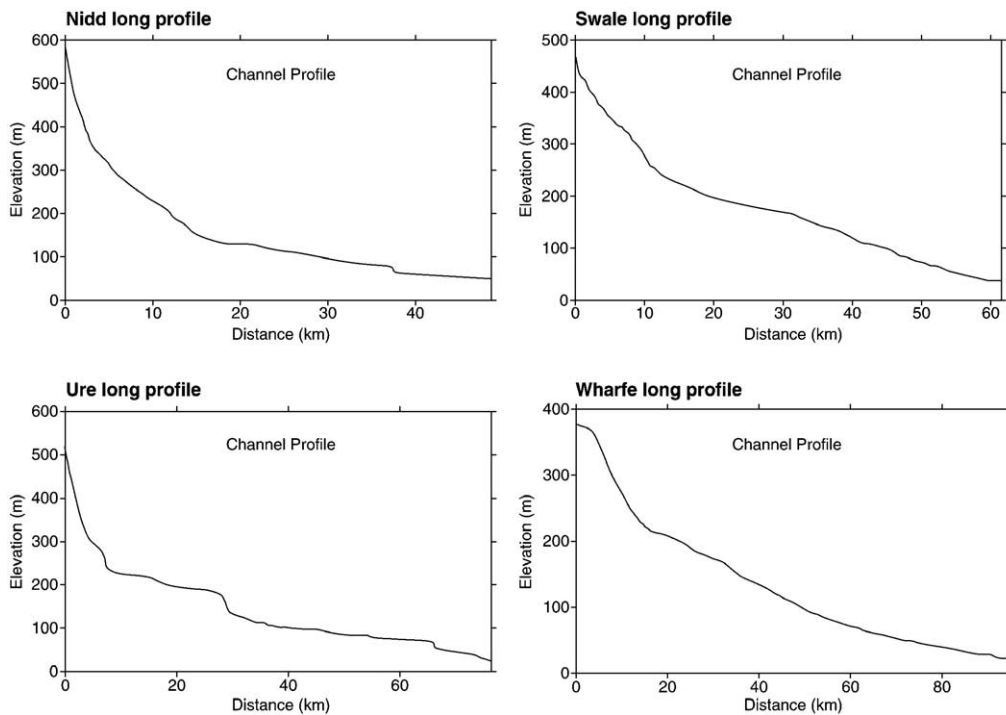

Fig. 3. Catchment long profiles.

soil creep. These allow material from slopes to be fed into the fluvial system as well as the input from landslides (both large- and small-scale—e.g. bank collapse). After the fluvial erosion/deposition and slope process amounts are calculated, the elevations and grain size properties of the cells are updated simultaneously. A variable time step is utilised (operating between 10^{-6} s and 10^4 s) that restricts erosion to 10% of the local slope, preventing computational instability. Therefore, despite being complex in operation, CAESAR only requires the

simple inputs of topography (a DEM), an hourly rainfall record and a land cover record to drive a sequence of erosion, deposition and landscape evolution. This is then used to simulate individual floods, responding to both local hydraulic responses from runoff events, as well as cumulative inputs (or deficits) arriving from up-catchment that may themselves have been triggered by previous conditions.

To test only the effects of different catchment morphologies, identical initial and simulation conditions were chosen for four basins. The climate input
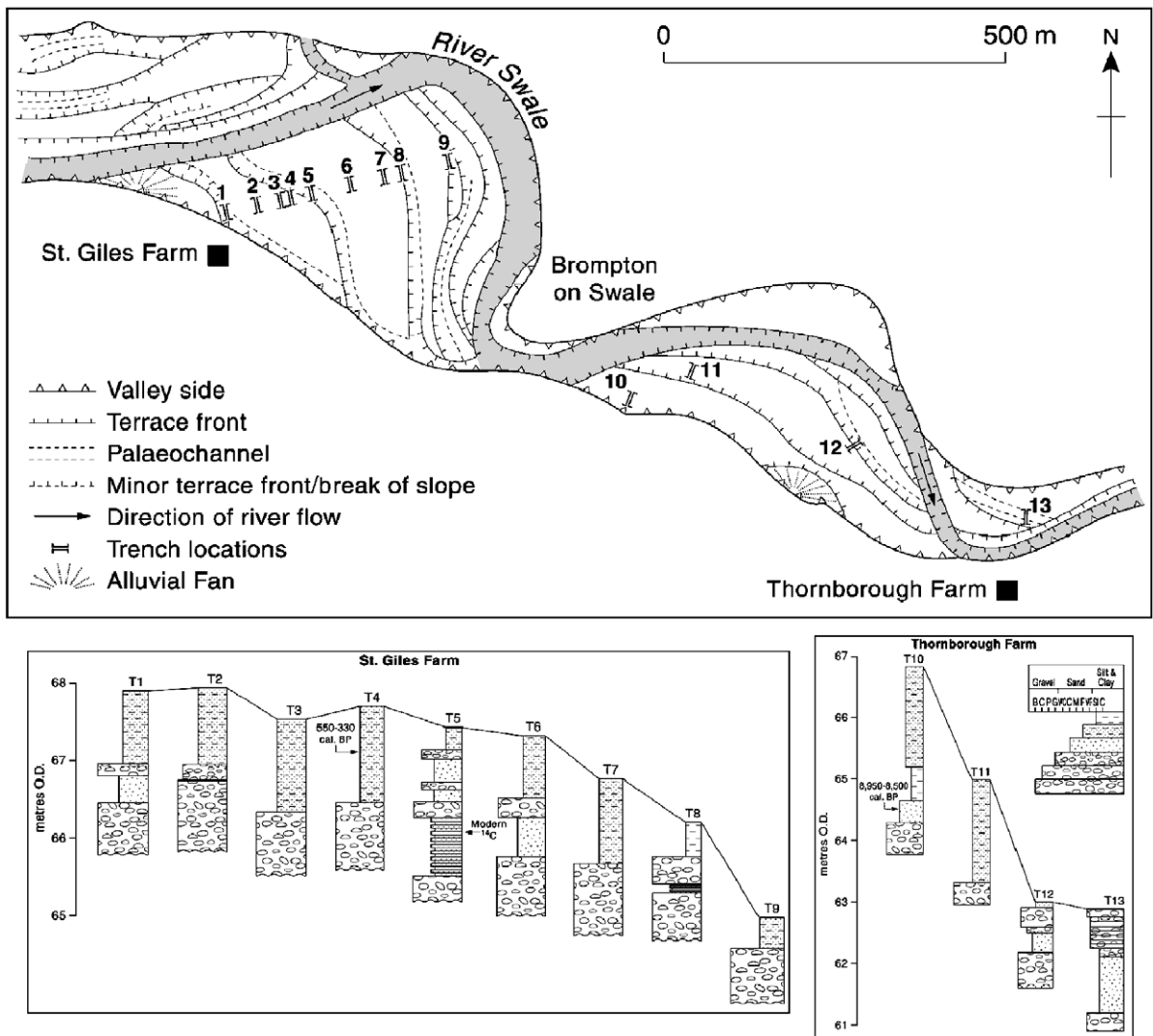

Fig. 4. Valley floor morphology and alluvial sediments on the River Swale at Catterick, Yorkshire (after Taylor and Macklin, 1997).

is derived from a combination of two proxy surface wetness indices derived from peat bogs in Northern England (Barber et al., 1994; from 6300 cal. BP to present) and Scotland (Anderson et al., 1998; from 6300 to 9000 cal. BP). These records were combined, interpolated and re-sampled at 50-year intervals. This was then normalised to values between 0.75 and 2.25 to create a rainfall or wetness index (Fig. 5). The model is then driven using a 10-year hourly rainfall record that is duplicated 5 times to cover 50 years and then multiplied by the rainfall index, creating a proxy rainfall record for the last 9000 years. There are few records of land cover for the regions modelled, so local palynological records (Tinsley, 1975; Smith, 1986) are used to develop a land cover index ranging from 2 (forested) to 0.5 (grassland; Fig. 5). This index is then used to alter a key parameter in the hydrological model that controls the magnitude and duration of the flood peak.

3. Study sites

Study sites comprise the four major northern and upland tributaries of the Yorkshire Ouse, U.K. (Fig. 1). The rivers Swale, Ure, Nidd and Wharfe drain the eastern slope of the Pennine Hills which form a dissected plateau rising to over 700 m developed on sandstone, gritstones, and limestone of Carboniferous age. The area underwent Quaternary glaciation, leaving valleys which are trough shaped in cross section, with exposed limestone scars on many valley sides, but generally without thick glacial deposits in the uplands. Valley moraines and filled moraine dammed lakes have been suggested for several valleys (King, 1960). The four valleys vary in size (Table 1), but with broadly similar hypsometric characteristics (Fig. 2). Their long profiles are contrasted so that for example, the Ure has a markedly stepped profile that was largely shaped
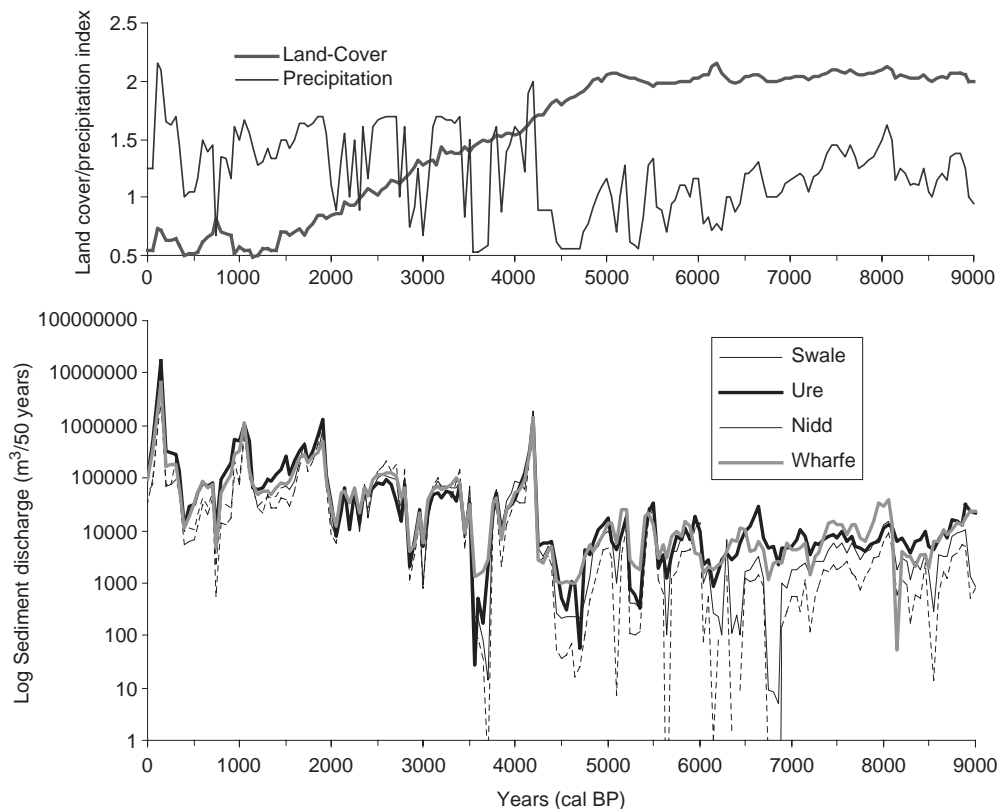

Fig. 5. The top frame shows the land cover and rain indices used to drive the model; the lower frame shows the log of sediment yield from the four simulations.

prior to the Holocene (Fig. 3). The upland plateau areas are dominated by moorland and rough grazing, with peats and stagnohumic and stagnogle soils, whilst pastureland dominates the flatter, terraced valley floors.

Fig. 4 shows valley floor morphology and the nature of valley fill sediments for a studied site near Catterick, Yorkshire (Taylor and Macklin, 1997). This shows evidence for episodes of incision and alluviation in a series of progressively incising river terraces. Additional details of the catchments and their hydrology are available in Jarvie et al. (1997) and Law et al. (1997). The nature of valley floor morphology and sediment is broadly representative of the alluvial systems modelled in this paper.

The known, site-specific history of coarse sediment accumulation, erosion, and transfer in these

upland valleys strongly suggests that inter- and intra-catchment modelling using CAESAR would be appropriate as a means of assessing likely differential response within and between catchments. During the Holocene they have responded to similar environmental changes affecting sediment transfers within bedrock valleys which have been inherited from prior Quaternary (or earlier) conditions. The catchments are also upstream of the influence of Holocene sea level changes which have affected sedimentation in the Ouse basin. The precise morphology of the river catchments at the beginning of the simulation (9000 cal. BP) is unknown, and to reconstruct this would involve considerable and largely speculative work. Therefore, to allow a systematic approach to be taken for all four basins, the present day surface is taken as an analogue.
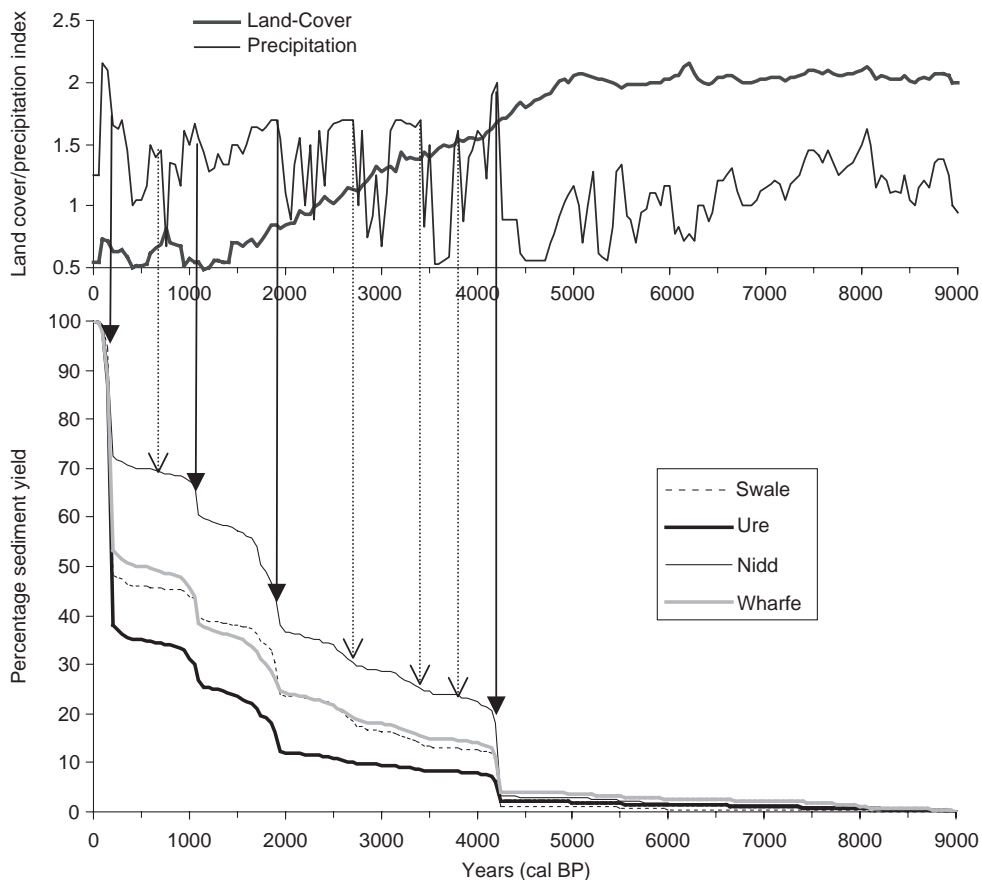

Fig. 6. The cumulative percentage of sediment yield from the four simulated catchments. Solid arrows indicate a linkage between wetness peaks in the driving climate record and significant changes in sediment discharge. Dashed arrows indicate a weak/nonexistent linkage.

This assumption is not wholly unreasonable, because following substantial valley floor incision into gravels over the Late Glacial–early Holocene transition, there is evidence that river bed elevation in the Yorkshire Dales has only varied by ±3 m during the Holocene (Macklin et al., 2000). The model surface is therefore derived from a 50-m resolution present day DEM, with the bedrock surface defined 3 m below. This provides a uniform 3-m layer of sediment and soil capped with a turf mat. Where stream powers are great enough, this allows channels to incise to bedrock and become supply limited. This parallels conditions found in the field, where earlier in the Holocene there was a plentiful supply of post glaciation sediment but later incision to bedrock has limited this supply (Merrett and Macklin, 1999). During the simulations, continuous sediment discharge data were recorded, and catchment elevations and grain-size data saved at 50-year intervals. By subtracting elevations from consecutive 50-year intervals, sediment budgets for the four catchments were calculated (Fig. 5).

4. Results

The modelled sediment discharges (Fig. 5) indicate that all four catchments behave in a broadly similar manner, with several short periods of high sediment discharges lasting 50–200 years. These peaks are synchronous with wetter climate spells, indicating that climate is the main driver of simulated sediment yields. However, after 2000 cal. BP, the peaks in sediment discharge are noticeably larger for similar-size climate peaks—showing how simulated deforestation can increase sediment discharge for a given storm event. This can also be clearly seen in Fig. 6, where there are much smaller jumps in cumulative sediment discharge to the climate peaks at 3200 cal. BP and 2500–2750 cal. BP (under forested cover) than to those at 1800 and 1000 cal. BP (deforested). Indeed, the Ure records a 3% increase from 4000 to 1900 cal. BP but a 25% increase from 1900 to 400 cal. BP after tree clearance. This strongly suggests that the removal of tree cover influences catchment response to
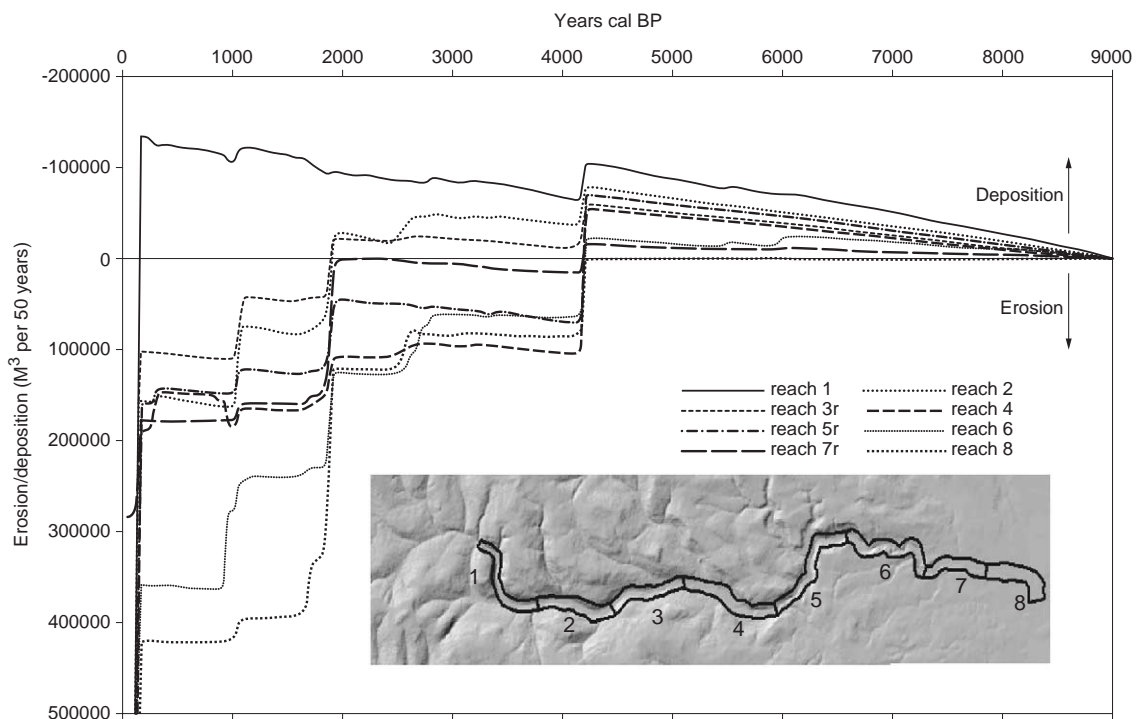

Fig. 7. Simulated cumulative sediment yields for the 8 reaches of the River Swale.

climate change by increasing the amplitude of the sediment peak for a given storm event.

Whilst the timing of the sediment peaks is synchronous across all four catchments, Figs. 5 and 6 show that there are notable differences in the size of the peaks between basins. The smaller Rivers Swale and Nidd both have a far 'flashier', spiky Holocene sediment discharge compared to the larger Wharfe and Ure basins (Fig. 5), which have less variable sediment yields. As expected, the larger basins produce greater totals of sediment output, but to compare the dynamics of sediment delivery, i.e. the relative magnitude of their response, the totals are plotted as cumulative percentages (Fig. 6). This normalises the sediment yield for all four basins to the same scale and demonstrates significant differences in catchment response. From 4200 to 400 cal. BP, the Nidd delivers 50% of its total sediment load, but during the same period the far larger Ure only 28%. Interestingly, the Rivers Wharfe and Swale have very similar shaped curves, despite the Wharfe draining nearly twice the area. This firmly indicates that whilst total simulated

sediment yield may reflect the catchment area, the timing and dynamics of sediment delivery are not controlled by size alone.

To investigate how sediment was moving within the catchments, the four study basins were divided into reaches approximately 5 km long. The positions of these reaches were carefully selected so inter-reach boundaries did not span major tributaries and, where possible, wider sections of valley floor were captured within a single reach. CAESAR saves the elevations of all cells at 50-year intervals and, by comparing elevations within reaches, simulated Holocene sediment budgets can be calculated. We have plotted modelled sediment volumes accumulated or removed on a cumulative basis for individual reaches for all four catchments over the Holocene (Figs. 7–13).

Results for the Swale (Figs. 7–10) show considerable variations between reaches, although most respond to the major climate peaks, similar to the catchment response as a whole (Figs. 5 and 6). This provides clear evidence of reaches being controlled by erosional thresholds, with most erosion occurring
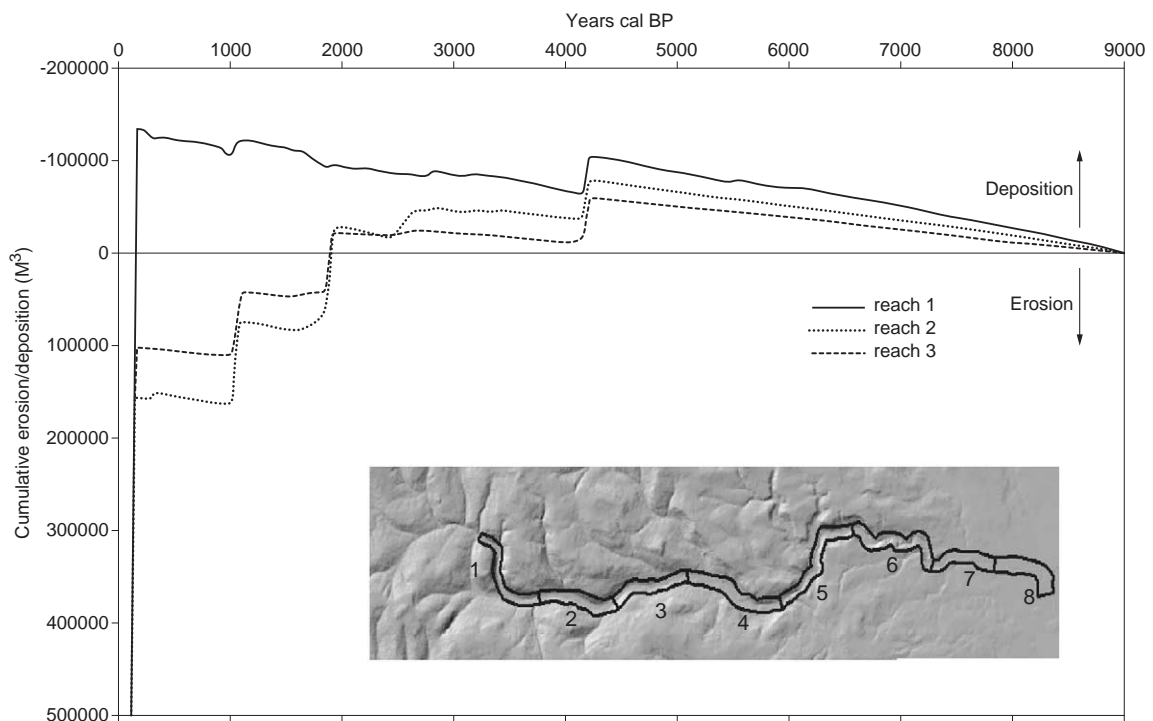

Fig. 8. Simulated cumulative sediment yields for the top three reaches of the River Swale.

during short peaks triggered by wetter episodes of climate, contrasting with little activity in intervening periods. Viewed together, they show that the valley floor has experienced progressive sediment loss during the Holocene.

Fig. 8 shows sediment deposition/erosion patterns in the top three reaches. Steady deposition is caused by input from the valley walls adding material to the edges of the floodplain. These three reaches are geomorphologically relatively simple, as reach 1 drains headwaters of the Swale, and reaches 2 and 3 only have one major tributary. Reach 1 shows considerable erosion at 4200 cal. BP, then steady accumulation until 400 cal. BP. This may be caused by material from upstream being transported clean through the reach, and there is only significant removal of valley floor material at 4200 and 400 cal. BP., when the floods are of significant magnitude to breach local erosional thresholds. Reaches 2 and 3 respond to more major climate episodes than reach 1, but reach 2 also responds at 2700 cal. BP unlike reach 3 where the response may be dampened by the volumes of sedi-

ment arriving from reach 2 upstream. Indeed, reach 3 has a smaller response to the 1800 and 1000 cal. BP peaks which again may be caused by the input of material from upstream. It is interesting to note that reach 1 has a tendency to accumulate sediment for most of the Holocene, whereas reaches 2 and 3 pass into a state of net removal after c. 2000 cal. BP.

In the middle two modelled reaches of the Swale (reaches 4 and 5, Fig. 9), the situation is more complex. Not only are reach responses triggered by local erosional thresholds, but these reaches are also receiving significant volumes of sediment from upstream, as well as from the major tributaries of Arkle Beck (upstream and north of reach 4) and Marske Beck (upstream and north west of reach 5). Reaches 4 and 5 behave similarly to 2 and 3 at 4200 and 1800 cal. BP, with substantial volumes of sediment removed in brief periods. At 800–1000 cal. BP, both reaches erode, but 50 years later, reach 4 aggrades, apparently receiving a delayed 'slug' of sediment (cf. Macklin and Lewin, 1989; Nicholas et al., 1995) from the tributary Arkle Beck. Overall two
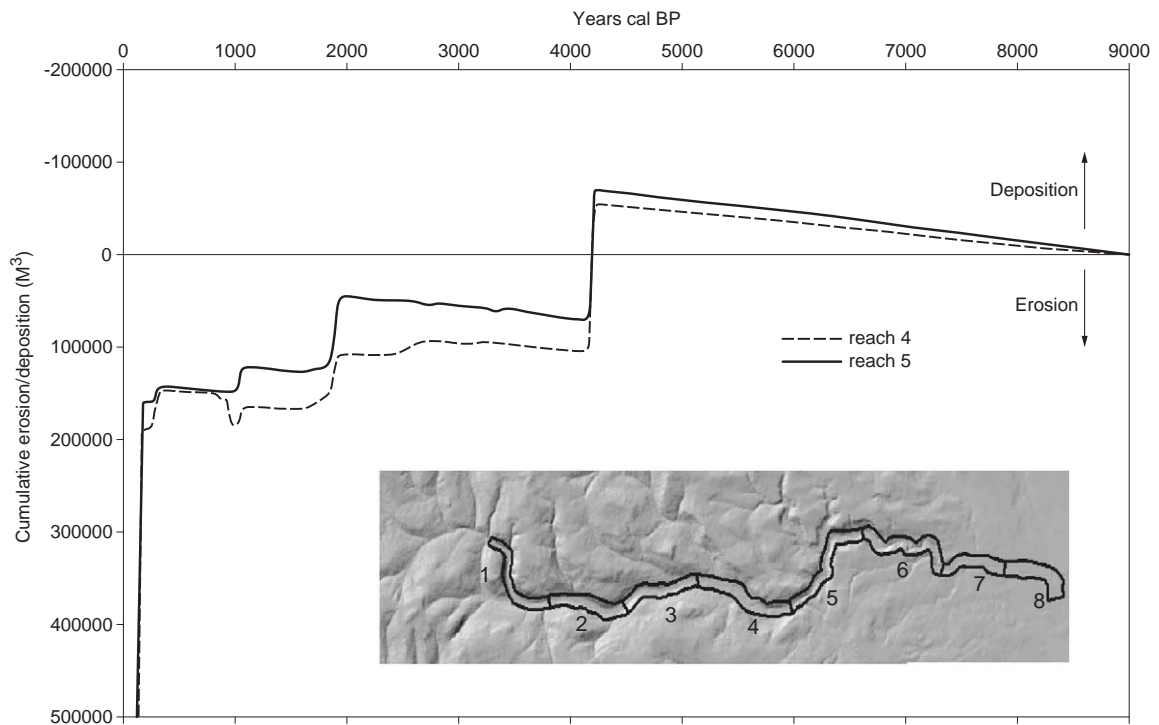

Fig. 9. Simulated cumulative sediment yields for the middle two reaches of the River Swale.

periods of slow sediment accumulation are indicated (before 4000 cal. BP and c. 2000 to 4000 cal. BP) separated by a major removal event. After c. 2000 cal. BP, more complexity of response is indicated.

Fig. 10 shows the lower three reaches located in the piedmont (reaches 6, 7, and 8) to lowland transition, and unlike the upper reaches, they receive little or no sediment from tributaries. Reach 6, at the margin of the Pennine uplands, appears especially sensitive to climate change, responding to all the wetter periods, including one at 6000 cal. BP. that no other reach shows. This may be due to the limited sediment storage capacity within the reach and/or it could relate to high local stream powers at a point in the catchment where the product of discharge and slope is maximised. This piedmont reach may be the most interesting from a geomorphological perspective as it is the best 'recorder' of climate changes. Reach 7 responds most weakly to the 4200 cal. BP peak, yet strongly at 1800 cal. BP and it is the only reach not to show major change during the Little Ice Age (LIA, c. 400 cal. BP). Possibly, this is caused by lower stream

powers or by receiving significant inputs from upstream. The valley sides adjacent to reach 8 are of low relief and consequently receive little or no material from creep. However, it is far more active than reach 7 and responds to all the main peaks, including those at 2800 cal. BP. Interestingly, there is a 100 year lag behind reach 6 for this peak—again possibly reflecting a slug of sediment passing through from upstream. Reach 8 responds to erosion loss events in a similar manner to reaches 6 and 7, but it shows little sign of accumulating sediment between events. This reach thus appears to respond to Holocene events as an erosion or transport zone without 'fill' periods, as what occurs further upstream.

Examining the other catchments, the Nidd (Fig. 11) shows a similar response to the Swale, with most reaches reacting at the same time but with a different magnitude of response. There is also evidence of a lagged response at c. 1700 cal. BP (reach 5) that may be caused by the influx of sediment from upstream reaches. However, compared to the Swale, the response to the LIA climate
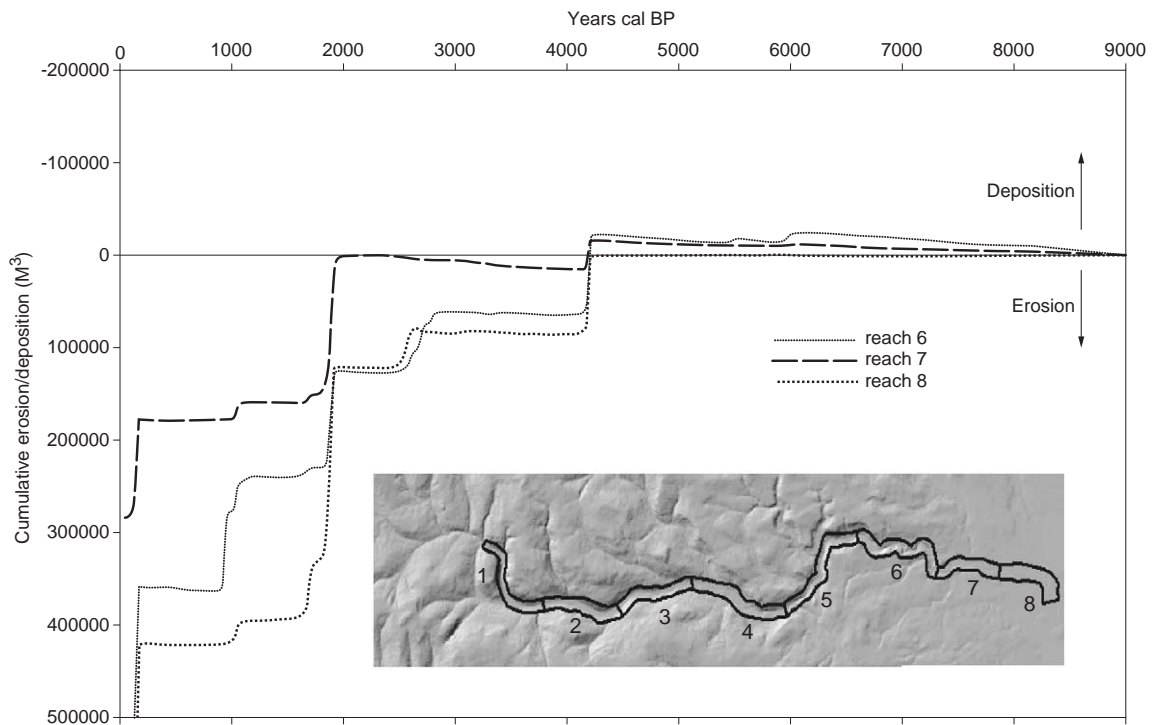

Fig. 10. Simulated cumulative sediment yields for the lower three reaches of the River Swale.
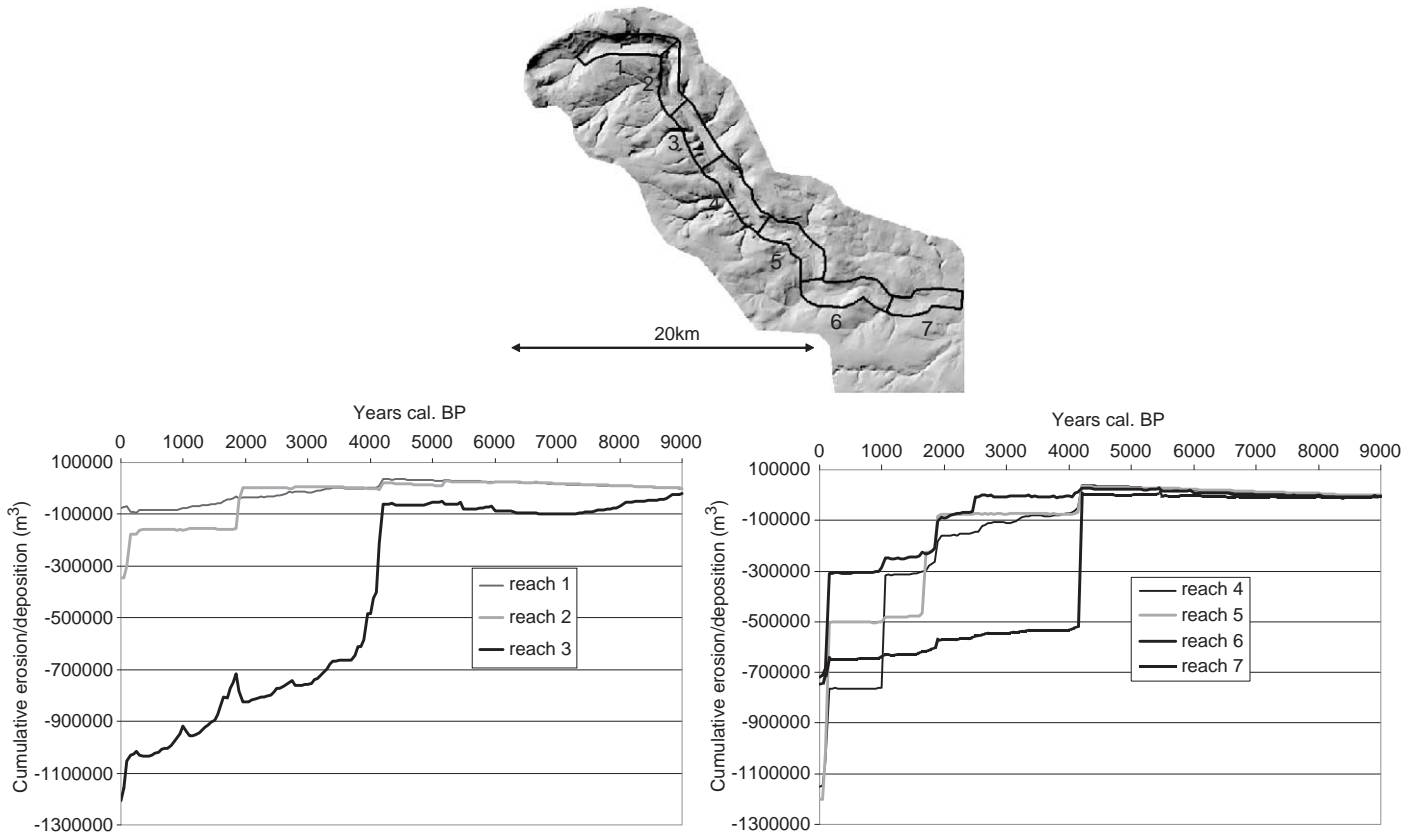
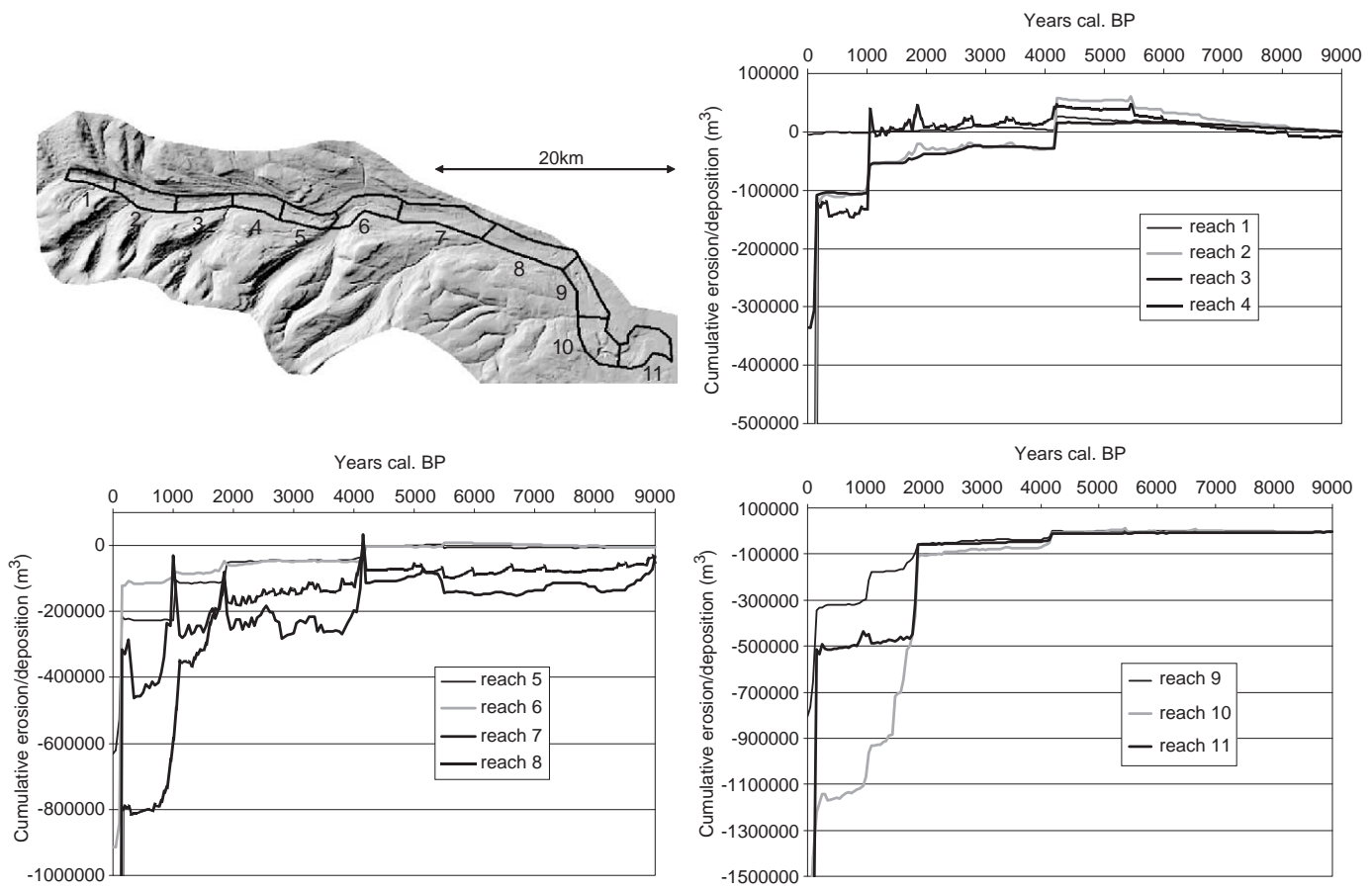Fig. 11. Simulated cumulative reach sediment yields for the River Nidd.

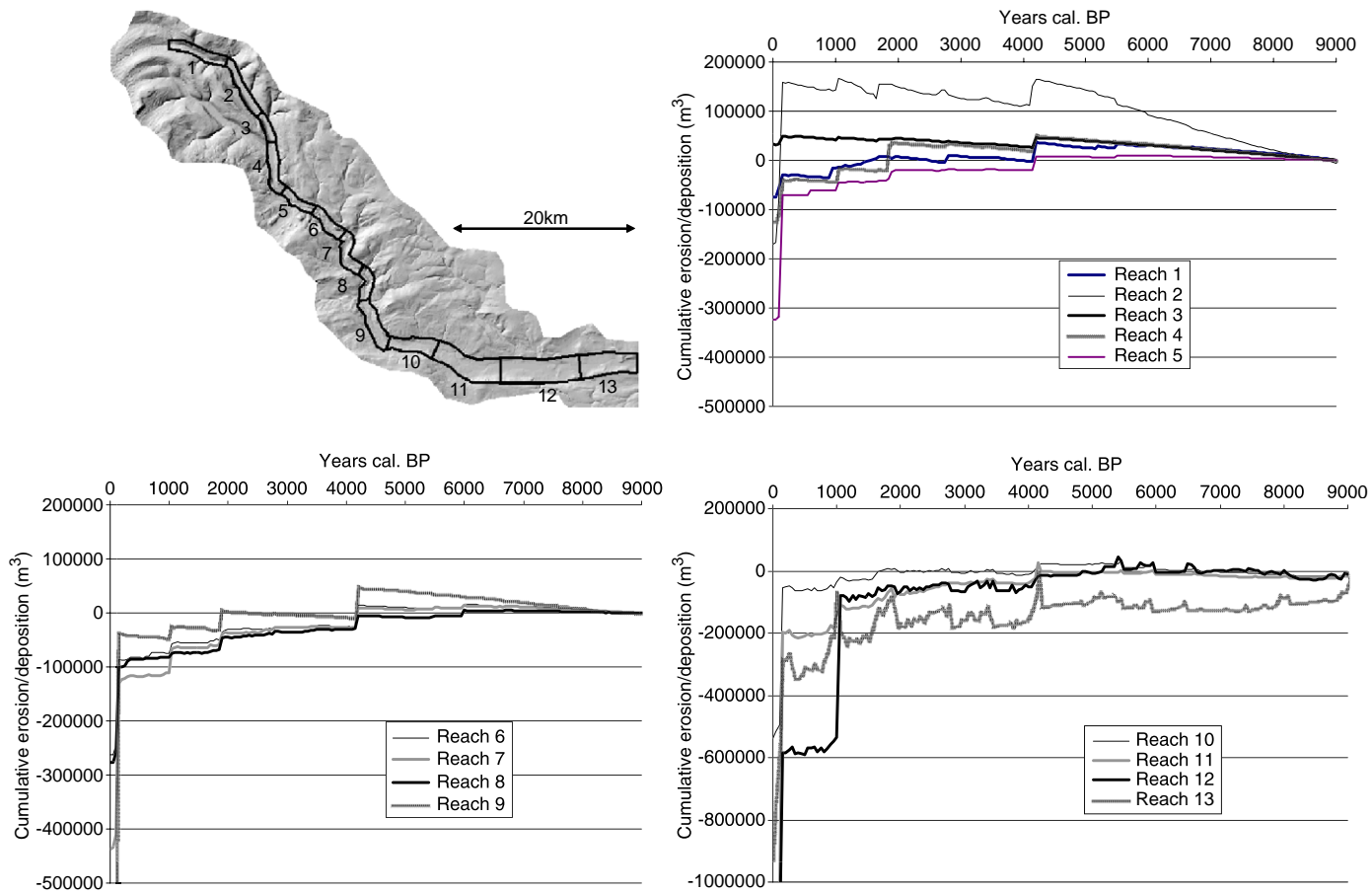Fig. 12. Simulated cumulative reach sediment yields for the River Ure.

Fig. 13. Simulated cumulative reach sediment yields for the River Wharfe.

deterioration is far smaller. There is also little evidence of net sediment accumulation during periods between erosion events.

The upper reaches of the two largest modelled catchments, the Ure and Wharfe (Figs. 12 and 13), behave in a broadly similar manner to the Swale and Nidd. However, reaches 7, 8, and 11 in the Ure, and 10, 11 and especially 12 and 13 in the Wharfe all record several periods of substantial deposition between 5500 and 1000 cal. BP. In contrast to other reaches, these are storing the sediment brought down from upstream and then exporting it at a later date. On the Wharfe, they are all low-relief shallow gradient reaches, and on the Ure in low gradient sub-basins— both ideal depositional environments. Some of these phases of deposition are significant, with in excess of $1\,000\,000$ m^3 of sediment deposited from c.1800 to 1600 cal. BP on reach 7 in the Ure. The upper reaches of both the Ure and Wharfe show net accumulation of sediment, the Ure until c. 4200 cal. BP, and the Wharfe for almost the whole of the Holocene. The lower reaches of the Wharfe show a sensitivity to early and late Holocene climate change. Reach 13 (the most downstream) appears to record environment fluctuations in a highly sensitive manner with marked depositional spikes followed by slow sediment removal.

When comparing the reaches in all four catchments, three styles of reach response become apparent, as shown in Fig. 14.

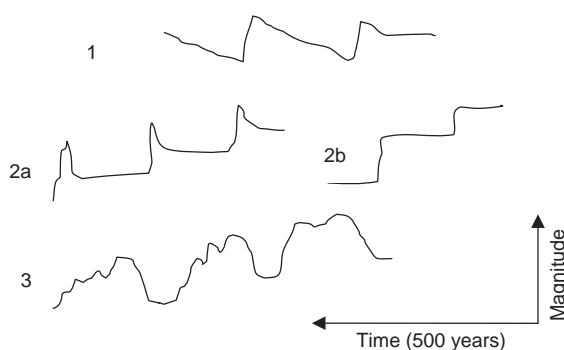1. Rapid erosion, sometimes followed by gradual accumulation over many hundreds of years. This is

typical of most of the upland reaches (e.g. Swale 1, Wharfe 2). Successive erosion lows may be higher (Wharfe 2) or lower (Wharfe 9) than previous ones, depending on the degree of depletion in the erosion phase and the degree of build up between such phases.

2. A short sedimentation spike, material from which is then rapidly eroded. This appears to represent rapid deposition following large amounts of erosion from upstream (e.g. Ure 7). A more common variant involves no sedimentation spike (2b) but merely erosion events lowering storage from one plateau to another (e.g. Swale most reaches, Nidd 4). These plateaus follow the gradual accumulation periods of style 1.

3. A rapid sedimentation spike which is then gradually depleted in a succession of episodes over several hundred years. This is found in the lower reaches of the Wharfe (13) where the volumes are sufficient to cause floodplain accretion of c. 0.5m. In some reaches (Wharfe 10–13, Ure 7–8) the response is much 'spikier' than above.

5. Discussion

Our detailed analysis of simulated reach reactions to environmental change reveals a response that is complex both within and between catchments. Although there are similarities between timings of erosion and deposition phases (largely corresponding to climate changes), there are considerable differences in the magnitude of river response at both the basin and reach scale. Locally, the magnitude of response is probably controlled by the local discharge, sediment availability and the channel and valley morphology of the reach (e.g. gradient and valley floor width). But the magnitude of geomorphic response to climate change also varies downstream, with upstream reaches showing a smaller response than downstream ones, which may be because stream powers, sediment availability, and sediment throughput are greater in the lower parts of the modelled river basins. Relationships between available sediment sizes and local stream power are likely to be important as much as their absolute magnitudes, whilst the available volumes of alluvial material must constrain potential response to, and recording of sediment-transfer events. Addition-

Fig. 14. Different patterns of erosion and deposition found in the simulations.

ally, reaches 8 and 11 on the Ure show a marked increase in erosion and sediment delivery after 2000 cal. BP. This follows simulated catchment deforestation and shows how certain reaches may be especially sensitive to changes in land use. Interestingly, this reveals that only a small length of the River Ure (c. 10 km) may be responsible for generating over 60% of the total catchment sediment discharge from 2000 cal. BP to present (reaches 9–11). This has important implications for forecasting how rivers may respond to future climate changes, particularly if relatively small regions have the potential to generate large volumes of sediment.

However, it is important to appreciate that reach response cannot be predicted solely on the basis of internal characteristics, as they are also receiving substantial volumes of sediment from upstream reaches. Delivery of this sediment may be nearly instantaneous in some reaches, but in other reaches delayed, which may be attributable to the passage of sediment 'slugs' or waves (e.g. reaches 4 and 8 on the Swale). Furthermore, over the duration of the Holocene, most reaches were static or slowly changing, but were punctuated by infrequent often short-lived periods of erosion, together with smaller spikes of deposition in some reaches.

It is perhaps that for the modelled rivers, the net tendency is for reaches to lose/yield sediment during Holocene, especially during relatively short episodes. Valley floor morphology in such circumstances should be characterised by incision episodes separated by extended periods of non-deposition or strath formation where rivers are laterally mobile and cut across earlier deposits. A staircase of largely erosional terraces (with a veneer only of lateral accretion deposits) could be anticipated, with a greater degree of incision as rivers occupy progressively lower levels of entrenchment in prior sediments. This may be contrasted with the picture elsewhere, in, for example, more lowland environments, where 'fill' events are more dominant in alluvial sequences.

The differential reach response indicates that some reaches are more sensitive to environmental change than others. This means also that some areas will be better recorders of environmental change, but importantly, this may not necessarily be related to gross volumes of catchment sediment output. All the catchments and reaches are responsive to the LIA

episode, but earlier episodes are variably recorded (e.g. compare reaches 1 and 2 on the River Swale). Erosional loss commonly wipes out any tendency to gain sediment overall—although in practice, sedimentation niches may remain at the margins of floodplain environments, which could record short periods of sedimentation. It should be noted that the reach values simulated here represent an average of that reach, and it is likely that within some of these reaches depositional zones will exist. However, sedimentation peaks are found in a number of middle and lowland reaches (Ure reaches 4, 7, and 8; Nidd reach 3; Wharfe reaches 10–13). Therefore, the reaches most sensitive to precipitation variations seem to be located in the mid or lower catchment (piedmont to lowland) environments, with intriguing early Holocene simulations on the lower Wharfe providing a highly complex sedimentation signature (see Fig. 13).

To this extent, field geomorphologists may find simulations using CAESAR useful for determining which areas of a river basin are most worthy of investigation in terms of the environmental sensitivity that alluvial deposits can provide. However, this study is a clear example of the caution necessary in basing geomorphic interpretation on only one or a few sites within a river basin (cf. Macklin et al., 1992). This study simulates changes in response to climate and land cover uniformly over the whole catchment—yet produces significantly different response in individual reaches solely as a result of internal controls. In light of this, the confidence of interpretations of previous studies of basin evolution based on one or two sites must be questioned, especially considering the greater degrees of freedom for variation within a real river basin.

These results also have important implications for modelling fluvial system change. As there is high variability between catchments, as well as differences in the style and degree of response between reaches, results cannot simply be copied from one catchment to another. To include the high levels of conditioning morphological variability, river basins will have to be modelled individually, and the whole catchment simulated, to effectively incorporate downstream sediment routing and storage.

The high levels of inter-catchment and inter-reach variability simulated here have been induced with

relatively well constrained driving parameters. For example, we have used simplified and uniform inter-(climate) and intra-catchment (morphology) initial conditions and drivers. Actual river basins have many more drivers and far greater degrees of freedom for variability. For example, rainfall is not spatially uniform, as was the case in these simulations; it is highly spatially and temporally variable. In reality, further examples of spatial variability can be found in vegetation cover and patterns, bedrock distributions, and human interactions. This raises the question as to whether variations in all these parameters have to be integrated in order to accurately model reach and catchment response. This is presently impossible, so a more prudent question might be which processes are most important, and based on that, which do we need to integrate and which are irrelevant?

When modelling large river systems over long timescales compromises have to be made, usually to aid simplicity and thus computational efficiency. CAESAR has several limitations that could influence the results presented here. In this application the grid cell size is relatively coarse (50 m) and, as previously mentioned, precipitation changes are implemented uniformly over the entire catchment. However, by comparing results from identical simulations (except topography) we can show that intra-catchment climate or land cover variations are not required to provide this differential response. It could be argued that variable responses are simply a facet of the model—indeed they must be! But we would argue that much of the behaviour shown by these simulations is consistent with field evidence in so far as it is available.

6. Validation

Validating these model runs is difficult as the model generates output topographies every 50 years and continuous hourly water and sediment discharge data for 9000 years of simulation. There are no field data sets that are comparable and it is not possible to track spatial aspects of sediment transfer with contemporary data. Previous long-term large-scale studies have compared model simulations to catchment hypsometric curves (Willgoose et al., 1991) and long profiles (Willgoose et al., 1991; Tucker and

Slingerland, 1994). More recently, Hancock et al. (2002) have parameterised slope process and sediment transport rates to hillslope plot experiments. However, here we are modelling river systems where the overall form and long profile has remained essentially similar since the Late Pleistocene. Therefore, we need an alternative methodology for validation. In a previous paper (Coulthard and Macklin, 2001), we compared the results of modelled sediment yields from the River Swale to a histogram of ^{14}C dated alluvial units from all of Great Britain. This showed a good correlation between the number, magnitude, and approximate timing of sediment peaks generated by the model. In that paper, we argued that we were using the River Swale as an exemplar for river system response to Holocene environmental change in GB. The reasoning behind this argument was that there were insufficient ^{14}C dates within the Swale to provide a suitable regional validation. In this paper we can now make a further step forward.

As a result of a series of studies undertaken as part of the UK Natural Environment Research Council's Land Ocean Interaction Study (LOIS) community research programme between 1994 and 2000 in the Yorkshire Ouse basin (Taylor and Macklin, 1997; Hudson-Edwards et al., 1999; Howard et al., 2000; Macklin et al., 2000), the chronology of Holocene river development in the region is now underpinned by 60 ^{14}C dates. This includes several sites on the Swale, Ure, Nidd and Wharfe at which the sequences of fluvial incision and fill have been established (as in Fig. 4 above). In Fig. 15, following the methodology recently set out in Macklin and Lewin (2003), we have plotted the cumulative of ^{14}C dates (16 in total) that mark modification in sedimentation style or rate, allowing the timing of geomorphologically significant changes in river activity to be picked out. These correspond well with the changes in the cumulative simulated sediment yields from all four catchments evident at 4200, c. 3000, 1800, and 1000 cal. BP. Of equal interest, however, are phases where the Holocene alluvial record indicates lower rates of geomorphic activity that match with periods of low sediment discharge from the model. This importantly indicates that the model is not only simulating the high sediment yield events, but also periods of quiescence. Nevertheless, despite these new ^{14}C dates, more are
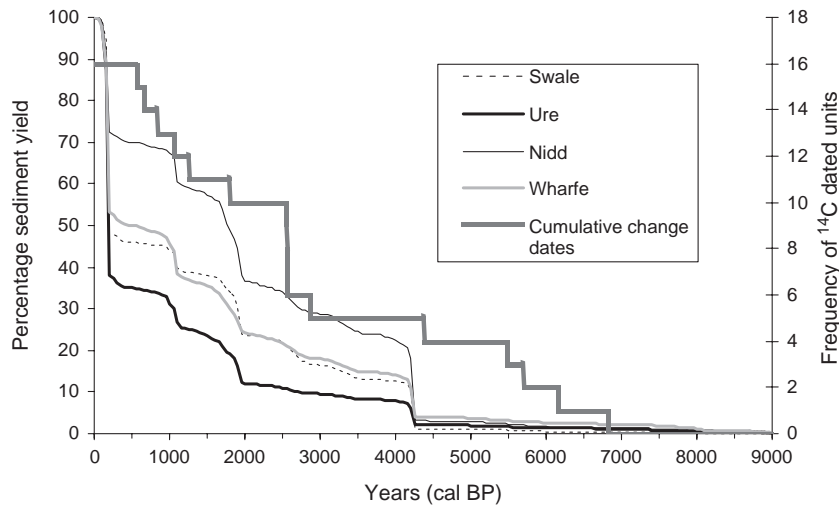
Fig. 15. Cumulative percentage sediment yields for all 4 catchments with the ^{14}C change dates.

still required to fully validate the performance of the model.

7. Conclusion

This study has modelled the response of four catchments to spatially generalised Holocene fluctuations in precipitation and land cover. A whole-catchment approach has allowed sediment volumes to be tracked downstream, including an analysis of the differential response of individual river reaches down-valley. Whilst there is some evidence that simulated activity bears comparison with the actual record of Holocene river erosion and alluviation, it should be appreciated that at this stage modelling involves some simplification both of the environmental record and the likely processes of sediment transfer involved. Further field evidence is needed for some of the simulated responses that CAESAR produces. Nevertheless, the exercise has important implications for both interpretation of the fluvial sedimentary record and for the forecasting of future impacts of environmental change:

1. River catchments process environmental changes in relatively complex ways, and simulations of continuous fluctuations in climate and land-use appear to produce bursts of sediment transfer activity (rapid removal together with some accumulation 'spikes') in relation to transport thresholds. At other times, there may be slow removal or slow accumulation of sediment in different reaches.
2. The four catchments modelled responded to environmental change to different degrees, not only with respect to overall sediment discharge but also in the variable scale of erosion and/or alluviation during particular periods of the Holocene.
3. Within a single catchment, reach sensitivity to environmental change varies considerably. Some periods are recorded only in some reaches, whilst higher potential sensitivity appears to occur in the piedmont area of the catchment analysed here. It appears that inter-reach transfers of sediment may have a considerable effect on delaying or even blanketing out-phased alluvial response, whilst erosion/sedimentation thresholds may be crossed significantly only in certain reaches.

In the future it will clearly be possible to improve model sophistication as environmental records are augmented and possibly differentiated within catchments, and as process modelling is improved. At this stage, however, the conclusions above seem robust, and the implications that need to be considered are clear enough. Catchment morphology in relation to sediment transfer processes and thresholds does make environmental responses complex and differential

according to the individual catchment or reach being considered. This has to be considered when attempting to predict the effects of environmental change.

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