Chapter 6
Modelling geomorphic response to environmental change

6.1 Introduction

As outlined in chapters one and two, interpretation of the effects of environmental change upon river catchments is hampered by low resolution dating techniques forcing us to infer links between catchment response and climate/landuse change. One of the principal aims of this model and thesis is to disentangle these environmental causes of change from the relative geomorphic effects.

Therefore, the aims of this chapter are to quantify the effects of environmental change on catchment morphology and sediment discharge over time-scales ranging from one flood to 100 years. By subjecting a model of the Cam Gill Beck catchment to different storm regimes and levels of vegetation cover, it is hoped that the relative effects can be separated from the causes. Furthermore, this will indicate how the catchment would respond to future changes in climate and landuse.

6.2 Methodology

6.2.1 Overview

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

1. To simulate the effects of changing vegetation cover on catchment hydrology, the TOPMODEL *m* parameter was altered. This changes the magnitude and response time of the hydrograph and values were chosen from previous applications (Beven, 1997; Kirkby Pers. Comm.). A broad range of values (from 0.005 to 0.02) were used, so that a wide range of vegetation cover scenarios were bracketed.
2. Storm magnitude was altered by multiplying an hourly ten year rainfall data set from 1985 to 1995 from Church Fenton by factors ranging from 1 to 4. Storm frequency was doubled by reversing the rainfall sequence, then adding it to the original sequence.

As the planned simulations would model up to 100 years of erosion, to compromise between spatial resolution and speed, a 2 x 2m DEM was used. The bedrock level was set at 1m below the surface giving the entire catchment a 1m initial soil thickness . Grainsize and initial conditions were initialised as in section 5.4.

6.2.2 Run details

The simulations were divided into three categories.

1. *Run 1:* 16 runs were carried out over a ten year time scale from identical initial conditions with different rainfall magnitudes and vegetation cover as detailed in Table 6.1. The initial topography was the 2m DEM into which a small channel was cut but had not developed a surface armour.
2. *Run 2:* Twelve of these runs (all up to rainfall magnitudes of 2 x) were then repeated from the conditions left after run 1 (above) for a further ten years. This was then repeated up to 9 times, representing 100 years of simulation to show variations sediment discharges over longer time scales.
3. Seven other runs were carried out representing other scenarios detailed in Table 6.2. *Noveg* is identical to *Sparse 2* except 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* are the same as *Sparse 1, Medium 1, and Dense 1*, but with twice the rainfall frequency.

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

	1 x	**1.5 x**	**2 x**	**4 x**
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*
V.Dense 0.020	*V. Dense 1*	*V. Dense 1.5*	*V. Dense 2*	*V. Dense 4*

Table 6.1. Detail of simulations carried out. The columns represent changing flood magnitude, from a ten year hourly rainfall. The rows represent different vegetation scenarios, the number corresponding to the factor altered in the hydrological model.

Run Name.	Run details.
Noveg	No resistive vegetation layer (Semi –arid simulation)
Defo	Use *Dense 1* after 100 years, then simulated deforestation.
Double	Use *Dense 1* after 100 years, then doubled rain magnitude.
DefoDouble	Use *Dense 1* after 100 years, then deforestation and R/f increase.
4dr12ha	Double flood frequency, Sparse vegetation (0.005)
4dr12hc	Double flood frequency, Medium vegetation (0.01)
4dr12hf	Double flood frequency, Dense vegetation (0.015)

Table 6.2. 'Other' runs.

6.3 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 6.1 shows the sediment discharges for run 1 (section 6.2.2), from equal initial conditions. The area of the bubble corresponds to the sediment discharge over the ten year cycle. Behind each bubble is the hydrograph for each run, the y axis running from 0 to 10 m^3s^{-1}. As run 1 is from bare initial conditions, with equal distributions of sediment throughout the catchment all of these simulations show a high sediment discharge generated by the removal of channel fines and surface vegetation. Figure 6.2 shows the average 10 year sediment discharge over 100 years from run 2. Here the sediment discharges have stabilised after run 1 and the simulations with a more powerful flood regime continue to produce higher sediment discharges. Figures 6.3 and 6.4 show scatter graphs of the same data described in Figures 6.1 and 6.2.

Both Figures 6.1 and 6.2 show an increase in sediment discharge with decreasing vegetation and increasing rainfall magnitude. In Figure 6.2, the change in sediment discharge if the rain magnitude is doubled (918 to 1859) is much greater than if the vegetation cover is reduced (918 to 1241). This is also evident in Figure 6.1, but to a lesser degree, again because of the high concentration of fines initially in the catchment. The trend-lines in Figures 6.3 and 6.4 show again how sediment discharge increases at a greater rate with rainfall magnitude changes than alterations in vegetation cover. Both Figures 6.1, 6.2, 6.3 and 6.4 show large increases in sediment discharge with combined changes of vegetation cover and rainfall (918 to 13088). Table 6.3 and Figure 6.5 compares the bedload discharges from runs *medium 1, 1,5* and *2* to nine other upland catchments (after Warburton and Evans 1998).

Figure 6.6. plots the sediment discharges of run2, from which the averages are taken for Figures 6.2 and 6.4. There was no continuation of *runs Sparse 4, medium 4, Dense 4* and *V. Dense 4* because of the very long time necessary to repeat the runs.

Table 6.4 details the results of run 3. *Noveg* had no resistive vegetation layer, representing a semi-arid environment shows a very large increase in sediment discharge 36959 as compared to 19327. *Defo*, *double* and *defodouble* show that doubling rain magnitude gives approximately twice the sediment discharge and the combined effects 17826 m^3. *4dr12ha* ,*hc* and *hf* with double rainfall frequency show an increase in sediment discharge of 15 % compared to *Sparse 1, Medium 1* and *Dense 1*.

Figures 6.7, 6.8 and 6.9 are all shaded plan views after 20 years simulation of run sparse 2. Figure 6.7 shows the whole catchment and the areas detailed by Figures 6.8 and 6.9 detailing the development of new channels.

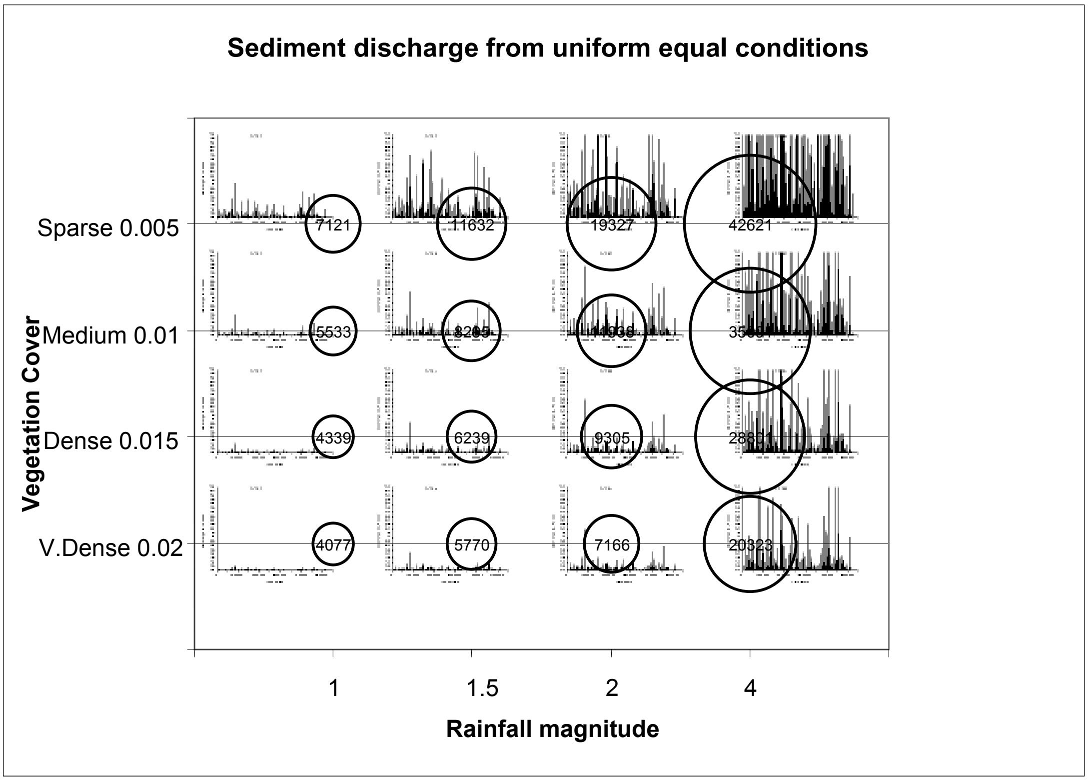

Figure 6.1 Sediment Discharge from run 1.

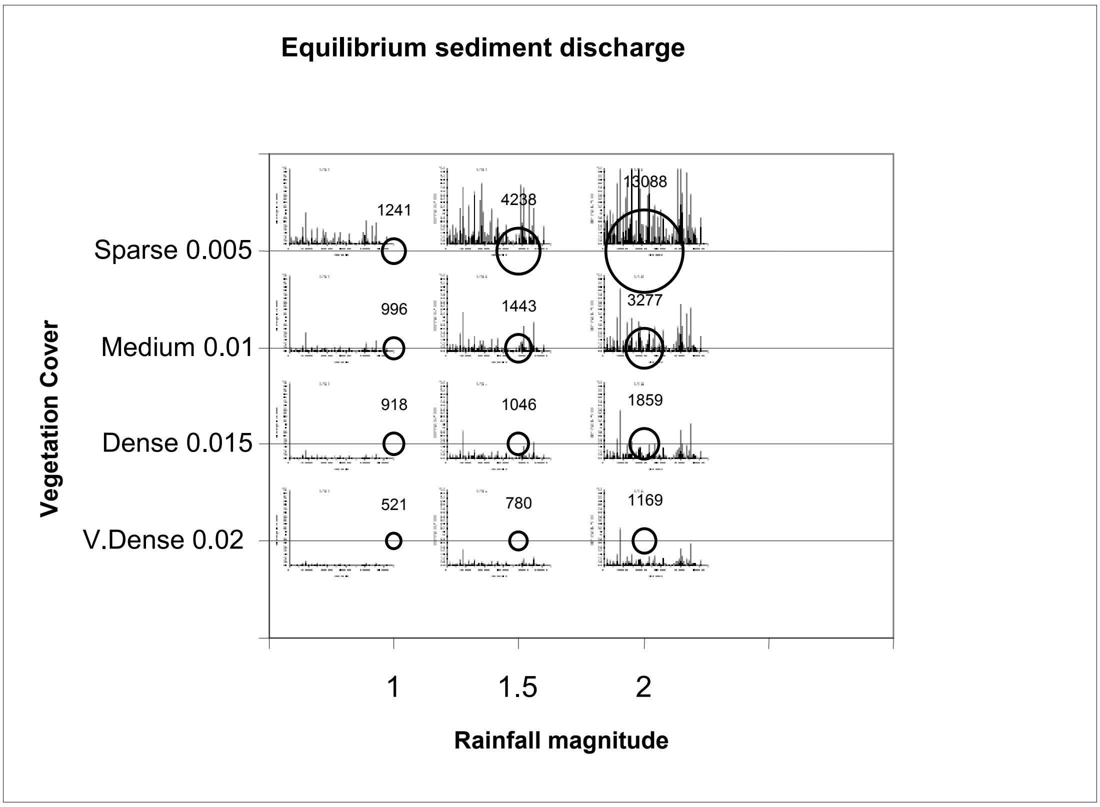

Figure 6.2. Averaged ten year sediment discharges for run 2

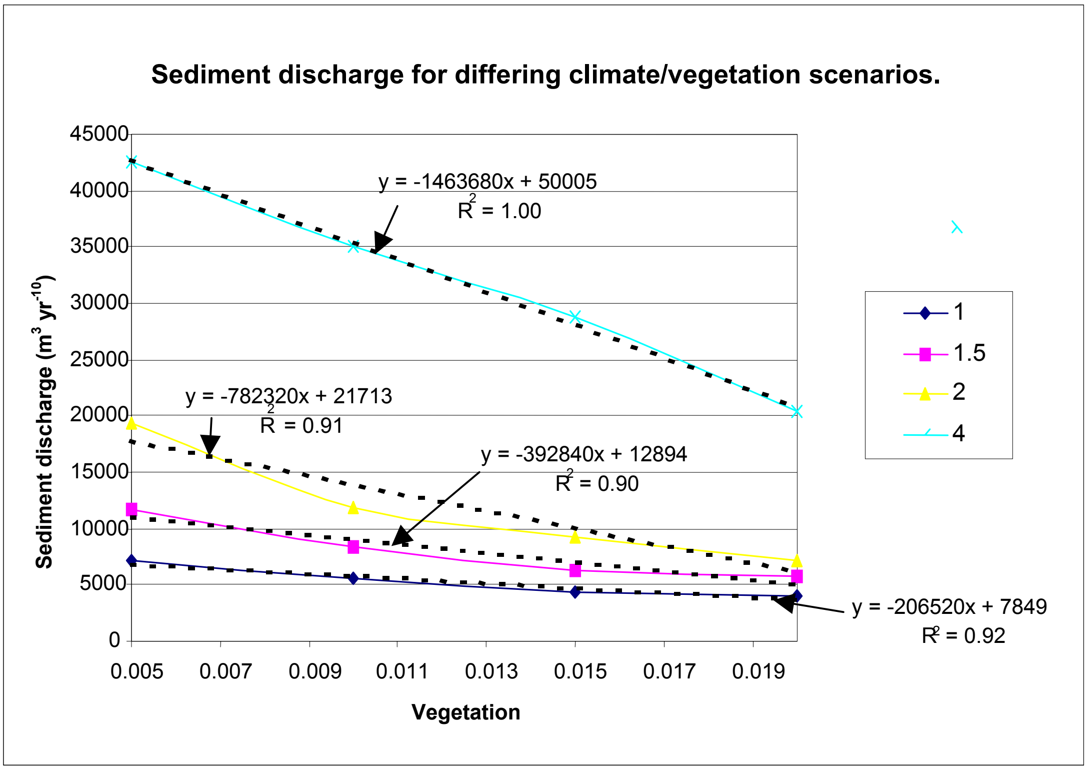

Figure 6.3.Relationship between vegetation, rainfall and sediment discharge.

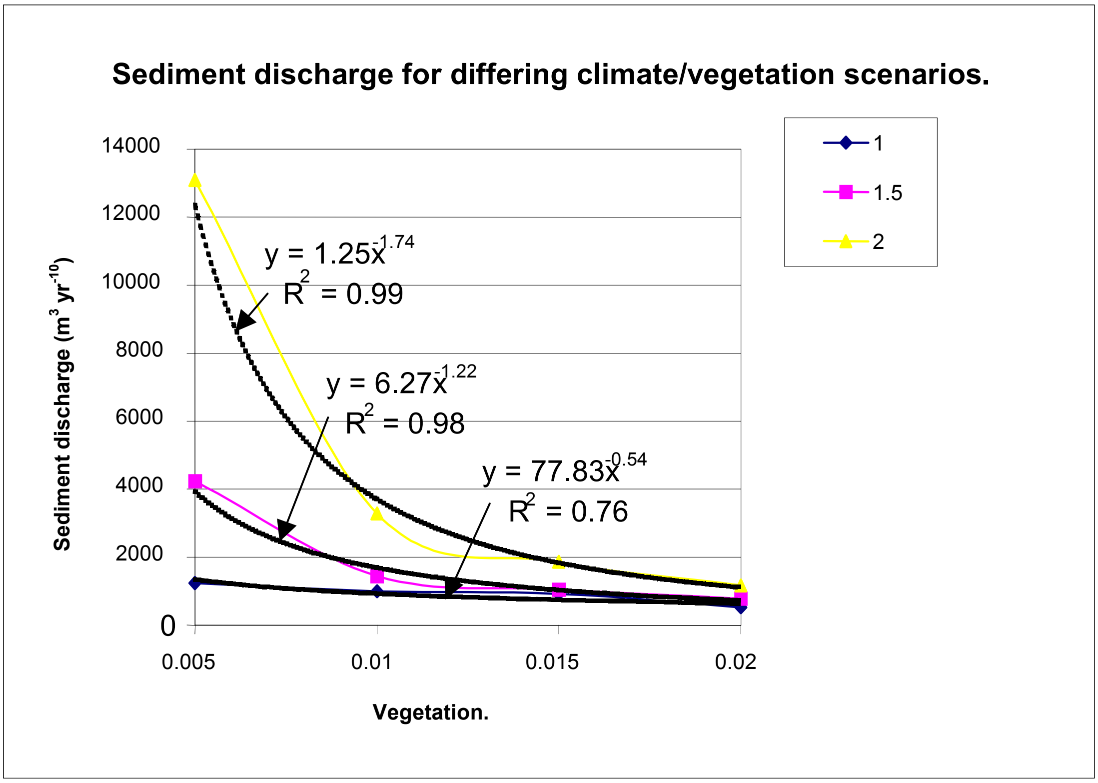

Figure 6.4.Long term relationship between vegetation rainfall and sediment discharge.

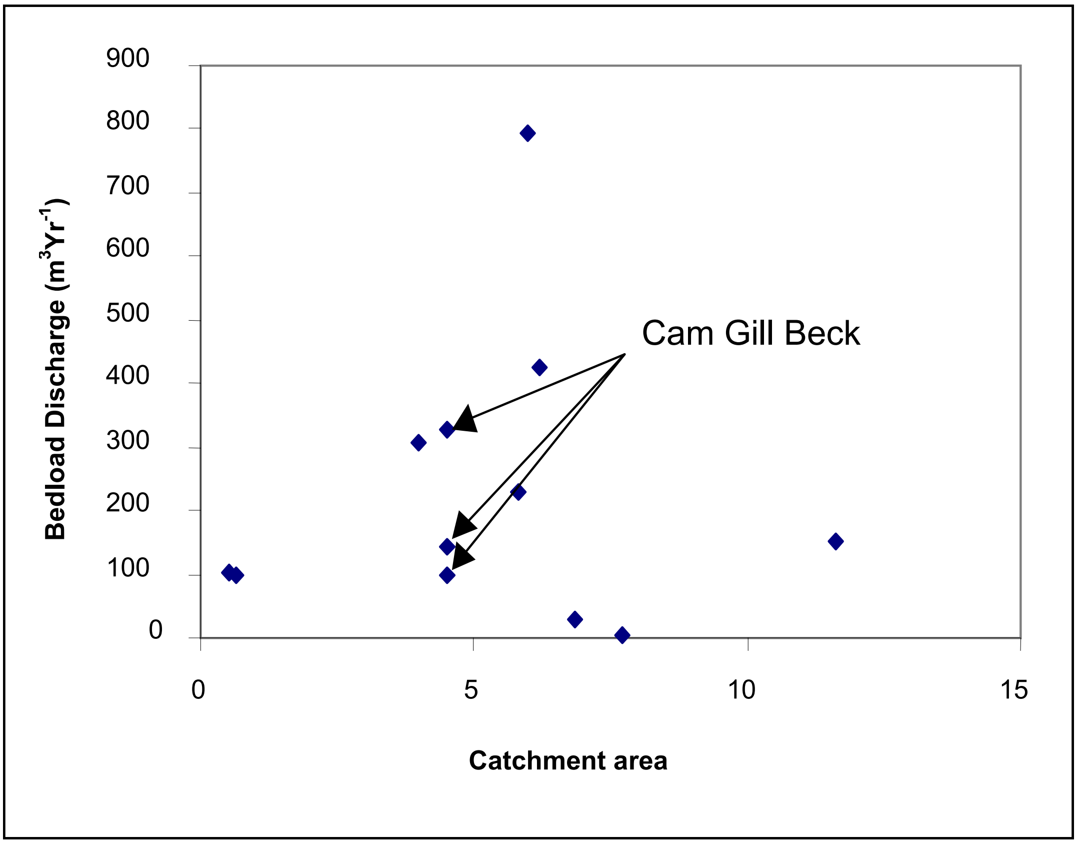

Figure 6.5 . Bedload discharge against catchment area from table 6.3.

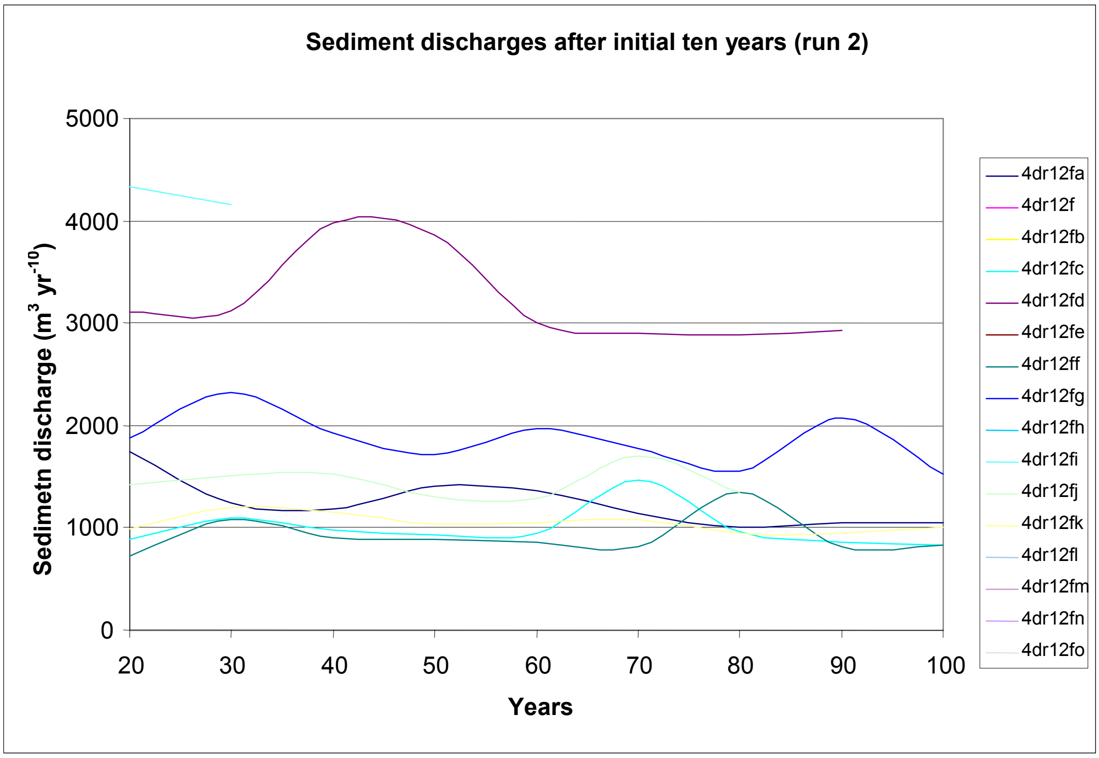

Figure 6.6. Fluctuating sediment discharges from run 2.

Catchment	**Area (km^2)**	**Bedload ($m^3\ yr^{-1}$)**	**Bedload ($m^3\ km^2\ yr^{-1}$)**	**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)
Langthwaite, 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	
Cam Gill Beck *(medium 1.5)*	4.5	144.3	32.06	
Cam Gill Beck *(medium 2)*	4.5	327.7	72.82	

Table 6.3. Bedload volume calculated assuming 2.65 t m^3 (after Warburton and Evans 1998).

Run Name.	**Run details.**	**Sediment Discharge.**
Noveg	No resistive vegetation layer (Semi –arid simulation)	36959
Double	Use *Dense 1* after 100 years, then doubled rainfall.	4281
Defo	Use *Dense 1* after 100 years, then deforestation.	2500
DefoDouble	Use *Dense 1*after 100 years, then deforestation and R/f increase.	17826
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

Table 6.4.Ten year sediment discharges from 'Other' runs.

Figure 6.7 here

Figure 6.8 Here

Figure 6.9 here..

6.4 Discussion

6.4.1 The impacts of climate change and deforestation

Figures 6.1 and 6.2 show a marked increase in sediment discharge with both a decrease in tree cover and an increase in rain magnitude. Whilst both factors have a significant effect on bedload discharge, the regression lines and equations in Figures 6.3 and 6.4 indicate that increases in rainfall magnitude have a greater impact. However, the combined effect of low vegetation and increased rain magnitude is far greater than their individual effects. As Figure 6.2 illustrates, decreasing tree cover and increasing rainfall magnitude give respectively 25 and 100% increases in sediment discharge, whereas together they generate a 1300% rise. Figure 6.4 displays regression lines showing how the sediment discharge increases almost exponentially (e 1.72) with a change in vegetation and rain magnitude. Furthermore, the runs *Defo, Double and DefoDouble* support these findings. They show 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.

Figure 6.10. Drainage networks from Dense 1, Medium 2 and Sparse 4.

The increase in sediment discharge is closely linked to the expansion of the drainage network (Figure 6.10). The greater runoff caused by deforestation and increased rainfall magnitude causes the existing channels to widen, incise, erode headward and cut new channels (Figures 6.8 and 6.9). This increased erosion, associated with the new channels generates a large supply of fresh sediment, which is reflected in Figure 6.1. However, as this new sediment is flushed from the system, the sediment discharge drops and stabilises at a new level (Figure 6.2). This discharge fluctuates, even when averaged over 10 years (Figure 6.6), 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 the larger drainage network from slope processes.

The new channels formed by the model in response to the increase in rainfall are of interest as they are largely formed where there are relic channels in Cam Gill Beck. Figures 6.7, 6.8 and 6.9 show plan views from the model output compared to aerial photographs of these areas, and clearly show channels produced by the model and those found in the field. Those on the western (left) side of the valley (Figure 6.8 A and B) are less defined because of the steeper slope and the straight lines on the photographs are dry stone walls. Presently in Cam Gill Beck these channels are inactive, vegetated and free from any bed material (e.g. Figures 6.8 B and 6.9 B). 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 stabilised 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 vegetation loss combined with increases in storm magnitude cause significant changes. The results presented here suggest that these relic channels are probably a feature of climate change, as 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 the activity of these channels 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 geomorphic 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 16mm/h for slope floods and 45mm/hr 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 6.10) may represent a threshold within the morphology of the whole catchment. As the model's initial conditions are from the relief generated by recent hydrogeomorphic conditions (Willgoose *et al*., 1994), the sudden increase in sediment discharge shown in Figure 6.1 is a reflection of the present channel networks inability to cope with the new rainfall magnitudes. Consequently, a catchment wide threshold is exceeded where existing relic channels are re-activated, 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 6.4, run *4dr12ha* has the same conditions as run *sparse1*, except double storm frequency, the sediment discharge is 7935 as opposed to 7121. With double storm magnitude, which is effectively the same volume of precipitation as *4dr12ha*, the sediment discharge is 19327. This presents strong evidence that the intensity of the storm is the dominant factor, which is re-enforced by the relationship between sediment discharges and the hydrographs shown in Figure 6.1 and Figure 6.11. For example, *Sparse1.5* and *Medium2* have a difference of less than 1% sediment discharge and very similar hydrographs. The other simulations were not duplicated with double frequencies as these first 3 runs showed little effect from doubling frequency.

1 Figure 6.11 Here

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Sparse4 has a significant impact on all levels of tree cover, with large storms pushing through the ameliorating effects of vegetation. The *noveg* simulation (Table 6.4) produces a morphology, sediment discharge and drainage network similar to that produced by *sparse4* despite having the same hydrological input as *sparse2.* 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.

6.4.2 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 6.5, Table 6.3). 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 6.5 resulting from different measuring techniques, difficulties of accurate measurement and the variation in the catchments 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, landuse and climate. But it demonstrates the model is operating within an expected range.

For further validation, Howard (1998 Pers. Comm.) C_{14} dated a charcoal sample from an exposed bank section on the River Wharfe, immediately above the Starbotton fan to 1500 AD +-75. This sample was overlain by 2m of sediment, implying that this material had been deposited and subsequently incised through. Calculations show that if this volume is extrapolated for the whole valley floor from Starbotton to upstream Buckden, this would correspond to 200 years of sediment production from 10 upstream catchments of Cam Gill Beck's size at a rate simulated by *sparse2*. Such a scenario is possible, as Merrett and Macklin (1999) have suggested that the 17th 18th and 19th Centuries were dominated by periods of high rainfall magnitude associated with the Little Ice Age (Lamb 1977) and there are 10 to 15 upstream catchments of comparable size to Cam Gill Beck.

Whilst these simulations 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 an limiting effect on incision, sediment supply and hydrology. Many other upland catchments in the Yorkshire Dales (Merrett and Macklin 1998 a) and the Northern Pennines (Merrett and Macklin 1998 b) are underlain by more friable sandstones and shales. Whilst 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 1m 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. Whilst some fine material will be deposited within the catchment, this assumption is supported by the domination of coarse boulders in deposits found in Cam Gill Beck. Furthermore, slope processes are simplistically represented 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 manipulation of the TOPMODEL *m* parameter to represent changing vegetation cover can be criticised. Altering *m* increases or decreases the magnitude of the hydrograph and the speed of its response to a given rainfall. This is apparent in Figures 6.11 and 6.12 where hydrographs for identical rainfall sequences with different *m* values are shown. However, it must be remembered that these changes in *m* are only a surrogate for changes in catchment hydrology caused by different levels of vegetation cover. There are no direct linkages between vegetation levels and sediment discharge. Within the model simulated vegetation changes only alters *m*, that changes the hydrology, influencing the hydrograph that in turn generates more or less fluvial erosion. The interactions of vegetation change with catchment hydrology and its impact on catchment sediment yield can be complex and altering *m* is only a simplistic representation. But it must be remembered that the aim of this study is to model catchment response to Holocene environmental change and is therefore concerned with changes over longer time-scales. If we ignore the immediate effects of deforestation, such as the release of sediment through ground disturbance or alterations in infiltration rates by soil compaction (Brooks *et al.* 1994), then the dominant long term impacts will be through changes in the hydrology as reflected by manipulating *m*.

The *m* values used in TOPMODEL applications are usually calculated from the recession curve of the hydrograph of the study catchment (Beven and Kirkby 1979). No such flow data were available for Cam Gill Beck, so *m* values were derived from reviewing previous applications of TOPMODEL and from Kirkby (Pers. Comm.). Beven (1997) listed over 20 applications, with *m* values from similar sized catchments (~5km^2) with a range of vegetation covers ranging from 0.004 to 0.02. As the values for Cam Gill Beck were unknown the model runs were deliberately chosen to bracket a wide range of possible scenarios. This is further illustrated by the very different hydrographs produced for the 16 runs (Figures 6.11 and 6.12). Therefore it is highly likely that the present day scenario for Cam Gill Beck lies within this range and this large number of different scenarios allow the relative effects of climate and vegetation cover change to be deduced. As a final justification, Robson *et al.*(1993) studied the Monachyle catchment in Balquhidder, Scotland, and noted *m* values of 0.021 when forested and 0.008 when deforested. For future validation and application of this model, gauging stations could be installed and values calculated for both forested and deforested catchments.

Despite these limitations, this modelling approach captures many of the complex interrelationships within a catchment, at a scale rarely achieved. The results are difficult to accurately validate and therefore should 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. Despite the model's initial application to Cam Gill Beck, its design is generic, allowing it to be applied to any small catchment which can be digitised, and this method shows great potential for application to other catchments in other environments especially semi-arid.

To continue investigating the effects environmental change, the model should be applied to a larger catchment areas including greater floodplains and depositional zones. As CA models ideally lend themselves to parallel programming the next step is to add parallel code, running sections or sub catchments on separate processors simultaneously. In theory (despite a diminishing returns effect) 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.

6.5 Conclusions

One key question asked in the introduction was whether deforestation or climate change has the greater effect? Despite lengthy simulations with a sophisticated, high-resolution model encompassing a wide range of scenarios, a precise causality is still not clear. Whilst the model indicates that climate has a slightly greater impact, vegetation still has a marked effect. As Macklin *et al* (1992a, p136) 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 shown schematically in Figure 6.12. Merrett and Macklin (1998a, 1999) show that in upland catchments there was an increase in flood magnitude around the early 18th 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), characterised 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 which 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 13088 m^3 of sediment over ten 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.

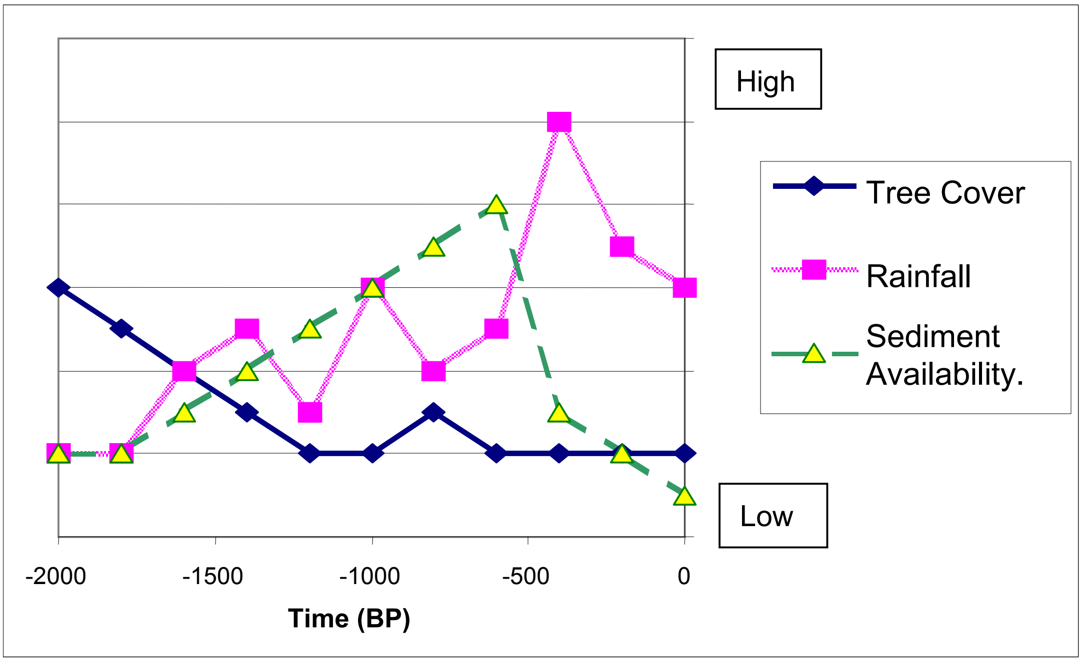

Figure 6.13. Conceptual diagram of Cam Gill Beck evolution.