Chapter 10

Synthesis and conclusions

10.1 Main conclusions

In chapter one, three main aims were outlined for this study. Firstly to investigate the effects of climate and vegetation cover change on upland rivers, secondly to simulate the role of extreme events and finally to model the Holocene evolution of an upland catchment. Chapters 6, 7, and 8 aimed to answer these questions and concluded that:

1. Vegetation cover and climate change both influence the sediment discharge and evolution of upland river catchments. Whilst climate may have a slightly greater impact, the combination of both climate and vegetation cover changes have a far more significant impact.
2. Examining the role of catastrophic flood events, chapter seven shows how the cumulative effects of many smaller floods generate a greater sediment yield than a single large event. However these large events are important and can drastically alter the nature of the valley floor.
3. Looking at the development of upland catchments over the Holocene, chapter eight used climate and vegetation cover records to simulate the evolution of Cam Gill Beck over the last 9300 years. This showed that there are important long term interactions between climate, vegetation cover and sediment discharge and revealed how soil creep controls sediment supply and therefore, ultimately, yield over extended periods.

10.2 General themes

When reviewing the results from chapters 6 to 9, several common themes emerge. Firstly, that anthropogenic deforestation has left our uplands especially vulnerable to the effects of increased rainfall magnitudes. These findings are especially pertinent in the light that recent GCM simulations predict that global warming may lead to a 15-20% increase in winter rainfall for Northern England (Conway 1998). Whilst this increase is not as great as the scenarios modelled in chapter 6, nor as great as the simulated Little Ice age in chapter 8, this model and other studies (Knox 1993) suggest that landscapes are especially sensitive to small increases in rainfall magnitudes. For Cam Gill Beck, such a predicted 20% increase in rainfall magnitude would lead to a 100 to 150% increase in sediment yield (Figure 10.1). Therefore, deforested upland regions such as Cam Gill Beck, could respond in an unexpectedly dramatic fashion to global warming with channel enlargement and incision, an extension of the drainage network (Figure 10.2) and a substantial increase in sediment delivery. Even heavily forested catchments would respond with an increase in sediment yield of at least 25%, although from a much lower current rate. This has obvious and previously unexpected consequences for erosion, downstream aggradation and braiding, flood control and catchment management. Furthermore, Starbotton sits upon the alluvial fan at the base of Cam Gill Beck, and there are many settlements built on similar fans throughout the Yorkshire Dales. Whilst this is an ideal location to avoid flooding in the main valley floor, a change in the climatic regime might expose them to a substantially increased risk from flooding or geomorphic change from the catchment above the fan. To protect against such change the model results suggest that re-aforestation would be the best measure, stabilising the hillslopes and moderating the flashiness of the storm hydrology.

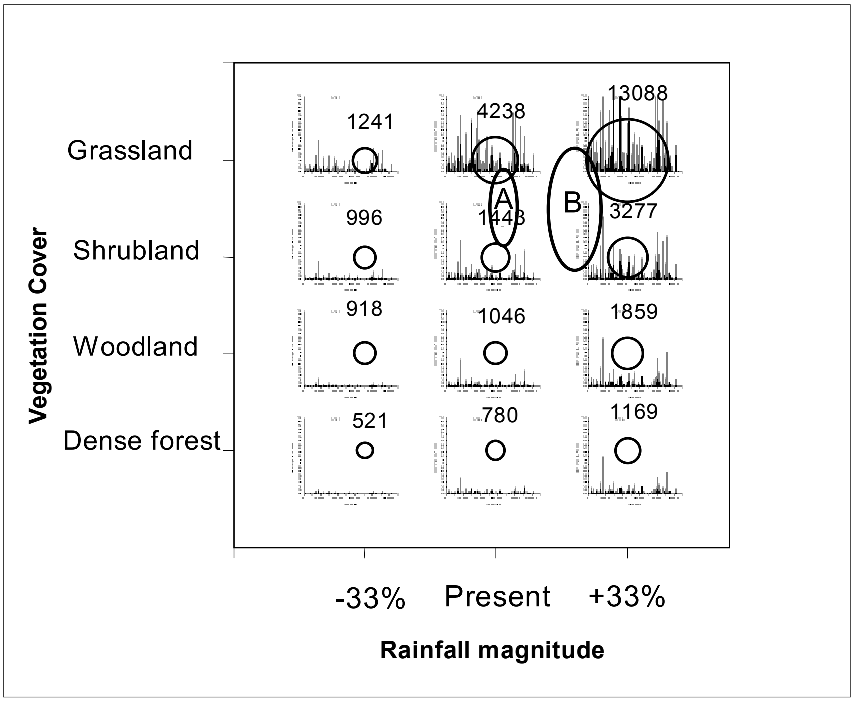

Figure 10.1. Bubble chart showing sediment discharges from chapter6.Ellipse A represents the present day vegetation cover/climate of Cam Gill Beck and B shows the increase in sediment yield caused by global warming forecasts of a 20% increase in rain magnitude.

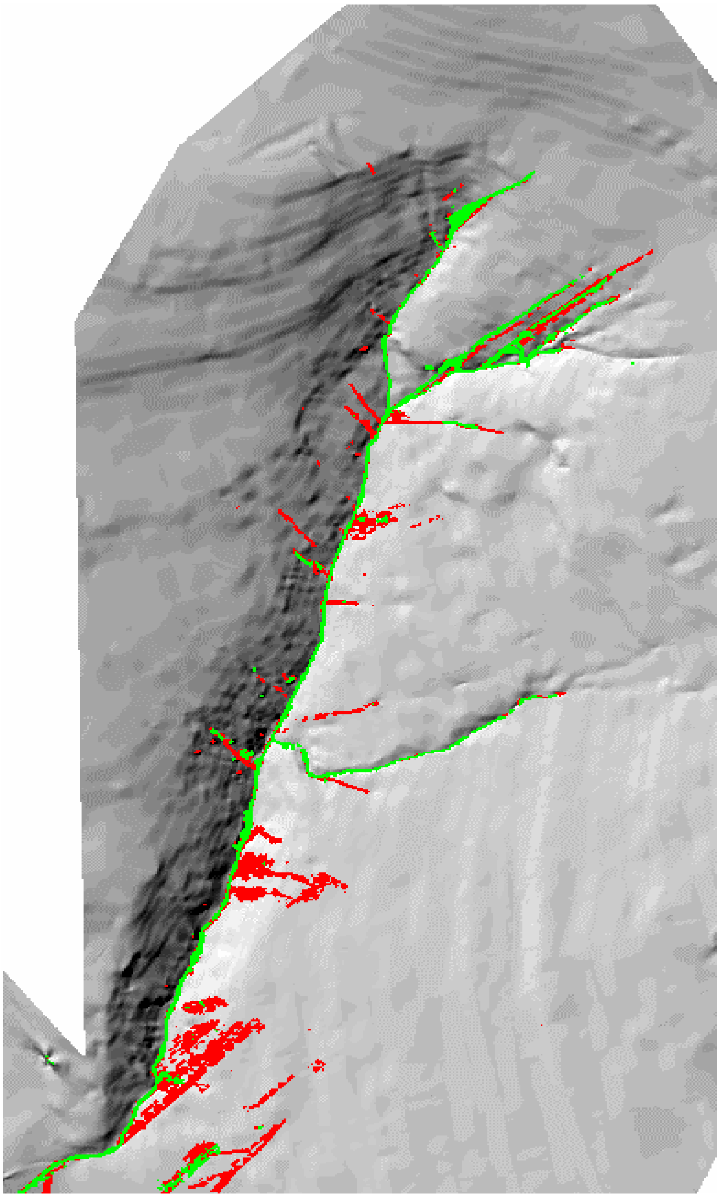

Figure 10.2. Shaded plan view of Cam Gill Beck DEM. Green areas show active channel areas simulated under present day climate and vegetation cover (grassland) conditions and red areas show the increase in drainage network produced by a 33% increase in rainfall magnitude.

A second common theme is the importance of connectivity and slope processes. Whilst the river channel removes material from the catchment, the slopes are the providers of sediment. There will be increases and decreases in the volume of sediment delivered in response to flood magnitude as a more aggressive stream network mines material from new channels (chapter 6.4.1, Figure 6.10) but in the long term the sediment supply from the slopes is the limiting factor (Chapter 8.4.1). The non linear sediment discharge is closely related to the input from landslides

(Chapter 9.4), showing that the level of connectivity between the slopes and river channels is an important element that must be integrated in long term modelling approaches. Furthermore, as this may be the most important process in catchment evolution it must be reliably represented. However, in temperate regions such as the Yorkshire Dales, it is difficult to accurately asses slope process rates due to the short periods of detailed observations (< 100 years) and the long time scale over which these processes operate (>100 years).

Thirdly, these simulations provide fresh evidence about the timing and causality of Holocene evolution in the UK's uplands. Previous workers have linked changes in the alluvial record to climate or land use changes, but the results of chapters 6, 7 and 8 clearly show that it is the combination of both that has produced this record. One of the aims of this study was to ascertain which was the most important factor, and though climate may have a slightly greater impact, the main conclusion is that the effects of climate change combined with deforestation are far greater than each factor acting on its own. The alluvial sequence will however be most closely linked to the flood record as reductions in vegetation cover may increase a catchments capability to produce sediment, but major floods are still needed to transport the extra material. The irregular size of the sediment discharge peaks show that the combination of the climate and vegetation cover change working with a limited sediment supply may be sufficient to drive the sequence of 4 or 5 Holocene river terraces found in many of the UK's river systems. In this simulation there are far more than 5 peaks, but this is a small steep catchment, with little opportunity for buffering. However, the different sizes of the peaks for identical size rainfall periods (Figure 8.4) show how sediment supply and storage, combined with peaks in climate could form the 4 or 5 terrace sequences found in the field. These simulations also warn us to be careful about interpreting solely from extreme flood deposits (Merrett and Macklin 1999), as these may not be an indicator of increases in rainfall magnitude. Whilst causing great change to valley floors they may not as important for sediment movement as previously thought. Furthermore, these results show how little we know about the land-use histories of the UK. Whilst records such as those collated by Barber *et al.* (1994) and Anderson *et al.* (1998) give us a good continuous account of Holocene climate the land use histories are derived from local pollen records and archaeological evidence. However, land use can be highly spatially variable, for example Cam Gill Beck may have remained forested whilst the neighbouring catchment above Kettlewell had been cleared.

10.3 Modelling advances

In answering the questions raised in the introduction, and furthering knowledge surrounding the roles of environmental change on upland catchments, the cellular model described in this thesis represents several advances on previous methodologies.

Firstly, the two-dimensional sediment transport model allows a more realistic representation of fluvial processes, including channel armouring and downstream fining, as well as enabling the storage and re-mobilisation of sediment within bars and over bank deposits. Secondly, the novel routing algorithm rapidly calculates channel flow allowing this model to be applied to an entire catchment instead of a single reach. Thirdly, the inclusion of real-world landscapes allows this model to move away from previous abstract representations, towards a meaningful simulation that can be rigorously validated using field evidence.

Whilst not offering the level of detail that CFD methods provide, this generic cellular model allows the simulation of scenarios that are pertinent to the many aspects of fluvial geomorphology which can only be assessed over substantial historical time spans and whole catchment areas. 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 these with sediment transport to simulate evolving channel patterns and bed-forms (Kirkby 1999). This is partly because changes in bed/floodplain topography can force a frequent re-definition 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 2-3 dimensional representation of erosion and deposition over several grainsizes which, in this study has allowed the simulation of bed armouring and the deposition of fines on lateral bars. Fourthly, CFD 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. Finally, 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.

10.4 Future work

Future work following on from this thesis may take two directions, firstly concentrating on improving the model parameters and operation and secondly applying the model to catchments in different environments over a range of temporal and spatial scales.

10.4.1 Model improvement

The parameters and transport laws used by the model can always be improved and refined. The integration of suspended sediment transport and experimentation with alternative sediment transport laws could also be tried. For example, the calculation of flow depth is a simple representation and improvements may include the use of the Chezy equation, integration of feedbacks involving bed roughness and the introducing of flow momentum effects. Outside of the fluvial areas of the model, improvements to the simple vegetation growth model and introducing spatial variation in both catchment hydrology and rainfall distribution would be worth investigation.

10.4.2 Alternative applications

The models design is generic and could easily be applied to other catchments, the only inputs being a suitable DEM and climate record. It realistically reproduces landforms used in field studies to interpret a fluvial history (e.g. river terraces and alluvial fans; figure 3) and could be used as a tool to investigate numerous geomorphic and engineering problems. There are numerous potential applications for this technique, for example assessing the impact of land management, land use and climate change, identification of zones of river instability, the simulation of alluvial architectures (Bridge & Leeder 1979) and application in different environments. For example, with the addition of different slope process modules, this model would be ideal for application to semi-arid river catchments and possibly the development of gully systems. The scale of study can also changed by altering the relevant scaling parameters. By increasing the grid cell size the model could be applied to much larger catchments. However careful attention must be paid to the effects of running the model with grid cells larger than the channel width. An alternative strategy could be to use parallel programming techniques where separate parts of the catchment are simulated simultaneously on separate computers and the results combined. The temporal scale could also be increased, simulating longer periods than the Holocene. Semi-arid environments may be especially suitable for such studies, as the lower frequency of storms would allow longer periods to be simulated than wetter temperate catchments. Alternatively, the time-scale and spatial areas or study could be reduced. For example, individual flood events could be studied in great detail, decreasing the size of grid cells and increasing the number of active layers to represent a larger stratigraphy.

10.5 Summary

The model presented in this thesis has provided an opportunity to explore the impact of climate change and land use scenarios, in the context of contemporary river and hillslope dynamics, over historically relevant time and space scales. It has been concluded that river catchments respond significantly to changes in vegetation cover and climate, but are disproportionately susceptible to changes in both together, and may therefore respond dramatically to future environmental change.