HYDROLOGICAL PROCESSES
Hydrol. Process. **15**, 165–173 (2001)

SOFTWARE REVIEW

HP TODAY

Landscape evolution models: a software review

T. J. Coulthard,* *Institute of Geography and Earth Sciences, University of Wales, Aberystwyth SY23 3DB, UK*

Introduction and context

The late 1970s saw the development of a series of physically based computer models that used a mesh of grid cells to represent a landscape and channel network (Anhert, 1976). These simulated landscape evolution by routing water across this mesh and changing the grid cell elevations to represent fluvial and slope erosion. With an increase in the power and availability of computers in the late 1980s and early 1990s, enhanced models were developed with more accurate representations of fluvial and slope processes (Kirkby, 1987; Willgoose *et al*., 1991, 1994; Howard, 1994; Tucker and Slingerland, 1994). These new models have revealed how interactions between, for example, hydrology, fluvial erosion, slope processes, tectonic uplift, climate and lithology influence the drainage network and catchment form. Current developments, again aided by enhanced computational capacity, have seen an increase in the size of catchment studied, a more detailed process representation, the use of an irregular mesh instead of grid cells (Braun and Sambridge, 1997; Tucker *et al*., 2000), and the application of these models to real river catchments to examine genuine environmental issues (Coulthard *et al*., 2000; Evans and Willgoose, 2000).

These models are important to both hydrologists and geomorphologists, as they take a holistic view, regarding the catchment as a whole, whereas frequently hydrology and geomorphic change are modelled as separate entities. As Willgoose *et al*. (1994) argued, the hydrology can determine the catchment form, yet the catchment form can alter the hydrology. This is increasingly relevant, given the onset of rapid global warming (Mann, 2000) as these models give us tools to explore the effects of changes in climate on hydrology and the whole river catchment.

However, modelling landscape evolution is especially hard, due to the large number of processes operating over a wide range of spatial and temporal scales, and how the importance of these processes changes over these scales. For example, soil creep may be inconsequential during a single flood, but cause massive changes over 20 000 years. Conversely, the exact location of a braided river section may prove irrelevant when considering thousands of years of valley aggradation, but very important when looking at shorter timescales, for example where to construct a bridge. To overcome the difficulties with changing spatial scales, the models reviewed here use three different techniques. CASCADE (Braun and Sambridge, 1997) and CHILD (Tucker *et al*., 1999, 2000) use an adaptive irregular mesh instead of a regular grid, so that areas where there is frequent activity (near river channels) have more nodes and thus more detail than a hill slope where there may be comparatively little activity. GOLEM (Tucker and Slingerland, 1994) and SIBERIA (Willgoose *et al*., 1991, 1994) solve this by using a sub-grid cell representation of the river channel. CAESAR (Coulthard *et al*., 1998, 1999, 2000) approaches this problem by using a large mesh of small cells, and concentrating 95% of the models' time on the active cells near the channel, whilst periodically checking the hill slopes. The problem of different temporal scales has been tackled by altering how hydrological, channel, geological and slope processes are represented within the models. Depending upon the application, some models have chosen to calculate erosion and deposition on a short term event based scale (e.g. CAESAR and CHILD), whereas others use long term averages over 100 year time steps (e.g. CASCADE).

All of these models are now available to download for free (with the authors' permission) and the full URLs are listed in the Appendix to this review. There are other models that are not covered in this review, and their omission is in no way a representation of their calibre. Furthermore, this review provides only a brief guide to these modelling packages, for a more in-depth evaluation, the reader is advised to examine the websites and consult the extensive literature.

SIBERIA

SIBERIA was designed to examine the relationships between hydrology, tectonics and catchment form over geomorphic timescales. It uses a grid of square cells and for every iteration the model determines a discharge for each cell according to a runoff constant and the contributing catchment area. If this discharge

* Correspondence to: Dr T. J. Coulthard, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, Wales, SY23 3DB, UK. E-mail: T.Coulthard@aber.ac.uk

exceeds a threshold (determined by the resistance of the slope material) then fluvial erosion will occur and material moved from one cell to another along the steepest line of descent. Importantly, this allows the channel network to grow or contract, according to the amount of discharge. This is coupled with a model to simulate diffusive slope processes, such as soil creep, rain splash and rock slides, so that material from slope cells could be moved to channels and eroded from the system. Initial applications of SIBERIA were used to investigate the interactions between hydrology and catchment form, and how tectonics and erosion combine to form a 'dynamic equilibrium' of channel network morphology. Recently SIBERIA has been improved to incorporate multiple flow routing, slope weathering, armouring and the ability to introduce fixed engineered structures (e.g. a bank) into the landscape. It has also been validated against experimental and field geomorphological data and is presently being applied to several environmental problems (Willgoose, personal communication) including the stability of a mining site (Evans and Willgoose, 2000).

SIBERIA is part of a suite of landscape analysis programs and was obtained by following instructions on the website. It came as a zip file containing an executable file for a PC and several sets of example data. The program is also available as FORTRAN code that can be compiled on machines with an F77 compiler. The website also features an excellent detailed manual, that is downloadable in .pdf format. This contains an introduction to the model and a list of all the parameters, detailing how to alter them and what effect they can have. This allows the user to input a DEM or landscape (possibly generated by a GIS package) and set the slope process rates and other model parameters.

The model operation was straightforward. After compiling and running the code, the user was prompted to enter the name of input files for the initial elevation and a boundary file. If none were entered the model used default settings of a randomly generated mesh. Further prompts asked the user what type of output was required and how often. 1000 time steps (which depending upon the parameters chosen may simulate 1000 years on a highly erosive site or 100 000 years on a harder surface) took approximately 5 min with a 40×40 mesh. The size of grid mesh that can be used is restricted by the memory of the computer, and a larger grid can considerably slow the operation of the model. During the run, SIBERIA flashed up text based representations of the drainage network and elevations, that were useful to check on the progress of the simulation. SIBERIA also periodically saved the grid cell elevations and other parameters to an output file. This allowed a completed run to be re-started from its finishing point, and the data could be plotted to show the surface elevations (Figure 1). An openGL visualization package is also available for SIBERIA output files. In summary, SIBERIA was very quick, straightforward, tested and well documented.

GOLEM

GOLEM was developed to look at long term landscape evolution (100 000 to 10 000 000 years) and linkages between erosion and tectonics. It uses square grid cells ($c.1$ km $\times$ 1 km), routes water down the line of steepest descent and includes representations of diffusive slope processes. Where a grid cell contains a channel, GOLEM allows two types, bedrock and alluvial. This importantly allowed the model to make the distinction between supply limited (bedrock channels) and transport limited catchments (alluvial). This is coupled to models of weathering and sediment production, so the effects of an arid environment (with low weathering rates) can be compared to that of a humid climate. Furthermore, GOLEM incorporates a tectonic model that allows the user to simulate uplift caused by the removal of sediment, and depression caused by sediment loading. Tucker and Slingerland (1994) used GOLEM to show that there were clear differences between landscapes that developed in supply and transport limited environments, and that escarpment retreat was caused by a combination of bedrock incision, low sediment production (supply limited) and flexural uplift which helped maintain erosion. Since these initial applications GOLEM has been augmented by several important additions. The model can now be run in the 'regional' or 'catchment' mode, which assumes the model uses different scale grid cells (1×1 km^2 compared to 50×50 m^2) and treats the processes slightly differently to compensate. Different sediment transport laws can be used and stratigraphies can be integrated, so that the model can have different layers of rock with variable resistances to erosion and slope failure angles. This allows

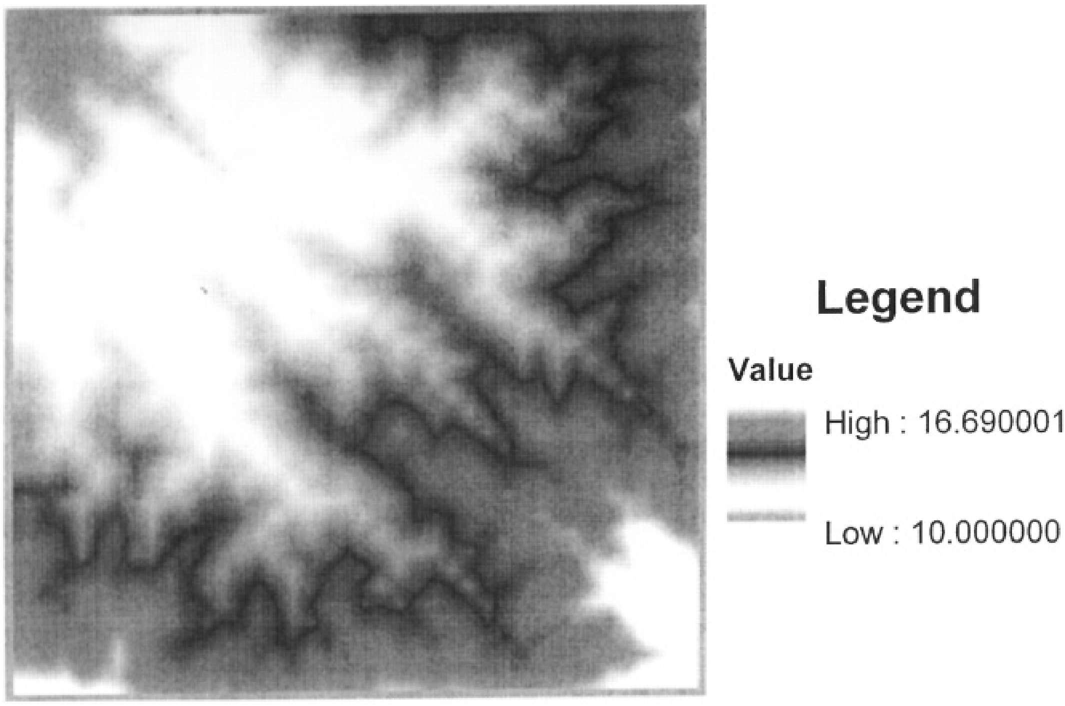

Figure 1. Output from SIBERIA, from a 40 × 40 mesh, displayed using ARCMAP

for example the simulation of the erosion of a softer grit/sandstone on top of a harder limestone.

GOLEM is freely available for non-commercial purposes and was easily downloaded from its website, along with sample data and a series of Mattlab extensions for visualization. GOLEM is written in a single C file and was easily compiled on several platforms (Linux 6.2, NT C compiler, Digital and SUN workstation were tried). The website contains a useful (though incomplete) manual that described the model's operation and the parameters involved. As with SIBERIA, GOLEM allowed the user to input their own initial surface.

Running GOLEM was simple and the model read an input file that defined the process parameters. Some variables, such as the size of the grid mesh, required alterations to the source code and re-compiling. GOLEM ran at a similar speed to SIBERIA, but contained no real-time output. At the end of the simulation, several data files were written containing surface elevations and drainage area information. The code was clear and easily changed so the elevations were output as a grid instead of a list of numbers to allow integration into ARC-INFO (Figure 2). To summarize, GOLEM was quick and straightforward in operation and useful for examining long time scales and the effects of tectonic uplift and loading.

CASCADE

CASCADE differs significantly from previous models, as it uses an irregular mesh or TIN (Triangular Irregular Network) instead of a square grid. This mesh is derived using Delaunay triangulation and erosion and deposition is carried out between the natural neighbour nodes of the mesh. This means that in areas where a high spatial resolution is required (river channels) more nodes can be used than, for example, on a hill slope. The mesh is self-adapting and deformable, so that nodes can be added or moved during simulations, allowing, for example, a new river channel to be added to a hill slope. The model uses the 'Cascade' algorithm to calculate the channel network and route water to the lowest neighbour. Other methods (e.g. GOLEM) require the nodes in the mesh to be ordered so that water can flow from highest to lowest, which can be time-consuming. The CASCADE method is a 'bucket passing algorithm' (Braun and

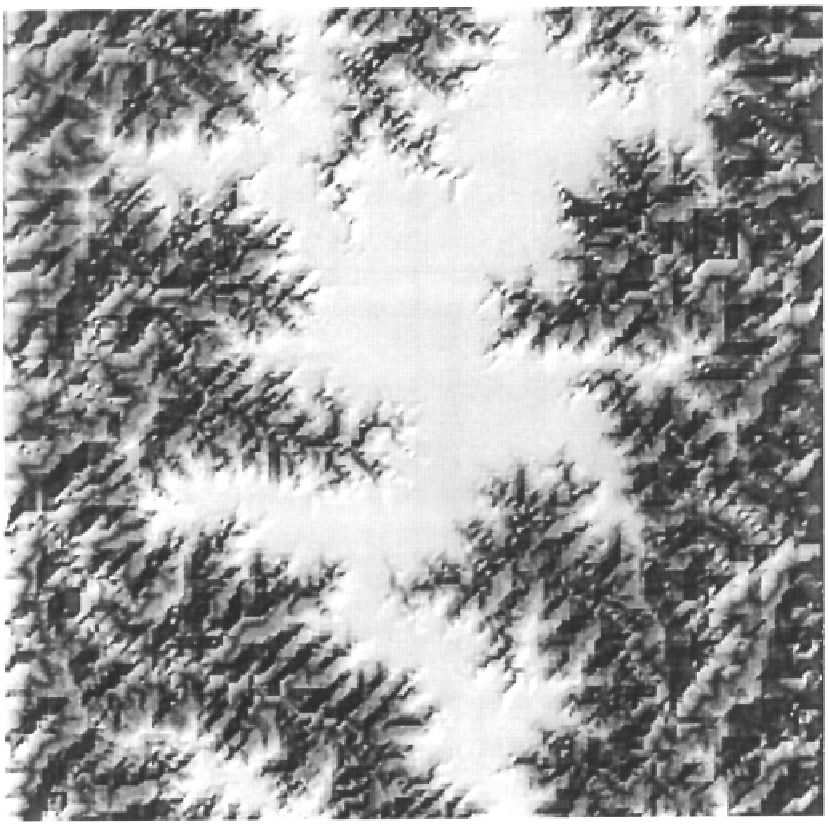

Figure 2. Output from a GOLEM run, generated from ARCMAP, with a 130 × 130 grid

Sambridge, 1997) where each node is given a 'bucketful' or set amount of water and asked to pass it to its lowest neighbour. After this, all nodes that have not received any water are local 'maxima' and placed at the top of a list. This process continues until all nodes have been accounted for, resulting in an ordered list in a fraction of the time. CASCADE has been applied to long term, large area simulations of millions of years, where each node spacing is approximately 1 km. It integrates basic diffusive slope processes with simple fluvial erosion and deposition based upon a carrying capacity.

The adaptable irregular mesh has allowed the simulation of complex geometries and the easy integration of tectonics, in particular horizontal movement. Such situations are hard to model with a fixed or regular mesh and excellent examples are shown in Braun and Sambridge (1997). They also claim that the irregular mesh overcomes some of the problems associated with using a regular grid, where forcing the water in only eight directions can result in an artificial symmetry developing.

CASCADE is not for open distribution and to download, the user must first contact Jean Braun for a username and password. When downloaded. CASCADE came as a tar file containing several FORTRAN and C sub-programs that required compilation on a Unix machine. The code, however, refused to compile on Linux 6.2, but was fine on a Digital machine and SUN workstation after alterations were made to the 'makefile'. Once in operation, CASCADE was the only model reviewed here to offer a graphical output of the model evolution (Figure 3). This showed a plan view of the landscape and drainage network, with different colour spots corresponding to the elevations. The default simulation (10 000 time steps of 100 years) ran in approximately 10 minutes on a fast Unix machine and produced output files of topography and discharge characteristics. No manual or user guide was available, but

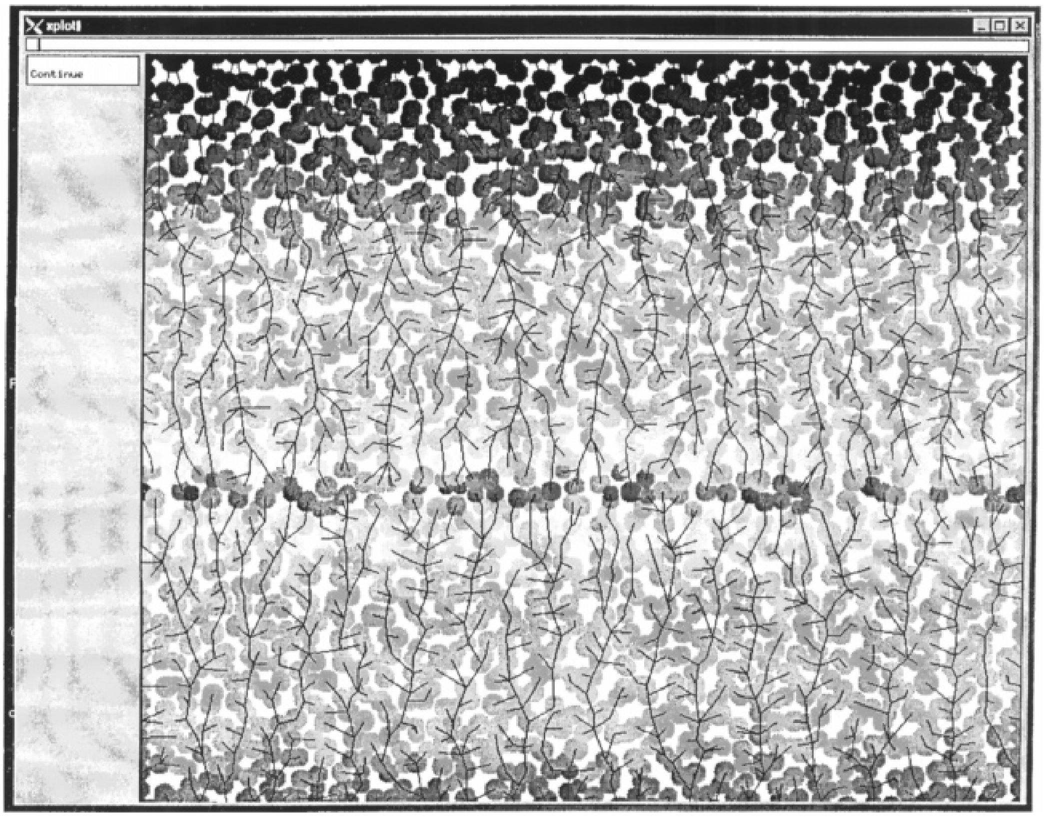

Figure 3. A screen shot of CASCADE running. This shows a central escarpment being eroded. The spots correspond to nodes of the irregular mesh. Reproduced by permission of Jean Braun, Research School of Earth Sciences, Australian National University

parameters controlling the erosion and tectonic functions could be altered by editing the FORTRAN code, then recompiling. CASCADE also allowed any initial surface to be loaded as X, Y and Z values. In summary, CASCADE offers a different methodology using novel algorithms that is ideal for complex geometries and horizontal tectonic movement, but presently contains simple process representations and proved complex to use.

CHILD

CHILD also uses an adaptable irregular mesh or TIN of nodes derived from Delaunay triangulation. Water is routed from node to node by the steepest slope using the CASCADE algorithm, but instead of using a fixed time step, every model iteration represents a storm event. This 'event' has a rainfall intensity and duration that are used to drive a hydrological model (there is a choice of four), which calculates how much water to add to each node. The fluvial erosion and deposition for this storm event are then determined and the elevation of the node updated accordingly. CHILD incorporates a more elaborate representation of fluvial processes, calculating a channel width and depth within the node. This drives detachment and transport limited sediment transport rules, a meandering model and overbank deposition routine. Furthermore, CHILD allows the user to specify different grain sizes, as well as record the age of deposits, which enables the model to construct simple alluvial stratigraphies. Tectonic uplift can also be included, but not horizontal movement as per CASCADE. CHILD has been applied to river catchments for timescales ranging from thousands to millions of years, though for longer simulations storm events have to be 'enlarged' to represent several years of erosion and deposition.

CHILD was available by e-mailing Greg Tucker from the CHILD website, but distribution may be

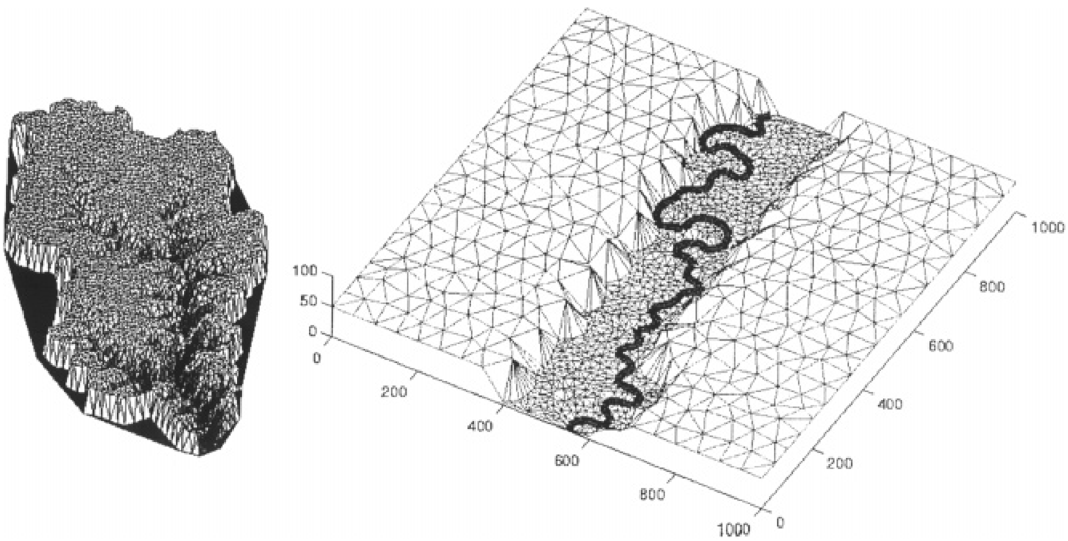

Figure 4. Examples of the irregular mesh used by CHILD. The first image details a catchment experiment, whereas the second shows a section of meandering channel

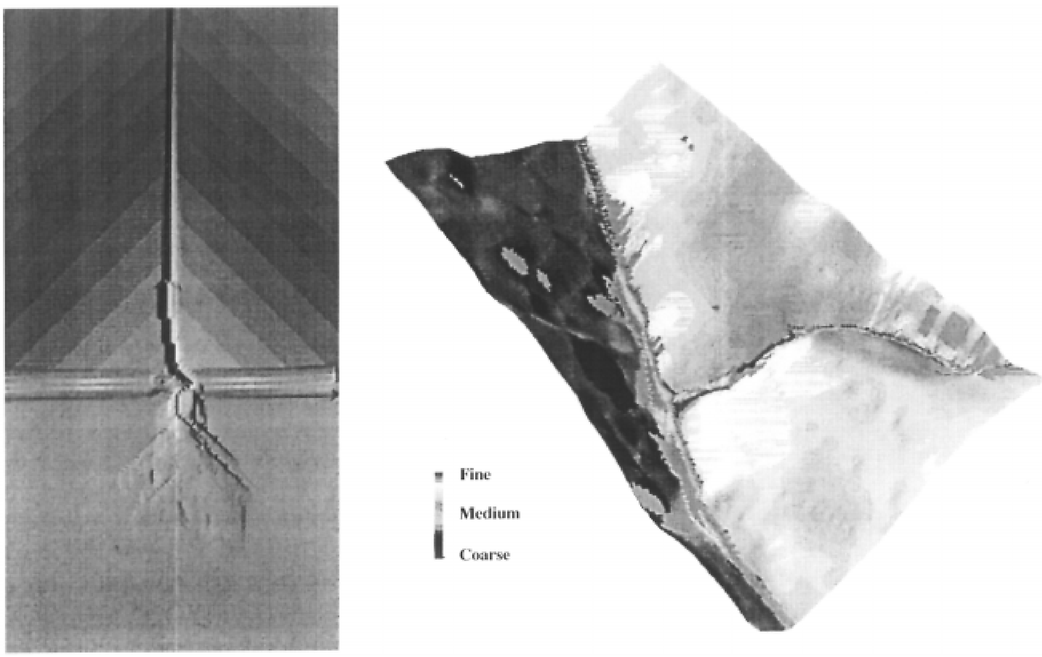

Figure 5. Results from the simple CAESAR demonstration of alluvial fan formation, and a confluence section from a larger simulation, detailing differences in surface grain size

subject to a licensing agreement. It is written in C++ and came as a zipped tar file containing numerous files and directories. Compilation was awkward, and the program could only be compiled on a Digital machine, though Tucker (personal communication) stated that CHILD will be made compatible with Linux and other Unix systems. A highly detailed manual can be downloaded from the CHILD website, along with a series of technical reports that describe the model and some examples. Most of the parameters for CHILD are read from an input file at run-time that allows the user to change, for example, climate, the hydrological model, erosion model, hydraulic geometry constants and the meandering model. The initial surface can be generated by the model, read from a data file as X, Y, Z co-ordinates or even read as an input from an ARC-INFO grid file. Output from the model is generated at time intervals specified in the input file, and includes ASCII files detailing node elevations, slopes, drainage areas, flow directions and surface grain size. In summary, CHILD is a sophisticated, well documented model with many excellent features. However, it was hard to compile and, due to its complexity, the source code may be difficult to modify.

CAESAR

CAESAR was designed to operate over timescales from 10 to 10 000 years and uses many (up to several million) small square grid cells (from 1 m to 50 m) to represent the landscape. This permits CAESAR to model fluvial processes in greater detail by allowing the channel to span several grid cells, instead of representing it within a single larger cell or node. An hourly rainfall record is used to drive a hydrological model that calculates cell discharge, which is then routed across the catchment using a novel 'scanning' multiple flow algorithm that negates the need for sorting grid elevations. Unlike steepest descent methods, this allows divergent flow, for example at an alluvial fan or in a braided section, and also removes some of the artificial symmetry created by forcing all the flow in one direction. CAESAR also models the erosion of up to nine different grain sizes using an active layer system enabling the formation of bed armour and alluvial stratigraphies. This is combined with a variable time step controlled by erosion rates, so that during a large flood, the time step may drop to a millionth of a second, yet expand to an hour during low flows. Representations of soil creep and mass movement are also integrated. CAESAR has been applied to small catchment in the Yorkshire Dales (<4 m^2) with 2 m grid cells to model catchment response to climate and land-use change (Coulthard *et al*., 2000), sediment waves and alluvial fan evolution (Coulthard *et al*., 1998), as well as at larger scales (400 km^2) with 50 m grid cells (Coulthard and Macklin, 2000). Furthermore, the results of these simulations have been validated with field data from flood records and alluvial stratigraphies. However, as CAESAR operates over smaller timescales, it fails to incorporate long term processes such as rock weathering, soil generation and tectonic uplift.

CAESAR was easily downloaded from the website, and came as a zip file containing a Windows 95, 98 and NT compatible executable file, with sample sets of data. Three versions were available, with different restrictions on the size of the grid mesh (smaller versions were designed for machines with limited memory). The source code was not freely available, though the authors may be willing to release it for some uses. The website also contained a basic manual explaining some parts of the model's operation and the parameters, as well as a thesis chapter providing a more detailed description of the model.

Running CAESAR simply involved double clicking the executable file. This brought up a text window that provided basic information as to how far the model had progressed and information on water and sediment discharges. A data file was read at the beginning of the run that could be altered to change the size of the grid, grain sizes, slope failure angles, vegetation cover and other model parameters. The model periodically produced ASCII grids of the surface elevations that could be read by ARC-INFO, as well as a file detailing the model stratigraphy. The demonstration models released on the website were limited to simulate for a maximum of 10 years, but longer term versions can be created upon request. A 10-year simulation of alluvial fan development on a 300×100 grid took approximately 14 hours. In summary, CAESAR was simple to use and produced a very high resolution output, but its ability to model long term simulations ($>10\,000$ years) is limited by the long run times and basic slope process representation.

Summary

Whilst similar in concept, these models all have different ways of modelling landscape evolution, and consequently some are better suited for certain applications than others. The choice of model will depend heavily upon the nature of the application, and to help potential users, the following four categories summarize the suitability of the models reviewed.

1. *Resolution, spatial and temporal*. Most of the models reviewed here can be applied over a wide range of time and space scales. However some (e.g. CASCADE and GOLEM) are better suited for large scale, long term simulations whereas others (e.g. SIBERIA, CAESAR and CHILD) may be better for shorter periods, where higher resolution is required. However, with all these models it should be remembered that increasing the number of mesh nodes and study period significantly lengthens the duration of a model run.

2. *Process representation*. CHILD, CAESAR and to a lesser extent GOLEM all model fluvial processes in more detail, including grain size and stratigraphy. Furthermore, CAESAR also models the channel topography with divergent flow and CHILD incorporates a meandering model. Conversely, SIBERIA and GOLEM contain better representations of slope processes including rock weathering. CAESAR fails to include tectonic effects and CASCADE is the only model to allow horizontal tectonic movement. All the models have been compared to natural drainage basins using drainage network characteristics, but only SIBERIA has been directly validated to measured erosion rates, and CAESAR to dated flood deposits.

3. *Ease of use*. None of the models reviewed here can be described as user friendly. None of them presently have a graphical user interface (GUI) and CASCADE is the only model to offer any real-time graphical output. Furthermore, to operate some of these models, a modicum of Unix and compiling experience is required. Direct programming skills are not essential to operate any of these models, but are useful when modifying parameters and model configuration. However, it must be recognized that these programs are research tools and therefore a greater emphasis is placed on the final outputs rather than user friendliness. Of those reviewed, SIBERIA and GOLEM were the easiest to use with the code and parameters being simple to modify. The programming required for irregular meshes is more complex and, as a consequence, CASCADE and CHILD were far more intricate in structure. Furthermore, existing raster DEMs are more easily integrated into the regular grid models than irregular grids.

4. *Area of application*. The variations between process representation and scale means that some models are better suited to simulating certain areas. For example, CAESAR was developed for smaller temperate catchments, so presently has no approximations for semi-arid slope processes. In contrast, GOLEM and SIBERIA have more flexibility in their slope models and also allow for weathering effects, enabling them to be applied in arid environments. Additionally, if the model is required to simulate a complex catchment, with, for example, entrenched meanders, CASCADE and CHILD with their irregular mesh may prove more suitable.

Future directions and conclusions

Future technical developments for these models could include the development of a Windows based front end and the application of parallel programming techniques. This could for example allow different subcatchments to be modelled simultaneously on separate processors. Indeed Braun and Sambridge (1997) describe how some of CASCADE's code is easily scalable for parallel processing. Given these techniques, the size resolution of catchment studied would in theory only be limited by the number of processors available (though a law of diminishing returns applies).

Future applications of these models include using grain size modelling (CAESAR and CHILD) and stratigraphy generation for the 3D modelling of alluvial architectures. These process driven models may prove ideal for this purpose as, instead of requiring sedimentary inputs to the basin, they generate their own from contributing catchments. Furthermore, versions of CAESAR are presently being developed to simulate the long term storage and re-mobilization of heavy metal contaminated sediments within river catchments. However, one area that urgently needs addressing is accurate model validation. Most of the models reviewed here have been run extensively on abstract, randomly generated catchments, but in order to believe the model results, simulations need to be carried out and validated with real catchments. This is difficult, as these models simulate thousands to millions of years of evolution. But by using retrovalidation, that is by simulating the past and comparing the results to present day landscapes, we can treat the models' results with confidence. The increased resolution of modern dating techniques, combined with field geomorphology, may allow this validation by, for example, comparing dated stratigraphic sequences with model outputs. This could allow the sophisticated models reviewed here to be used to address real environmental problems, as SIBERIA already is (Evans and Willgoose, 2000), with a high degree of certainty.

The models presented in this review have a wide range of uses for hydrologists and geomorphologists, from teaching examples to research tools. Whilst initially difficult to use, with a little perseverance, they can easily be used to investigate relationships between hydrology, climate, land-use, tectonics and catchment form.

Acknowledgements

I would like to thank Jean Braun, Greg Tucker and Garry Willgoose for their help with and comments on this review.

Appendix: Reviewed model websites

SIBERIA: http://www.eng.newcastle.edu.au/∼cegrw/GRWpages/siberiahp.html
GOLEM: http://www.mit.edu/people/gtucker/Golem/GolemMain.html
CASCADE: http://rses.anu.edu.cau/ ∼ jean/
CHILD: http://platte.mit.edu/ ∼ child/
CAESAR: http://www.coulthard.org.uk/

Other landscape evolution modelling sites

Alan Howard's basin model: http://erode.evsc.virginia.edu/
ZSCAPE: http://www.tcd.ie/Geology/adens/zscape.html

References

Anhert F. 1976. Brief description of a comprehensive three-dimensional process-response model of landform development. *Zeitschrift für Geomorphologie, Supplementband* **25**: 29–49.

Braun J, Sambridge M. 1997. Modelling landscape evolution on geological time scales: a new method based on irregular spatial discretization. *Basin Research* **9**: 27–52.

Coulthard TJ, Macklin MG. 2000. How sensitive are river systems to climate and land-use changes? A model based evaluation. *Journal of Quaternary Science*, in press.

Coulthard TJ, Kirkby MJ, Macklin MG. 1998. Modelling the 1686 flood of Cam Gill Beck, Starbotton. upper Warfedale. In *The Quaternary of the Eastern Yorkshire Dales: Field Guide*, Howard A, Macklin MG (eds). Quaternary Research Association: London: 11–18.

Coulthard TJ, Kirkby MJ, Macklin MG. 1999. Modelling the impacts of Holocene environmental change on the fluvial and hillslope morphology of an upland landscape, using a cellular automaton approach. In *Fluvial Processes and Environmental Change*, Brown AG, Quine TM (eds). Wiley: New York; 31–47.

Coulthard TJ, Kirkby MJ, Macklin MG. 2000. Modelling geomorphic response to environmental change in an upland catchment. *Hydrological Processes* **14**: 2031–2045.

Evans KG, Willgoose GR. 2000. Post-mining landform evolution modelling. 2. Effects of vegetation and surface ripping. *Earth Surface Processes and Landforms* **25**: 803–824.

Howard AD. 1994. A detachment limited model of drainage basin evolution. *Water Resources Research* **30**(7): 2261–2285.

Kirkby MJ. 1987. Modelling some influences of soil erosion, landslides and valley gradient on drainage density and hollow development. *Catena Supplement* **10**: 1–11.

Mann ME. 2000. Climate change: lessons for a new millennium. *Science* **289**: 253–254.

Tucker GE, Bras RL. 2000. A stochastic approach to modeling the role of rainfall variability in drainage basin evolution. *Water Resources Research* **36**(7): 1953–1964.

Tucker GE, Slingerland RL. 1994. Erosional dynamics, flexural isostasy, and long-lived escarpments: a numerical modelling study. *Journal of Geophysical Research* **99**: 12 229–12 243.

Tucker GE, Lancaster ST, Gasparini NM. Bras RL, Rybarczyk SM. 2000. An object-oriented framework for hydrologic and geomorphic modeling using triangulated irregular networks. *Computers and Geosciences*, in press.

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.

Willgoose G, Bras I, Rodriquez-Iturbe I. 1994. Hydrogeomorphology modelling with a physically based river basin evolution model. In *Process Model and Theoretical Geomorphology*, Kirkby MJ (ed). Wiley: Chichester, UK: 3–22.