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Modelling geomorphic response to environmental change in an upland catchment

T. J. Coulthard,[1]* M. J. Kirkby[2] and M. G. Macklin[1]
[1] *Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, SY23 3DB, UK*
[2] *School of Geography, University of Leeds, Leeds, LS2 9JT, UK*

Abstract:

In the UK's upland catchments river terraces and alluvial features indicate a history of periodic aggradation and degradation linked to Holocene changes in land use (primarily deforestation) and climate change (altering flood frequency and magnitude). Although both factors are important, calculating their individual effects is complicated by the likelihood of their concurrent alteration.

To investigate the relative impacts of land use and climate change, a cellular model is applied to the upland catchment of Cam Gill Beck, above Starbotton, North Yorkshire. This is divided into 1 million 2 m by 2 m grid cells, to which a range of process laws are applied. These include approximate expressions for mass movement rates, soil creep, the influence of vegetation and hillslope hydrology, as well as fluvial erosion and deposition in ten grain-size fractions. This provides a good representation of valley floor geometry while retaining a fully dynamic interaction with the surrounding valley sides. Previous applications of this model have shown the detailed formation of bars and berms as well as examples of braiding, avulsion and channel change.

Running on a Silicon Graphics Origin 2000 computer, an ensemble of simulations were completed, bracketing a wide range of environmental scenarios involving changes in flood frequency, magnitude and vegetation cover. Over time-scales ranging from 10 to 100 years, these showed that decreasing tree cover and increasing rainfall magnitude individually produced similar 25% to 100% increases in sediment discharge, whereas in combination they generated a 1300% rise. Furthermore, channels formed by the model in response to increase rainfall magnitudes are located where relic channels are found in Cam Gill Beck, implying that these are the products of previous periods of high rainfall magnitudes. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS model, environmental change, river, catchment

INTRODUCTION

Since the retreat of the Late Devensian ice sheets from the Yorkshire Dales, river terraces and alluvial fans preserved in upland valley floors attest to a history of periodic aggradation and degradation. Some authors have stipulated that such changes in sedimentary regime were caused by disturbances in land use, associated with deforestation and early agricultural activity, and there is considerable evidence of increased sediment yields from catchments coinciding with periods of land use change (Ballantyne, 1991). More recently, by using improved palaeoclimatic records and higher precision dating techniques, wetter periods of climate have been related to increases in sediment yields and aggradation, and relatively dry periods to incision (Macklin and Lewin, 1993). The situation is undoubtedly complicated, however, by concurrent changes in

*Correspondence to: T. J. Coulthard, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth SY23 3DB, UK. E-mail: T.Coulthard@aber.ac.uk

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land use and climate. Furthermore, the climate and land-use viewpoints are largely interpreted by assuming that periods of aggradation or incision coincide with changes in land use or climate. Thus, although we have a good understanding of the cause, we have no direct link with the effect.

Similarly, modelling approaches have tended to concentrate on process–form relationships explaining how, but neglecting to ask why, landforms have developed. This is partly explained by the complexity of modelling the numerous processes interacting within a drainage basin that operate over a wide range of spatial and temporal scales. For example, the previous inherited channel geometry, vegetation, lithology, sediment supply (Merrett and Macklin, 1998a, 1999), slope–channel coupling and the flashiness and shape of the flood hydrograph (Knighton, 1998) all have roles. Unlike many reach-based modelling schemes (e.g. Nicholas and Walling, 1997; Bates *et al*., 1997) and other methods using computational fluid dynamics (CFD), a cellular model developed at Leeds (Coulthard *et al*., 1996, 1998, 1999) has succeeded in combining these factors within one high-resolution framework. This is achieved by dividing the catchment into 2 m by 2 m grid cells within which process laws are applied in relation to each cell's immediate neighbours. Examples from this model have shown the formation of berms, braids and terraces at a 1 m^2 resolution, as well as non-linear behaviour caused by interplay between slope and channel processes (Coulthard *et al*., 1996, 1998).

This paper aims to quantify the effects of environmental change on catchment morphology and sediment discharge over periods ranging from one flood to 100 years. By using a cellular model of Cam Gill Beck, North Yorkshire, UK to simulate different storm regimes and land-use scenarios, it is hoped that the relative effects can be disentangled from the causes. Furthermore, this will indicate how the catchment would respond to future changes in climate and land use.

METHODOLOGICAL APPROACH

Model description

The model concept, which is summarized below, is simple, although its operation is complex and for a full description and discussion readers are referred to Coulthard *et al*. (1996, 1998, 1999).

The model is applied to Cam Gill Beck, a small (4·2 km^2) upland tributary of the River Wharfe, North Yorkshire, UK (Figure 1). The catchment is steep, falling from 700 m (Buckden Pike) to 230 m over 3 km. The underlying lithology is predominantly Carboniferous Limestone, with Carboniferous grit and sandstones above 500 m (Raistrick and Illingworth, 1949). The climate is wet and temperate with an annual average rainfall in excess of 700 mm, and present-day land cover is rough pasture and moorland. Land-use history is scant, but nearby palynological records indicate the area was deforested by 2000 years BP (Tinsley, 1975; Smith, 1986). For the model, catchment relief was digitized from 1 : 10 000 scale Ordnance Survey map contours. This data, supplemented by EDM surveyed detail for the valley floor was combined using the TOPOGRID command in ARC-INFO to create a 2 m^2 resolution digital elevation model (DEM), of one million equal sized grid cells (see Figure 5). Initial grain-size distributions were derived by averaging valley floor samples from five locations.

Within this topographic representation the model assigns each grid cell properties of elevation, discharge, vegetation, water depth and grain size. For every model time-step, these values are altered in accordance only to their immediate neighbour and four groups of processes.

The first set is a model of hillslope hydrology, using an adaptation of TOPMODEL (Beven and Kirkby, 1979) with an exponential soil moisture store. Output from this hydrological model is then routed as subsurface flow according to a multiple flow algorithm as discussed by Desmet and Govers (1996) (Equation 1)

$$Qi = Q_0 \frac{S_i^x}{\sum S_i^x} \tag{1}$$

where Qi is the fraction of discharge delivered to the neighbouring cell i from the total cell discharge (Q_0) in

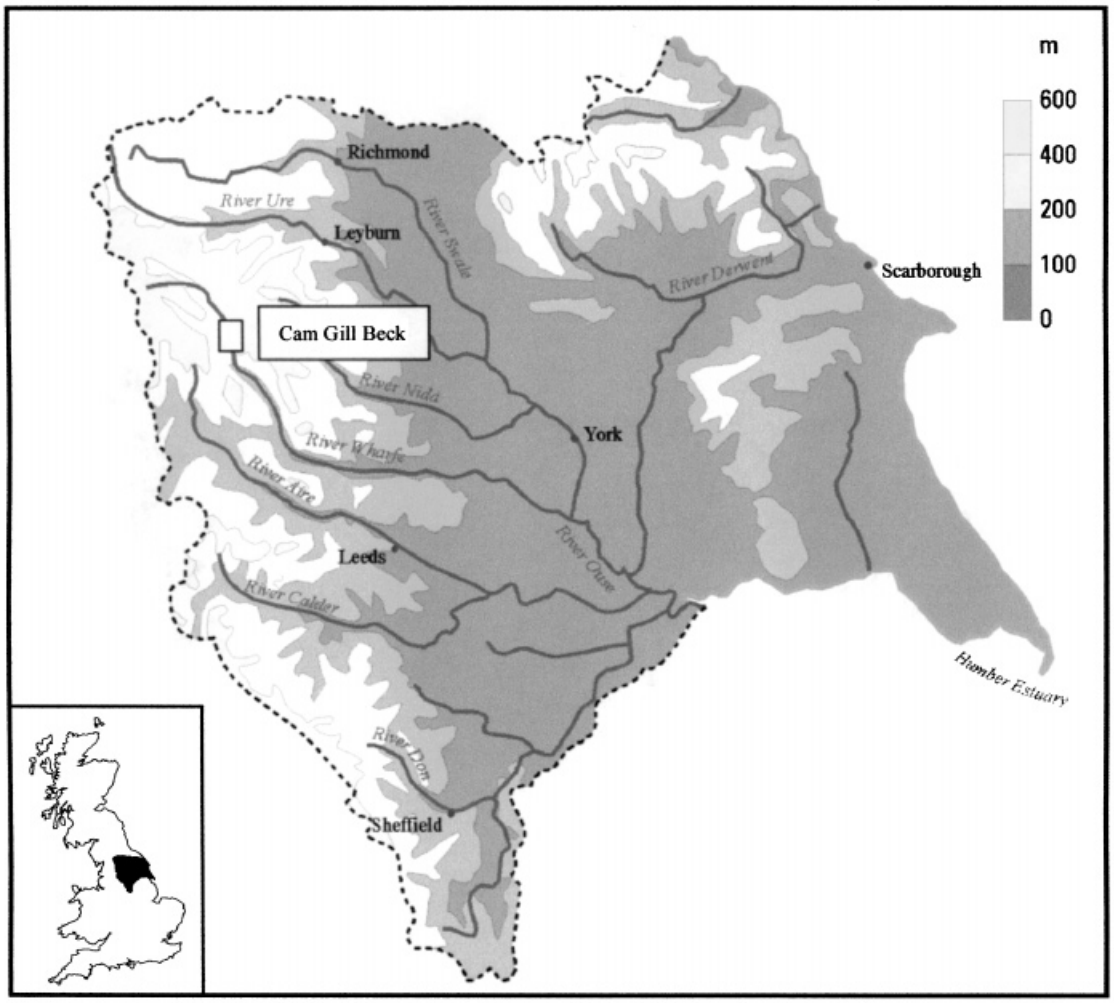

Figure 1. Location and relief of Cam Gill Beck

m^3/s^{-1}, according to the slope S between the cell and its relative neighbours i numbering from $1-x$ (x ranging from 3 to 8 depending on the number of neighbours). When this subsurface flow exceeds a threshold (Equation 2) it is treated as surface runoff

$$\text{threshold} = KSDx^2 \tag{2}$$

where K is hydraulic conductivity, S is slope and Dx is the horizontal spacing.

The second part is a hydraulic routing scheme, which calculates flow depth and routes this surface runoff. Depth is determined using an adaptation of Manning's equation

$$d = \left(\frac{Qn}{S^{0.5}}\right)^{3/5} \tag{3}$$

where d is depth (m), Q is discharge, n is Manning's roughness coefficient and S is the slope. Water is then

routed according to Equation (4), where unlike Equation (1) the depth of flow as well as cell elevation is incorporated

$$Q_i = Q_0 \frac{[(e+d)-e_i]^x}{\sum [(e+d)-e_i]^x} \tag{4}$$

where e is the elevation and d is depth of water (m) for each neighbouring cell i. The calculation of depth is important because it allows flow to be routed over as well as around channel obstacles.

Thirdly, fluvial erosion and deposition are calculated from the flow depth and bed slope using the Einstein (1950) equation. Sediment transport is calculated for nine separate grain-size fractions in whole phi units from 0·004 to 1·024 m coupled to the channel bed through 11 active layers (Parker, 1990; Hoey and Ferguson, 1994), each 0·2 m in depth. This allows a surface armour to develop and records a 2·2 m stratigraphy for each cell. A protective turf vegetation mat is represented by an additional resistive surface layer, and bedrock by an unerodible layer 1 m below the surface.

Finally, mass movement occurs when slope angles between cells exceed a threshold set to 45 degrees. This procedure is iterative, so a small failure at the base of a slope can propagate upwards. Where adjacent to channels, material from mass movements is added to the active layers of the channel, allowing the introduction of fines from landslips directly into the fluvial system.

Changes in cell elevation resulting from fluvial erosion and mass movement are updated simultaneously and time-steps are varied so that net rates are restricted to 10% of the average slope, preventing inaccuracies and computational instability. Owing to the large number of calculations required for such a large grid, the model was written in C and run on the Silicon Graphics Cray Origin 2000 at the Manchester Computing Centre, High Performance Computing (HPC) centre.

To mimic environmental change in Cam Gill Beck, two key variables were altered.

1. To simulate changing vegetation cover the TOPMODEL *m* parameter was altered, affecting the hydrograph peak and its rate of rise and fall in response to a storm. The value of *m* is usually calculated from the recession curve of the hydrograph but as this was unavailable for Cam Gill Beck, it was derived from previous TOPMODEL applications (Beven, 1997) and M. J. Kirkby (Personal Communication).
2. Storm magnitude was altered by multiplying an hourly 10 year rainfall data set form 1985 to 1995 from Church Fenton (SE 515370, altitude 15 m) by a factor ranging from 1 to 4. Despite this data set originating from a lower location, multiplication by 1·5 produced very similar magnitudes and frequencies to that from nearby Coverdale (SE 014787, altitude 240 m) during 1997–1998. Storm frequency was doubled by reversing the rainfall sequence and adding it to the original sequence.

Run details

The simulations were divided into three categories.

1. *Run 1:* 16 runs were carried out spanning a 10 year time period from the same initial conditions, but with different rainfall magnitudes and vegetation cover as detailed in Table I. These initial conditions were with a small channel already formed but left unarmoured.

Table I. The columns represent changing flood magnitude, from a 10 year hourly rainfall. The rows represent different vegetation scenarios, the number corresponding to the factor altered in the hydrological model

	1*	1·5*	2*	4*
Sparse 0·005	*Sparse 1*	*Sparse 1·5*	*Sparse 2*	*Sparse 4*
0·010	*Medium 1*	*Medium 1·5*	*Medium 2*	*Medium 4*
0·015	*Dense 1*	*Dense 1·5*	*Dense 2*	*Dense 4*
Very Dense 0·020	*V. Dense 1*	*V. Dense 1·5*	*V. Dense 2*	*V. Dense 4*

Table II. 'Other' runs

Run Name	Run details	Sediment discharge (m^3)
Noveg	No resistive vegetation layer (semi-arid simulation)	36 959
Double	Use *Dense 1* after 100 years, then doubled rainfall	4281
Defo	Use *Dense 1* after 100 yeras, then deforestation	2500
DefoDouble	Use *Dense 1* after 100 years, then deforestation and rainfall increase	17 826
4dr12ha	Double flood frequency, sparse vegetation (0·005)	7935
4dr12hc	Double flood frequency, medium vegetation (0·01)	6430
4dr12hf	Double flood frequency, dense vegetation (0·015)	5872

2. *Run 2:* 12 of these runs (all up to rainfall magnitudes of 2*) were then repeated from the conditions left after run 1 (above) for a further 10 years. This was then repeated up to nine times, representing 100 years of simulation to show how the sediment discharges stabilized.
3. Seven other runs were carried out representing other scenarios shown in Table II. *Noveg* is identical to *Sparse 2* except that there is a reduced threshold for the surface vegetative layer, simulating a semi-arid environment. *Defo*, *Double* and *DefoDouble* all use the results of *V.Dense 1* after 100 years simulation as initial conditions, then reduce vegetation to 0·005, increase rainfall by 2 and both together respectively. *4dr12ha*, *hc* and *hf* have vegetation levels of sparse, medium and dense respectively, but with twice the rainfall frequency.

After every 10 years of operation the elevation set was saved for comparison with the starting conditions.

Results

From all the runs, sediment discharges were calculated by subtracting the finished DEM from the initial DEM using the CUTFILL command in ARC-INFO.

Figure 2 shows the sediment discharges for run 1, from equal initial conditions. The area of the bubble corresponds to the sediment discharge in m^3 over 10 years. Behind each bubble is the hydrograph for each run, the *y* axis running from 0 to 10 m^3/s^1. As run 1 is from bare initial conditions, with equal distributions of sediment throughout the catchment, all these simulations show a high sediment discharge produced by the removal of channel fines and surface vegetation. Figure 3 shows the average 10 year sediment discharge over 10 years from run 2. Here the sediment discharges have stabilized after run 1 and the simulations with a more powerful flood regime continue to produce higher sediment discharges.

Both Figures 2 and 3 show an increase in sediment discharge with decreasing vegetation cover and increasing rainfall magnitude. In Figure 3, the change in sediment discharge if the rain magnitude is doubled (918 to 1859 m^3) is much greater than if the vegetation cover is reduced (918 to 1241 m^3). This also is evident in Figure 2, but to a lesser degree, again because of the high concentration of fines initially in the catchment. Both Figures 2 and 3 show large increases in sediment discharge with combined changes of vegetation cover and rainfall (918 to 13 088 m^3). Table III and Figure 4 compare the bedload discharges for runs *Medium 1*, *1·5* and *2* with nine other upland catchments (Warburton and Evans, 1998).

Table II details the results of run 3. *Noveg* had no resistive vegetation layer, representing a semi-arid environment, and shows a very large increase in sediment discharge 36 959 m^3 as compared with 19 327 m^3. *Defo*, *Double* and *Defodouble* show that doubling rain magnitude gives approximately twice the sediment discharge, and the combined effects produce 17 826 m^3. *4dr12ha*, *hc* and *hf* with double rainfall frequency show an increase in sediment discharge of 15% compared with *Sparse 1*, *Medium 1* and *Dense 1*.

Figures 5–7 are all shaded plan views after 20 years simulation of run *Sparse 2*. Figure 5 shows the whole catchment and the areas detailed by Figures 6 and 7, which show new channels produced.

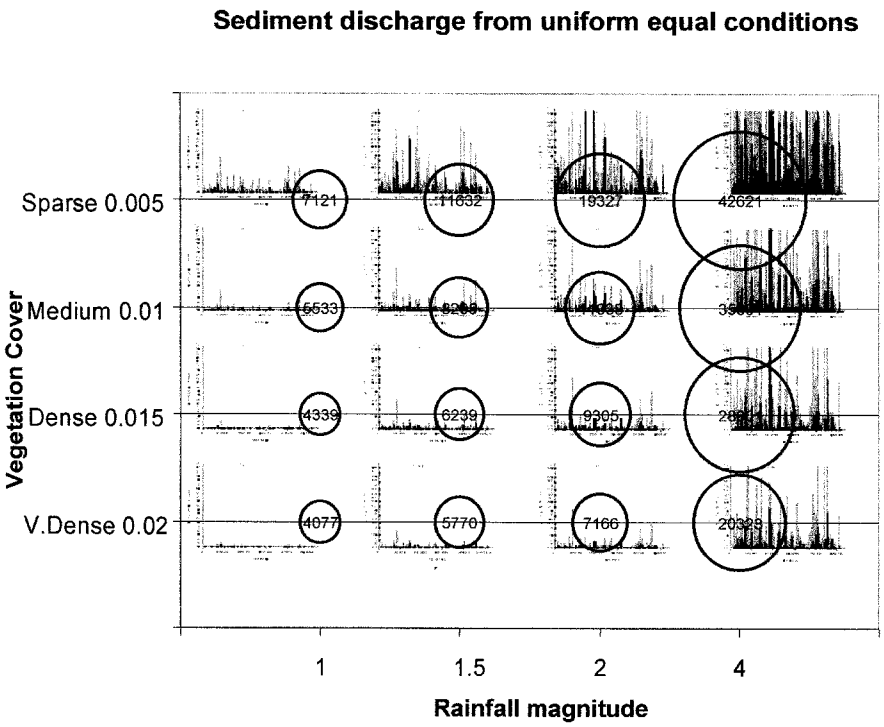

Figure 2. Ten year sediment discharges from run 1

DISCUSSION

The impacts of climate change and deforestation

Figures 2 and 3 show a marked increase in sediment discharge with a decrease in tree cover and with an increase in rain magnitude. Although both factors have a significant effect on sediment discharge, increases in rainfall magnitude have a greater impact. The combined effect of low vegetation cover and increased rain magnitude, however, is far greater than their individual impacts. As Figure 3 illustrates, decreasing tree cover and increasing rainfall magnitude give 25% and 100% increases respectively in sediment discharge, whereas together they generate a 1300% rise. The runs *Defo*, *Double* and *DefoDouble* support these findings, showing how doubling the rainfall magnitude increases the sediment discharge more than a comparative decrease in tree cover, but the combination of both leads to a massive rise.

The increase in sediment discharge is closely linked to the expansion of the drainage network (Figure 8). The greater runoff caused by deforestation and increased rainfall magnitudes causes the existing channels to widen, incise, erode headward and cut new channels (Figures 6 and 7). This increased erosion, associated with new channels generates a large supply of fresh sediment, which is reflected in Figure 2. However, as this new sediment is flushed from the system, the sediment discharge drops and stabilizes at a new level (Figure 3). This discharge fluctuates, even when averaged over 10 years, but remains within a set range, possibly representing a dynamic equilibrium. This long-term change in sediment discharge with flood regime is maintained by the continuing input of material into a larger drainage network from slope processes.

The new channels formed by the model in response to an increase in rainfall are of interest because they are largely formed where there are relict channels in Cam Gill Beck. Figures 5, 6 and 7 show plan views from the model output compared with aerial photographs of these areas, clearly showing the channels produced by the model and those found in the field. Those on the western (left) side of the valley (Figure 6A and B) are less well defined because of the steeper slope and the straight lines on the photographs are

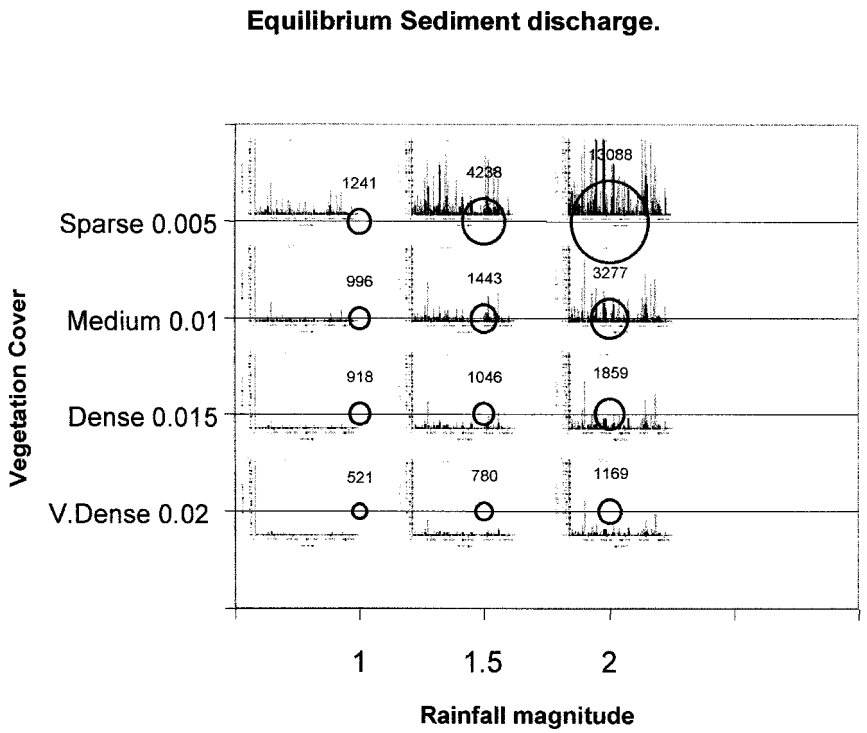

Figure 3. Averaged ten year sediment discharges for run 2

Table III. Bedload volume calculated assuming 2·65 t/m^3 (after Warburton and Evans, 1998)

Catchment	Area (km^2)	Bedload (m^3/year)	Bedload (m^3/km^2/year)	Source
Monachyle, Balquidder	7·7	6·1215	0·795	Stott *et al.* (1986)
Kirton, Balquidder	6·85	29·044	4·24	Stott *et al.* (1986)
Beckthorn, Cumbria	0·5	102·025	204·5	Newson and Leeks (1985)
Coledale, Cumbria	6·0	795	132·5	Newson and Leeks (1985)
Lanthwaite, Cumbria	4·0	307·4	76·85	Newson and Leeks (1985)
Allt a'Mhuillin, Ben Nevis	6·19	426·491	68·9	Richards and McCaig (1985)
Allt a'Mhuillin, Ben Nevis	5·82	227·614	39·11	Richards and McCaig (1985)
Rough Sike, Moor House	0·63	97·6658	155·02	Warburton and Evans (1998)
Trout Beck, Moor House	11·6	149·46	12·84	Warburton and Evans (1998)
Cam Gill Beck (*Medium 1*)	4·5	99·6	22·13	This paper
Cam Gill Beck (*Medium 1·5*)	4·5	144·3	32·06	This paper
Cam Gill Beck (*Medium 2*)	4·5	327·7	72·82	This paper

dry stone walls. Presently in Cam Gill Beck these channels are now largely inactive, grassed over and free from any bed material (e.g. Figures 6B and 7B). Harvey (1996) has identified a similar condition in the Howgill Fells, where the gully systems are much bigger and longer than those presently active. He suggests that this was caused by changes in vegetation increasing the sediment supply and reducing erosion thresholds. Ultimately, he argues, these gullies were stabilized by vegetation, reducing the drainage density. The simulations described in this chapter appear to contradict this view. Even large changes in the vegetation levels have a small individual effect on the drainage density and sediment discharge. However, catchment-wide

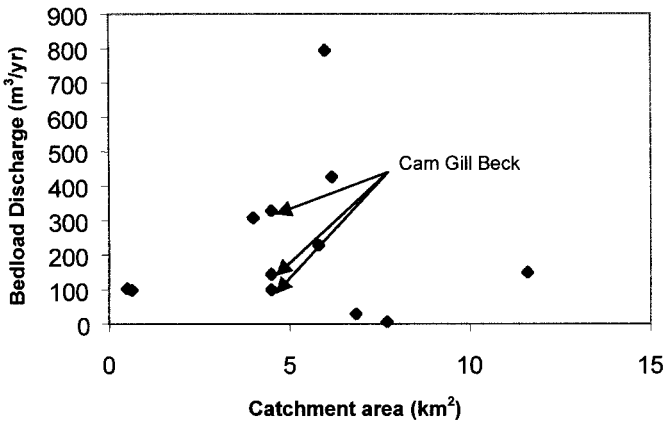

Figure 4. Bedload discharge against catchment area from Table IV

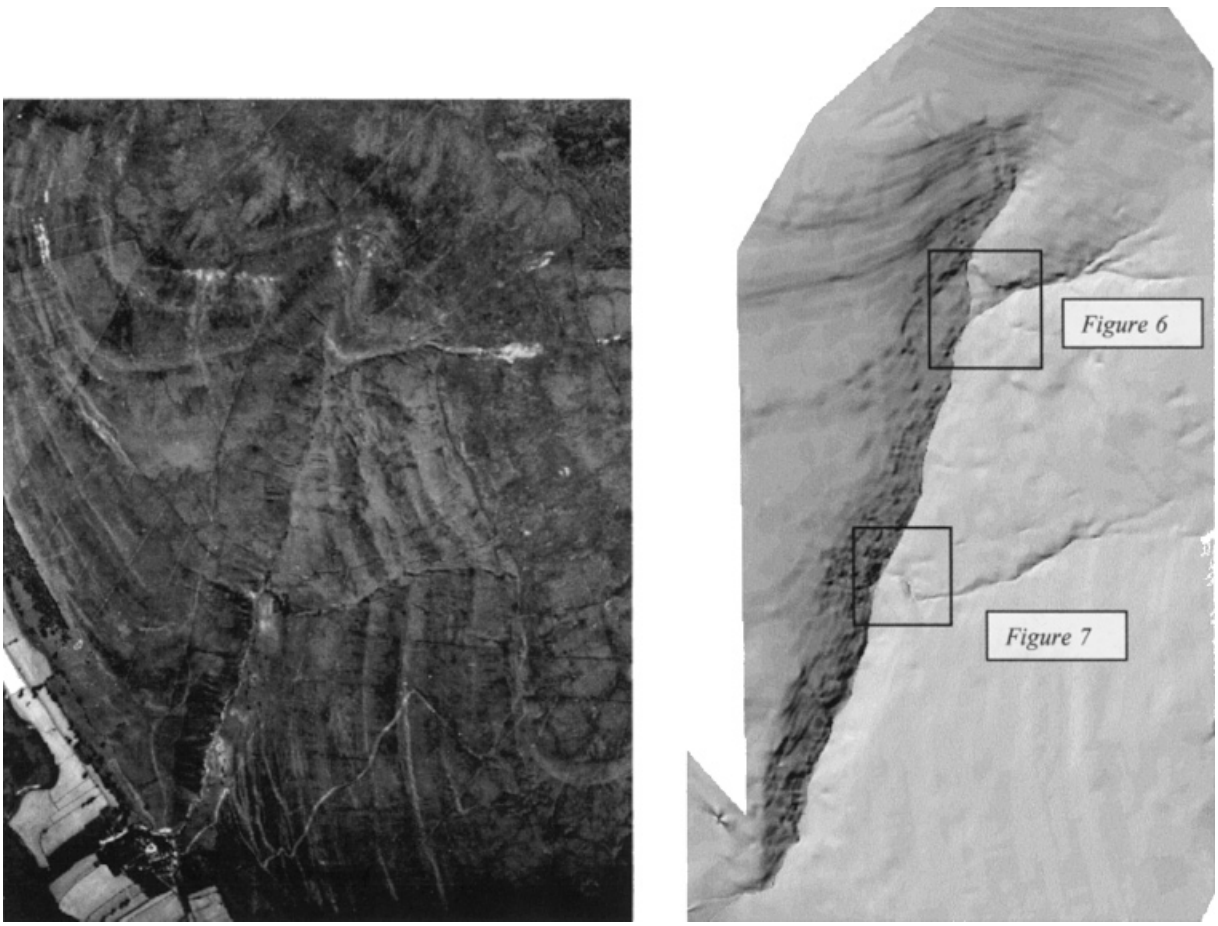

Figure 5. Plan view of Cam Gill Beck from the model and aerial photograph

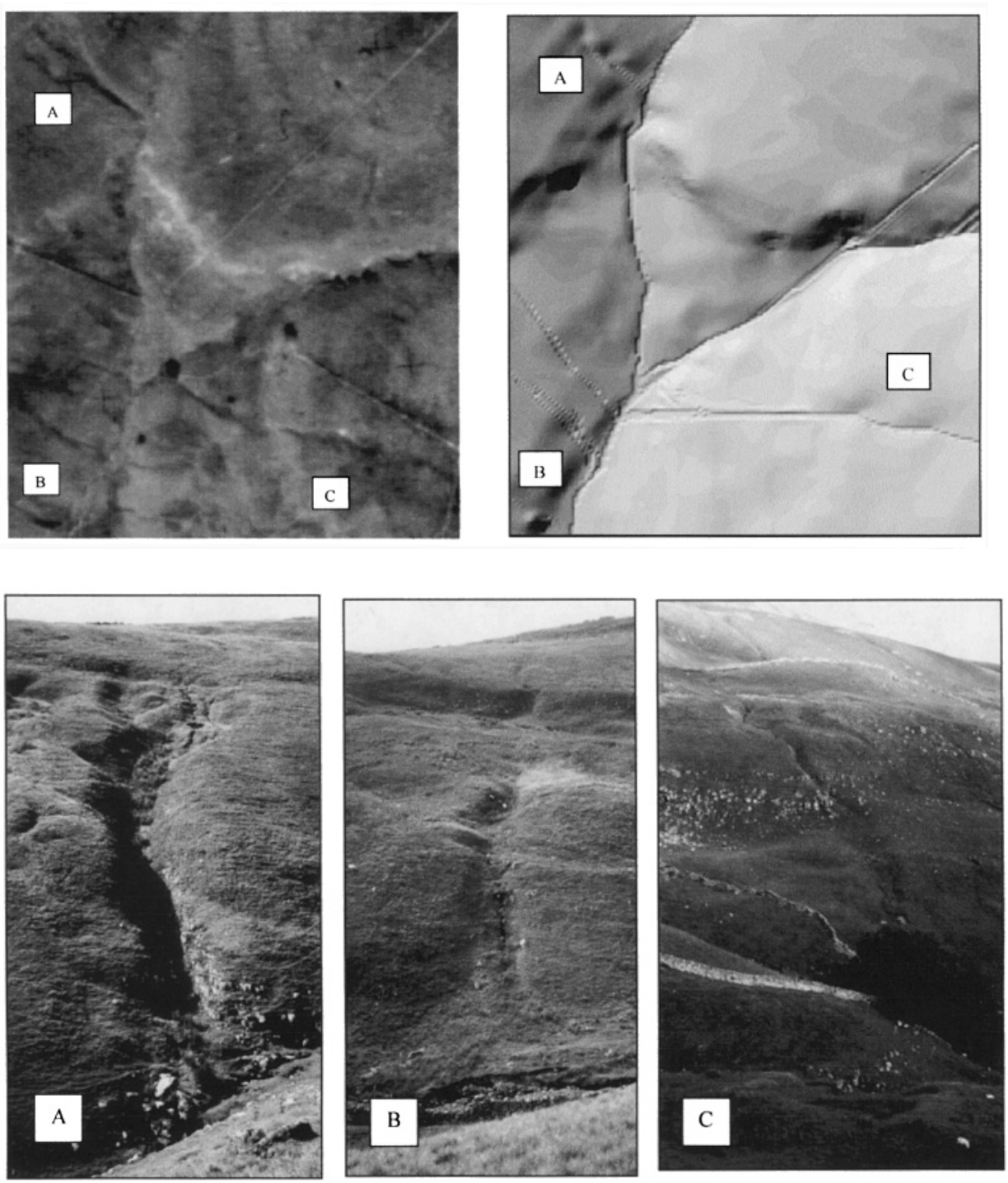

Figure 6. Aerial photograph and model output of section highlighted in Figure 5, with photographs of channels at A, B and C. All pictures are taken from the opposite side of the valley

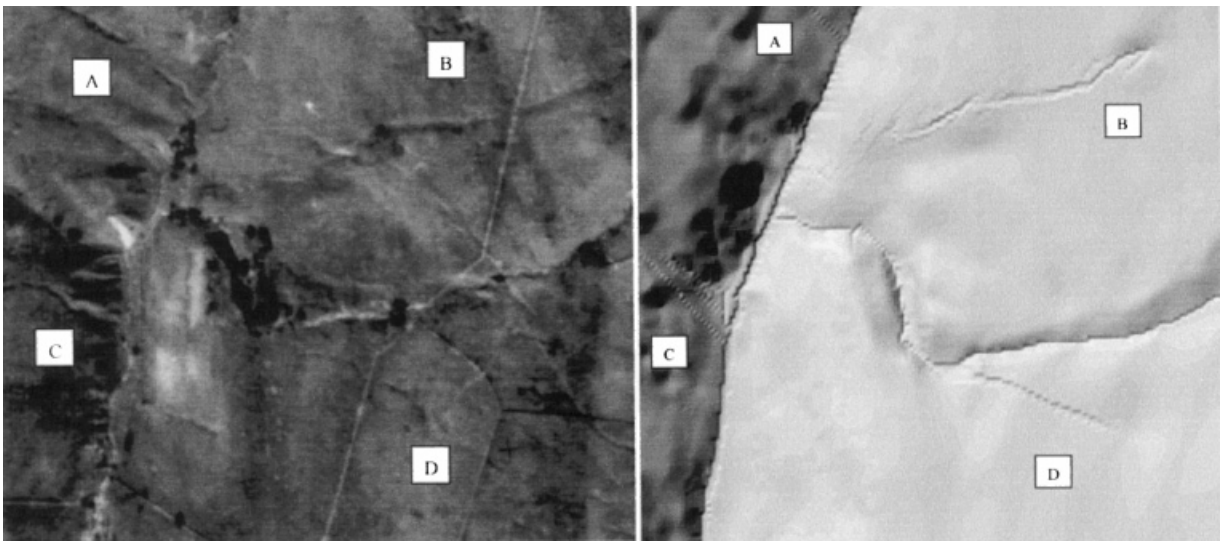

Figure 7. Aerial photograph and model output of section highlighted in Figure 5, with photographs of channels A, B, C and D

vegetation loss combined with increases in storm magnitude cause significant changes. The results presented here suggest that these relict channels are probably a feature of climate change, because if they were caused by changes in vegetation alone, given the sparse grass cover today, they would surely be active instead of redundant. Furthermore, this implies that if these channels' activity is controlled by a change in the climate regime, they may be an important indicator of changes in storm magnitude. Upland areas are therefore both sensitive indicators of environmental change and important areas of sediment production.

This large increase in sediment discharge and drainage network may be triggered by an exceedence of geomorphological thresholds. Such thresholds have been suggested by other authors, for example Newson (1980), who developed the term *effective* flood. He suggests that there are two types of flood, slope and channel, and identified a rainfall threshold of 16 mm/h for slope floods and 45 mm/h for channel floods, above which there is major geomorphological change. In Cam Gill Beck one threshold may be due to the protective vegetative layer being breached at stream heads and in hollows, increasing sediment supply. Another threshold is if flood magnitudes increase the channels armour layer may be breached, again releasing sediment. At a larger scale, the widespread expansion of the drainage network (Figure 8) may represent a threshold within the morphology of the whole catchment. As the model's initial conditions are from the relief generated by recent hydrogeomorphological conditions (Willgoose *et al*., 1994), the sudden increase in sediment discharge shown in Figure 2 is a reflection of the present channel network's inability to cope with the new rainfall magnitudes. Consequently, a catchment wide threshold is exceeded whereby existing relict channels are reactivated, extended and new ones formed, releasing a pulse of sediment.

Other authors have commented on the relative roles of flood frequency and magnitude. The model shows a much smaller effect from increasing the storm frequency than magnitude. For example in Table II, run *4dr12ha* has the same conditions as run *Sparse 1*, except double storm magnitude, but the 10 year average sediment discharge is 7935 m^3 as opposed to 7121 m^3. With double storm magnitude, which is effectively the same volume of precipitation as *4dr12ha*, the sediment discharge is 19 327 m^3. This presents strong evidence that the size of the flood is the dominant factor, which is re-enforced by the relationship between sediment discharges and the hydrographs shown in Figure 2. For example, *Sparse 1·5* and *Medium 2* have a difference of less than 1% sediment discharge and very similar hydrographs. The other simulations were not duplicated with double frequencies as these three runs showed little effect from doubling magnitude.

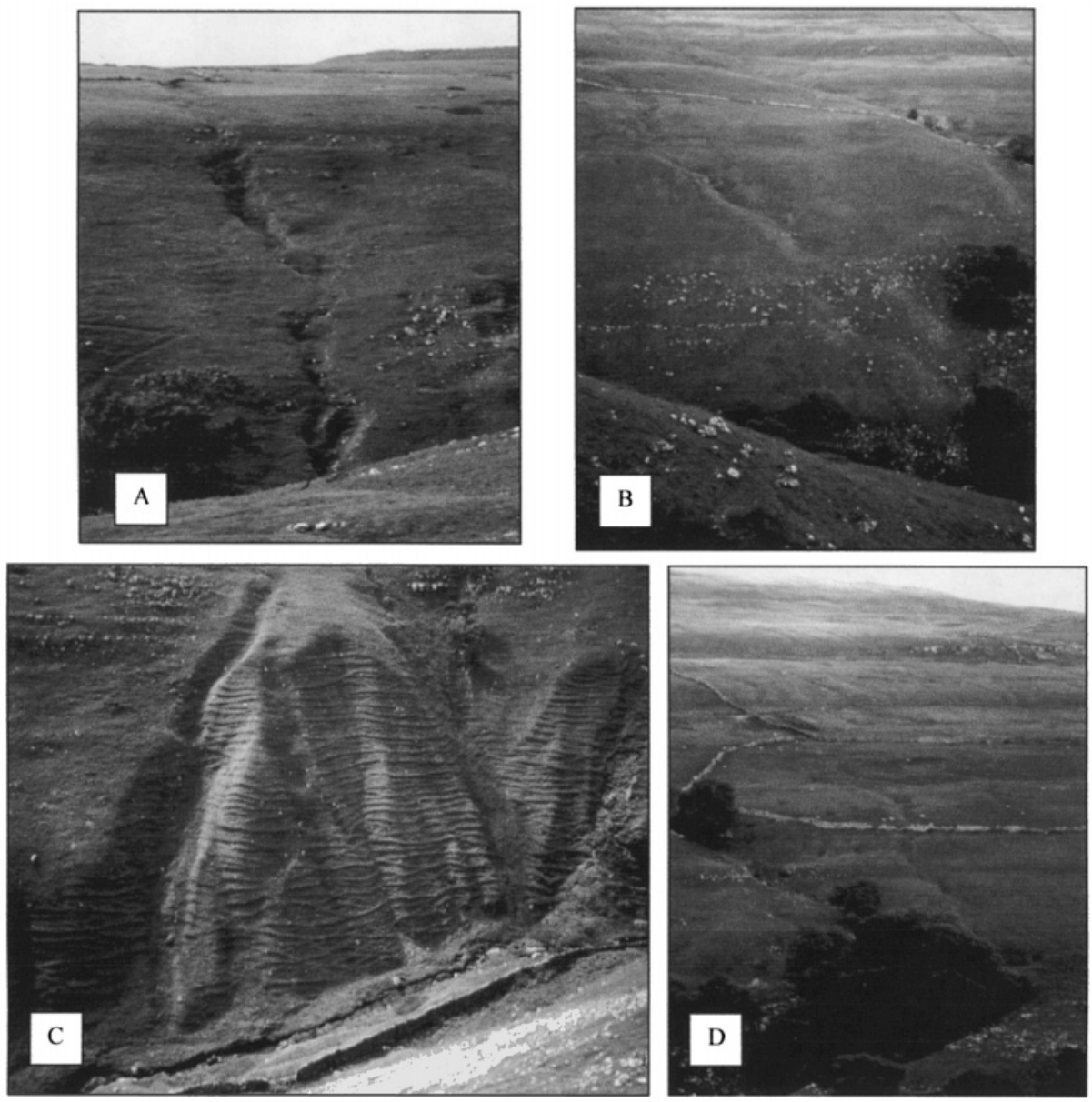

Figure 7. Continued.

The very high rainfall magnitude run, *Sparse 4*, had a significant impact on all levels of tree cover, with large storms pushing through the ameliorating effects of vegetation. The *Noveg* simulation (Table II) produces a morphology, sediment discharge and drainage network similar to that produced by *Sparse 4* despite having the same rainfall input as *Sparse 2*. This is caused by the removal of the tough vegetative layer, allowing easy surface erosion. However, these simulations represent extreme episodes of intense rainfall and semi-arid conditions that are not found in the Yorkshire Dales, although they do show how the model is capable of simulating a wide range of environments.

Figure 8. Drainage networks from runs *Dense 1*, *Medium 2* and *Sparse 4*, showing the expansion of network with increased wetness

Model validation and limitations

As there are no bedload measurements for Cam Gill Beck, direct comparisons with the model results are not presently possible. However, the results from runs *Medium 1*, *Medium 1·5* and *Medium 2* compare favourably with those measured from nine upland UK catchments (Figure 4 and Table III). Unfortunately this direct validation is hampered by the small number of catchments measured, and major differences between them. This is demonstrated by the large amount of scatter in Figure 4, resulting from variations in measuring techniques, difficulties of accurate measurement and the variation in the catchment's morphology (Warburton and Evans, 1998). Possibly it is unreasonable to compare results in this manner, as there are many differences between the catchments, such as lithology, relief, slope, vegetation, land use and climate, but it shows that the model is operating within an expected range.

Although these results could be interpreted as being representative of steep upland catchments in general, it must be remembered that the mechanically resistant Carboniferous Limestone that underlies Cam Gill Beck has a limiting effect on incision, sediment supply and hydrology. Many other upland catchments in the Yorkshire Dales (Merrett and Macklin, 1998a) and the Northern Pennines (Merrett and Macklin, 1998b) are underlain by more friable sandstones and shales. Although these can also provide a hard resistant bed layer, they incise more readily, producing more coarse bed material. Furthermore, limestone is eroded slowly by solution, often leaving a thin soil, whereas sandstone weathers into blocks and boulders, developing a deeper soil. In Cam Gill Beck, especially on the steep side slopes, the soils are frequently thinner than the 1 m depth prescribed by the model's initial conditions. Consequently, model sediment supply and thus sediment discharge may be over estimated. Conversely, sediment discharge may be underestimated as suspended sediment transport is not represented, with all material treated as bedload above 4 mm. Although some fine material will be deposited within the catchment, this assumption is supported by the dominance of coarse boulders in deposits found in Cam Gill Beck. Furthermore, slope processes are represented simplistically, with no feedback between soil saturation and slope failure angle. Brooks *et al*. (1993) demonstrated that this may be an important interaction between climate change and sediment production.

The limestone heavily influences the hydrology, with a series of shake holes around the 500 m contour on the eastern side of the valley. This subsurface drainage is largely accounted for by the choice of the '*m*' parameter in the hydrological model, but the model does tend to create channels on the slopes below these shake holes. Furthermore, as mentioned in the method section the '*m*' parameter for the hydrological model cannot be calculated and the rainfall record is from a nearby lowland site. However, the ensemble of 12 runs effectively brackets all potential scenarios.

Within this cellular model, the representation of fluid flow may only be simple, but this could be described the models greatest asset. The speed at which water depths are calculated has allowed every flood event in

100 years, over a whole catchment, to be simulated at a high temporal and spatial resolution. Although not offering the level of detail that CFD methods provide, this generic cellular model allows scenarios that are pertinent to many aspects of fluvial geomorphology to be assessed over historically relevant time and space scales. The CFD models have proved capable of simulating the dynamics of fluid motion over a wide variety of situations, but there are still considerable problems in the coupling of these with sediment transport to simulate evolving channel patterns and bedforms (Kirkby, 1999). This is partly because changes in bed/floodplain topography can force a frequent redefinition of the mesh of nodes, which can prove highly time consuming, especially if a curvilinear approach is used (Bates *et al*., 1997). With this cellular model, erosion or deposition is simply integrated by raising or lowering the appropriate cell. This has allowed the use of a relatively sophisticated two- and three-dimensional representation of erosion and deposition over several grain-size categories, which, in previous examples, has shown the development of simple pool–riffle sequences (Coulthard *et al*., 1996), bed armouring and the deposition of fines on lateral bars (Coulthard *et al*., 1998, 1999). The CFD models and reach-based studies are also restricted by their reliance on boundary conditions, such as the input of water and sediment at the top of the reach. By modelling the entire catchment, many of these boundary conditions are removed. Instead of stipulating a sediment input to a study reach, or prescribing a set flood discharge, this generic cellular model simply takes a DEM and rainfall record, calculates the hydrology, creates its own sediment inputs from slope processes and incision, and allows the channel pattern and catchment morphology to evolve. Furthermore, by integrating several model components within the same uniform cellular framework, the problems of incorporating models of different processes operating at different scales are resolved.

However, there are three key areas for improving this cellular model. Firstly, the channel is not allowed to be smaller than the grid cell size, which clearly is sometimes an unrealistic representation, as there may be smaller channels on the hillslopes or even in features such as rills (Favis-Mortlock, 2000, this issue). The choice of grid-cell size is usually a compromise between the size of the area studied, the length of time simulated and the detail required. More information is required as to the effects or inputs from smaller channels and methods for their integration. Secondly, there is no spatial variation in rainfall or vegetation cover over the study catchment. For a small area such as Cam Gill Beck, this may not be a significant factor, but over larger catchments this will have important effects. Finally, there is scope for experimentation with different hydraulic equations. The Chezy–Manning equation could be adapted for determining water depths, and feedbacks between the bed roughness and depth calculation could be introduced.

Despite these limitations, the authors believe that this modelling approach captures many of the complex interrelationships within a catchment, at a scale rarely achieved. As the results are difficult to validate accurately, they should possibly be viewed in a more qualitative than quantitative manner, as understanding the relationships between environmental factors and form is perhaps more important than the values themselves. For future work, as cellular models ideally lend themselves to parallel programming, the next step is to add parallel code, running sections or subcatchments on separate processors simultaneously. In theory (despite diminishing returns) the only limitation on the size of area to be studied is the number of processors available. Likewise, the spatial resolution could be increased to study a smaller area in greater detail over longer time-scales.

Ultimately, all models are compromised representations of reality. For this cellular model the accuracy of water depth and flow is sacrificed so that the effects of erosion and deposition over a whole catchment over extended periods of time can be examined. The CFD models are forced to undertake a different compromise, forsaking the study of a whole catchment to concentrate on the movement and extent of water within a detailed reach. Computing power is increasing dramatically every year, so eventually high-resolution, three-dimensional flow representations incorporating detailed sediment transport equations for whole river systems will become a realistic possibility. However, until this happens the 'meso' scale cellular approach adopted here provides the best available means to answer important questions about long-term changes in whole river catchments.

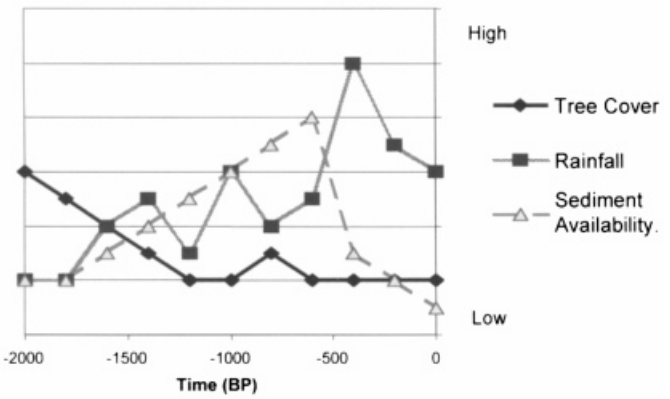

Figure 9. Conceptual diagram of Cam Gill Beck evolution

CONCLUSIONS

One key question asked in the introduction was which has the greater effect, deforestation or climate change? Despite lengthy simulations with a sophisticated, high-resolution model encompassing a wide range of scenarios, a precise causality is still not clear. Although the model indicates that climate has a slightly greater impact, vegetation still has a marked effect. As Macklin *et al*. (1992, p. 136) stated,

> *'Anthropogenic activity and climate change need not be considered as competing hypotheses for explaining the timing and pattern of Holocene alluviation and river erosion . . . River response to environmental change should instead be viewed in terms of a continuum between these two factors.'*

The model results certainly support this observation, but importantly reveal how the combination of climate and vegetation change have a much greater effect than these factors changing in isolation.

In the context of the Yorkshire Dales, this notion supports our knowledge of the historical river basin development as described schematically in Figure 9. Merrett and Macklin (1998a, 1999) show that in upland catchments there was an increase in flood magnitude around the early eighteenth century. This corresponds with other studies (Rumsby and Macklin, 1996) showing a period of climatic instability linked with the end of the Little Ice Age (Lamb, 1977), characterized in upland Britain by large storm events (Macklin *et al*., 1992). Prior to this, Smith (1986) and Tinsley (1975) document the slow decline in forest cover over the last 5000 years in catchments adjacent to Cam Gill Beck. The consequence of this is that the catchment was likely to be 'primed' with sediment released by land use change that is moved by the increase in flood magnitude caused by climate change. This scenario is similar to the conditions for the simulations giving the highest sediment discharges, runs *Sparse 1·5* and *Sparse 2*, producing 4238 and 13 088 m^3 of sediment over 10 years respectively. Thus, the combination of reduced tree cover and high rainfall magnitudes expand the drainage network, giving a massive increase in sediment discharge (1300%). Therefore, based on modelling results and historical evidence, the recent development of Cam Gill Beck and many other upland rivers in the Yorkshire Dales could be described as being climatically driven, but culturally primed.

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