Chapter 8
Simulating the Holocene evolution of Cam Gill Beck

8.1 Introduction

The village of Starbotton sits 10m above the main valley floor of Wharfedale, on a alluvial fan debauching from Cam Gill Beck. Alluvial fans have a dual role in many river systems, acting as both stores of sediment and the connection between upland river systems and the main valley floor and trunk stream. Furthermore, they have a significant role in valley floor evolution, in some cases pushing the trunk stream over to the other side of the valley, as with Cam Gill Beck.

Periods of fan aggradation have been linked with land use change (Harvey and Renwick 1987, Ballantyne 1991) and increases in flood magnitude and frequency associated with climate change (Merrett and Macklin 1999). However uncertainties exist as to how influential these factors are, as well as other effects such as vegetation cover and sediment supply. Chapter 6 attempted to address the way in which changes in climate and vegetation cover affect upland catchments, but it is not known how variations in sediment delivery induced by these environmental changes affect alluvial fan evolution. Furthermore, questions remain as whether fans such as Cam Gill Beck are relic Pleistocene features or were formed, or enlarged extensively, during the Holocene.

Chapter 6 showed how sediment delivery might have changed due to climate and vegetation cover, however, over the Holocene these 100 year sequences only represent 'snapshots' and may only be a transient response to changing conditions. As discussed in 2.4.3, there are now relatively detailed indices of wetness and temperature over the last 10 000 years, which when coupled to a land use history, gives a reasonable account of the drivers of Holocene environmental change. This provides the basis for modelling the long term interactions between climate, land-use and sediment supply, and comparing these results to the sedimentary record observed in other river systems.

Thus, the aims of this chapter are to simulate the Holocene evolution of Cam Gill Beck and to evaluate how the long term interactions between climate, land use and sediment supply affect catchment sediment discharge and alluvial fan development.

8.2 Method

To drive a Holocene simulation of erosion and deposition, a record of the climate and land use was required. For the climate signal, the wetness index from Anderson *et al.* (1998) was used as a factor by which the rainfall sequence used in Chapters 6 and 7 was multiplied. Using the results from chapter 6 as a guide, the magnitude of this wetness index was altered so that the rainfall sequence was changed by factors ranging from 0.75 to 2.15, where 1.3 was the average (Figure 8.1). Despite originating in Scotland, this record was chosen as it extends back 9300 years, as opposed to the 7000 of the Barber *et al.* (1994) index. For the land-use component, a vegetation cover history (Figure 8.2) was reconstructed from local data (Smith 1986, Tinsley 1975) and from archaeological records in the area (Howard, pers comm. , Martlew, Pers. Comm.). This describes the catchment as being covered with woodland until 3500 BP after which deforestation occurred at a steady rate over 1000 years. There was some re-growth during the middle-ages following the Black Death and cover increases slightly during wetter periods to represent a slight increase in vegetation cover due to the wetter antecedent conditions.

Initial conditions and assumptions for topography, grainsize and soil cover were then defined. As this simulation was designed to represent a period 100 times longer than those in chapter 6, a 3m by 3m grid resolution was chosen which allows a much faster execution, at the expense of some channel detail and form. Previous simulations had used the existing topography of Cam Gill Beck for the initial conditions. However as this model run was designed to investigate the evolution of the alluvial fan it was necessary to remove part or all of the existing fan topography to re-create the early Holocene initial conditions. As the age and depth of the fan was unknown, the whole fan was removed from the DEM, re-constructing the valley floor some 5-10m lower than present (Figure 8.3). Although this may not represent the initial conditions with certainty, this assumption would show if the fan could have been formed by late Holocene alluvial processes or partially formed during de-glaciation.

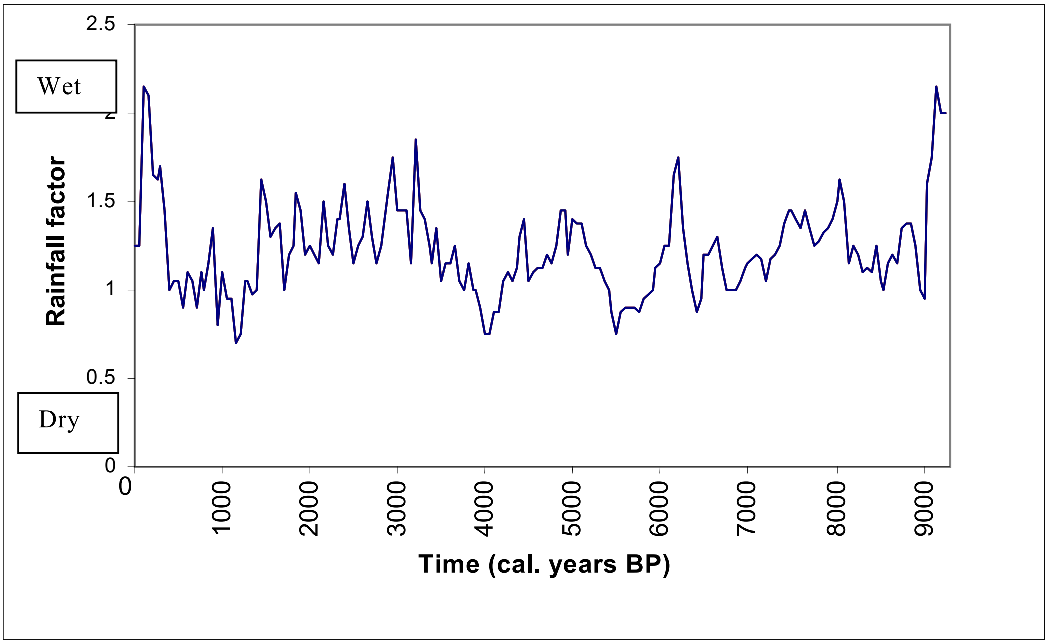


Figure 8.1 Climate record derived from Anderson et al. (1998).

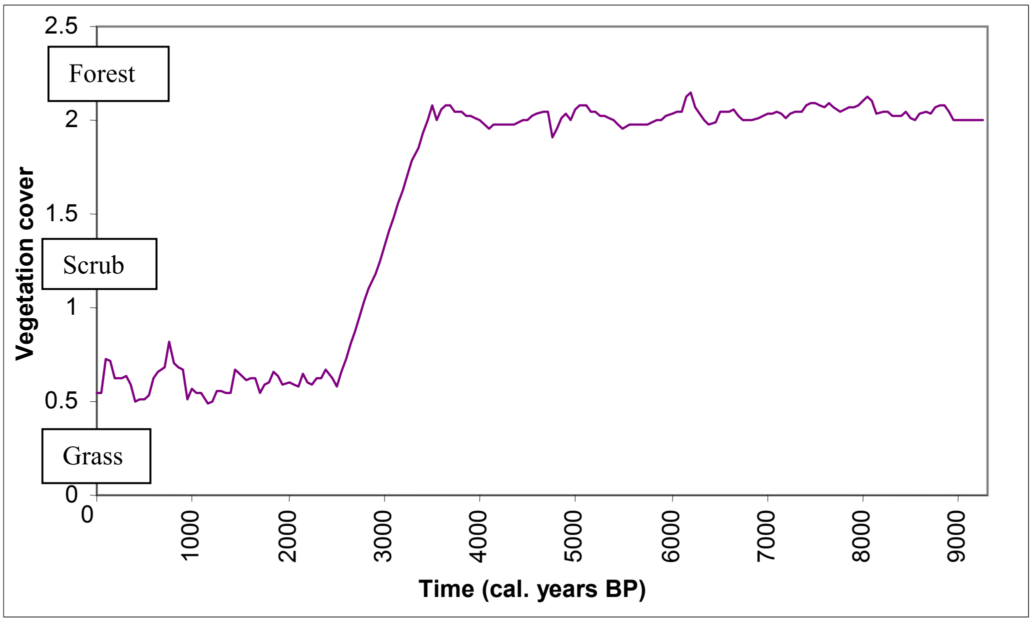
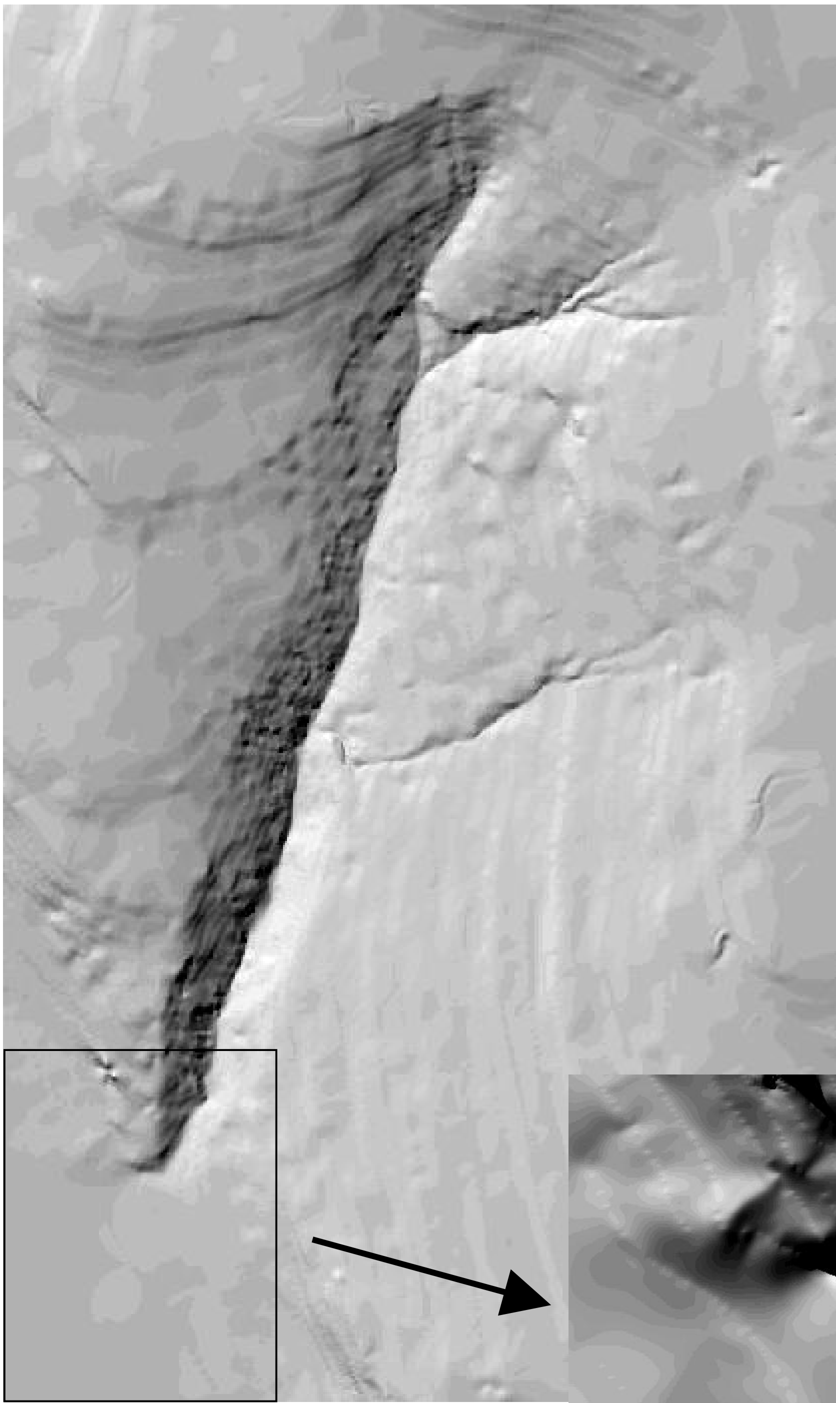


Figure 8.2 Land use record.

The simulations in chapters 6 and 7 used a surface covering of soil 1m thick, but as this model was operating over periods 100 times longer and the model contains no method for developing soils, an initial layer of 2m was used. Boundary conditions were chosen so water and sediment could pass over the southern edge, as if flowing down Wharfedale, but only water could flow off the western edge which represented the opposite valley side and the river Wharfe. Elevation and grainsize data were saved every 50 years of simulation to allow sediment discharges to be calculated.



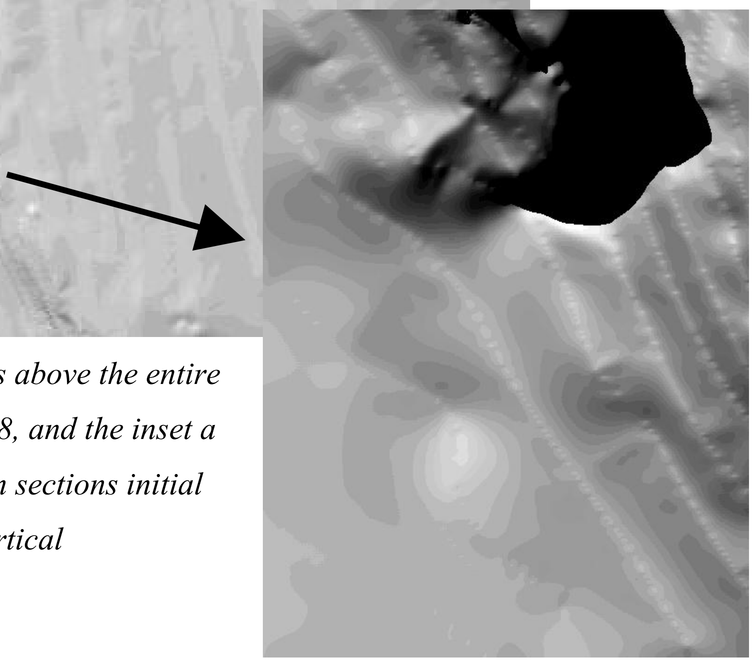


Figure 8.3. This shows above the entire DEM used in chapter 8, and the inset a zoomed view of the fan sections initial conditions (3 times vertical exaggeration).

8.3 Results

Three separate sediment discharges are shown in Figures 8.4 to 8.9, and to prevent confusion, the 'catchment sediment discharge' refers to the volume removed from the catchment above the fan. 'Fan accumulation' is the volume of material deposited on the alluvial fan and the 'sediment leaving fan' is the volume leaving the catchment and fan. Figure 8.4 shows the simulated catchment sediment discharge, responding to changes in climate and vegetation levels described in Figure 8.1 and 8.2. Figure 8.4 clearly shows that changes in sediment discharge are synchronous with the varying climate signal. There is also an increase in the amplitude of sediment discharge after deforestation.

Figure 8.5 shows the relationship and trend lines obtained by plotting 50 year mean catchment sediment discharge plotted against 50 year mean rainfall levels. The deforested points are taken from 2500 BP to present and the pre-deforestation points from 9250-3500 BP. The statistics from the regression lines in Figure 8.5 are given in Table 8.1. Figure 8.6 compares the simulated catchment sediment discharge for Cam Gill Beck with the frequency of dated alluvial units found in the Yorkshire Ouse catchment. The dated units frequency is calculated by totalling the number of units every 50 years including the error ranges of the radio-carbon dates. Figure 8.7 shows the climate, vegetation cover and cumulative catchment sediment discharge for Cam Gill Beck. Figure 8.8 shows the rainfall level, vegetation cover, fan volume and sediment leaving the fan, clearly demonstrating a switch between fan accumulation and sediment leaving the fan. Figure 8.9 shows the cumulative totals for fan accumulation and sediment leaving the fan.

Figure 8.10 details the evolution of the alluvial fan from 9000 to 0 BP at 1000 year intervals. The left hand frame shows a shaded plan form view of the section highlighted in Figure 8.3, with a 300% vertical exaggeration to show more detail of the surface features. The right hand frame shows the volume of material eroded or deposited in the 50 years immediately before the date. These values were chosen as opposed to the total eroded or deposited over the 1000 year time between pictures, as this shows the state of the fan at that time instead of the average over the 1000 years.

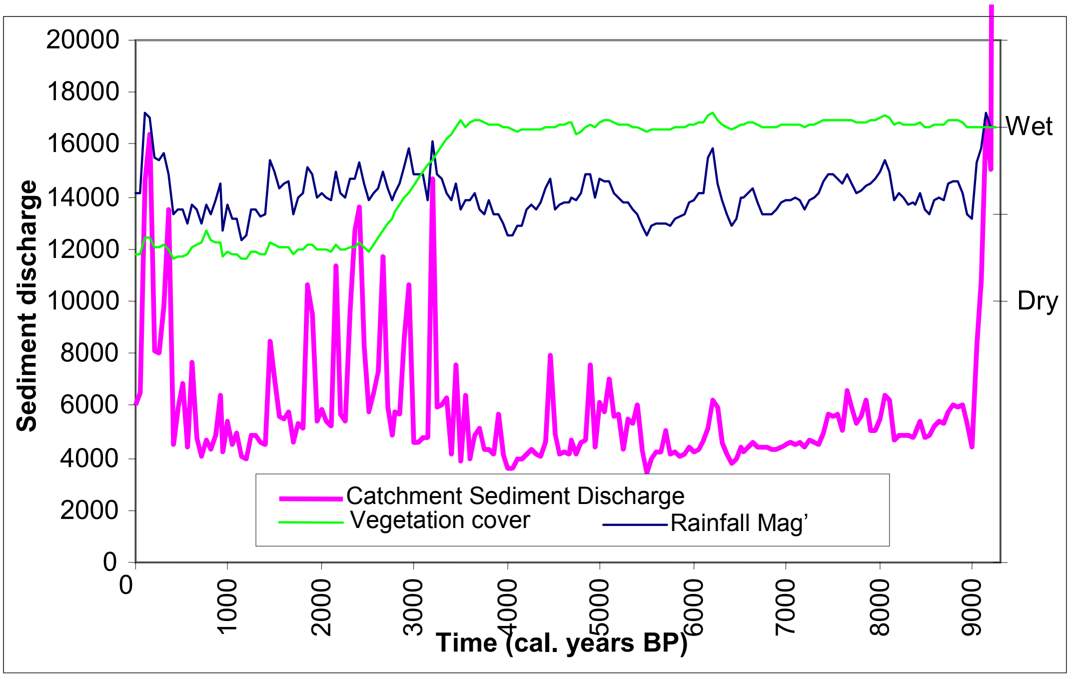


Figure 8.4. Catchment sediment discharge with climate and vegetation cover.

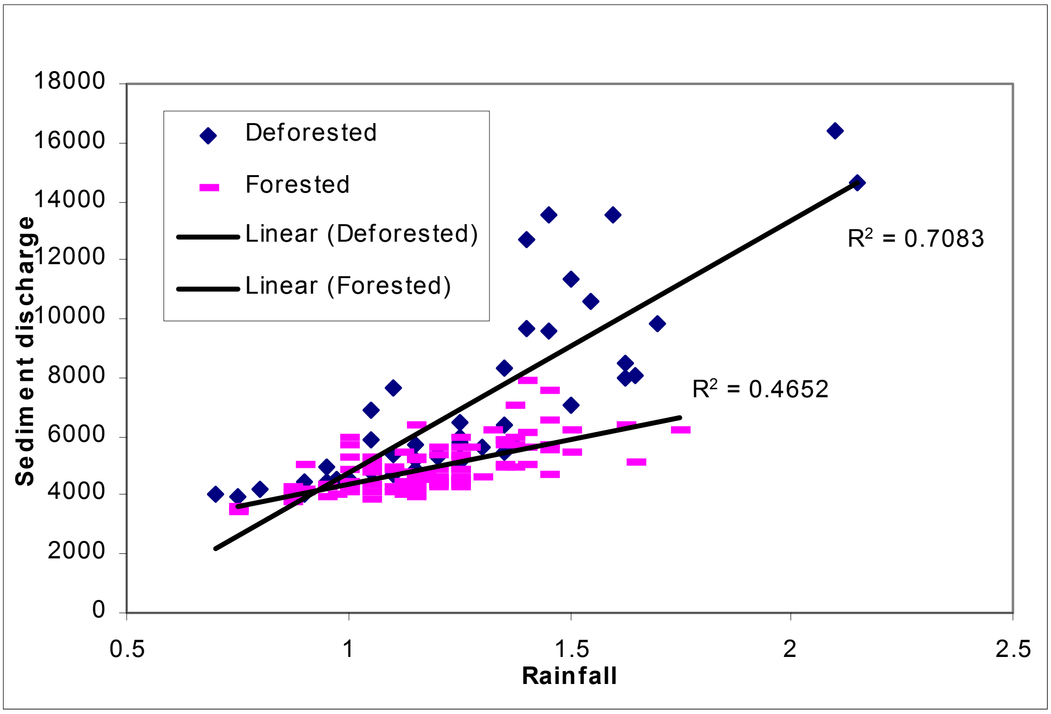


Figure 8.5. Scatter plot and regression lines of sediment discharge and rainfall magnitude.

Regression data from rainfall and sediment discharge *before* deforestation.

Regression Statistics	
Multiple R	0.682085
R Square	0.46524
Adjusted R Square	0.460334
Standard Error	617.1822
Observations	111

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	36122024	36122024	94.8299	1.69E-16
Residual	109	41519612	380913.9		
Total	110	77641637			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	1433.277	358.4164	3.998915	0.000116	722.9077	2143.646	722.9077	2143.646
X Variable	2958.867	303.8455	9.738064	1.69E-16	2356.656	3561.079	2356.656	3561.079

Regression data from rainfall and sediment discharge *after* deforestation.

Regression Statistics	
Multiple R	0.84242
R Square	0.709672
#Adjusted R Square	0.703623
Standard Error	1675.96
Observations	50

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.3E+08	3.3E+08	117.3302	1.74E-14
Residual	48	1.35E+08	2808844		
Total	49	4.64E+08			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3774.49	1010.496	-3.73529	0.000498	-5806.23	-1742.76	-5806.23	-1742.76
1.25	8560.134	790.2705	10.8319	1.74E-14	6971.19	10149.08	6971.19	10149.08

Table 8.1. Regression statistics from figure 8.6.

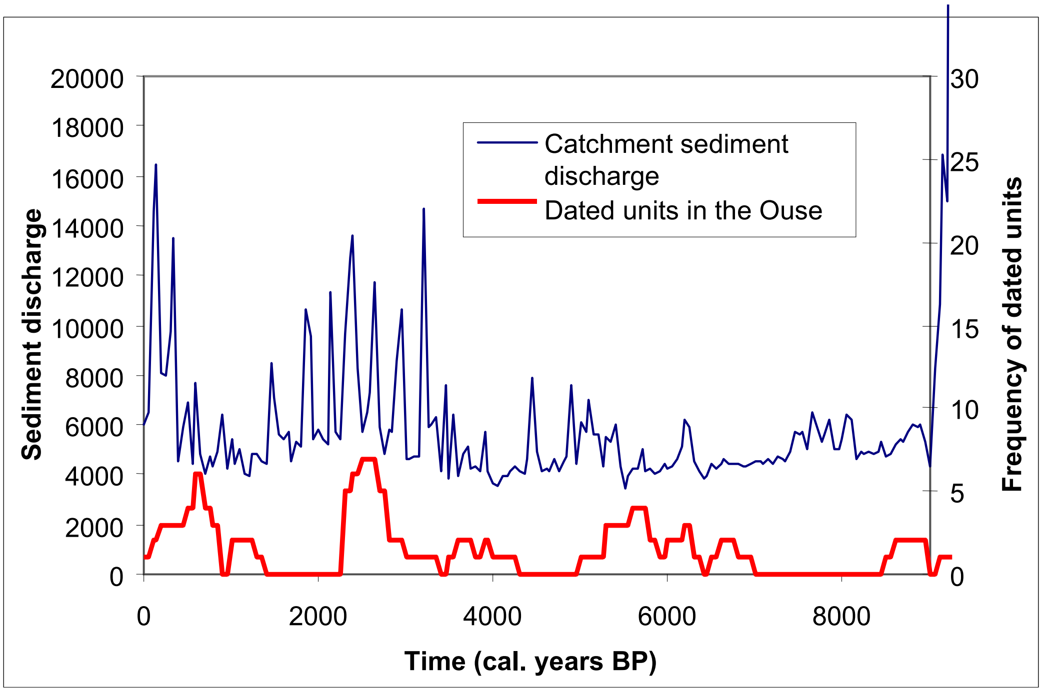


Figure 8.6. Catchment sediment discharge compared to dated Ouse flood units.

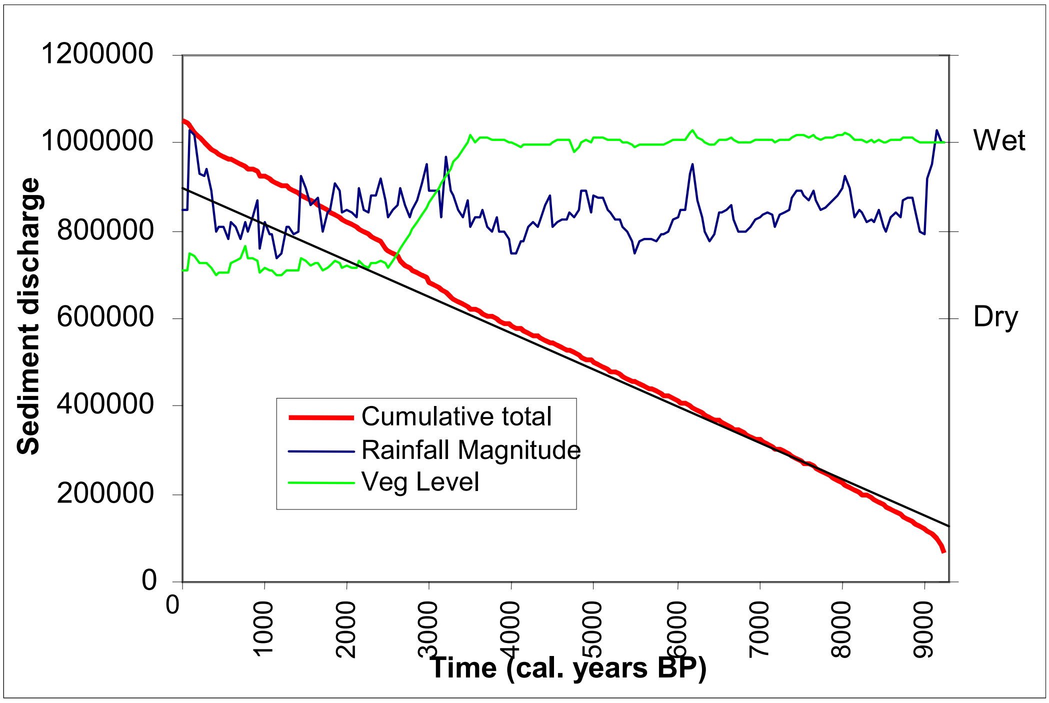


Figure 8.7. Cumulative total of catchment sediment discharge.

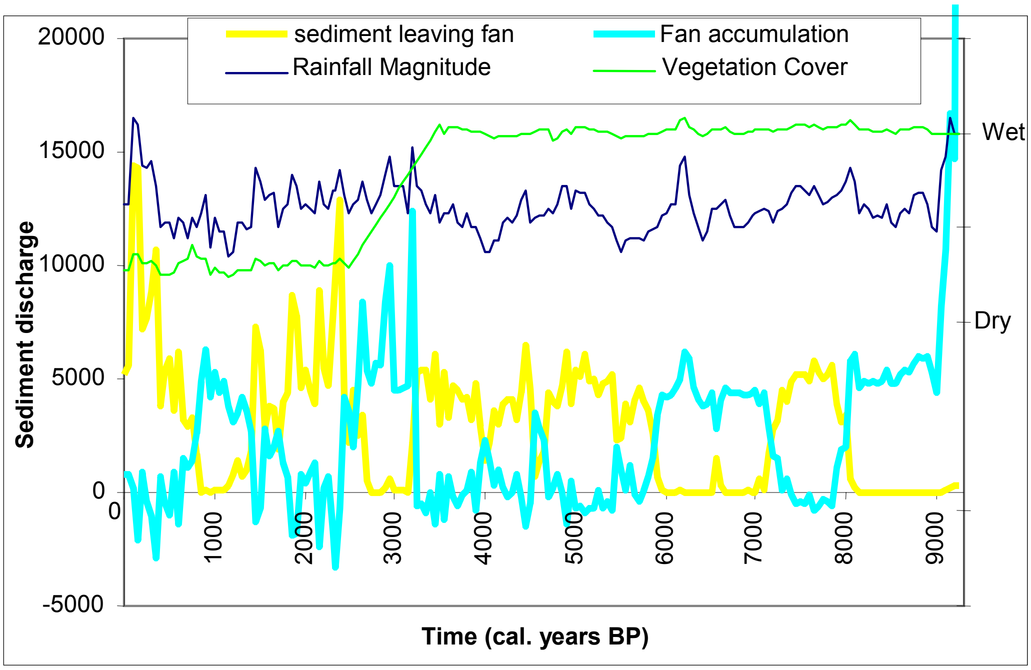


Figure 8.8. Fan accumulation and sediment leaving fan, plotted with rain factor and vegetation cover

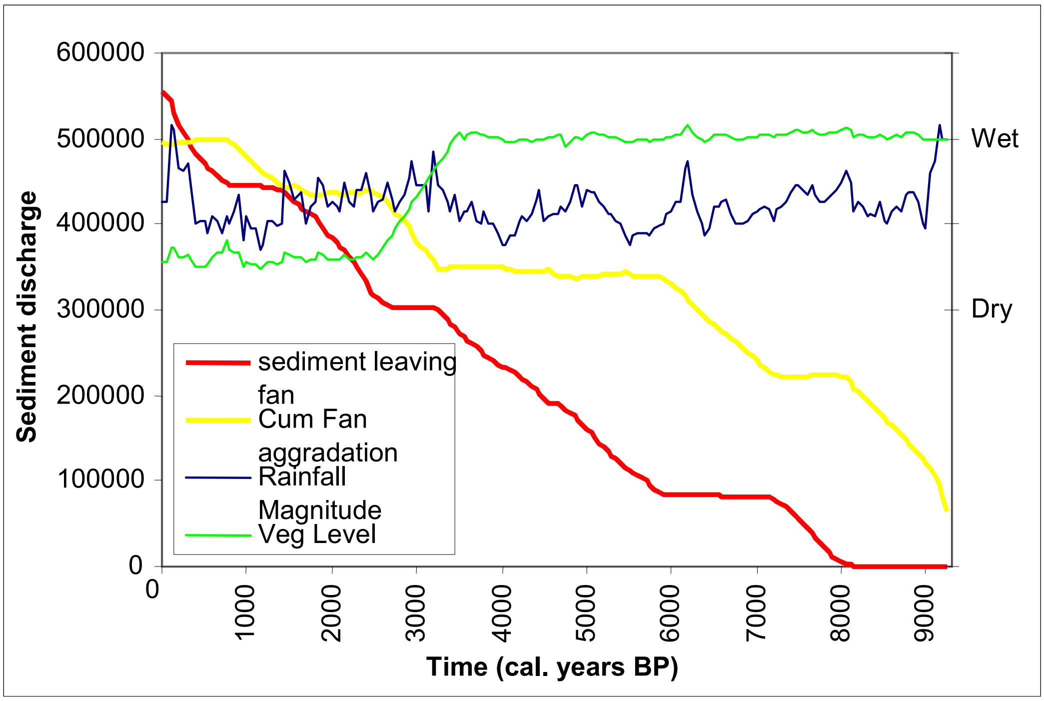


Figure 8.9. Cumulative chart of fan accumulation and sediment leaving fan.

Figure 8.10 page1

Figure 8.10 page2

Figure 8.10 page3

Figure 8.10 page four

Figure 8.10 page 6

Figure 8.11

Figure 8.12

8.4 Discussion

8.4.1 Long term sediment discharge

Chapter 6 established that a combination of climate and land use change can generate a 1300% increase in sediment discharge. The findings from this simulation of Cam Gill Beck's Holocene evolution re-affirm this.

Regression analysis of these data (Figure 8.5) suggests that deforestation can increase a catchment's sediment discharge for a given flood event. This is also apparent visually in Figure 8.4, where there is a substantial increase in the amplitude of the sediment discharge following deforestation. Furthermore, the steeper line of the deforested data shows an enhanced sensitivity to changes in climate. For example low rainfall magnitudes (1) have a similar effect upon both forested and deforested. But higher rainfall magnitudes (1.5-2) can produce a far higher sediment discharge on a deforested catchment. However, when 95% confidence limits for each line are considered (Table 8.1), there is an overlap, so that although these general trends are evident they are not significantly different. Furthermore, the heaviest periods of rainfall all occur whilst the catchment is deforested which may skew the results, especially the two outliers in Figure 8.5. Additionally, there is considerable scatter within Figure 8.5 with different sediment discharges for the same rainfall magnitude and land cover. This indicates that there may be non-linear responses within the catchment possibly linked to transient phenomena and small scale sediment storage. This is discussed further in chapter 9. Therefore, whilst not statistically significant, the removal of vegetation cover increases catchment sediment discharge for a given rainfall event. Furthermore, river catchments are more sensitive to variations in climate when deforested.

The two largest peaks in sediment discharge occur at 3200 and 500 BP, corresponding with a sharp transition from dryer to wetter climates. Such a change around 3200BP was noted by both Anderson *et al.* (1998) and Barber *et al.* (1994), and increased alluvial activity has been recorded in river systems across the UK during these periods (Macklin and Lewin 1993). Unexpectedly, the peak at 3200 BP occurs whilst the catchment still has a strong vegetation cover leading to two alternative conclusions. Firstly, large storms will effect a catchment despite the ameliorating effects of vegetation cover. Secondly, that the peak in sediment discharge may be caused by a build up of sediment adjacent to river channels or in dry proto-streams during the preceding drier 3000 years. Further evidence for such sediment accumulation is given by the smaller peak immediately after 3200, at 3000, which is far lower than the peaks at 2500 and 2750 BP despite a wetter climate, suggesting that the 3200 peak temporarily exhausted sediment supply. However, precise conclusions are hard to draw as these peaks occur during changing levels of vegetation cover and there is the continuing influence of non linear processes (discussed further in chapter 9). The peaks in sediment discharge after 500BP are the largest and are formed in response to wetter periods during the Little Ice Age (LIA). In the uplands, Merrett and Macklin (1999) and Rumsby and Macklin (1996) found historical records of increased flooding as well as a considerable number of large flood deposits linked with climatic deterioration during this period. Merrett and Macklin (1999) suggest that there are two periods of flood activity during the LIA, from AD 1750-1800 and AD 1870-1910 with a period of incision at the start of the second period caused by a decrease in sediment supply. This simulation supports these findings, with two large LIA peaks at 1700 and 1900 with a sharp drop in sediment discharge in between them. As with the 3200 peak, this drop appears greater than the dip in the driving climate sequence suggesting that this is caused by a temporary exhaustion in sediment supply. This discontinuity in response is small and there are no delays between the peaks in climate sequence and sediment discharge, which suggests that there is a high degree of connectivity within the system with relatively little sediment storage. This is not unusual, as Cam Gill Beck is short and steep, with little room for storage. Greater delays between erosion and delivery could be expected in larger systems with sections of broad, low gradient valley floor.

Figure 8.6 compares the simulated sediment discharge to the frequency of dated stratigraphic flood units in the Yorkshire Ouse basin, and shows that the increases in sediment discharge from Cam Gill Beck corresponds loosely with periods of stream activity and deposition in the broader region. For the last 4-500 years, Figure 8.6 is an inappropriate comparison as this diagram contains only ^{14}C dates and this recent period lies on the useable limits of ^{14}C dating. If the flood units dated by lichenometry during this period by Merrett and Macklin (1999) were added, Figure

8.6 would show a massive increase at this time. Furthermore, this graph importantly indicates that sequences found in alluvial stratigraphies may be constructed from changes in flood frequency and magnitude caused by both climate and vegetation cover change.

In analysing the results of this simulation, it is important to be aware that this climate and land-use sequence is not defined with any certainty. The climate record is from Scotland, not the Yorkshire Dales and is susceptible to local irregularities in weather, measurement and dating. Therefore, whilst this record compares favourably with Barber *et al.*'s (1994) record, it cannot be treated as a precise record of the Holocene climate at Cam Gill Beck. Similarly, the land use history is equally susceptible to error, being drawn from regional palynological evidence and local knowledge. Ironically, we have a far better record of previous climates than of our ancestors agricultural activities. Thus, it must be remembered that the quality and accuracy of the data driving the model may continue to have a large effect upon its outcome.

Whilst Figure 8.4 shows a strongly fluctuating sediment discharge, the cumulative total (Figure 8.7) rises at a steady rate. There is a break in the slope at 3200 BP, and if the sediment discharge continued at the pre 3200 BP rate, the total final sediment discharge to date would be 900 000 m^3, 66% of the total actually simulated. However, when viewed as a cumulative total, the fluctuations in sediment discharge caused by land cover and climate change do not appear as severe as those described over a shorter time scale in chapter 6. This may be explained by two reasons. Firstly, Figure 8.4 represents a long term average whereas chapter 6 used 100 year sections, which represent just two data points in Figure 8.4. Thus, although there are continued periods of wetness these are averaged out by the drier periods.
Secondly, the steady increase of the line indicates that Cam Gill Beck is sediment supply limited. There is an increase in sediment discharge in response to environmental change driven by the retreat of stream heads, expansion of the drainage network and stream incision (Chapter 6.4.1). But over longer periods the supply of sediment into the network from hillslope processes is restricting the total sediment discharge. The steady rise of this cumulative total implies that a process operating at a constant rate is the limiting factor, and in this model the only process with no temporal change in rate is soil creep. Therefore, over long time scales, in

temperate supply-limited catchments like Cam Gill Beck, diffusive slope processes such as soil creep may be the dominant control over sediment discharge. Unfortunately as soil creep operates at very low rates, it is difficult to accurately quantify rates of change and how these may respond to environmental change, e.g. wetter weather. Certainly during the early Holocene, there is widespread evidence in the UK's uplands for enhanced creep and gelifluction (Ballantyne 1991). Therefore, soil creep may be both the most important factor and the weakest link in the model parameterisation. Whilst for 100 year runs the input of soil creep is negligible, over long time scales greater than 1000 years its importance increases and a more accurate model representation may be required.

Spatial variation in changes in vegetation and thus hydrology are not incorporated in this model. It is assumed that the catchment changes as a whole, by altering the *m* value (as discussed in section 6.4.2). This may have important effects on where sediment was produced. For example if one tributary were deforested first, it would be expected to produce sediment at different times to the rest of the forested catchment. However, we simply have no knowledge of how the deforestation of Cam Gill Beck took place, it may have been rapid or a slow deterioration over several hundred years.

The model also fails to account for snow-melt or the effects of heavy rain on snow that can be an important generator of large floods (Newson, 1975). This may be particularly important in the Holocene evolution of Cam Gill Beck, especially during the climatic deterioration of the LIA. However, attempting to predict past volumes of snowfall and the snow-melt hydrology is difficult, with snowmelt floods having very different magnitude/frequency populations to rainstorm events (Church 1988), and are thus presently beyond the scope of this project. Furthermore, snow-melt is often associated with the high but steady release of water that will flood large river systems, whereas the formative events in small catchments such as Cam Gill Beck are probably convective thunderstorms (section 2.5).

8.4.2 Alluvial fan development

Figure 8.10 shows plan views of alluvial fan development. Figure 8.8 and 8.9 show alternations between the accumulation of material on the fan and the movement of sediment through the fan out of the system. The first four frames from 9000 to 6000BP show fan aggradation with a braided channel form. From 5000 to 4000BP there is incision and channel stability with a single channel. This is replaced at 3000BP by a major period of aggradation, with a switch to stability at 2000BP, aggradation at 1000BP and incision by the end of the run. There are other changes in the sediment delivery and fan channel form and deposition as shown in Figure 8.8. The erosion/deposition frames (Figure 8.10) clearly show the periods of aggradation and the multiple channels created by the sediment splaying out over the surface of the fan. Stability/incision is associated with a largely single channel acting to transport material down across the fan and out of the catchment. The change at 3200 BP seems to be driven by the wetter climate which leads to an increase in sediment delivery to the fan. This influx of sediment caused the channel pattern to change and the fan to aggrade. However, some of these changes or switches between aggradation and stability/incision have no such obvious causes, for example those at 6000 and 7200 which occur during dry periods. Furthermore, the largest peak in rainfall (100 to 500 BP) causes incision unlike the aggradation at 3200 BP.

Closer examination shows that these periods of fan aggradation occur when the stream flows to the west, and incision when flowing to the south. Unfortunately this condition seems to be forced by the model's boundary conditions. These allow both sediment and water to flow off the southern edge, but only water off the western side. Therefore when the channel diverts to the western edge the fan aggrades as sediment cannot escape.

At Cam Gill Beck, the fan spills out across the valley floor until it is met by the opposite valley wall and the River Wharfe. When the initial boundary conditions were designed, it was necessary to prevent material eroding from this westerly edge as this is effectively the opposite valley wall, but somehow the effects of the trunk stream had to be incorporated. Trial runs showed that preventing the water and sediment from escaping from this westerly edge forced the fan to develop only in the southerly direction and when water and sediment were both allowed to escape, the fan barely formed at all. Unfortunately it took five months of simulation to discover that the compromise boundary conditions may be heavily influencing the results. Therefore the results from the simulation of the Starbotton alluvial fan evolution must be treated with some caution, especially if direct comparisons are made between the model results and present day fan topography.

Despite these inaccuracies, much can be gleaned from the dynamics of this alluvial fan simulation. Although the switching between aggradation and incision may be influenced in timing and location by the boundary conditions, it is unlikely that the switch itself is caused by them. Indeed, this channel position switching is more likely to be restricted by the boundary conditions as the incorrect aggradation of sediment on the western side will restrict channel movement. This change in fan behaviour, the sudden movement of channel position, pattern and characteristics may be an important interaction. Harvey (1999 pers. comm.) suggested that fans in the UK can be divided up in to two groups. The first type where the threshold between aggradation and dissection is largely event related, and those that lie much closer to intrinsic thresholds where destabilisation may occur without a major triggering event. In this simulation the change at 3200 BP appears to be caused by a sudden increase in flooding like Harvey's event related type. However, all the other changes appear to have no triggering mechanism, especially those at 7300 and 5900 BP which switch from aggrading to incising and from incising to aggrading both at times of identical mild climate. This suggests that the 'switches' may, as Harvey suggested, be caused by instabilities within the system, so that even relatively simple catchments like Cam Gill Beck have the potential to produce a complex response.

This switch may be an important mechanism controlling the connectivity between the tributary and alluvial fan unit and the main trunk river. This simulation shows that there is a sudden change in sediment delivery from the trunk stream to the alluvial fan. Although the volumes were influenced by the boundary conditions, if these were discounted, there is still a shift in sediment delivery, channel position, pattern and thus connectivity. This means that we cannot assume a direct linkage between upland catchments and the valley floor. In upper Wharfedale, for example, Starbotton is one of a series of three fans (the others at Buckden and Kettlewell) and one or more of these fans may have been feeding material into the main valley floor

whilst the others were not. In effect a chain of switches sometimes feeding material into the trunk stream and sometimes not. Therefore, we should not be looking for too strong a link between alluvial fan development and environmental change.
Although inaccurate, the influence of the boundary conditions raises further questions. In real alluvial fans what effect does the underlying topography around the fan have? What are the effects of a trunk river at the base of the fan? Does it trim the toe or does the obstruction caused by the fan block the main trunk river and cause aggradation? This is an area for future research, which could be explored by simulating the development of a range of alluvial fans with different size catchments, slopes and fan deposition areas.

Unfortunately the errors made with this simulation reduce the value of direct comparison to the Starbotton fan. Figure 8.11 shows a contour plot of the depth of material deposited during the 9300 year run and Figure 8.12 how this compares with the present day topography. Despite the boundary conditions probably forcing too much aggradation on the western side, the amount deposited is far less than the present day fan, especially on the southern side. This may be due to the model under-estimating the volume of material produced by Cam Gill Beck for deposition on the fan, but is probably caused by an incorrect initial topography. When creating the initial DEM surface too much material was probably removed from the present day topography, effectively leaving the model with too large a hole to fill. Additionally, the simulation covers only the last 9300 years, whereas some 14 000 years have elapsed since the retreat of the last glaciers. Furthermore, the years immediately following de-glaciation were probably an intensive period of geomorphic activity and fan formation, as the landscape was barely vegetated which coupled with melting ice sheets provided a plentiful supply of sediment and water. There is local evidence of enhanced activity during this time with several melt-water features in the region (Howard and Macklin 1998) so that it is likely that a large proportion of the material presently under Starbotton was formed during this period. In retrospect, a more accurate approach may have been to start with a partial fan. However at Starbotton, as Phillips (1996) stated '*the initial conditions are not just unknown, but unknowable*'

8.5 Conclusion

The long-term simulation of Cam Gill Beck re-affirms the findings of chapter 6, that changes in vegetation cover can dramatically increase catchment response to climate change. However, when averaged over longer periods, dramatic increases in sediment discharge due to climate change are moderated by the sediment supply limited nature of such temperate catchments. Therefore, when examining longer periods (greater than 2500 years), changes in the rates of diffusive slope processes such as creep may be a critical factor. The episodic development of the alluvial fan at the base of Cam Gill Beck suggests that the Holocene behaviour of such fans is not simply related to climate or land-use changes, but may be the result of other unknown factors or instabilities within the system. Finally, this chapter shows that this cellular model is a viable method of simulating the long term evolution of small river catchments and alluvial fans.