Available online at www.sciencedirect.com

Geomorphology 90 (2007) 192–207

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

Cellular modelling of river catchments and reaches: Advantages, limitations and prospects

T.J. Coulthard [a,*], D.M. Hicks [b], M.J. Van De Wiel [c]

[a] *Department of Geography, University of Hull, Hull, HU6 7RX, UK*
[b] *NIWA, Christchurch, New Zealand*
[c] *Department of Geography, University of Western Ontario, London, Ontario, Canada N6A 5C2*

Accepted 15 October 2006
Available online 4 May 2007

Abstract

The last decade has witnessed the development of a series of cellular models that simulate the processes operating within river channels and drive their geomorphic evolution. Their proliferation can be partly attributed to the relative simplicity of cellular models and their ability to address some of the shortcomings of other numerical models. By using relaxed interpretations of the equations determining fluid flow, cellular models allow rapid solutions of water depths and velocities. These can then be used to drive (usually) conventional sediment transport relations to determine erosion and deposition and alter the channel form. The key advance of using these physically based yet simplified approaches is that they allow us to apply models to a range of spatial scales (1–100 km^2) and time periods (1–100 years) that are especially relevant to contemporary management and fluvial studies.

However, these approaches are not without their limitations and technical problems. This paper reviews the findings of nearly 10 years of research into modelling fluvial systems with cellular techniques, principally focusing on improvements in routing water and how fluvial erosion and deposition (including lateral erosion) are represented. These ideas are illustrated using sample simulations of the River Teifi, Wales. A detailed case study is then presented, demonstrating how cellular models can explore the interactions between vegetation and the morphological dynamics of the braided Waitaki River, New Zealand. Finally, difficulties associated with model validation and the problems, prospects and future issues important to the further development and application of these cellular fluvial models are outlined.

Keywords: Cellular models; CAESAR; Sediment transport; Flow routing; Meandering; Validation

1. Introduction

A broad array of numerical models has been developed with the aim of modelling river systems. These range from simple 1-dimensional models of flood inundation, through complex 2- and 3-dimensional simulations of flow patterns within channels (Lane, 1998), to models of whole river basin evolution over geological time scales (Coulthard, 2001; Willgoose, 2005; Codilean et al., 2006). However, despite this range of models and their success, two fundamental problems have significantly hampered their applicability: (1) the integration of sediment transport with fluid flow and (2) issues relating to temporal and spatial scales.

---

[*] Corresponding author.
E-mail address: T.Coulthard@hull.ac.uk (T.J. Coulthard).

0169-555X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2006.10.030

1.1. Sediment transport integration

Comparatively few 1-, 2- and 3-D flow models for channels and floodplains have attempted to integrate sediment transport, erosion and deposition. This is an important omission, as alluvial channels are not static or fixed; their form is generated by the interactions of the flow with sediment transport processes. Water erodes, transports and deposits the sediment, yet sediment arrangement ultimately determines where the water flows. Therefore, any model that fails to account for this can only be capable of providing a snapshot of flow patterns within the context of a river's lifetime. This may be acceptable if the channel does not change (e.g. is non-alluvial or heavily engineered) or if we are only interested in relatively short periods of study where the channel form will not change significantly (e.g. individual floods). But this imposes obvious limitations on the time scales that can usefully be modelled. There are, however, good reasons for the omission of sediment transport from such models.

1. When a model erodes and deposits sediment, it changes the topography, or morphology, of the river channel. This causes two problems. Firstly, the grid or mesh used to represent the channel and floodplain within the model has to be re-sized and possibly re-defined. Depending upon the model structure, recalculation of the mesh or grid can be time consuming. Secondly, if the topography is changed then the flow field must be re-calculated in order to determine how changes in the river bed and banks will alter the flow patterns. In a complex CFD (computational fluid dynamics) 2- or 3-dimensional flow model, calculation of the flow field (flow depths and velocities) may take several minutes or even hours to complete. If this is to be carried out for every time step of the model's operation it can substantially impede the progress of the model.
2. The introduction of sediment adds another layer of complexity to the modelling process. Sediment has to be entrained, deposited and moved from cell to cell. This requires a whole set of new processes to be integrated, such as changes in sediment concentration in the water column or across the channel, fall velocities, entrainment conditions, flocculation processes, etc. This can create fresh uncertainties as well as computational constraints. For example, during operation of the CAESAR model discussed later, calculating sediment transport processes occupies over 70% of the model run time.
3. This added complexity is compounded by problems with our comprehension of sediment transport processes. Even though we only have a limited understanding of water flow processes in channels, we have far less knowledge of how sediment transport processes operate (see later).

Nevertheless, sediment transport has been integrated into 1-, 2- and 3-D models. Brunner and Gibson (2005) have added a sediment transport component into the 1-D HEC-RAS model, and Nicholas and Walling (1998) have added a suspended sediment transport and deposition component to a 2-D model which has successfully modelled field-observed deposition patterns. Fang and Wang (2000) and Rüther and Olsen (2005) have integrated suspended sediment transport into a 3-D flow model, and Kassem and Chaudhry (2002) linked bedload transport to a 2-D model to simulate the development of a channel bend which was favourably compared to laboratory results. Van De Wiel and Darby (2004) also simulated the development of bed topography and bank erosion along a meandering channel. There are several limitations with the models described above, which reflect the difficulties described in points 1–3. Most are restricted to simulating a single bend or short reach of a river, and some have limited process representation, for example only simulating suspended sediment deposition, forgoing bedload transport and entrainment.

1.2. Scale issues

Despite the wide range of fluvial models available, there are few that simulate over time scales of 1–100 years and at spatial scales of 1–100 km^2. These scales are especially pertinent as they correspond with engineering time scales and human life spans and memory, as well as with most periods of detailed records and measurements. This gap largely arises for computational reasons and reflects model design. As previously mentioned, modelling flow (and especially sediment transport) is complex and the time taken to calculate flow fields can restrict complex flow models to apply only to reaches of limited extent. For 2- and 3-D CFD models this is because the time taken to calculate the flow field over this grid largely depends on the number of cells or points it contains and its complexity. A simple rectangular channel on a flat floodplain can be represented with a few points (100's to 1000's), but if we include the topographic heterogeneities found in natural channels we need far more points to include the channel and floodplain features that can influence flow.

An extreme example is that, to model a complex 2 km by 1 km reach of the Waitaki braided river in New Zealand, over 1.5 million grid cells were required, that took several hours to calculate a flow field using Hydro2De (Hicks, personal communication). This presents a time and space scale dilemma, as small areas can be simulated in high detail for short periods, yet to model larger areas for longer times, the spatial resolution has to be compromised in ways that can reduce model accuracy and application.

Conversely, in order to simulate large areas over long time periods, landscape evolution models (LEM's) have been developed. These typically operate over entire catchments at timescales ranging from centuries to millions of years. A brief synopsis of their advantages and limitations follows, but for more in-depth reviews and discussion, see Coulthard (2001), Willgoose (2005), Codilean et al. (2006) and Van De Wiel et al. (in press). In order to simulate much longer time periods and larger areas, LEM's make a number of simplifications. Spatially, grid cells may represent 50 by 50 m to 200 by 200 m areas of the catchment modelled. Temporally they may use time steps ranging from days to a century, and erosional processes may be estimated as time-averages instead of being calculated for individual events (e.g. for a flood). Fluvial processes are simplified with flow frequently only routed in the direction of steepest descent, which allows convergent flow patterns (e.g. dendritic drainage networks) but not divergent (e.g. in braided channels or on alluvial fans). Furthermore, river channels can only be one cell wide so small channels (e.g. 10 m width) are represented within a much larger cell (e.g. 100 m by 100 m). Unlike the more complex flow models, these LEM's all simulate fluvial erosion and deposition and this allows them to model, for example, how catchment morphology can change in response to tectonics (e.g. Willgoose et al., 1991; Tucker and Slingerland, 1994) and climate changes (Tucker and Slingerland, 1997). LEM's are ideal for exploring long term, large scale interactions between tectonics, climate, fluvial and slope processes, but are less well suited to studying shorter time periods. This is because of the averaging of erosional rates across several events, and because some of the processes modelled may be inappropriate and the coarse spatial resolution can blur the results. For example, to simulate how a 20 km reach of river may respond to changes in flood frequency and magnitude over a 100-year period, 50–100 m grid cells would be too coarse to represent the necessary detail in floodplain and channel topography. Furthermore, processes such as slope runoff and tectonic uplift could be unimportant, yet there may be locations where divergent channel flow must be adequately represented.

This presents somewhat of a dichotomy of model types, with a gap between high resolution yet computationally demanding flow models, and coarse resolution models (both in time and space) of long term catchment development. Neither approach would appear ideal for engineers, or for researchers who may require a model that includes the important interactions of flow and sediment, and that operates over time scales of 1–100 years and medium spatial scales.

Over the last ten years, several ‘reduced complexity’ cellular models have been developed that are beginning to fill this scale gap and address many of these issues. Cellular models in geomorphology can be defined as representing the modelled landscape with a grid of cells, over which the development of the landscape is determined by the interactions between cells (for example fluxes of water and sediment) using rules based on simplifications of the governing physics (Nicholas, 2005). In fluvial geomorphology, cellular models use simplified or ‘relaxed’ versions of the complex flow equations used in CFD models. This allows a substantial increase in speed of operation, which in turn enables them to be applied to long reaches and large catchments over ‘useful’ time scales. Importantly, the increase in computational speed and simplicity also allows these models to include sediment transport processes between cells, meaning that morphological change can also be modelled.

The first of these cellular models was the braided river model of Murray and Paola (1994). This simulated the development of a braided river by routing water discharge over a grid of cells representing the channel and braid plain according to local variations in bed slope. Erosion within these cells was then carried out according to simple discharge-dependent erosion rules, and the eroded material was transported to adjacent cells again according to bed slope. Their simple flow model allowed divergent and convergent flow, and importantly the width of channels was represented across one or more cells. There were no calculations of depth, momentum or velocity yet the model produced qualitatively realistic braided patterns. Importantly, it reproduced the *dynamic behaviour* of a braided channel with the downstream and lateral migration of bars and channels. By simplifying (sometimes grossly) the laws of physics (Lane, 2005), Murray and Paola (1994) recreated the basic conditions that cause a river to braid: laterally unconstrained flow, mobile bed material and erodible banks. This simple model represented a paradigm shift in both how we look at braided rivers and how we model them. For fluvial models, it indicated that perhaps we do not have to pursue reductionist approaches by trying to simulate every process operating within a river channel in great detail. It also raised the possibility of simulating the general behaviour of fluvial systems using a far simpler approach. This 'experimental' approach is important for researchers, as often a qualitative understanding of the dynamics of a system is more important than a quantitative solution.

Following their 1994 paper, Murray and Paola (1997) carried out an extensive review of their model and subsequently integrated a simple vegetation growth model to examine how stabilizing the braid plain with vegetation would alter the channel pattern (Murray and Paola, 2003). More recently, Doeschl-Wilson and Ashmore (2005) compared results from the Murray and Paola model with experiments from a flume model of a braided stream and found that although the numerical model can adequately predict general flow patterns in the flume, it had shortcomings in predicting flow depth and velocity. Though this may be taking the capabilities of the Murray and Paola model too far, as it was never intended to be a scale model of a braided river prototype *per se*, but was designed to simulate the generic dynamic behaviour of braided systems (Paola, personal communication). The Murray and Paola model also inspired the development of a series of similar cellular models. Coulthard et al. (1996, 1998) developed a cellular automaton model of river catchment evolution that was further developed into the CAESAR model (Coulthard et al., 2000, 2002, 2005). This model built upon the flow routing methodology developed by Murray and Paola (1994, 1997) by including a calculation of flow depth, a more detailed representation of sediment transport using multiple grain sizes, and hillslope processes (e.g. landsliding and soil creep). CAESAR has been applied to a range of river catchments and reaches (4 to 40 km^2) with grid cell sizes ranging from 2 m by 2 m to 50 m by 50 m. A full description of the CAESAR model can be found in Van De Wiel et al. (2007-this issue). Thomas and Nicholas (2002) developed a cellular model of braided rivers (termed CRS) that used a flow model that built upon and refined the Murray and Paola method. They applied this to a 470 by 230 m reach of the Aroca River, New Zealand with 1 m grid cells, and favourably compared the simulated inundation extents and flow velocities to results from a 2-D CFD model of the same reach (Hydro2de). Cox et al. (2005) have also compared and reviewed the flow routing capabilities of the Murray and Paola method, the CRS and CAESAR models. There is also a series of reduced complexity flood inundation models based upon the Lisflood model (Bates and De Roo, 2000), which uses kinematic wave equations to route a wave of water down the main river channel, then where banks are overtopped uses a cellular algorithm to route flow across the floodplain.

Nicholas (2005) outlined the principles and issues of cellular modelling in fluvial geomorphology, commenting that cellular models represent "one of the most important advances in fluvial geomorphology over the past decade". However, Nicholas (2005) notes that there are technical issues, such as flow routing algorithms that tend to concentrate flow disproportionately, and many difficulties with validation. Nevertheless, Nicholas (2005) recognises the significant potential for multi-scenario 'what if' modelling and the capability for simulating extended time scales that can, for example, allow the effects of climate change on fluvial geomorphology to be modelled. On a more philosophical note, Nicholas (2005) comments that cellular models may also encourage open mindedness when developing models, and that they can challenge reductionist ideals.

As noted above, these recent model developments provide considerable potential to simulate morphological change in river catchments and reaches over pertinent time and space scales (e.g. 1–100 years and 1–100 km^2). The defining qualities of these cellular models are their operation over these 'intermediate' time and space scales; their inclusion of erosion, deposition and morphological change; and the way that within the model channels are treated as one or more cells wide. In this paper, we outline some of the major issues facing these new 'reduced complexity' cellular models and discuss ways in which they may be solved. These issues are discussed in relation to the three areas of water routing, erosion and deposition, and lateral erosion. We then illustrate how these cellular models can be applied, explore their limitations, and finally discuss the implications for the future of cellular models in fluvial geomorphology.

2. Water routing issues

A flood passes down a river as a wave that gradually attenuates downstream. The size and timing of the passage of this wave depend upon the volume of the water and how it interacts with the channel and floodplain — both downstream and upstream. For example, high flow floodplain inundation reduces the volume of water transmitted downstream in-channel, which may then reduce the extent of inundation downstream. Ideally, numerical models of river flow should integrate such 'non-steady' flow, but this imposes significant computational restrictions upon the operation of a model. If we develop a hypothetical cellular model and divide the reach of channel and floodplain we wish to model into grid cells, we then have to move water between grid cells. Simply described, volumes of water should be routed from cell to cell as a function of (for example) the volume of water in the contributing cell and the slope between that and the receiving cells. However, we are restricted in our calculations, because attempting to use too high a time step and move too much water from one cell to another, can result in a spiky or unstable water surface. In other words, the passage of water across a modelled floodplain has to be iterative and the cells have to fill up gradually from the contributing cells. This may not be especially restrictive across a small floodplain, but if we have a reach of c.1000 cells long, it may take at least (if not substantially more than) 1000 iterations for the water to reach the outlet. A second, similar computational limitation of non-steady flow models is that water cannot be routed between cells faster than it is flowing, otherwise instabilities can develop (this is a violation of what is known as the Courant condition). Hence, the simulated time step must be set or adjusted dynamically according to the calculated flow velocity. For example, a grid cell spacing of 1 m, with flow at 2 m s^{-1}, necessitates a time step of 0.5 s or less. Therefore, non-steady flow models can be computationally slow.

To increase the speed of operation, the Murray and Paola model, CAESAR and CRS all use a steady flow solution of the flow field. These models do not route a flood wave through a reach, instead they route the same volume of water through the entire reach (or catchment). Hence, increases or decreases in discharge as a flood passes can be simulated as quasi-steady flow, where the changes are applied synchronously across the whole reach. The Murray and Paola (1994) model 'pushes' the discharge to the three cells in front (in the general direction of flow down a reach) according to the relative bed slopes between the contributing cell and the receiving cells. This was a simple and effective approximation, but only allowed water to flow up to 45° from the main direction of the valley floor or braid plain. Thomas and Nicholas (2002) improved this substantially by routing to the 5 (and subsequently 7) cells in front, allowing water to flow to approximately 80° from the main direction. The differences this makes are clearly illustrated in Fig. 1, where the same flow is routed down a reach of the braided Waitaki River, New Zealand. Here the Murray and Paola routing method restricts flow to a central portion, whereas the Thomas and Nicholas CRS scheme covers a far wider proportion of the braid plain.

Importantly, these quasi-steady flow methods allow water depths or distributions to be calculated across the

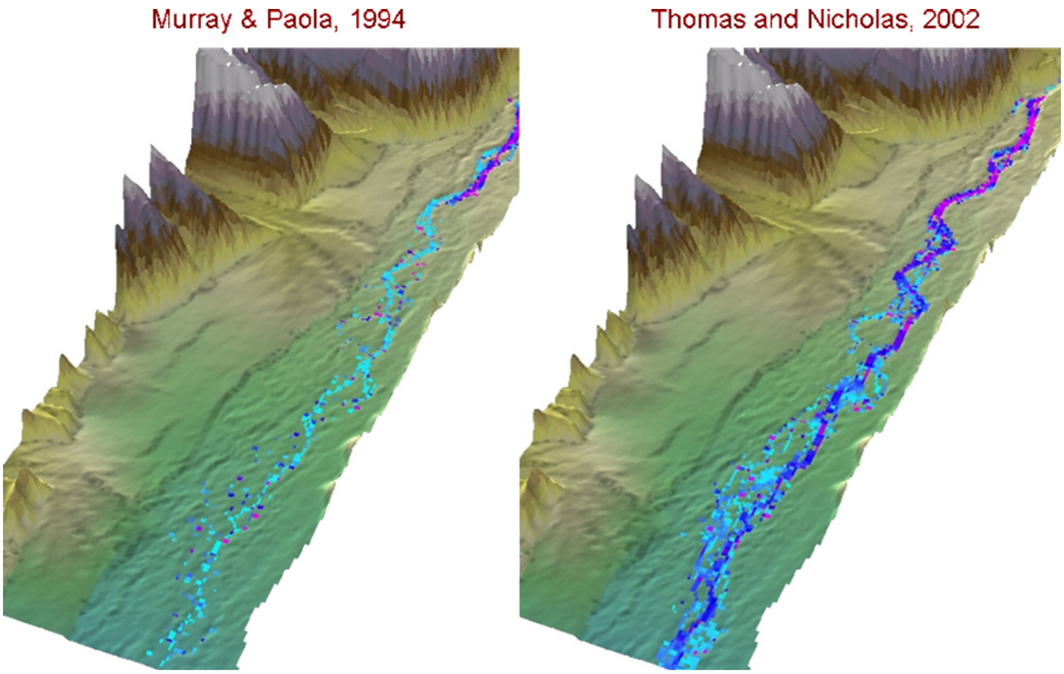

Fig. 1. A comparison of water routing algorithms over a 20 by 4 km DEM (50 m resolution) of the Waitaki Braided river, New Zealand. The image to the left is using Murray and Paola's (1994) method of routing to the three cells in front, and the image to the right uses Thomas and Nicholas's (2002) CRS model that routes to the seven cells in front.

whole grid with one set of calculations, as opposed to the iterative solution required by the non-steady flow methods. However, the main limitation with both these schemes is that they only route in one general direction. This approach may be appropriate for many braided reaches, but many rivers, especially with meandering patterns, have sections where flow directions are the opposite to that of the main valley floor slope. To overcome these problems, the CAESAR model uses a scanning algorithm that 'pushes' water across a grid to the cells in front (as in the Murray and Paola and CRS methods) but does this in four directions (left, right, up and down), noting the maximum flow depth at a point from all of the scans. This maximum depth is very close to that calculated by using conventional multiple flow routing algorithms, but the method is much faster. Further details of this method are provided in Coulthard et al. (2002) and in Van De Wiel et al. (2007-this issue). The limitations of the Murray and Paola and CRS type of algorithm in a meandering stream are clearly shown in Fig. 2, where it is applied to a section of the River Teifi in Wales, UK. Here the single direction models fail to route flow past the first major meander, and subsequently all flow is pooled and forced up over the floodplain. Using the CAESAR scanning algorithm, flow is successfully routed through all the meanders.

By using a steady state solution with the scanning algorithm, CAESAR can calculate a flow field across a 300 by 800 cell grid in less than 0.1 s. But why do we need the fast solution that these steady flow solutions can offer? As discussed in the Introduction, this speed is essential if we are to model morphological change. If we change the surface over which the model operates, we have to re-calculate the flow field. There are further advantages to rapid, steady flow solutions as the increase in speed also allows us: firstly, to extend the time that can be simulated from one including only individual floods to a series of floods occurring over decades to centuries; secondly, to increase the spatial extent that can be modelled; and thirdly, to increase the resolution or level of detail by using smaller pixel sizes to capture greater topographic and other detail.

However, we must be aware that quasi-steady flow solutions do not necessarily represent the passage of a flood wave accurately, and this may, for example, have impacts on the simulated duration and extent of areas inundated during a flood. This may in turn lead to different rates of sedimentation in a coupled flow and transport model that could, in turn, lead to the development of a floodplain with a quite different topography. Alternatively, such differences may prove to be negligible in other cases. The choice of a quasi-steady over a non-steady flow solution is presently one of practicality, as the increase in speed presently allows us to integrate morphological change as well as simulate changes over larger areas and longer times. However, further research is required in order to ascertain whether the steady or non-steady methods cause significant differences in sedimentation patterns.

3. Erosion/deposition methods

Erosion and deposition within alluvial channels are characterized by the movement of bedload and suspended load, and by processes caused by the interaction of multiple grain sizes (e.g. bed armouring). This already complex situation is further hampered by the historical contingency of fluvial sediment, as a 'memory' of previous episodes of erosion and deposition is stored within the channel or floodplain stratigraphy. Thus the past behaviour of a river, the present-day fluvial processes, and interactions between the two all contribute to conditioning its future response. As previously discussed, many fluvial models do not include erosion and deposition, though some have integrated suspended sediment models (e.g. Nicholas and Walling, 1998; Stewart et al., 1999).

A key advance of cellular models is their integration of erosion and deposition, but this is often carried out in a basic way. For example, Murray and Paola (1994, 1997) used a series of 'general' sediment transport functions to simulate the development of a braided river ranging from a simple function of discharge to exponential relationships with discharge, and the addition of discharge threshold functions. They found that all of these functions led to a braided pattern being generated as long as the relationship between discharge and sediment transport is exponential to some degree. However, they exclude the effects of multiple grain sizes or suspended sediment. Within the CAESAR model, Coulthard et al. (1999, 2002) have attempted to address several of these issues by using firstly the Einstein–Brown (Einstein, 1950) and, more recently, the Wilcock and Crowe (2003) bedload transport formulae (Van De Wiel et al., 2007-this issue). These formulae are integrated within an 'active layer' system using multiple grain sizes, allowing armouring, selective transport and a stratigraphy to develop. More recent developments include the integration of suspended sediment, which allows the model to simulate floodplain alluviation and levee development. Full descriptions, with examples, are provided by Coulthard et al. (2002) and Van De Wiel et al. (2007-this issue).

The integration of bedload transport relationships within fluvial models is a significant step, but there are

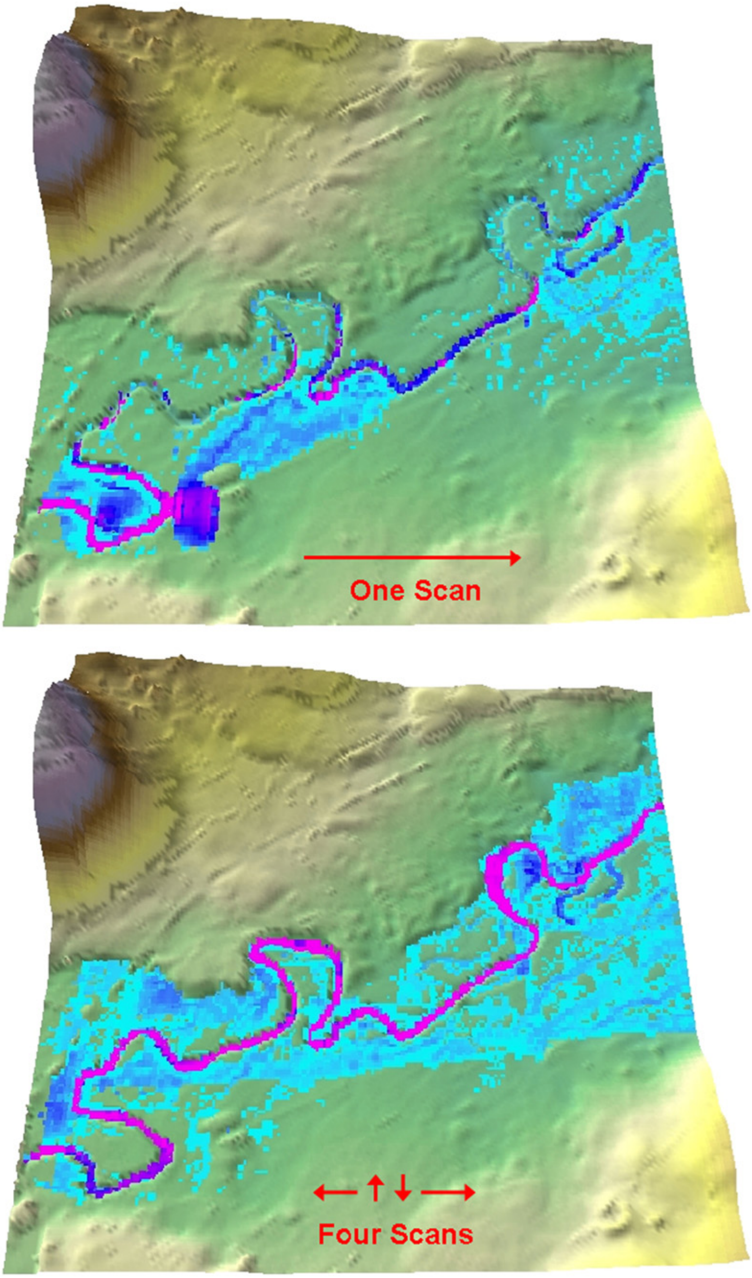

Fig. 2. Differences between using a single flow routing direction and a scanning algorithm as suggested by Coulthard et al. (1998, 2002). The DEM is at 10 m resolution, of a 2 km by 2 km reach of the River Teifi, Wales. Flow is from left to right and the simulated flood size is 100 $m^3 s^{-1}$.

notable problems with the relationships used. There are many equations to predict sediment transport (e.g. Bagnold, Einstein, Parker, Meyer–Peter Muller) but they are at best semi-empirical and site-specific, based upon relating field or flume measurements of bedload transport rates to flow parameters (e.g. shear stress, velocity, stream power etc.). Therefore, they perform well in contexts similar to those in which the data upon which they were developed were gathered, but less well in other situations. Gomez and Church (1989) clearly illustrated this point with their comparison of 12 formulae applied to 8 different data sets. None predicted accurately, the Bagnold equation was the best overall performer, and only three others providing reasonable predictions over all the data sets. Furthermore, these relationships were developed largely using crosssectional average measurements, and averages of flow characteristics. Even within a cross section there is considerable heterogeneity, and using a cellular model we can model sediment transport within every grid cell, not simply averaged over cross sections. The ideal bedload transport relationship for cellular models would therefore be based on 2 dimensional (at least) measurements of flow and bedload at 1 m spacing over a 1 km (or greater) reach, through a range of flow conditions over a considerable time (a year at least). At present, this is clearly impossible. Furthermore, there are many other uncertainties associated with sediment transport, including the cohesive effect of fine/coarse sediment mixtures, the effects of vegetation, how gravel moves through the bed, as well as the accuracy of the active layer system. CAESAR now uses the Wilcock and Crowe surface-based sediment transport relationship (Van De Wiel et al., 2007-this issue), which differs from formulae developed under equilibrium transport conditions with uniform bulk substrate characteristics. So, whereas CAESAR may offer a level of sophistication in its implementation of bedload transport beyond what Murray and Paola or the CRS offer, it is worth remembering that the laws on which it is based are at best flawed to some degree, and may sometimes be explicitly wrong when underlying assumptions are violated.

4. Lateral erosion techniques

Lateral erosion is an important fluvial process, whether in the generation and migration of meander bends, in the movement of braided channels or in the adjustment of channel size to an altered flood regime. Murray and Paola (1994) found that a lateral erosion term was essential to create a dynamic braiding pattern and they used a simple scheme whereby bed material was moved from one cell to another adjacent to the main flow direction according to the lateral bed slope and the rates of downstream erosion. However, this representation cannot be applied where flow is not in the main direction of the valley floor, e.g. around a meander. Therefore, the addition of lateral erosion within a generic cellular model is not straightforward. Cellular models use simplifications of flow equations and do not provide terms for momentum transport or secondary circulation, both of which are important to the lateral erosion processes. Furthermore, within a cellular model an individual cell only has ‘knowledge’ of itself and its neighbour’s properties; it cannot determine whether it is part of the inside, outside or middle of a bend or whether it is within a bend at all. A cell only has ‘knowledge’ of its local situation, whereas lateral erosion is driven by regional processes (in the sense of channel-floodplain scales).

Coulthard and Van De Wiel (2006) developed a prototype methodology for integrating lateral erosion and meandering within the CAESAR model. A fuller description is provided by Van De Wiel et al. (2007-this issue) and by Coulthard and Van De Wiel (2006), but here we offer an outline and discuss some of the implications of the method. Firstly, the radius of curvature is set by determining ‘edge’ cells (those that have a submerged boundary) then counting the number of wet and dry cells around these edge cells. This gives a very local indication of whether a cell is on the inside or outside of a bend, and by smoothing this across more than five cells a regional value for cell curvature can be calculated. From this term, bank erosion can be inversely related to the radius of curvature (using a basic implementation of the relationship shown by Hickin and Nanson (1984) assuming a constant width). However, whilst this describes lateral erosion along the outer bank, for meandering to occur deposition has to occur on the inside edge of the bend. This is not so straightforward, and preliminary techniques determine a cross-stream gradient according to the radius of curvature term and use this to move sediment perpendicular to the main channel direction (Coulthard and Van De Wiel, 2006). This results in the migration of meander bends as shown in Fig. 3. Here, the migration of the bend can clearly be seen, with the development of bends towards the base of the image. Migration of the larger loop is restricted by the higher topography. It is also interesting to note how a point bar has developed on the inside of all bends where there has been channel migration.

This lateral erosion method is still in development, and there are several philosophical and technical issues to overcome. By using the local planform (radius of curvature) to determine channel migration, we are using a symptom of lateral erosion to drive it, instead of modelling the cause. This differs from the simplifications used to calculate flow depths and to route water, as these simplified ‘rules’ are based upon physical laws as opposed to a geometric relationship. However, if this representation of lateral erosion replicates observed meander behaviour, perhaps we may for some purposes accept it. On more technical issues, determining channel edges is simple during less-than-bankfull flows, but when the floodplain is inundated the edges of the channel are lost. Unfortunately we cannot use sudden changes in water depth to calculate edges as inside edges can be gradual, for example where a point bar has formed. However, whilst this clearly shows that the method requires refinement, it nevertheless illustrates

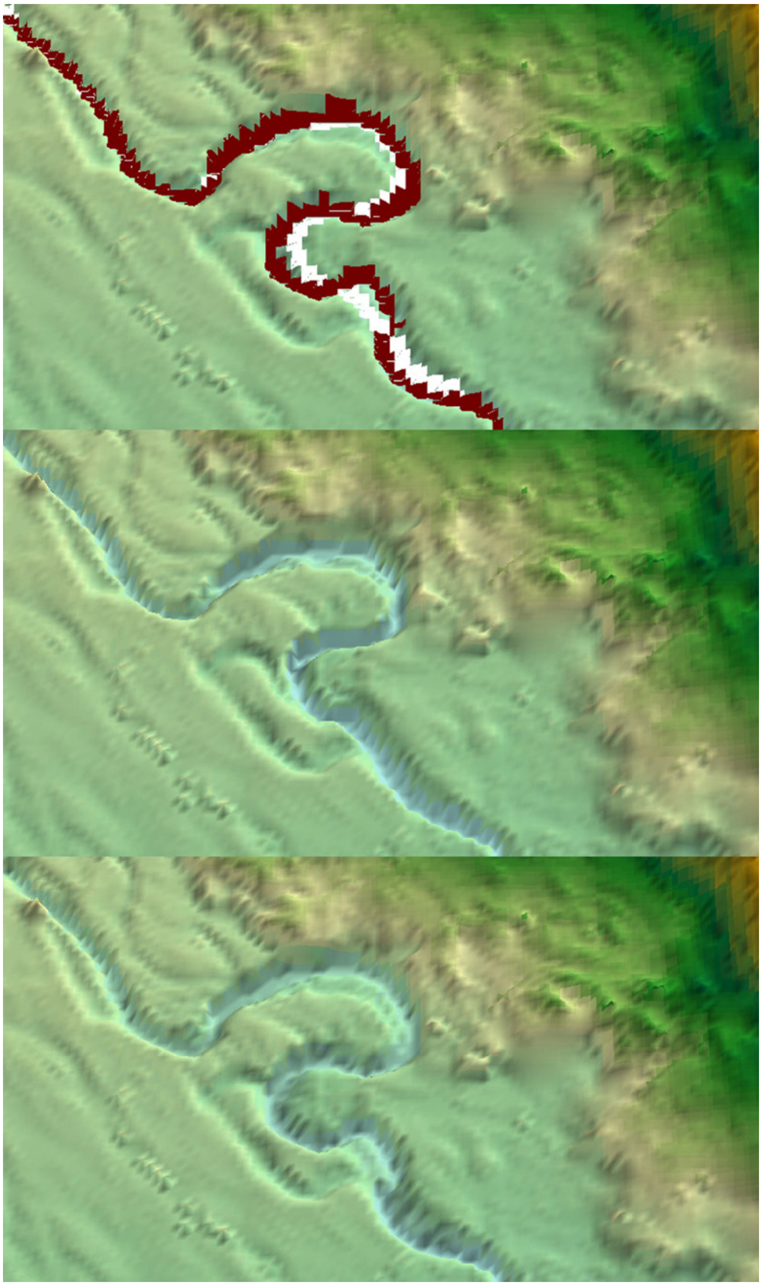

Fig. 3. Examples of lateral erosion from the CAESAR model. These are 3-D shaded images of a section of floodplain from the River Teifi Wales. Flow is from top left to bottom right and the length of reach is approximately 500 m, grid cell size is 10 m. The top image shows the initial topography with the initial channel position in white and the final channel position in black. The middle image shows the initial topography. The lower image shows the final topography.

how it is possible to model meander development within a cellular framework.

5. Examples

The previous sections have illustrated how cellular models have the potential to model fluvial systems over medium (decadal/centuries) time and space scales, but have also shown that there are significant problems. To illustrate this potential we now explore an application of the CAESAR model to a contemporary management problem in a braided river in New Zealand. The lower Waitaki River, New Zealand, is a large gravel-bed braided river draining

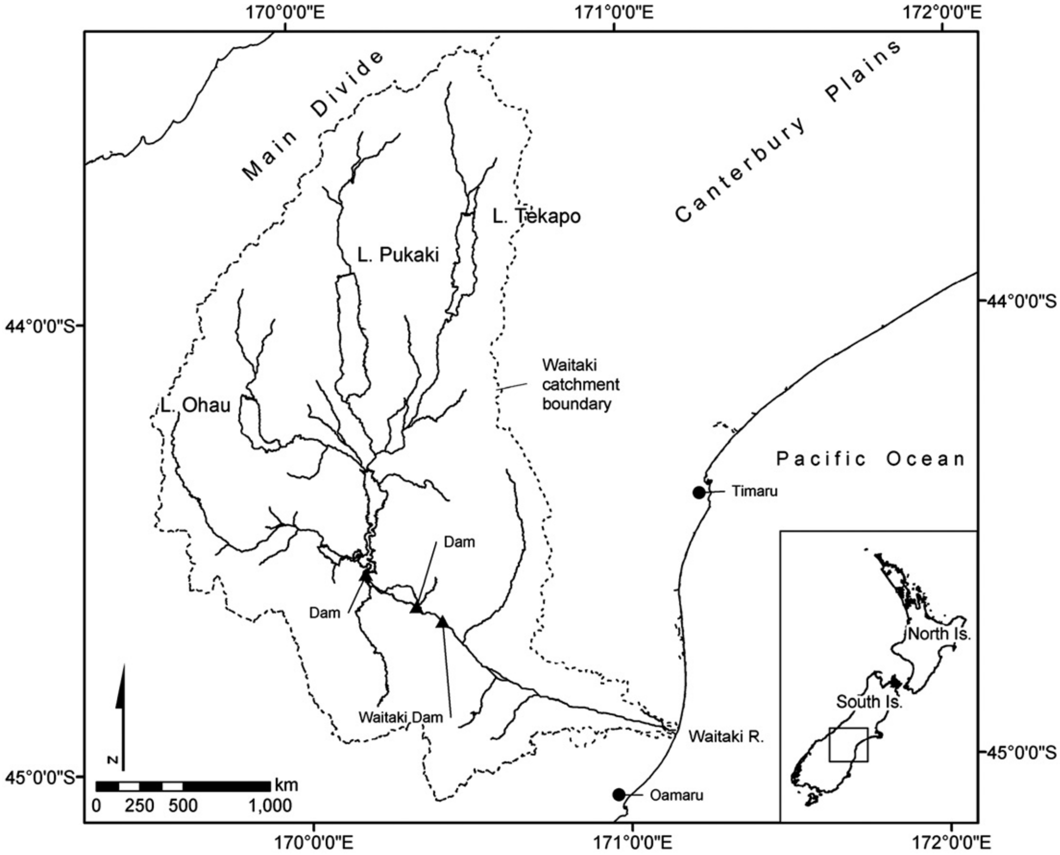

Fig. 4. The Waitaki River basin, South Island, New Zealand.

9760 km^2 of the eastern South Island, New Zealand (Fig. 4).

During the last 100 years, there has been an increasing problem with exotic vegetation encroaching across the braid plain (Tal et al., 2004; Hicks et al., 2004) (Fig. 5). This has been exacerbated by a reduction of peak discharges (that had naturally helped to restrict vegetation growth), by upstream dams and lake control structures associated with hydro-electric power schemes. The vegetation (mainly willows, broom, gorse, and lupins) is perceived to have had several effects upon the braid plain. Firstly, by increasing the hydraulic roughness over vegetated islands and along the braid plain margins, vegetation has caused peak flows to inundate a greater area and thus increase the chance of flooding adjacent agricultural land. A vegetation control programme has been implemented to mitigate this flooding hazard, with spraying to maintain a ‘fairway’ bare of vegetation whilst willow growth is actively encouraged along the margins of the fairway to keep the river position fixed laterally. Secondly, by stabilizing the braid plain, the vegetation may have reduced downstream sediment supply, hindering the river’s natural attempt to recover from its own braid plain the bed-material trapped in the hydro-reservoirs upstream.

We have used CAESAR to simulate morphological changes in a 20 km by 4 km reach of the Waitaki immediately downstream of Waitaki Dam, the dam that is furthest downstream. The model was run over a 50 m grid DEM made from a resampled LiDAR survey. It contained nine separate grainsize fractions, run through 11 active layers, using the Wilcock and Crowe (2003) surface-based multi-fraction bedload transport relationship. The initial size grading of all cells and layers was set to the average grading from 30 bulk field samples collected from bars along the lower river. Vegetation effects were simulated in two ways. The first allowed surface vegetation to grow dynamically, wherever there was no inundation, and increased the resistance of riverbed surfaces (e.g. bar tops) to erosion by current scour. This used a simple linear growth model, with erosion resistance increasing with vegetation maturity until a maximum level was attained. Four different

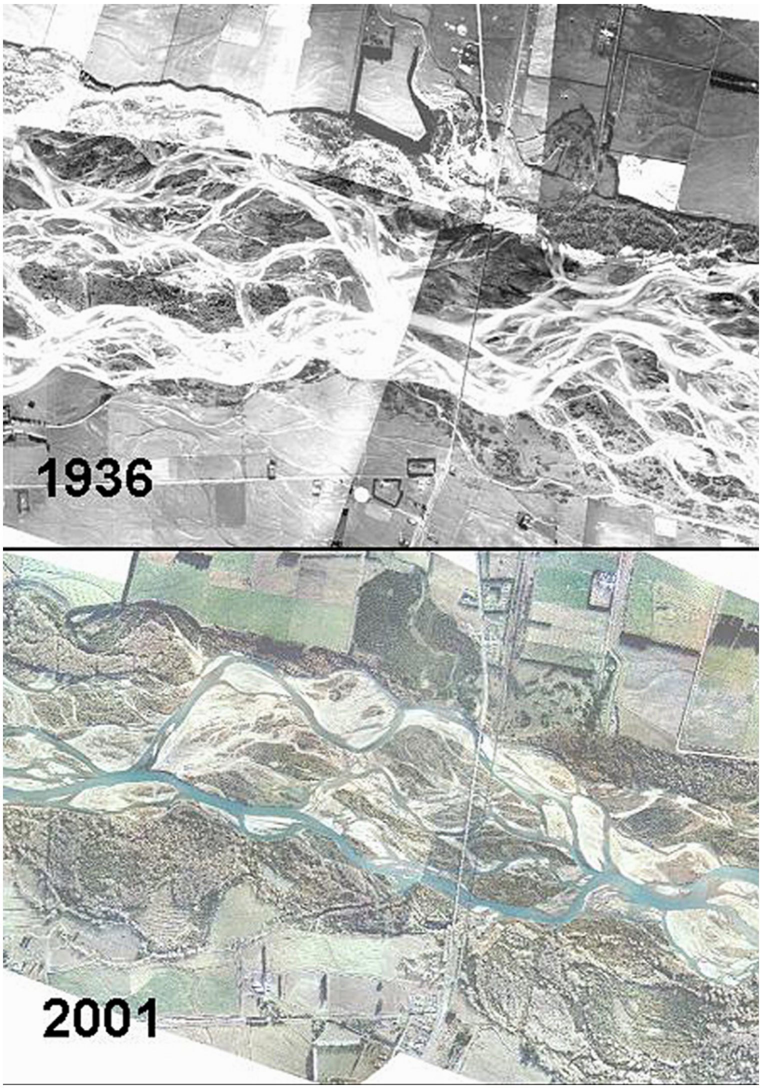

Fig. 5. 1936 and 2001 aerial photographs of the Waitaki floodplain illustrating the development of vegetation across the braid plain.

growth rates were used, so that the surface vegetation matured in 5, 3, 2, and 1 years. Secondly, rates of lateral erosion were altered to simulate the binding and strengthening properties of riparian vegetation on river banks. This effect was not dynamic, and the rates remained constant; again, four different erosion rates were simulated. All simulations were driven by a 20-year duration series of daily mean discharge, as recorded at the Kurow gauge near the upstream end of the reach (Fig. 4).

Fig. 6 presents the sediment yields from the reach from the first model for the different vegetation growth rate scenarios. The pre-dam bedload yield (derived from a sediment budget analysis) is also plotted on Fig. 6, and indicates that the model is generating sediment yields within the expected range. It clearly shows that altering the rates of surface vegetation growth can reduce the sediment yield at the downstream boundary. However, when combined with decreasing lateral erosion rates, instead of further reducing erosion rates it dramatically increases them. This is due to the vegetation narrowing the channel, reducing the level of braiding, effectively ‘corralling’ flow into a main channel. This is shown in Fig. 7, where aggressive vegetation growth has reduced the channel to a single thread. This has resulted in a dampening of instabilities (channel changes, avulsions) and an increase in sediment yield, as flow is now concentrated in one enlarged and incising central channel. Initial expectations were that increased vegetation growth rates would reduce sediment yield through

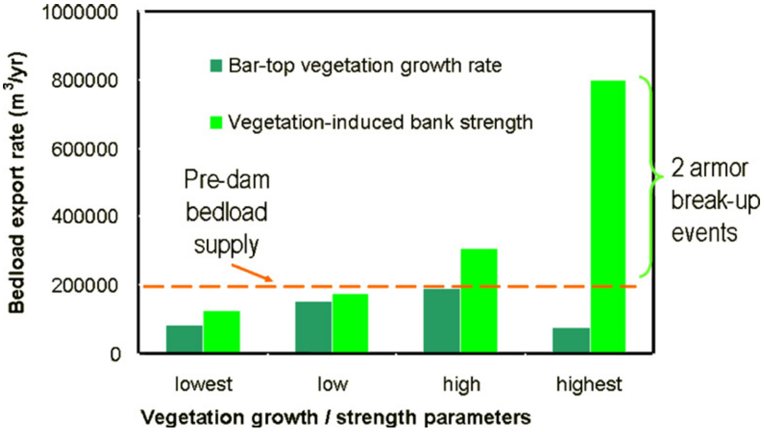

Fig. 6. Sediment yields from different CAESAR model runs.

riverbed and bank stabilization. Instead, it created a more effective channel that breached armour layers and mined material from the bed. Therefore, possibly the best management strategy to maintain gravel supply to the coast may be to let the vegetation grow. On the downside, the flood hazard might well increase downstream, and the area of braided river habitat would certainly decrease.

This example provides a good illustration of the usefulness of 'experimental' cellular modelling. Precise data on the exact position of channels or braids cannot be provided because of the simplifications of the model, but CAESAR provides a great deal of information about the dynamics of the system. Indeed, these simple simulations suggest how vegetation changes interact with flow and sediment transport patterns to produce an unexpected result, with implications for the strategic management of the river — a result that may well warrant more robust investigation.

6. Discussion: validation issues

An important area only briefly mentioned above is validation. Determining whether a model is correct by comparison to field data is vital if we are to value model output. Validation of flow depths and inundation areas is

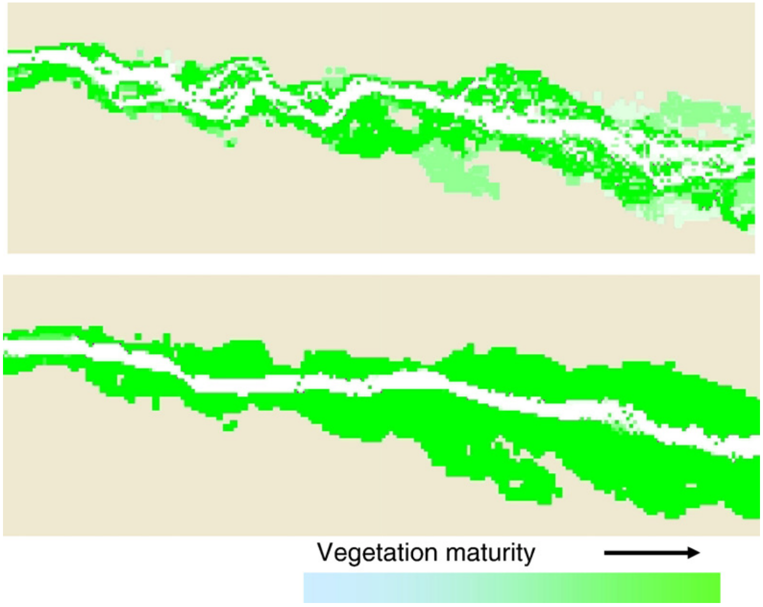

Fig. 7. Images of spatial extents and ages of vegetation after 5 years and 20 years of simulation on the Waitaki River, New Zealand. The modelled reach presented above is the same reach as that shown in Fig. 1.

relatively straightforward where there are suitable data to compare against. For example, Thomas and Nicholas (2002) compared results of their CRS model to output from a more sophisticated 2-D hydraulic model (Hydro2e) and Cox et al. (2005) compared results from Murray and Paola, the CRS and CAESAR models to surveyed flow depths for the River Feshie in Scotland. However, whilst flow depths and inundation areas can readily be compared between models and with field data, suitable data for erosion and deposition are more difficult to find. There are few continuous bedload data sets, with most measurements being averaged over weeks, months or years. The Waitaki example described above shows how limited the validation opportunities are, with comparisons of modelled bedload yield only possible with estimates of annual averages based around hydro-reservoir entrapment rates.

An alternative is to compare results to data that show changes in planform. For example, sequences of aerial photographs or historical maps can be used to show meander development (e.g. Hooke, 1984; Braga and Gervasoni, 1989) or changes in gravel bar areas within streams (e.g. Lane et al., 2003). Similarly, for braided systems channel changes or topological metrics such as the braid index can be used to compare modelled planform to reality. Paola (2001) suggested that for models designed to simulate high level system characteristics (e.g. channel planform) it may be unsuitable to compare predictions of lower level properties (e.g. flow patterns). However, the use of planform data can be limited by the frequency of aerial photographs or map editions — with each only representing a single moment in time, which may not be suitable for rapidly changing systems such as braided rivers. Repeat topographic surveys could also provide an ideal method for measuring morphological changes over time, but these can be labour intensive, and expensive in the case of remotely sensed (e.g. LiDAR) data. Similarly, they can also be restricted by the frequency of survey. However, even with detailed topographic surveys it is difficult to be precise about what the initial boundary conditions were. In particular (for the modelling of the Waitaki described in this paper) the initial bedload and subsurface grain size distribution can have a significant effect on the levels of incision and subsequent deposition that may occur.

An alternative for validation is to look at the longer, more 'blurred' sedimentological record. Modelling longer time scales (100's to 1000's of years), Coulthard and Macklin (2001) and Coulthard et al. (2005) compared model outputs to histograms of ^{14}C dated flood units from the UK. This is a good example of retro-validation; they simulated the past 9000 years and compared the results to the present day stratigraphic record. This technique is ideal for longer-term studies, but is hampered by the temporal and spatial resolution of dated flood units. ^{14}C can at best date within 50-year margins, and spatially, each date only represents one point within a catchment (Coulthard et al., 2005). Coulthard and Macklin (2003) also use a comparison between modelled and field measured heavy metal contaminated sediment patterns as a method for model validation.

One method that shows great promise for validating cellular fluvial models is comparison with flume data. Doeschl-Wilson and Ashmore (2005) carried out a detailed comparison of the Murray and Paola braided river model with a 16 by 2 m flume run. This comparison showed that the numerical model did not replicate many of the features found within the laboratory model, but it illustrated how this method may be ideal for validation and model development. Within a controlled laboratory environment, it is possible to measure flow velocities, depths, topographies, and sediment discharges at higher temporal and spatial resolutions than could be achieved in the field. Although this could be described as validating a model with a model, physical flume models can be relatively well scaled and constrained to fit field examples.

However, when applying such cellular models to natural environments, the heterogeneity of the latter presents a major problem. For example, changes in bed roughness, differences in sediment inputs to a reach, changes in water inputs, fluctuations in climate and sediment delivery and vegetation changes can all influence the behaviour of a river system. These variations and uncertainties are hard, if not impossible, to replicate within a generalised numerical or physical model, and underscores the idea that a cellular model is best validated against system-scale properties that average across the heterogeneities.

The difficulties associated with validating cellular fluvial models raise the question of how close to reality they can be. This is a difficult question to answer, especially given the issues raised in the previous section. Possibly a more pertinent question is: how close to reality do they have to be? A common, seductive and valid goal of numerical modelling is to try to replicate as accurately as possible what is happening in the system modelled. But in complex natural systems, such as rivers, there are always going to be levels of detail that cannot be modelled. For example, how important is the formation of a channel bar, or the deposition of a cluster on the bar, or the size of a pebble on the cluster, or the size of the sand under the pebble? Similarly, how important is it that we simulate or account for every single burst of turbulence within a channel? The answers to these more philosophical questions depend upon the context of study, as these may all be vital for a detailed CFD study of flow around a pebble, yet irrelevant for the Holocene evolution of the entire river system (unless, of course, that evolution is sensitively dependent on very local-scale processes). Therefore, at present cellular models should not be used for exact prediction (for example to tell an engineer how much a bank will erode laterally in 10 years). Rather, they should be used for exploration — to understand how rivers behave and what causes them to change. This could then permit advice to the engineer on what sections of the river bank are most likely to erode, at which point more robust numerical approaches could be applied at practicable time and space scales. At present, we think these models should not be used in a strictly quantitative way, but more to produce qualitative answers. There are certain similarities between some cellular models and the kinds of physical model developed by Schumm et al. (1987), which are not a precise representation of a prototype, but provide an understanding of generic behaviour. As a scientific tool, there is much that can be learned from their application. They are ideal for hypothesis testing and exploring 'what if' scenarios. The above example from the Waitaki clearly shows how we can explore, simply, how vegetation, flow and sediment transport all interact to influence sediment yield and the planform of the river.

7. Conclusion

The relative simplicity of cellular models provides the potential to model a wide range of fluvial and geomorphic processes within one framework. Within fluvial modelling, there is a tendency to model only certain sets of processes. For example, there are several models developed for simulating meandering streams (e.g. Howard, 1992; Darby et al., 2002; Olsen, 2003) and several others for braided streams (e.g. Murray and Paola, 1994; Thomas and Nicholas, 2002; Lunt et al., 2004). Yet meandering rivers frequently contain sections that are braided, and braided streams have sections where there is meandering. Within geomorphology, there is a tendency to categorise and divide landscapes into component forms, regions or types. Yet within this apparent diversity of process there is a unity of landscape. Distinctive processes cause changes in form, for example, suspended sediment transport and deposition produces smooth regular floodplains, whereas bedload transport and deposition tends to produce relic point bars, or braided patterns with a different style of floodplain. Yet the processes also operate together. Despite the fact that several of the examples of cellular models we have described here are for braided rivers, cellular models provide a real opportunity to combine sets of processes from different environments and to bridge this divergence of process–form relationship. With the addition of suspended sediment and lateral erosion to models such as CAESAR, the range of processes found in meandering low energy lowland rivers is combined with that found in braided higher energy environments. This raises the potential to explore fascinating research topics in the future, and indeed, to understand better the apparent thresholds between different morphologies.

Ultimately, however, cellular models may not be seen as the best solution. At present they offer a good compromise between speed and accuracy for experimental modelling at useful time and space scales. As computing power and better algorithms are developed, more complex implementations, using CFD for example, may eventually supersede them. However, it could be argued that this increase in computational capability will also make cellular models faster, more powerful and therefore able to be applied to even larger areas, at greater resolutions and over longer time scales. Despite this optimism, there are two factors that will ultimately limit all fluvial models. Firstly, if the aim is to model non-steady flow, then routing water across a model domain (whether it be cells or a finite element mesh) can only be at rates below the velocity of the water. Similarly, we cannot route sediment from cell to cell any faster than its calculated rate of movement. Secondly, there are restrictions on computational stability that prevent us from changing the elevations of cells more than a fraction of the difference between them and adjacent cells. We cannot move too much sediment in any one time step. Both these are computational limits to the ultimate speed, area of application and resolution of fluvial models.

Acknowledgments

MJV was funded by NERC grant NER/A/S/2001/00454 and TJC was partly funded by the University of Wales research fund. DMH was funded under FRST contract CO1X0308. We would also like to thank Dr Gez Foster, Jeremy Walsh, Joe Wheaton and Clare Cox who have all contributed to the development of the CAESAR model. Prof. John Lewin, Prof. Mark Macklin, Dr Andrew Nicholas and two anonymous referees all provided useful discussion and feedback.

CAESAR itself is freely available for download at http://www.coulthard.org.uk.

References

Bates, P.D., De Roo, A.P.J., 2000. A simple raster-based model for flood inundation simulation. Journal of Hydrology 236, 54–77.

Braga, G., Gervasoni, S., 1989. Evolution of the Po River: an example of the application of historic maps. In: Petts, G.E. (Ed.), Historical Change of Large Alluvial Rivers: Western Europe. Wiley, Chichester, pp. 113–126.

Brunner, G.W., Gibson, S., 2005. Proceedings of the World Water and Environmental Resources Congress. 442 pp.

Codilean, A.T., Bishop, P., Hoey, T.B., 2006. Surface process models and the links between tectonics and topography. Progress in Physical Geography 30 (3), 1–27.

Coulthard, T.J., 2001. Landscape evolution models: a software review. Hydrological Processes 15, 165–173.

Coulthard, T.J., Macklin, M.G., 2001. How sensitive are river systems to climate and land-use changes? A model-based evaluation. Journal of Quaternary Science 16, 347–351.

Coulthard, T.J., Macklin, M.G., 2003. Modeling long-term contamination in river systems from historical metal mining. Geology 31 (5), 451–454.

Coulthard, T.J., Van De Wiel, M.J., 2006. A cellular model of river meandering. Earth Surface Processes and Landforms 31, 123–132.

Coulthard, T.J., Macklin, M.G., Kirkby, M.J., 1996. A cellular automaton fluvial and slope model of landscape evolution. In: Abrahart, R.J. (Ed.), Proceedings of the 1st International Conference on Geocomputation, University of Leeds, 17–19 September 1996, Leeds, UK, pp. 168–185.

Coulthard, T.J., Kirkby, M.J., Macklin, M.G., 1998. Non-linearity and spatial resolution in a cellular automaton model of a small upland basin. Hydrology and Earth System Sciences 2, 257–264.

Coulthard, T.J., Kirkby, M.J., Macklin, M.G., 1999. Modelling the impacts of Holocene environmental change in an upland river catchment, using a cellular automaton approach. In: Brown, A.G., Quine, T.A. (Eds.), Fluvial Processes and Environmental Change. John Wiley, Chichester, pp. 31–46.

Coulthard, T.J., Kirkby, M.J., Macklin, M.G., 2000. Modelling geomorphic response to environmental change in an upland catchment. Hydrological Processes 14, 2031–2045.

Coulthard, T.J., Macklin, M.G., Kirkby, M.J., 2002. A cellular model of Holocene upland river basin and alluvial fan evolution. Earth Surface Processes and Landforms 27, 269–288.

Coulthard, T.J., Lewin, J., Macklin, M.G., 2005. Modelling differential catchment response to environmental change. Geomorphology 69, 222–241.

Cox, C., Brasington, J., Richards, K., 2005. Predicting reach scale flow patterns using reduced complexity cellular schemes. EGU General Assembly, Vol 7. EGU05-A-01646.

Darby, S.E., Alabyan, A.M., Van De Wiel, M.J., 2002. Numerical simulation of bank erosion and channel migration in meandering rivers. Water Resources Research 38 (9), 1163. doi:10.1029/2001WR000602.

Doeschl-Wilson, A.B., Ashmore, P.E., 2005. Assessing a numerical cellular braided-stream model with a physical model. Earth Surface Processes and Landforms 30, 519–540.

Einstein, H.A., 1950. The bed-load function for sediment transport on open channel flows. Tech. Bull., vol. 1026. USDA, Soil Conservation Service, p. 71.

Fang, H.W., Wang, G.Q., 2000. Three-dimensional mathematical model of suspended-sediment transport. Journal of Hydraulic Engineering, ASCE 126 (8), 578–592.

Gomez, B., Church, M., 1989. An assessment of bed load sediment transport formulae for gravel bed rivers. Water Resources Research 25 (6), 1161–1186.

Hickin, E.J., Nanson, G.C., 1984. Lateral migration rates of river bends. Journal of Hydraulic Engineering 110 (1111), 1557–1567.

Hicks, D.M., Walsh, J., Coulthard, T.J., 2004. Effects of changing flow regime, sediment supply, and riparian vegetation on the morphology of the braided Waitaki river, New Zealand. Eos Trans. AGU 85 (47) (Fall Meet. Suppl., Abstract H42B-01).

Hooke, J.M., 1984. Changes in river meanders: a review of techniques and results of analysis. Progress in Physical Geography 8, 473–508.

Howard, A.D., 1992. Modelling channel migration and floodplain sedimentation in meandering streams. In: Carling, P.A., Petts, G.E. (Eds.), Lowland Floodplain Rivers: Geomorphological Perspectives. John Wiley, Chichester, pp. 1–41.

Kassem, A.A., Chaudhry, M.H., 2002. Numerical evolution of bed evolution in channel bends. Journal of Hydraulic Engineering, ASCE 128 (5), 507–552.

Lane, S.N., 1998. Hydraulic modelling in hydrology and geomorphology: a review of high resolution approaches. Hydrological Processes 12, 1131–1150.

Lane, S. N., 2005. Braided rivers and the question of sufficient physics. EGU General Assembly, Vol 7. EGU05-A-01815.

Lane, S.N., Westaway, R.M., Hicks, D.M., 2003. Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. Earth Surface Processes and Landforms 28, 249–271.

Lunt, I.A., Bridge, J.S., Tye, R.S., 2004. A quantitative, three-dimensional depositional model of gravelly braided rivers. Sedimentology 51, 377–414.

Murray, A.B., Paola, C., 1994. A cellular model of braided rivers. Nature 371, 54–57.

Murray, A.B., Paola, C., 1997. Properties of a cellular braided stream model. Earth Surface Processes and Landforms 22, 1001–1025.

Murray, A.B., Paola, C., 2003. Modelling the effect of vegetation on channel pattern in bedload rivers. Earth Surface Processes and Landforms 28, 131–143.

Nicholas, A.P., 2005. Cellular modelling in fluvial geomorphology. Earth Surface Processes and Landforms 30, 645–649.

Nicholas, A.P., Walling, D.E., 1998. Numerical modelling of floodplain hydraulics and suspended sediment transport and deposition. Hydrological Processes 12, 1339–1355.

Olsen, N.R.B., 2003. Three-dimensional CFD modeling of self-forming meandering channel. Journal of Hydraulic Engineering, ASCE 129 (5), 366–372.

Paola, C., 2001. Modelling stream braiding over a range of scales. In: Mosley, M.P. (Ed.), Gravel-Bed Rivers V. New Zealand Hydrological Society, Wellington, pp. 11–38.

Rüther, N., Olsen, N.R.B., 2005. Three-dimensional modeling of sediment transport in a narrow 90° channel bend. Journal of Hydraulic Engineering, ASCE 131 (10), 917–920.

Schumm, S.A., Mosley, M.P., Weaver, W.E., 1987. Experimental Fluvial Geomorphology. Wiley Interscience, New York, p. 413.

Stewart, M.D., Bates, P.D., Anderson, M.G., Price, D.A., Burt, T.P., 1999. Modelling floods in hydrologically complex lowland river reaches. Journal of Hydrology 223, 85–106.

Tal, M., Gran, K., Murray, A.B., Paola, C., Hicks, D.M., 2004. Riparian vegetation as a primary control on channel characteristics in multi-thread rivers. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology: Hydraulic, Hydrologic, and Geotechnical Interactions. American Geophysical Union, Washington, pp. 43–58.

Thomas, R., Nicholas, A.P., 2002. Simulation of braided flow using a new cellular routing scheme. Geomorphology 43, 179–195.

Tucker, G.E., Slingerland, R.L., 1994. Erosional dynamics, flexural isostasy, and long-lived escarpments: a numerical modeling study. Journal of Geophysical Research 99 (B6), 12229–12243.

Tucker, G.E., Slingerland, R., 1997. Drainage basin responses to climate change. Water Resources Research 33 (8), 2031–2047.

Van De Wiel, M.J., Darby, S.E., 2004. Numerical modeling of bed topography and bank erosion along tree-lined meandering rivers. In: Bennett, S.J., Simon, A. (Eds.), Riparian Vegetation and Fluvial Geomorphology. Water Science and Application. American Geophysical Union, Washington, pp. 267–282.

Van De Wiel, M.J., Coulthard, T.J., Macklin, M.G., Lewin, J., 2007. Embedding reach-scale fluvial dynamics within the CAESAR cellular automaton landscape evolution model. Geomorphology 90, 283–301 (this issue). doi:10.1016/j.geomorph.2006.10.024.

Van De Wiel, M.J., Coulthard, T.J., Macklin, M.G., Lewin, J., in press. Modelling the response of river systems to environmental change: progress, problems and prospects. Earth-Science Reviews.

Wilcock, P.R., Crowe, J.C., 2003. Surface-based transport model for mixed-size sediment. Journal of Hydraulic Engineering, ASCE 129 (2), 120–128.

Willgoose, G., 2005. Mathematical modelling of whole landscape evolution. Annual Review of Earth and Planetary Sciences 33, 433–459.

Willgoose, G., Bras, I., Rodriquez-Iturbe, I., 1991. Results from a new model of river basin evolution. Earth Surface Processes and Landforms 16, 237–254.