Chapter 9

The role of non-linear processes

9.1 Introduction

Chapters 6, 7 and 8 have described applications of the model at a variety of scales and concentrated on both quantitative and qualitative results. These have demonstrated that a river catchment is a dynamic system within which there are many interacting processes. Some of these interactions are non-linear, giving a complex response, which can be characteristic of chaotic systems (3.5.4). This chapter takes examples from chapters 6-8 as well as results from additional simulations detailing examples of apparent chaotic behaviour, and discusses their importance and relevance.

9.2 Examples of non linearity

Examples of apparent non-linear behaviour have already been highlighted in chapters 6, 7 and 8, and these will be used together with results from another model run. This simulation was carried out on a 1m grid cell size DEM with no vegetation cover and grainsize conditions as used in previous chapters. Fifteen equal sized floods with a maximum discharge of $1.5m^3s^{-1}$ were simulated with the elevations between each flood saved and used to calculate the volume of material eroded or deposited. Additional simulations were carried out with the mass movement functions disabled to investigate the causes of sediment discharge. Examples of non-linear behaviour from both this run and chapters 6, 7 and 8 can be drawn into two groups, non linear sediment discharges and the landforms produced.

9.2.1 Non-linear sediment discharges

Figure 9.1 shows the sediment discharge from the run carried out for this chapter. The first five floods give a large sediment discharge, as fines were removed from the system. Subsequently, the catchment displays a deterministic non-linear pattern of behaviour, with irregular peaks in the sediment discharge. This may be attributed to the movement of small 'slugs' (Nicholas *et al.* 1995) of sediment downstream and the consequent re-mobilisation of these in later floods as discussed in 7.5. Other simulations, show these peaks in activity can be also be linked to the input of landslides, mass movement producing an input of hillslope fines to the armoured channel. Episodes of fluvial erosion and deposition correspond largely with the rising and falling limbs, respectively, of the hydrograph again as observed in 7.5. However, there are sporadic episodes of activity during periods of low flow resulting again from the input of small landslips which could be likened to bank failure. Figure 9.2 details sediment discharges from chapter 6, showing how these non-linear fluctuations continue even when averaged over ten years.

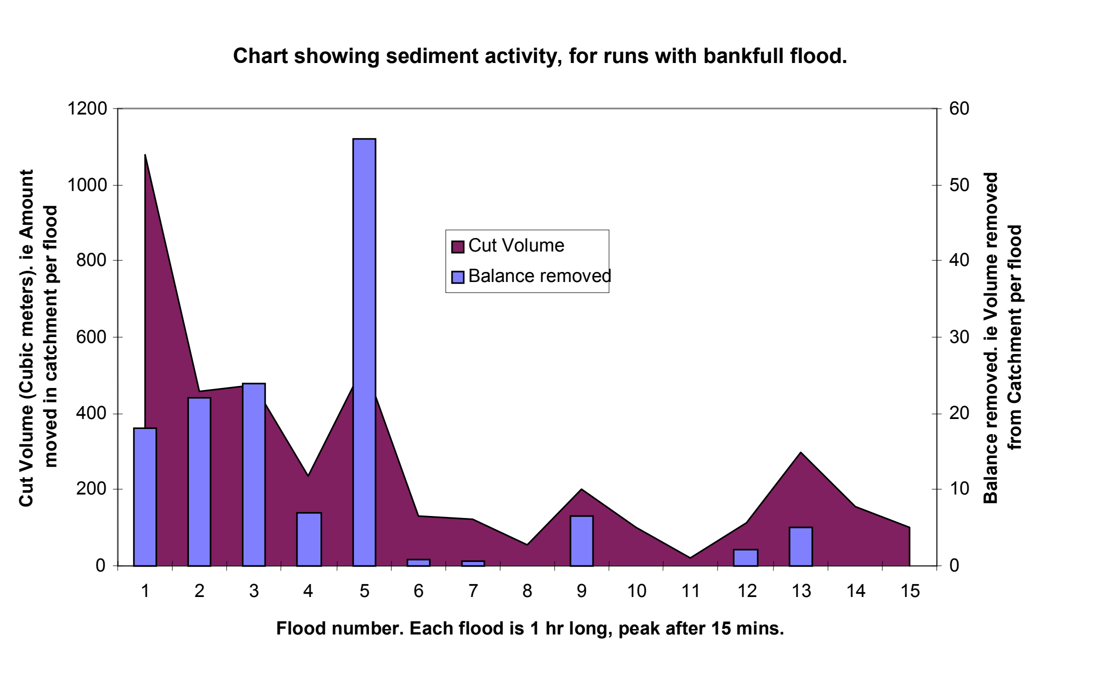

Figure 9.1 Graph showing volume of sediment moved and removed from the catchment for each flood.

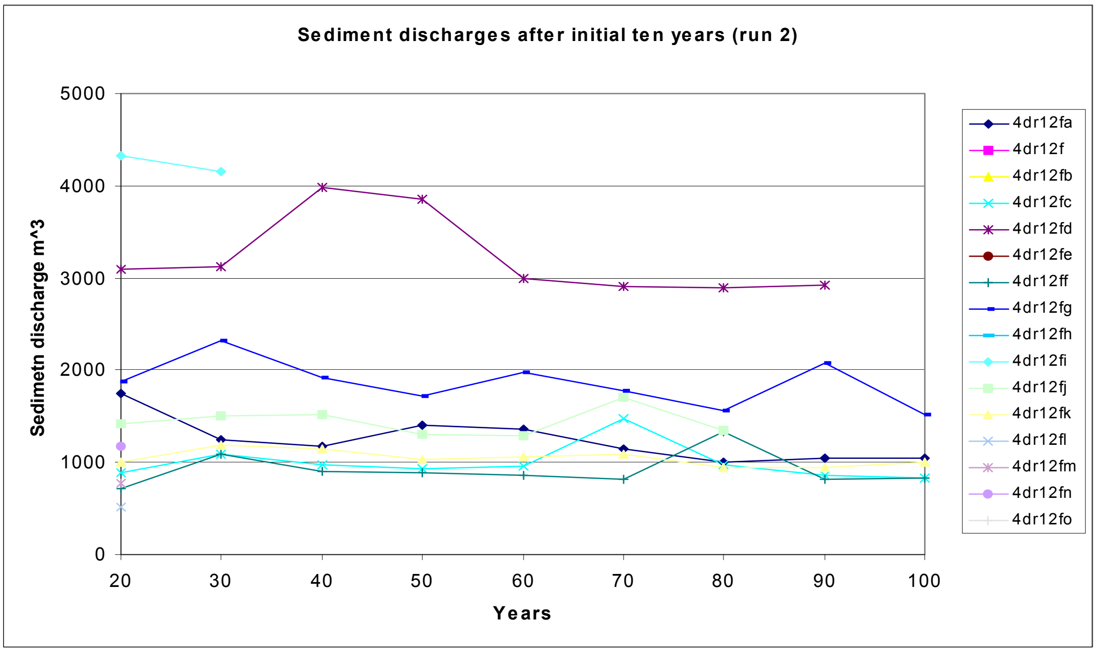

Figure 9.2. Sediment Discharge averaged over ten years from chapter 6.

9.2.2 Land form development

Figures 9.4 and 9.5 show valley floor evolution at the confluence of the two main upland channels. Figure 9.4 shows the initial conditions, where a small discharge has been applied to the catchment and Figure 9.5 shows the same region after the fifteen floods. These views show the development of several features. The series of flood events have led to the development of a fan at the mouth of the right hand tributary, formed from fines eroded in upland areas. This has caused the widening of the channel opposite and downstream. During the rising and falling limb of the hydrograph, a multiple channel forms, as the large sediment influx causes the channel to diverge and converge. Figure 9.6 corroborates these observations, showing the grainsize distribution for the section after the fifteen floods, with 'armouring' down the centre of the multiple channels and fine material deposited at the base of the fan.

Figure 9.7 details the section outlined in Figure 9.3. Figure 9.7a shows a shaded plan view, Figure 9.7b the grainsize and 9.7c four cross sections. Here flow (from top to bottom) emerges from a narrow section into a wider part of the valley floor resulting in deposition and the formation of a coarse deposit on the right bank of the channel. 30m downstream the tail of this deposit is being eroded as the valley floor narrows and steepens, forming a deposit of fines on the left bank. These features are similar to a boulder berm and side bar / terrace in plan form, elevation and grainsize. Cross sections from the model (Figure 9.7c) compare favourably with those from a field survey (Figure 9.7d).

Figure 9.8 shows how the stream head section highlighted in Figure 9.3 incises and develops over the 15 floods. This incision and stream head development occurs irregularly despite the same flood being applied, suggesting a non-linear response. Figures 8.11 show how the channel pattern in the alluvial fan changes and avulses from one area to another during the simulation carried out in chapter 8. Whilst one change in particular is probably caused by a sudden shift to a wetter climate (8.5), the others have no obvious cause and may therefore be initiated by non-linear instabilities within the river catchment or alluvial fan itself.

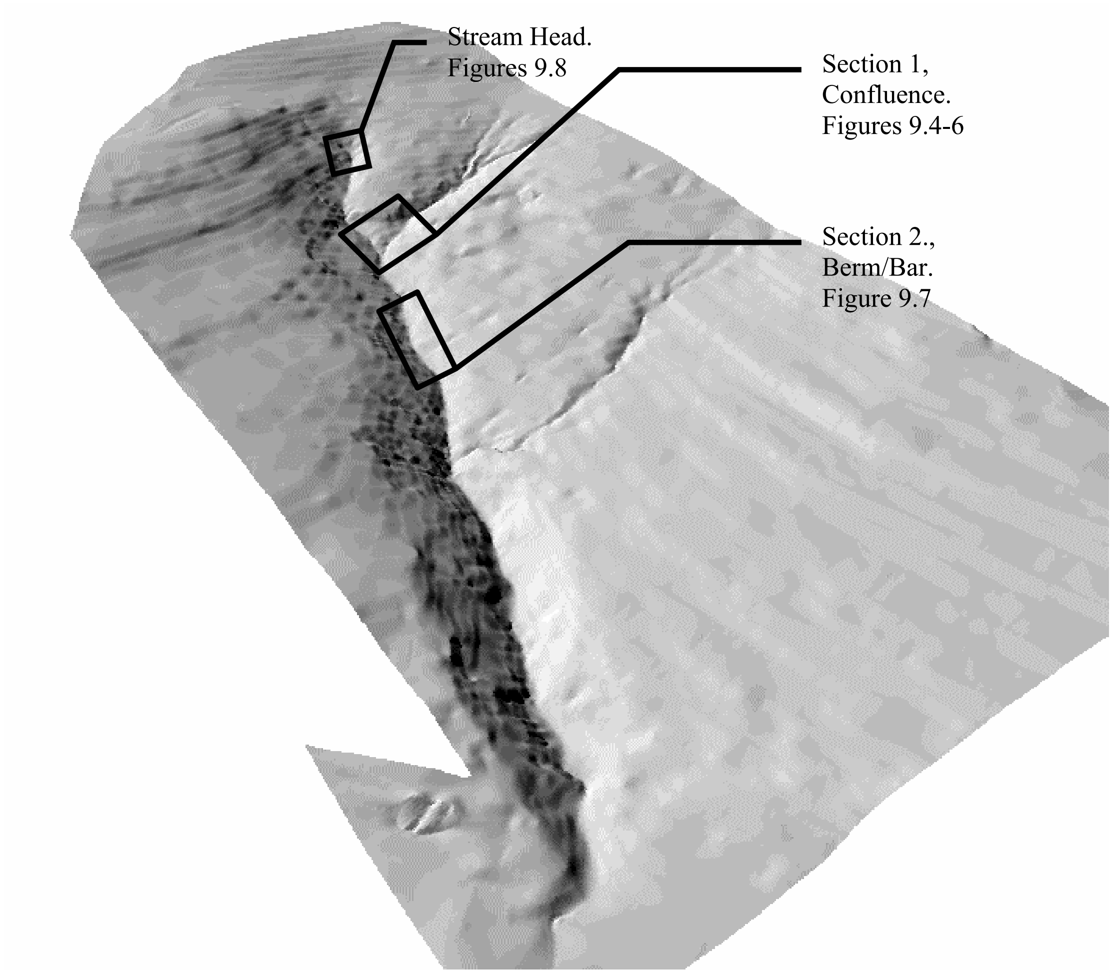

Figure 9.3.Draped image of Cam Gill Beck,detailing locations of Figures 9.4-8.

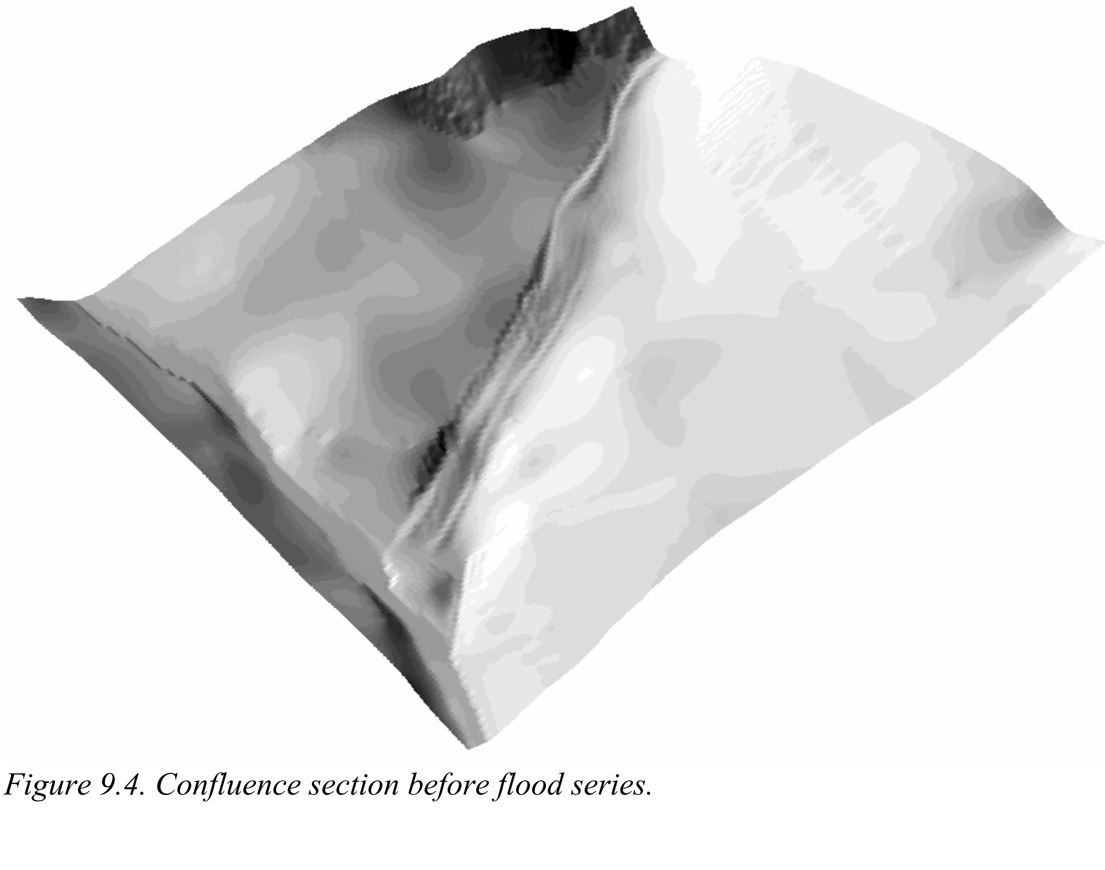

Figure 9.4. Confluence section before flood series.

Figure 9.5. Confluence section after 15 floods of bankfull discharge.

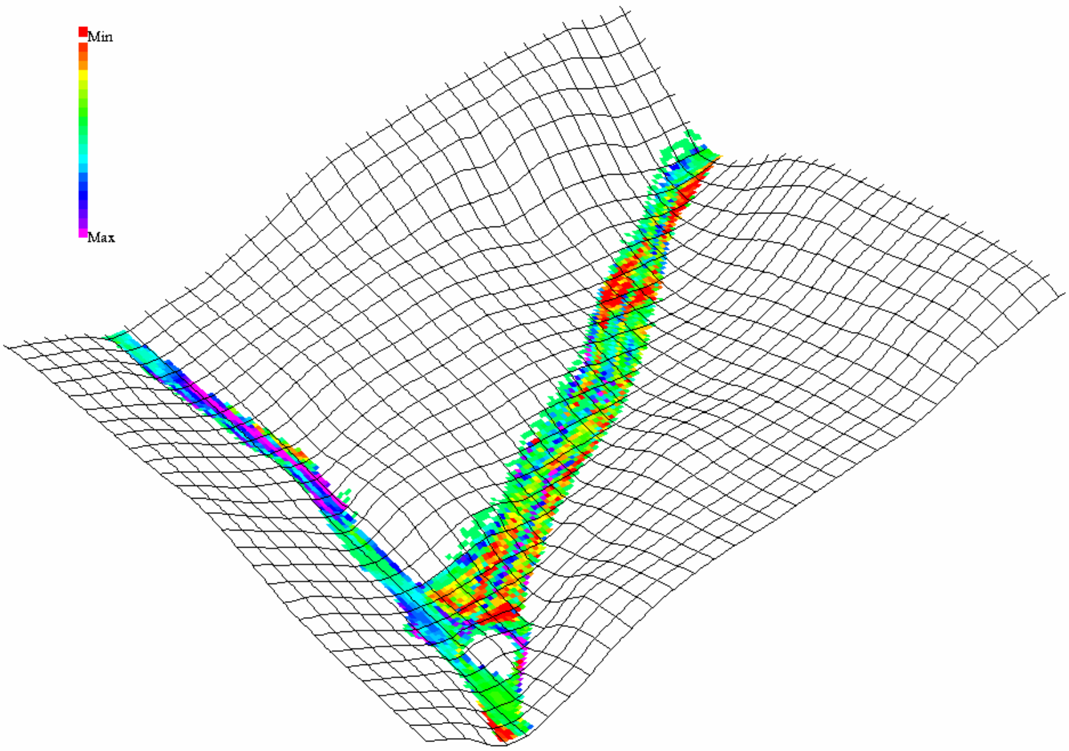

Figure 9.6. Grainsize Composition of confluence section.

Figure 9.7

Figure 9.8 page 1

Figure 9.8 page2

9.3 Discussion

The variations in sediment discharge from 15 identical floods (Figure 9.1) may at first appear to be erroneous, but similar observations have been reported from field studies. For example, Lane and Richards (1997) observed different sediment discharge characteristics from a pro-glacial stream from the same size flood, and sediment rating curves rarely show a simple functional relationship between discharge and sediment transport rates (e.g. Bathurst *et al*., 1987; Lane and Richards 1997). Furthermore, over shorter time scales, bedload 'pulses' have also been observed (Hoey 1992, Nicholas *et al.* 1995). Therefore, the unpredictable short term sediment discharges generated by the model demonstrate a partial decoupling between the hydrograph and sediment transport processes. That is, there cannot be much sediment transport without a flood, but a flood does not always lead to sediment transport.

When the landslide module is disabled, there is a substantial reduction in the magnitude of sediment pulses, indicating that mass movement is an essential supply of sediment to the channel. However, the non-linear discharge still continues, implying that the re-mobilisation and dispersal of sediment through out the basin is also an important aspect of the systems behaviour. For example, the deposition of a clast may result in the lateral migration of the channel towards a pre-existing deposit, re-mobilising fresh material. Figures 9.4 and 9.5 provides an example of such behaviour, where the braided channel pattern moves laterally, re-working sediment. However, these interactions are complex, as Lane and Richards (1997) state: *'Discharge and sediment supply act together to control river channel change'.* Furthermore, the grainsize and channel armouring will also have an effect upon sediment re-working, as Hoey and Ferguson (1997) stated '*Surface grain size adjustment is potentially an important degree of freedom in river response to any environmental change'.* Figure 9.6 provides an example of this, showing areas of fines on lower slopes where sediment is stored and coarser grainsize where there is armouring in the channels. Throughout the fifteen runs, there is a constant interaction between the channel and these stores, being re-mobilised and dispersed on some floods, yet left on others.

Figure 9.2 demonstrates that this non-linear sediment discharge continues over longer time scales, despite being averaged over 10 years. Whilst the variations are far smaller than those from the 15 floods, they still change by up to 30%. The implication of this is that the short term sediment fluctuations described above cannot be completely removed by averaging over long periods.

Over the course of the 15 floods, the stream head highlighted (figure 9.8) incises, producing a lobe of sediment below. However, close examination of these frames show that this development occurs irregularly, not gradually, with some floods generating considerable incision, others none. Therefore, as the floods are equal, this may be caused by instability generated from the feedbacks between incision and mass movement. Furthermore, this instability may be another factor contributing to the irregular sediment discharge.

Switches in the channel position on the alluvial fan simulated in chapter 8, and the switches between fan aggradation and incision (8.5) do not have an obvious cause. One at 3200BP appears to be caused by a sudden shift to a wetter climate, but the other switches occur during periods of moderate climate and small floods suggesting an internal instability.

The one additional example of potentially chaotic behaviour is the model's sensitivity to initial conditions. When the elevation data is saved to file, the values are truncated to 6 decimal places. When these data is re-loaded and the model run, different results emerge from when the values are retained in the computer memory at their full length.

Are all these complex responses simply a condition of the model design? What happens to this response if more processes are integrated or improved, such as a better hydrological model, or slope representation? Sensitivity testing (4.5) hints that whilst altering the laws used gives different results, they remain similar. For example with Figure 9.7, if this is run with a different sediment transport law, the exact dimensions of the berm / terrace sections are different, but their form and location is the same. Computational instabilities could explain non linear outputs, but to maintain stability, the amount eroded or deposited between each cell is limited to within a few percent of the local slope. Furthermore, the results are deterministically non linear, not stochastic. This means that simulations carried out with identical initial conditions on the same computer give exactly the same results.

The implications of a model generating such non-linear responses are considerable. This means we cannot rely upon a simple regression based model to predict behaviour, because the response of the system is complex. The spatially distributed nature of the system means that we have to account for processes throughout the basin. It is not the ‘random’ input from weather systems that is solely responsible for the non-linear behaviour of our fluvial systems, there is an inherent chaotic instability within the whole system. This instability can partly be accounted for by averaging the values, yet even when the ten year means ten year sections (Figure 9.2) show significant fluctuations. Unfortunately, nearly all contemporary fluvial modelling schemes, fail to account for non linear behaviour in any form and therefore may be wrong. Indeed the inability to successfully apply one law with one set of parameters universally (e.g. sediment transport equations) bears testament to this.

The level of non-linear behaviour seems intrinsically linked to the issue of resolution. Should we account for every minor detail or can a distribution or average accurately represent a situation? For example, the importance of a large landslip in changing the landscape is obvious, but can we ignore the grains movement? If we assume our landscape to be a chaotic system, highly sensitive to initial conditions, then the grain’s action is important, as is the butterfly effect to a climate modeller. Lane and Richards (1997) seem to confirm this idea, suggesting that fluvial system behaviour is highly dependent upon its context. This presents a major problem for a modeller in selecting an appropriate level of resolution. For example, if studying the Rhine Basin, how far should we account for the turbulence generated by the movement of a 5mm clast? In principle the answer is not clear, as there are critical moments when it influences the outcome, but in practice computational limits effectively exclude such a high level of detail. The cellular approach used here directly addresses these issues as the effects of catchment scale processes such as hydrology and slope processes can be studied, as well as incorporating the smaller scale catchment dynamics such as the in channel storage and re-mobilisation of sediment. This provides a clear advantage over previous models in which separate slope and channel modules are coupled together. With these schemes, different spatial and time scales have to be resolved and feedbacks have to be explicitly defined. Furthermore, this model demonstrates synergistic behaviour, showing that the overall basin behaviour cannot be simulated simply from the sum of its individual component processes.

Even using a high resolution model as described here, some processes are averaged such as sediment transport. If catchment behaviour is unstable, and sensitive to small perturbations in initial conditions, how can we ever incorporate changes that are so small to appear inconsequential, yet may prove to be important? Paola (1996) treats a 'whole' braided river system as a stochastic one, and finds the addition of a random element contributes to the accuracy of estimates of total flow and sediment flux. However, a chaotic system whilst appearing to give stochastic response is in fact deterministic. The LAB (Bridge and Leeder 1979) model of alluvial architecture is driven by an avulsion frequency, derived from a probability distribution around an observed mean. Whilst there are many other limitations to their approach (Heller and Paola 1996), similar approximations may represent one answer. Another approach may take the form of an AI answer, such as a fuzzy logic application or 'training' a neural net to incorporate this chaotic element. However, we may never get a true deterministic answer, having to rely upon an average of model runs, as climate modellers do.

9.4 Conclusions

Non linearities in basins are crucially important at all scales and we will never be able to fully account for all of them. It is not practical for large basin scale models to simulate three-dimensional flow around clasts, yet the broader impact of such small scales must be incorporated. Similarly, three-dimensional coupled flow and sediment transport models will have to account for irregularities in the time and space distribution of the arrival of sediment from upstream. Ultimately, the accurate incorporation of such factors will determine the power of our next generation of geomorphological models. Given the increases in computer power and advances in modelling techniques, it may prove that these 'chaotic' terms are the most important.