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Modelling the response of river systems to environmental change: progress, problems and prospects for palaeo-environmental reconstructions

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Abstract

Over the last decade several computational models, and several types of model, have been developed to simulate the response of river systems to environmental change over time scales of decades to millennia: hydrological models, flood inundation models, channel morphology models, channel network models, models of river meandering and river braiding, alluvial stratigraphy models, and landscape evolution models. Each type of model simulates different aspects of a river's response to changes in environmental inputs such as climate and land-use – and to changes in these inputs. And each type of model has its abilities, advantages and limitations. We provide an overview of the different types of model that have been developed, and we evaluate their suitability for testing hypotheses about past environmental conditions, as well as for investigating the response of alluvial river systems to future environmental change. Additionally, we discuss the general issues and problems of computational modelling (e.g. scale and resolution, data availability, process representation, process parameterization, model calibration, non-linearity, and uncertainty), and the extent to which these hamper the usefulness of the models as a tool in environmental landscape studies. Finally, we identify trends in computational modelling research to outline possible future directions of the discipline.

Keywords: computational modelling, environmental modelling, river systems, fluvial geomorphology, quaternary

1. Introduction

Rivers are amongst the most dynamic geomorphological elements of the landscape. Through continual erosion and deposition they create, destroy or alter their own morphology as well as that of the adjoining valley floor. Short term geomorphological processes, such as bank failure or sediment entrainment and deposition, over time result in distinctly recognizable morphological features like meander cut-offs, point bars, channel bars and islands, ox-bow lakes and river terraces.

The rates, magnitude and frequency of these processes are largely determined by the physical properties of the substrate, whether sediment or rock, and by predominant climate and land-use conditions. Hence, any change in these environmental conditions will affect the evolution of the river system and the alluvial landscape. For example, an increase in rainfall intensity can instigate a higher sediment supply from the hill slopes and thus in a higher sediment load in the river channel, thereby transforming a previously meandering channel into a braided river system. Such changes in morphology and dynamic behaviour of the river are recorded in the alluvial stratigraphy, which, therefore, can be seen as an archive of past environmental change (e.g. Maddy *et al.*, 2001; Brierley, 2010). Hence, an understanding of alluvial systems and interpretation of alluvial archives can be used to infer environmental conditions during the Holocene and earlier periods.

Unfortunately, there are some disadvantages to this approach. First, river response to the environmental signal is usually spatially and temporally variable throughout the catchment (Richards, 2002), as shown by recent model-based studies (e.g. Coulthard *et al.*, 2005). Obtaining a full perspective of the alluvial history, and thus the past environmental conditions could, therefore, require a complete three dimensional analysis of the entire alluvial valley. However, in practice this is near impossible, even with new technologies like ground-penetrating radar or airborne remote sensing. A second and more fundamental problem is that, even with a full three-dimensional analysis of the alluvial valley, the alluvial archive rarely provides a complete reconstruction of past environmental conditions. During the geomorphological evolution of the alluvial valley, erosional processes can partly or wholly destroy components that have been built up through earlier depositional processes. Thus, parts of the alluvial archive are erased through the lateral erosion or vertical incision of the river channel, which creates corresponding gaps in the reconstruction of past environmental conditions (Lewin and Macklin, 2003). Finally, generalization of field observation is further complicated by the uniqueness, spatial and temporal variability, and non-repeatability of the environmental conditions driving the morphological processes in a catchment. These issues hamper the interpretation of present-day alluvial geomorphology as a tool for past environmental reconstruction. However, computational and physical models can complement field-based studies to partly alleviate these problems.

Physical models, *i.e.* controlled laboratory experiments, offer some potential for gaining additional insights in the effects of environmental change on landscape morphology (e.g. Hasbargen and Paola, 2000; Bonnet and Crave, 2003; Hancock and Willgoose, 2003; Raff *et al.*, 2004; Hickson *et al.*, 2005). However, this potential is limited. There are many uncertainties concerning the downscaling of space and time in physical experiments (Schumm *et al.*, 1987; Peakall *et al.*, 1996). Even if temporal and spatial scales could be sufficiently and unambiguously compressed, the experimental studies would still be complicated by the sensitivity of the experimental system to initial conditions and the number of external parameters to be controlled (Schumm *et al.*, 1987; Peakall *et al.*, 1996).

Computational or numerical models provide an alternative approach to address some of the shortcomings of alluvial systems as archives of environmental change. The underlying idea is that the models represent a controllable virtual world which replicates the salient aspects of the real world (Kirkby, 1990; Darby and Van De Wiel, 2003; Bras *et al.*, 2003). Moreover, this virtual world can be analysed, fully and non-intrusively, at any point in space and time. Hence, computational models of alluvial river systems and their morphological dynamics could be used to test hypotheses about past environmental conditions, or to run what-if scenarios to evaluate the impacts of future environmental change (e.g. land-use change, climate change, or even river engineering). However, computational modelling has many difficulties of its own, which are mainly associated with translating the real world into a numerical world (Kirkby, 1990; Haff, 1996; Darby and Van De Wiel, 2003).

We assess the current status of numerical modelling as a tool for studying the impacts environmental change on river systems and fluvial landscapes. The bulk of the paper is divided in two sections. In the first section, we give an overview of the various types of computational models that have been developed, highlighting the properties, potential and limitations of each type of model. This section addresses what sorts of questions may be investigated with the different types of model. Subsequently we discuss the broader issues of computational modelling in quaternary fluvial geomorphology, which affect all of the different types of models – as well as the prospects of dealing with these issues. This second section addresses the suitability and reliability of computational models as a tool to investigate the response of river systems to environmental change.

2. Types of models

Over the last decade many different types of computational models have been developed, which simulate different aspects of alluvial system behaviour. There are many different ways to classify these models: chronologically, by modelling technique (process-based, black-box, optimization), by mathematical technique (statistical, analytical, numerical), by computational technique (cellular automaton, finite difference, finite element), but the most fundamental classification concerns what the models actually simulate, or attempt to simulate (figure 1). Thus, in the context of modelling impacts of environmental change on river systems, distinction can be made between flow models, which simulate fluxes of water through a catchment or reach, and geomorphic models, which simulate change in landforms and topography. The former type includes hydrological models (figure 1A) and flood inundation models (figure 1B), while the latter type includes channel morphology models (figure 1C), alluvial stratigraphic models (figure 1D), meander models (figure 1E), braided river models (figure 1F), channel network models (figure 1G), and landscape evolution models (figure 1H). In the following paragraphs an overview of these modelling techniques is given, with emphasis on their suitability for modelling the effects of environmental change.

2.1. Hydrological models

Hydrological models and rainfall-runoff models simulate the distribution, routing and retention of flow through the catchment (e.g. Beven *et al.*, 1989; Todini, 1996; Szilagyi and Parlange, 1999; Raff and Ramírez, 2005; Moore, 2007). In essence, these models transform a spatial and temporal distribution of precipitation into a discharge throughout the system. Typically, the output of hydrological models consists of a series of hydrographs at one or more points in a catchment (figure 1A; figure 2). These hydrographs can be related to the input data, *i.e.* precipitation record, to study the hydrological conveyance properties of the system. In this respect, hydrological models are able to simulate the frequency, magnitude and duration of flood events and of droughts, under current, predicted and hypothetical climate and land-use scenarios.

However, hydrological models suffer from two significant drawbacks that limit their suitability for modelling long-term catchment response to environmental change. First and foremost is the fact that they do not simulate sediment fluxes and, hence, cannot represent the geomorphological dynamics of the landscape. Thus, they implicitly assume that the catchment's topography remains constant during the simulation – an assumption which is invalid in many cases. As mentioned earlier, geomorphological processes can cause significant changes in topography (e.g. channel incision or widening, alteration of channel pattern, capturing of tributary networks), particularly over the larger timescales that are of interest to environmental modelling, *i.e.* centuries or millennia. Moreover, these changes can alter the hydrological behaviour of the catchment, which would render the hydrological simulations irrelevant. The second drawback of hydrological models concerns their calibration and validation. Because hydrographs themselves do not persist in the landscape, calibration and validation is limited to historical times, where discharge data are available. For earlier simulations, the discharge must be derived by proxy, for example through the geomorphic imprints of specific flood or flood periods (e.g. Baker *et al.*, 1983).

Nonetheless, hydrology is a vital component of landscape evolution, which fosters interactions with flow hydraulics, geomorphological processes and vegetation. Hence, it is important to incorporate catchment hydrology when modelling the response of fluvial systems to environmental change.

2.2. Flood inundation models

Flood inundation models simulate the spatial and temporal extent of inundation resulting from individual storm events (figure 1B; figure 3). They are mainly used to assess the flood risk of floods of specific magnitude or return interval, and usually operate on a reach scale (e.g. Bates and

De Roo, 2000; Beffa and Connell, 2001; Horritt and Bates, 2001; 2002; Dutta *et al.*, 2007). The flow field is derived by applying numerical techniques to solve or approximate the Navier-Stokes equations that govern the basic principles of fluid flow (*i.e.* conservation of mass and momentum of flow). One-dimensional models, which consider the flood depths at a series of cross-sections, are the most common. Spatial flood extent is obtained by interpolating the predicted water surface at successive cross-sections and intersecting this with a digital terrain model. In two- and three-dimensional models the flow field (*i.e.* flow depths and flow velocity) is calculated over a network of computational cells or nodes covering the channel and floodplain, and the inundation pattern is derived explicitly from these flow field calculations. The flow field of flood flows can be highly complex, as it is strongly influenced by both channel geometry and floodplain topography, which requires careful treatment of wetting and drying of cells within the model.

The applicability of flood inundation models to environmental change problems is rather limited. On first glance, they could be used, and indeed frequently are used, to evaluate the impacts of environmental change, and in particular climate change, on flood risk and inundation for future scenarios. In practice, however, the inability of flood models to simulate sediment fluxes and geomorphological change seriously hampers this potential, as it is unrealistic to assume that the river channel and the topography of the floodplain will not alter in the intervening time. A possible alternative might be to use flood inundation models in conjunction with landscape evolution models (see below), where the latter are used to estimate future morphologies over which the flood inundation models can operate (Van De Wiel *et al.*, 2005).

2.3. Channel morphology models

Channel morphology models (figure 1C; figure 4) simulate sediment fluxes and morphological change in river channels, usually on a reach scale (e.g. Fang and Wang, 2000; Guo and Jin, 2002) or smaller sections, like individual bends or confluences (e.g. Kassem and Chaudhry, 2002; Rüther and Olsen, 2005). Most current models focus on in-channel flows and the morphological evolution of channel bed features (figure 4), such as pools, riffles, bars and dunes (e.g. Cao *et al.*, 2003; Rathburn and Wohl, 2003). Recently, other aspects of channel morphology have been incorporated in these models, including river width adjustment and bank erosion (e.g. Nagata *et al.*, 2000; Darby *et al.*, 2002), and the simulation of overbank sediment fluxes and associated morphological changes of the floodplain (e.g. Nicholas and Walling, 1997; 1998; Hardy *et al.*, 2000; Thonon *et al.*, 2007). Like flood inundation models, channel morphology models rely on solving or approximating the Navier-Stokes equations for conservation of mass and momentum of flow to derive the flow field. In addition, the entrainment, transport and deposition of sediment is calculated, usually using empirical relations, to derive morphological changes. The computational demands of these models can be very high, because the boundaries of the flow field can change due the coupling between flow field and channel morphology, which requires frequent recalculation of flow conditions. As a consequence, channel morphology models are generally constrained to relatively small spatial and temporal scales.

Channel morphology models are mainly used in water resources engineering applications, but are increasingly applied in geomorphology as tools for understanding river processes. However, they are currently not applied for environmental change studies, due to the extensive data requirements and the demands on computational power for long-term larger scale studies. However, these models could provide a basis for future modelling, if computation times can be drastically reduced.

2.4. Alluvial stratigraphy models

Stratigraphic models simulate the vertical development of alluvial systems through time. A three-dimensional, spatially diverse sequence of stratigraphic units of different age is constructed by modelling the erosion and deposition of sedimentation units (figure 1D; figure 5). The first stratigraphic models were developed in the late 1970's (Bridge, 1975; Bridge and Leeder, 1979), and by 1990 had become significantly more sophisticated (Koltermann and Gorelick, 1996; Paola, 2000).

These models have been designed to operate at a range of spatial scales, from individual bends (e.g. Cardenas and Zlotnick, 2003), over extensive channel reaches (e.g. Bridge and Mackay, 1993; Webb, 1994; 1995; Heller and Paola, 1996; Teles *et al.*, 1998; 2001; Jerolmack and Paola, 2007), to entire basins (e.g. Koltermann and Gorelick, 1992; Rivenæs, 1997; Syvitsky *et al.*, 1998; Morehead *et al.*, 2001). Depending on how the stratigraphic units are derived within the model, a distinction can be made between structure imitating and process imitating models (Koltermann and Gorelick, 1992; 1996; Karsschenberg *et al.*, 2001). Structure imitating models (e.g. Holden *et al.*, 1998; Teles *et al.*, 1998; 2001; Deutsch and Tran, 2002; Ramanathan *et al.*, 2010; Guin *et al.*, 2010) attempt to simulate floodplain development by repeated placement of different fluvial structures (point bars, overbank deposits, crevasse splays, channel bars). Both temporal occurrence and spatial location, geometry and size of each structure are determined stochastically. These models generally are conditioned to replicate a prescribed morphology. Process imitating models (e.g. Bridge and Mackay, 1993; Webb, 1994; 1995; Heller and Paola, 1996; Gross and Small, 1998; Karssenberg *et al.*, 2001; Jerolmack and Paola, 2007; Karssenberg and Bridge, 2008) attempt to simulate the salient processes responsible for the development of the structures (sediment fluxes, channel avulsion), which results in more realistic simulated sedimentary architecture (Karssenberg *et al.*, 2001; Karssenberg and Bridge, 2008). Although the process imitating models could in principle be fully deterministic, they usually retain a stochastic component (e.g. temporal and spatial occurrence of avulsion). However, they are not conditioned to conform to prescribed landscape characteristics and are normally used for generic interpretations of the stratigraphic evolution of alluvial systems. Recently attempts have been made to combine the advantageous properties of both structure imitating and process imitating models in a hybrid form (e.g. Karssenberg *et al.*, 2001; Edington and Poeter, 2002; Karssenberg and Bridge, 2008).

The main application of stratigraphic models is the simulation of the heterogeneity of subsurface facies, particularly with respect to the permeability of aquifers and the potential existence of petroleum reservoirs. However, process imitating stratigraphic models might also be used to investigate the effects of environmental change on the construction and preservation of alluvial structures. A suite of hypothetical "what if" scenarios could be run to evaluate the sensitivity of the simulated alluvial landscape to a range of specified climatic or environmental settings. However, the often highly simplified process representation in stratigraphic models might limit the potential to investigate river system response to environmental change with sufficient detail (e.g. channel geometry is usually prescribed rather than resulting from the interaction between flow and sediment processes). Furthermore, the stochastic aspect of most alluvial stratigraphic models prohibits repeatability of the simulations, and complicates interpretation of "what-if" scenarios as it is generally unclear whether any observed differences in the simulated landscapes are due to the effect of changing the environmental conditions in the scenarios, or simply to the stochastic nature of the model.

2.5. Meander evolution models

Meander evolution models simulate the evolution of channel planform in single-thread meandering rivers, over time-scales of up to several millennia (figure 1E; figure 6). In their basic form, they simulate channel flow to drive a simple hydraulic bank erosion mechanism from which channel migration rates are derived (e.g. Howard and Knutson, 1984; Liverpool and Edwards, 1995; Lancaster and Bras, 2002). Usually, a linearized one-dimensional flow model with adaptations to account for secondary flow effects (e.g. Johannesson and Parker, 1989; Odgaard, 1989; Seminara and Tubino, 1992; Zolezzi and Seminara, 2001) is used in meander evolution models, although alternative flow models are employed as well (e.g. Liverpool and Edwards, 1995; Lancaster and Bras, 2002). Additionally, non-linearized models have been developed more recently (e.g. Bolla Pittaluga, 2010). Bank erosion all of these models is normally calculated from flow velocity and channel curvature by means of an empirical erodibility coefficient. Currently, all meander evolution models assume uniform channel width, so that point bar build-up along the inside bend matches bank erosion on the outside bend. This assumption allows lateral channel migration to be directly equated with outer bank erosion. More complex models (e.g. Howard, 1992; 1996; Sun *et al.*, 1996; 2001a; Stølum, 1997; 1998) simulate channel migration in a similar manner, but place the evolution of the meandering channel in the context of a dynamic floodplain. Thus, the river can adjust both laterally (channel migration) and vertically (incision and aggradation), and new point bar deposits and abandoned meander cutoffs can be preserved. Additionally, these models simulate overbank deposition by incorporating simple algorithms with decaying rates of sedimentation away from the channel.

The more complex meander evolution models have a greater potential for investigating river system response to environmental change, as they integrate the simulation of planform evolution of meandering rivers with vertical floodplain evolution to create a three-dimensional stratigraphic archive. However, there are some important limitations with these schemes. First, they simulate meandering channels as being single-threaded, whereas rivers may have islands, or fluctuate between being braided and meandering. Second, they assume a fixed channel width, which reduces their capability to change channel dimensions in response to environmental change. And third, there is no continuity of sediment, as they (largely) assume that material is deposited on the inside edge of the bend at the same rate it is eroded along the outside bank. This is rarely the case in reality, as the geometry of channels means more sediment is eroded at the outside edge than can be deposited on the inside (Lauer and Parker, 2008).

2.6. Braided river models

Braided rivers have been extensively studied due to their dynamism and potential as aquifers/hydrocarbon reservoirs. Initial models were based on random walks (Howard et al., 1970; Krumbein and Orme, 1972; Webb, 1994) creating random yet statistically valid patterns. But these had no basis in process, and were static, therefore not capturing the dynamic, migrating nature of braided channels. Murray and Paola (1994) created a paradigm shifting cellular model of braided rivers that simply routes water across a ‘reach’ of grid cells, eroding and depositing material according to flow discharges (figure 1F; figure 7). This alters the topography and cell elevations, so on consecutive iterations water flows in different areas, causing different erosion and deposition patterns. These interactions result in the emergence of a braided channel pattern that migrates and evolves in a seemingly realistic way. This work was important, as it showed how the simple interactions of flow and sediment transport in a laterally unconstrained environment could lead to the complex pattern of braiding.

Comparison with flume studies has shown that, although the braid patterns are realistic, these models do not accurately represent flow depth and flow velocities in the channels (Doeschl-Wilson and Ashmore, 2005). Nonetheless, the cellular models are useful in simulating the behaviour of braided river systems. Following the initial study of Murray and Paola (1994), subsequent work led to the development of more advanced cellular braided river models with improved flow routing (Thomas and Nicholas 2002; Thomas *et al.*, 2007), and investigative studies on the effects of vegetation on river braiding (Murray and Paola, 2003). If coupled with meander models (above), braided river models could be a promising method to simulate fluvial response to environmental change. Unfortunately, meander models are restricted to single-thread channels and existing braided river models cannot simulate meandering. However, initial findings from Coulthard and Van De Wiel (2006) suggest that the integration of meandering and braiding in cellular models might be possible.

2.7. Channel network models

Channel network models simulate the development of a catchment's drainage pattern (figure 1G; figure 8). There are two main types of channel network models: random walk models and optimal channel network models. Occasionally a third type, simplified landform evolution models, is also considered (e.g. Hergarten and Neugebauer, 2001). In our classification this third type is included with landscape evolution models (next section).

Random walk models, which originated in the 1960s (Leopold and Langbein, 1962; Scheidegger, 1967), create a drainage network over a catchment by assigning a random flow direction to each node in the landscape. The resulting pattern bears reasonable resemblance to the drainage pattern of natural river basins, but the topology-based calculation procedure does not provide any insights as to how natural drainage networks develop. This shortcoming is partially addressed by optimal channel network models (OCNs), which simulate channel erosion to establish the catchment's drainage network (figure 8). The erosion algorithm does not directly replicate physical processes, but rather applies a optimization principle which minimizes or maximizes a specified property over the catchment. Commonly the minimization of total energy dissipation is chosen for this purpose (e.g. Rodríguez-Iturbe *et al.*, 1992; Rinaldo *et al.*, 1992; Sun *et al.*, 1994), although other optimization strategies could be used as well (e.g. the minimization of stream power or entropy production, or the maximization of friction factor or sediment transport capacity). The use of these optimization principles is not undisputed, as their theoretical foundations remain unclear (Mosselman, 2000; Darby and Van De Wiel, 2003). Nonetheless, OCNs yield realistic looking drainage networks, with statistical and fractal properties similar to those observed in natural basins (e.g. Rinaldo *et al.*, 1992; 1993; Rigon *et al.*, 1993). However, they provide little information on landscape morphology, other than the topology of the channel network. Additionally, OCNs only consider the final equilibrium state of the drainage pattern, and are thus unsuitable for investigating the evolution of river systems, neither in response to individual storm events nor in response to long-term environmental change.

2.8. Landscape evolution models

Landscape evolution models (LEMs) are physically-based process models that attempt to replicate the salient processes that form the landscape (figure 1H; figure 9). Most models simulate hydrological processes, fluvial processes and hillslope processes, but other processes (glacial, aeolian, tectonic) are sometimes included as well. LEMs typically operate across complete river catchments over spatial scales of 10 to 1000 km^2 (e.g. Howard, 1994; Willgoose *et al.*, 1991;

Tucker and Slingerland, 1994, Braun and Sambridge, 1997; Coulthard *et al*., 1999; Schoorl and Veldkamp, 2001), but can equally be applied to sub-catchment scales (e.g. Coulthard *et al*., 2002; Peeters et al., 2006; Van De Wiel *et al*., 2007; Temme *et al*., 2009). Their time scales of operation vary from decades and centuries to millennia or even millions of years, according to the nature of the problem under consideration.

LEMs simulate landscape evolution by routing water over a catchment digital elevation model (DEM) and changing individual grid cell elevations according to fluvial and slope processes, usually discriminating between slope and river cells. Importantly, the inclusion of a wide range of processes enables a comparatively comprehensive simulation of a catchment's response to environmental change, which not only considers the direct impacts of each process, but also incorporates the interactions between different processes and the associated feedback mechanisms. For example, the inclusion of the hillslope processes is relevant not only for the overall landscape evolution, but also for the development of the fluvial system itself. As slopes are the main suppliers of sediment to the channels, they indirectly influence the dynamics of sediment movement and storage on the valley floors. On the other hand, hillslope processes themselves partly depend on the ability of the fluvial system to evacuate sediments. Hence, LEMs allow for direct coupling of slope and fluvial processes, mimicking the catchment wide interactions that can influence fluvial behaviour.

These models may therefore seem, at first glance, ideally suited for modelling fluvial response to environmental change. Indeed, some models have been successfully applied so (Tucker and Slingerland, 1997; Coulthard and Macklin, 2001; Coulthard *et al.,* 2002; Tucker, 2004; Peeters et al., 2006; Temme and Veldkamp, 2009). Nonetheless, there are important issues that can hamper their application. One of the main challenges of landscape evolution modelling is to reconcile the various spatial and temporal scales of operation of the different processes within the model. For example, the rates of sediment movement by soil creep and by fluvial transport differ by several orders of magnitude, but both require adequate representation within a model. Additionally, the inclusion of a large number of processes within these models increases the uncertainty of their output and complicates their calibration and validation (see below). Furthermore, as a result of the high computational demands of landscape evolution models, they have thus far been run on relatively coarse resolution grids where the landscapes's heterogeneity and the behaviour of river system itself cannot be fully resolved. For example, a 100 m wide grid cell may be assigned as a 'river' cell, though in reality it may contain a channel only 10 m wide. Finally, there are significant difficulties in determining initial conditions and validating the model results. As a consequence, many studies shy away from genuine catchments and are based on abstract landscapes with theoretical examples (e.g. Willgoose *et al.*, 1994; Tucker, 2004; Coulthard and Van De Wiel, 2007; Van De Wiel and Coulthard, 2010).

However, recent work has led to significant developments on these issues. Initially designed to simulate fluvial response to environmental change, the CAESAR model incorporates many of the fluvial processes not found in other models, such as divergent flow, bed armouring, and multiple grainsize sediment transport (Coulthard *et al.,* 2000; 2002; 2005). Recently, several modifications have been made to the model, including suspended sediment transport and lateral erosion (Van De Wiel *et al.*, 2006; Coulthard and Van De Wiel, 2006). To tackle spatial resolution problems, some workers have developed an adaptive and variable size mesh, e.g. the CHILD model (Tucker *et al.*, 2001), which allows detailed resolution in complex fluvial areas, with a coarser mesh size on relatively homogenous zones such as hillslopes. Alternatively, the CAESAR model uses increased spatial resolution on a regular grid, *i.e.* many smaller square grid cells, to represent fluvial processes in great detail, but optimize temporally by only checking slope cells periodically (Coulthard *et al.*, 2000; 2002; Van De Wiel *et al.*, 2007).

2.9. Discussion and summary

Various types of computational models have been developed, which allow simulation of river response to environmental change, be it climate change, land-use change or vegetation change. Particularly, these models allow testing of different hypothesis about past environmental change, or to run scenarios to evaluate the impacts of future environmental change. Testing hypotheses typically involve running simulations with assumed initial conditions (e.g. topography, vegetation cover, soil depth) and known environmental forcing conditions (e.g. land-use change, climate), or vice-versa. The resulting simulated geomorphology can then be compared with present morphological observations, to check if the assumed conditions are plausible. It should be noted, however, that plausibility of the assumed conditions does not imply veracity of the assumed conditions, due to the potential of numerical or geomorphological equifinality (see below). Evaluation of the impacts of future change typically involves developing one or more scenarios for those future changes, the simulation results of which can be compared to and contrasted with the results of a no-change base scenario.

The various types of model simulate different aspects of the river system (Figure 1) and operate on different temporal and spatial scales (Table 1). They therefore allow different questions to be asked of the model. Thus, the choice of which type of model should be used depends on what is being investigated. For example, to test which environmental conditions give rise to an observed meandering planform geometry of palaeochannels, a suite of simulations with a meander model would be most suitable, whilst for investigating the impact of a specific palaeoflood, a flood inundation model would be more appropriate. Similarly, the spatial or temporal scale can also dictate the type of model (Table 1). For example, for reach-scale simulations on a yearly or decadal time-frame, channel evolution models would be more suitable than landscape evolution models, whilst for catchment-scale simulation over several millennia, alluvial stratigraphy models or landscape evolution models would be recommended.

Overall, landscape evolution models are the most versatile of the models available, and can address the widest range of issues. By modelling the whole catchment, thus integrating hydrological, fluvial and slope processes, they negate many of the difficulties imposed by other approaches (e.g. boundary conditions, slope/channel coupling). Importantly, they model all parts of the catchment, all of the time. Despite their shortcomings (i.e. high computational and data demand), landscape evolution models may, therefore, provide the ideal basis for modelling the response of fluvial systems to environmental change (Table 1).

3. Issues in modelling

From the above discussion it is clear that computational models may be a fruitful tool to investigate palaeo-environmental changes in climate, vegetation cover, land-use and the response of a river system to these changes. However, the increased use of numerical models in geomorphology has resulted in an increased awareness of their limitations. Knowledge of a model's limitations is an important factor in running simulations and interpreting the results. In this section we discuss the main issues that affect the computational modelling of fluvial response to environmental change: representation of space, representation of time, process representation, data availability, calibration and validation, and uncertainty. The first three of these issues are fundamental considerations in developing or choosing a model, as they determine how the real word is translated in a numerical language. They thereby largely determine the nature of the questions that can be asked of the simulations. The latter three issues are more practical considerations, relating to the feasibility of the simulations and reliability of the results. However, an understanding of all six issues is important in assessing and interpreting a model's simulations. Although many of these issues are closely related, they are discussed separately for convenience and clarity. However, the links between them are made explicit where appropriate.

3.1. Representation of space

Most numerical models discretize physical space on a grid or mesh consisting of a finite number of points. Spatially variable physical properties or characteristics (e.g. elevation, water depth, flow velocity, roughness, sediment concentration, *etc.*) are represented on this grid by a set of discrete values. The grids normally are either two- or three-dimensional, with the former representing only the planform structure of the area under consideration, whilst the latter also incorporate the sub-surface structure. Some grids are referred to as being 2½ dimensional, which essentially means they are two-dimensional grids with information on the third dimension (i.e. elevation values) recorded at each of the grid points. Digital Elevation Models (DEMs), thus are 2½ dimensional grids. The spacing of points in the grids can either be regular (usually square or hexagonal) or irregular (usually consisting of irregular triangles), depending on the nature of the model. It is, in general, easier to solve the mathematical equations governing the model on regular grids, whilst irregular grids normally achieve better computational efficiency.

Spatially, geomorphological systems can be viewed on a hierarchy of scales: every geomorphic system consists of a series of ever smaller, lower-level systems, and is at the same time part of a sequence of ever larger, higher-level systems (De Boer, 1992). Numerical simulation of geomorphological systems implicitly involves three levels of this spatial hierarchy, which can be directly related to the grid (Darby and Van de Wiel, 2003). The largest of these levels is the area under investigation, *i.e.* the whole grid. Generally, no geomorphological processes are explicitly modelled on this scale. Instead, observing or deducing changes and patterns at this level usually is the purpose of the simulation. The second level is represented by the spacing of individual grid points or cells. This is the level where the governing processes are explicitly modelled, and hence forms the core of the model (see *process representation*, below). The third and smallest level of processes is commonly referred to as the sub-grid level. Sub-grid processes have characteristic lengths which are smaller than the grid point spacing, and can therefore not be resolved within the model. Rather than simulating these processes explicitly on the sub-gridlevel, they are represented implicitly in the models, by considering their aggregate effects at the grid element level. Usually this requires assumptions of the spatial and temporal occurrence of sub-grid processes to be made (see *uncertainty*, below).

When representing space in a computational model, *i.e.* when constructing the grid, two elements must be considered: scale and resolution. The scale of the model is determined by the overall area or domain of the study site, whilst the resolution is a measure of the point density of the discretization and determines the level of detail at which both the site and the processes will be represented. For any particular problem, the choice of scale and resolution will depend on the nature of the problem, the required or desired accuracy of the simulations, the availability of input data, and the computational resources available.

As is clear from the overview above, different types of models operate on different scales, varying from individual meander bends, over channel reaches to entire catchment (table 1). Although these smaller scales can be suitable for some specific problems, the most appropriate spatial scale for studying the impact of environmental change on river systems in a general sense, appears be the catchment. This unit provides a natural boundary, as any morphological change in the catchment's river system is be governed largely by the water and sediment fluxes deriving from within the catchment. Smaller scales, e.g. sub-catchments or reaches, are unlikely to capture all the relevant processes that contribute to a catchment's geomorphological evolution, in particular the spatial variations in generation and modulation of sediment fluxes (Richards, 2002).

Whereas the catchment suggests itself for the choice of scale, choosing the resolution of a model is not as straightforward. The grid resolution, *i.e.* the density of the spatial discretization, can have a significant impact on the model (Olsen and Kjellesvig, 1998; Hardy *et al.*, 1999; Schoorl *et al.*, 2000). It is often thought that higher resolution implies higher simulation accuracy. This idea stems from a confusion between accuracy and detail. However, it is perfectly possible to have a very detailed and very wrong model. Usually, both the number of processes to be modelled and the data requirements of the model increase with finer resolution, which results in increased model complexity and uncertainty (also see *data availability* and *uncertainty*, below). Additionally, the required computational resources (time and processing power) generally increase exponentially with resolution. Hence, the choice of appropriate resolution needs to balance the requirements of the problem at hand, with knowledge of governing processes, model complexity, availability of data, as well as with the budget for computational resources.

Thus, it is not trivial to select the resolution for running simulations of the impact of environmental change on river systems. Much depends on the nature of the study, or which aspects of the river system are considered relevant, as is reflected in the range of resolutions of existing models (Table 1). Nonetheless, there has been a general trend towards higher resolution in landscape evolution modelling over the years, which can be expected to continue in the near future, as process understanding, data availability and computational resources continue to improve. This anticipated increase in spatial and temporal resolution may be useful (or necessary) for a more realistic simulation of alluvial system behaviour in landscape evolution models. Currently, the relatively coarse spatial resolution of these models (> 30 m) is not well suited to capture the details of alluvial and in-channel flow processes, which drive the construction and destruction of alluvial landforms. Several processes which can be considered influential in the development of alluvial systems cannot be represented at those resolutions (e.g. point bar deposition and growth, island formation, bank failure). Hence, higher resolution simulations (< 5 m) are likely to be required for the effective simulation of alluvial river systems. However, this also requires adaptation of landscape evolution models to reflect in-channel processes, which can increase the model's complexity and, hence, the uncertainty and duration of the simulations.

3.2. Representation of time

As with the representation of space, the time dimension is also discretized, into time steps. The model's calculations are iterated at each time step, and temporal change or evolution in the modelled system is represented by successive changes in the values of the physical properties on the spatial grid. Also analogous to the representation of space is the need to define a scale and resolution of the discretization of time. The time scale represents the total duration of the simulated time span, whilst the resolution reflects the size of the time steps, *i.e.* the spacing between successive points in time for which calculations are performed.

For the types of models included in this review, time scales vary from days or weeks, over year and decade to centuries or millennia, depending on the nature of the model (see table 1). An optimal choice of time scale depends on the purpose of the model. For example, when the aim is to simulate a specific historic flood event, a time scale of a few days or weeks will be most appropriate. When the aim is to simulate the response of river systems to environmental change, the optimal scale would be much larger, as both environmental change and the morphological response of the fluvial landscape may take decades, centuries or even millennia to express themselves. Although the morphology of river systems can reflect responses to individual storm events (e.g. Knox, 1993; Williams, 1978), climatic change, in particular, is not expressed by the occurrence of individual storm events, but rather by clustering of extreme events (Starkel, 1999). Additionally, there is a timelag between process and form in the landscape (Montgomery and Dietrich, 1992; Richards, 2002). For example, the development of an alluvial fan or a floodplain, in response to an increased sediment inflow, may take several decades or even centuries, while the land-use change that instigated it might have taken only a few years. Thus, any model that tries to simulate the morphological response of a river system to environmental change should operate on centennial time scales at a minimum, since the current alluvial architecture of many river systems reflects changes over these scales during the Holocene (Starkel, 1990; Knox, 1993; Macklin and Lewin, 1993; 2003; Macklin *et al.*, 2005). Longer timescales, operating over hundreds of thousands of years, and including glacial and interglacial stages (Koltermann and Gorelick, 1992; Starkel, 1999), might give additional insights in landscape formation and evolution, under a wider range of processes (e.g. glaciation or tectonics). However, this enhanced variability in morphological processes is not essential to simulate a first order response of the fluvial landscape to environmental change. Hence, centennial to millennial time scales appear to be an optimal choice for numerical investigation of the impacts of environmental changes on river systems.

On the other hand, the temporal resolution of the simulations should be sufficiently small to capture landform altering events. The maximum time step would, therefore, be at the level of individual flood events, which can have a significant impact on the geomorphology of the landscape (e.g. Knox, 1993; Williams, 1978). However, it could be argued that this resolution is still too coarse, and that the short-term variability in rainfall, *i.e.* fluctuations within a single storm event, can also affect the hydrological and geomorphological impact of the event (Van De Wiel, 1998; Parsons and Stone, 2006). Furthermore, in many process-based models, the discretizations of space and time are not independent of each other. Instead they are linked via the Courant-Friedrichs-Lewy-criterion (Vreugdenhil, 1994; Lane, 1998), which states that the propagation of fluxes within the system may not exceed grid spacing during any given time step. This restriction is required to avoid numerical instabilities in the model. The adoption of finer spatial resolutions thus also requires finer temporal resolutions.

However, increased temporal resolution, *i.e.* smaller time steps, also augments the demands on the specification of temporal boundary conditions (see *data availability*, below), and on computation resources. When choosing the temporal resolution, it is, therefore, necessary to balance the level of process detail with the available computational and data resources. A possible technique to achieve this balance is through the use of variable time steps, whereby the model adjusts the time step according to the geomorphic activity of the flow. Thus, the temporal resolution is relatively large when discharge and stream power are low, but becomes gradually finer as discharge and stream power increase. Using this technique, the time steps can vary from less than a second at peak flow to more than an hour at base flow.

3.3. Process representation

An important step in the modelling process is deciding which processes are to be included in the model. This is nearly always a subjective and qualitative choice, which partly depends on the nature of the study, the spatial and temporal scales under consideration, and the modeller=s assessment of the relative importance of different processes. In discussing process identification one can distinguish between primary and secondary processes. Primary processes are those that play a major role in landscape evolution at the scales and resolutions under consideration. Normally, all primary processes would be included in a model. Secondary processes have a lesser direct impact on landscape evolution, but may significantly affect the primary processes that do (Bronstert, 1999). Few studies have been explicitly designed to determine what the primary processes driving change in a particular landscape are (but see Tucker et al, 2006). With respect to the simulation of Holocene landscape evolution, primary processes might include surface run-off and channel flow, fluvial sediment transport and landsliding, whilst secondary processes could include sub-surface flow, vegetation dynamics and tectonic uplift. The inclusion or exclusion of second-order processes often is a subjective choice by the modeller, partly based on the envisaged application of the model. Moreover, the distinction between the primary and secondary processes is to some extent scale-dependent, such that processes that are considered secondary on one scale may be considered primary on another. For example, tectonics may not be worth including when simulating 1000 years of river development in a tectonically quiescent catchment, but might be a necessary component over a 100000 year evolution. Conversely, explicit representation of bed armouring may be essential for a model attempting to simulate changes in the alluvial valley over a few centuries or millennia, but would be largely irrelevant on a 2 million year time scale.

There are two dominant modelling philosophies on process representation: reductionism and synthesism. The reductionist approach represents processes on a first principles basis and aims to include as many primary and secondary processes as feasible. The main assumption behind this approach is that the inclusion of more processes in the model will result in enhanced realism in the simulations. There are two downsides to this approach. First, there always will be a number of processes (geomorphological, ecological, climatological, anthropogenic, etc.) which are not explicitly included in a model and which arguably could have a bearing on the simulation results. Second, inclusion of multiple processes also increases the models' complexity, and thus their computational demands and simulation uncertainty (see below). The value of such trends towards additional reductionism is therefore often debatable (e.g. Bronstert, 1999; Kirkby, 2000; Beven, 2002b). The synthesist approach tries to bypass these disadvantages, and explicitly aims to keep the model as simple as possible. The resulting models are also referred to as reduced-complexity models (Brasington and Richards, 2007; Nicolas and Quine, 2007; Nicholas, 2009). Here the idea is to keep the model structure simple, by removing as many processes as possible from the model, or by merging their formulations in as few equations as possible, whilst still maintaining realistic simulations. In doing so, the first principles formulation is often abandoned for simpler empirical relations. The reduced-complexity models are therefore sometimes considered to be less rigorous than the reductionist models. Nonetheless, reduced complexity models are often used for quaternary environmental modelling (especially LEMs, but also braided river models, meander models and alluvial stratigraphy models), because their simpler structures and lower computational demands facilitate simulations over longer time scales.

After the relevant processes have been decided on, a mathematical formulation thereof is derived. For some processes a theoretical equation can be obtained, usually from Newtonian physics (e.g. mass failure). However, for most hydrological and geomorphological processes, only empirical relations are available (e.g., sediment entrainment and transport, bank erosion rates, weathering). The derivation of an appropriate mathematical formulation is specific for each model type. Detailed discussion of this topic is beyond the scope of this paper, but can be found elsewhere (e.g. Pelletier, 2008; Tucker and Hancock, 2010; or the papers cited in Section 2 above). Mathematical formulation of physical processes usually requires the introduction of one or more parameters (e.g. roughness coefficient, sediment transport rate, erodibility coefficient, etc.). These parameters have empirical, calibrated or approximated values, and their presence adds uncertainty to the model predictions. This uncertainty proliferates as the number of parameters increases, due to the possibility of parameter interaction.

The introduction of additional parameters, and hence more uncertainty, is the main reason for not including the secondary processes in the model. Although the inclusion of secondary processes might add to a model's realism from a conceptual point of view, it may also result in higher uncertainty. It is, therefore, often debatable to what extent the benefits from a more comprehensive model, including secondary processes, compare with the increased model complexity and uncertainty. Whether it is necessary, or even desirable, to expand our models with evermore processes ultimately depends on the balance between the benefits of process inclusion and the detrimental effects on uncertainty, data requirements and computational power (Brooks and Tobias, 1996; Haraldsson and Sverdrup, 2004). Ideally, a model would be tested with and without the additional secondary processes, to verify their assumed significance in affecting the primary processes, and to measure their impact on the uncertainty of the simulations.

3.4. Data availability

All computational models need data to work with. With respect to simulating the impacts of environmental change on river systems, two types of data can be discerned: initial conditions and external forcing conditions. Initial conditions specify the spatial distribution of essential data at the start of the simulation (e.g. terrain elevation, water depth, sediment grain sizes, roughness coefficient, *etc.*). External forcing conditions specify temporal and spatial changes in the forces operating on the river system during the simulation (e.g. precipitation (catchment-scale models), inflow discharge (reach-scale models), anthropogenic land-use change, tectonic uplift, *etc.*).

The issue of data availability is closely linked to resolution. Initial conditions generally need to be specified at the same resolution as the model's grid. Hence, as the spatial resolution of the model increases, so does the demand on the data describing the initial conditions. In recent years, new technologies have emerged that might facilitate the measurement of some initial conditions on sufficiently high spatial resolutions. The foremost of these are the advances in remote sensing, in particular airborne radar and LiDAR (Lane and Chandler, 2003; Lane *et al.*, 2003; Bellian *et al.*, 2005; Wang and Philpot, 2007), and ground penetrating radar (Neal, 2004), which allow for high resolution representation of present topography, present land use, and subsurface structures, such as the depth of regolith. For many other initial conditions, however, the data are sparser, due to the logistic difficulties of manual sampling at high resolution. Sediment grain sizes, soil cohesion and in-channel topography, for example, are usually measured at a limited number of locations and subsequently averaged, aggregated, interpolated or extrapolated to obtain values over the entire spatial grid. Due to the spatial heterogeneity of many of these input data, their accuracy is dubious in many situations. The problem is even more acute for simulations of past environments. Unfortunately, there are no LiDAR images from the early Holocene, and initial conditions for past landscapes must be derived either from reconstructions based on the fluvial landforms and sedimentary deposits preserved in the present landscape, or from analogy with present landscapes. Such reconstructions, however, are typically of very coarse spatial resolution and subject to considerable uncertainty. Their use in palaeo-environmental simulations therefore adds to the uncertainty of the simulation results (see *Uncertainty* below).

A similar problem relates to the temporally and/or spatially variable external forcing conditions, which need specification at the same resolution as the temporal resolution used in the model. This is especially pertinent for rainfall data (catchment-scale models) or inflow discharge (reach-scale models). In some cases rainfall data is available at high temporal resolution for recent times and sometimes even for historical times, but even then at low spatial resolution. In general, however, Quaternary climate data is reconstructed from proxy data such as tree rings (e.g. Gunnarson et al., 2003; Shapley et al., 2005), speleothems (e.g. Charman et al., 2001; McDermott, 2004), tufa layers (e.g. Kano *et al.*, 2004), and peat bog stratigraphy (e.g. Blundell and Barber, 2005). Most of these reconstructed data have a temporally coarse resolution (often annual or decadal), which by far exceeds the temporal resolution of the models (often hourly or finer). Simple interpolation of the long-term climate data to fit the temporal resolution of the model does not capture the short-term variability in precipitation, associated with individual storm events. Hence, an alternative technique is required to reconstruct this short-term variability. For this purpose, probabilistic or stochastic techniques are commonly used to generate temporally variable rainfall patterns for which the daily, monthly or annual mean is the same as that obtained from climate reconstruction or prediction (Veneziano and Iacobellis, 2002; Pathirana *et al.*, 2003; Gyasi-Agyei, 2005; Rupp et al, 2009). However, these statistical techniques generally make a series of assumptions which, by definition, have not been verified for Quaternary climates.

3.5. Calibration and validation

Normally, after a model is developed, it is tested before being put to use as an explanatory or predictive tool. This is a form of quality assurance and usually involves the simulation of a situation for which observed data are available, and comparing the results of the simulation with these observed data. Because models have a number of parameters, whose values can be adjusted by the user, the testing process is usually split in two phases: calibration and validation. Calibration is the process by which the values of the model parameters are optimized for a given dataset, *i.e.* the values are adjusted to assure optimal agreement between simulated and observed data. The central idea is that these optimized values can then be transferred to other (similar) scenarios, involving either different catchments or the same catchment at a different time. The validity of this argument is tested in the validation process, where the model is applied using the calibrated parameter values, and where the simulated results are compared with a second, independent dataset.

Although commonly applied, this process of calibration and validation is not undisputed (Oreskes *et al.*, 1994; Koperski, 1998; Beven, 1996, 2002a; Odoni and Darby, 2002; Refsgaard *et al.*, 2004). It suffers from three major shortcomings. The first is the fact that different scenarios might require different parameter values. The validation part of the process only confirms the applicability of the parameter values the dataset used, and does not provide confirmation of the applicability of the transferability to other datasets. Subsequent validation on other datasets would strengthen the argument of parameter transferability, although such additional analyses are rarely performed.

The second shortcoming is the assumption of uniqueness of the optimized parameter values. However, there may be several combinations of parameter values that result in equally acceptable agreement between simulated and observed calibration data - a concept known as model equifinality (Beven, 1996; Beven and Freer, 2001). The likelihood of this phenomenon occurring increases as the number of parameters increases. Model equifinality is problematic in computational modelling as it is usually impossible to select one of the possible sets of parameter values over the others (although some might be discarded on theoretical grounds). It is then unclear which of the sets of parameter values should be used for the validation process and for model application. Furthermore, model equifinality raises theoretical problems. The calibrated parameter values can, in some cases, be used to gain insight in process dominance and process relevance. Model equifinality, however, suggests that there may be several acceptable sets of parameter values and, hence, several combinations of processes that replicate realistic landscapes. In general it is unclear which of these sets of parameter values, if any, corresponds to reality. Additionally, it might be possible, at least in some cases, that the model equifinality reflects actual equifinality in the natural system, i.e. the idea that the same observed present landscape structure may have originated from different processes or from different initial conditions (Culling, 1987; Phillips, 1997).

The final major shortcoming is that the hypotheses and assumptions underlying the model cannot be verified or falsified using the simple calibration and validation technique (Oreskes *et al.*, 1994). Validation and confirmation occurs only on a scenario basis, and it is always possible to attribute any error of the simulations to inaccuracy of the initial or external forcing conditions, rather than to inaccuracy of the model's hypotheses. Furthermore, it is usually possible to add a new feature to the model, *i.e.* an additional processes to be modelled, such that the adapted model will produce better agreement with observed data, without discarding the existing model hypotheses (Koperski, 1998). These three shortcomings of the simple calibration and validation procedure are now commonly recognized by the modelling community, and alternative techniques that explicitly recognize and address these issues are being put forward (Beven, 2002b; Refsgaard *et al.*, 2004).

However, aside from these generic shortcomings of the calibration and validation process, modelling long-term changes in geomorphological systems poses an additional problem, which is arguably more limiting: namely deciding which datasets and which metrics (*i.e.* which aspects of the data) will be used for comparison between modelled and observed data. The main problem of the apparently obvious method is the paucity of available data. For example, the most obvious metric is elevation or topography. However, detailed topographic data are generally only available for present-day or recent landscapes. Comparing observed data with modelled data then raises the question whether any discrepancies are due to the model's performance or due to the accuracy of the available measurements, which are also simply representations of reality rather than reality itself (Bevington and Robinson, 1992). Nonetheless, comparison of simulated and observed topographic changes over these short periods is generally thought to be indicative of the model's performance. However, they cannot be extrapolated to evaluate the model over longer timespans, since comparison of elevation changes in long-term simulations is impractical due to the uncertainties in recreating a detailed initial topography of the landscape as it was several centuries or millennia ago. An alternative metric might be discharge, which can be evaluated in the current landscape in a way similar to hydrological models. For any point in the catchment, the observed hydrograph resulting from a storm event can be compared with the modelled hydrograph at that point. However, this again assumes that the measurements are the correct values. Moreover, this would only test the hydrological components of the model. Extension to sediment fluxes, where sediment discharge is used as the metric, is not practical as this is subject to large uncertainties in initial conditions arising from heterogeneity and antecedent events (e.g. depth of the weathered regolith, soil moisture, soil cohesion).

We would suggest that any quantitative metric that requires detailed comparison between observed and modelled data is unsuitable, due to the uncertainties in initial conditions and the inherent non-linearity of geomorphological models. Instead, a more qualitative metric must be used, where the overall dynamics of the simulations are compared with observed data. In this respect, the most suitable metric is the morphological evolution of the alluvial reaches, where changes over time can be compared with information obtained from landforms and alluvial stratigraphy. Thus, comparison can be made between temporal coincidence of periods of incision or aggradation, periods of lateral erosion dominance, and periods of braiding or meandering. It should be noted, however, that when a model has been evaluated only on these broader aspects of morphological behaviour, its predictions must also be interpreted along the same terms.

3.6. Uncertainty

Uncertainty is a much debated issue in hydrological modelling (Beven, 1996, 2002, 2006; Haff, 1996; Bronstert, 2004; Montanari, 2007; Todini and Montavan, 2007), but gets less attention in geomorphological modelling. As a concept, it is related to “error” in the engineering literature, which describes the distribution by which natural observations and model predictions are expected to deviate from each. However, in many non-linear models, such as geomorphological landscape evolution models, the error is impossible to calculate, and an approximation is made instead. In this sense, the uncertainty reflects the degree to which we are unable to calculate the error of the model.

Ideally, modelling studies should include estimates of uncertainty with the presented simulation results. This idea has been intensively promoted for hydrological models (Beven, 1996, 2002) and is, in theory, equally applicable to geomorphological models. In practice, however, estimating uncertainty is computationally intensive and requires a Monte Carlo approach where many simulations are run (Beven and Binley, 1992; Spear *et al.*, 1994; Beven and Freer, 2001).

This approach is currently unfeasible for geomorphological simulations of environmental change, where a single simulation may run for several weeks or months (using current high-end desktop computers). However, it does raise the question as to whether anticipated future advances in computational power would best be used to further refine process representation of the models, or to quantify the models' uncertainties (Beven, 2002b). Nonetheless, even though uncertainty is currently rarely quantified in geomorphological models, its existence should at least be acknowledged explicitly.

There are many sources of uncertainty in geomorphological models. Haff (1996) distinguishes between model imperfection, process omission, occurrence of external forcing, lack of knowledge of initial conditions, unresolved heterogeneity, and sensitivity to initial conditions. Some of these sources of uncertainty can be influenced by the modeller, whilst others are inherent to the concept of modelling and cannot be influenced.

Although conceptually different, process omission and model imperfection are related from a modeller's point of view. Process inclusion introduces uncertainty due to imperfection of the process representation. The latter can arise either from lack of knowledge about geomorphological processes or their interactions, or from a simplified mathematical formulation. Process inclusion may also require additional parameterization and can increase data requirements. Process omission, on the other hand, simplifies the model, but also introduces uncertainty due to incompleteness. Thus, although the modeller has some influence over the type of uncertainty, it is a lose-lose situation (damned if you do, damned if you don't). Furthermore, it may be difficult to assess *a priori* whether including a particular process, thereby introducing additional complexity, parameterization and data requirements, will introduce more uncertainty than omitting the process altogether. In general, sensitivity analyses are required to see what level of uncertainty is introduced by the inclusion of additional processes.

Lack of knowledge of initial conditions is directly related to the issue of data availability (see above). Initial conditions are often interpolated or extrapolated from sparse measured data, or estimated by analogy with different catchments. This obviously introduces uncertainty, which can to some extent be influenced by the user. Denser sampling of measurements, for example, is likely to reduce the uncertainty associated with the interpolation. But even if measured data were available at every grid point, there would still be uncertainty associated with the initial conditions, because of measurement inaccuracy and unresolved heterogeneity. The latter refers to the fact that each of the initial conditions (e.g., vegetation cover, soil type, grain size distribution) is represented by a single value at a grid point or cell, while in reality their distribution may vary on the sub-grid scale. For example, with a regular point spacing of 5 metres, each grid point would represent an area of 25 m^2. Over this area different vegetation species and grainsize distributions may vary considerably, yet they have to be represented with a single value at the grid point. Appropriate averaging or aggregation is not necessarily straightforward or meaningful, and will always introduce uncertainty. Although this uncertainty may be reduced by considering smaller grid cells, *i.e.* increasing the resolution of the model, heterogeneity is inherent in geomorphological systems and cannot be eliminated from the model. As these considerations apply for every point on the grid and for every initial condition, landscape models evolution models have a large scope for this type of uncertainty.

Knowledge of the external forcing is, in general, another source of uncertainty. Data on external conditions are often extrapolated or interpolated from sparse temporal measurements (e.g. climate prediction and reconstruction). Likewise, the external conditions are subjected to a temporal form of unresolved heterogeneity, where variations within a time step are ignored (e.g.

hourly rainfall). However, for the particular case considered herein, *i.e.* the modelling of the impacts of environmental change on river systems, these issues are usually less problematic. That is, the models are generally applied in a what-if mode, where the external forcing conditions are assumed to be known and where the object of the simulation is to see how a catchment responds to a change in these external conditions.

Finally, it should be noted that models which perform best after calibration may not be the same models that deal best with uncertainties in the input data (Shrestha and Nestmann, 2009). This casts doubt on the validity of the calibration process of those models which are less capable of dealing with uncertainties, since the calibration data themselves may be subject to uncertainties. Ideally, when evaluating the uncertainty of model predictions, the a-priori uncertainty of the input data and the calibration data should be accounted for, for example by considering the probability distributions of the input data and of the parameter values (Todini, 2007; Shrestha and Nestmann, 2009).

3.7. Non-linearity

Models of the effects of environmental change on river systems are non-linear by nature (Phillips, 2003; Coulthard and Van De Wiel, 2007). The non-linearity is exhibited both by the governing processes of catchment evolution (e.g. Gomez and Phillips, 1999) and by the external forcing conditions, *i.e.* climate and land-use. It is expressed by the presence of feedbacks between morphological processes and landscape, by the existence of intrinsic thresholds within the system, and by a sensitivity to the initial conditions (Phillips 2003; Coulthard and Van De Wiel, 2007). The latter implies that small changes in the initial state of the landscape or in external conditions can result in large changes in the simulation predictions. The uncertainty of initial and external forcing conditions, due to both interpolation and heterogeneity, is thus further augmented by the non-linearity of the model. This augemented uncertainty is inherent in the nature of geomorphological modelling, due to the non-linearity of geomorphological evolution itself, and cannot be influenced by modeller or user.

A related issue is that of self-organized criticality (Bak *et al.*, 1987, 1988), indicative of a scale-invariance in the dynamics of the system. Effectively, the system organizes itself around a dynamic equilibrium in such a way that identical external disturbances to the system can initiate internal responses of highly variable magnitude. This phenomenon is most famously studied in the collapse of sandpiles (e.g. Bak *et al.*, 1987, 1988; Rosendahl *et al.*, 1993; Laurson *et al.*, 2005), but has also been observed in both physical and numerical simulation of geomorphological processes (Stølum, 1996; Sapozhnikov and Foufoula-Georgiou, 1997; Fonstad and Marcus, 2003; Van De Wiel and Coulthard, 2010). For example, identical rainfall events over a catchment can result in non-linear sediment dynamics at the catchment outlet (Coulthard and Van De Wiel, 2007; Van De Wiel and Coulthard, 2010). This effectively renders the catchment system unpredictable, in the sense that it is impossible to predict the exact geomorphic response to any particular change in environmental forcing conditions. However, it might still be possible to detect the impacts of environmental change in the overall dynamics of the system, e.g. in the distribution of the magnitudes of sediment yield (Van De Wiel and Coulthard, 2010).

Thus, non-linearity of processes, self-organized ciriticality, and uncertainty of initial conditions effectively implies that detailed at-a-point predictions over long time periods are untrustworthy (Morton, 1993). However, this does not mean that simulation results are arbitrary or meaningless. Although small changes in initial conditions might significantly alter the detailed morphology of the river system, there are constraints on the possible alterations. Mostly, the constraints are such that the overall morphology of the catchment is not significantly affected. In other words, the system as a whole is less affected by changes and uncertainties in the initial conditions, than localized morphology. For example, a river channel might be located in a different part of the alluvial valley as a consequence of a small change in initial topography, but the channel type (meandering or braided) and its capacity for conveying flow and sediment will still be similar. In this context it is worth reiterating that model predictions must be interpreted in terms of the same qualitative metrics as those used for calibration and validation, *i.e.* the temporal coincidence of larger scale alluvial activity.

3.8. Discussion and summary

In view of the issues and limitations highlighted in the preceding paragraphs, one might well ask if there is any merit at all in the modelling of geomorphological response of fluvial systems to environmental change. Our answer is: "Yes, there is, provided one proceeds with care". In spite of the limitations and uncertainties, numerical modelling is often the only feasible way to study and predict catchment response to environmental change. The temporal and spatial scales involved render field-based monitoring studies impractical, whilst laboratory-based experimental studies suffer from problems related to spatial downscaling of processes and temporal upscaling of the rates thereof. Apart from scale, the uncertainty of initial conditions and the non-linearity of the processes are the biggest problems in understanding the impacts of environmental change on the evolution of catchments and river systems. However, these problems are not unique to numerical modelling, as both field-based and laboratory-based studies are subject to the same uncertainties and non-linearity.

Numerical simulation of morphological change, however, has a distinct advantage over other methods of study, in that it allows for full control over initial conditions and parameters: their values may be uncertain, but they can be specified. This has several benefits. First, it means that the model's sensitivity to change in initial conditions or parameter values can be investigated, and possibly evaluated. In this context, the uncertainty is used as an advantage rather than a limitation, as it can be considered to be an indication of risk in management related studies (Beven, 2000). Second, it implies that the numerical experiments are repeatable, at least in deterministic models. And third, it allows for hypothetical "what-if" scenario modelling. This is arguably the most important benefit of numerical models, particularly in the context of evaluating the impact of environmental changes on the geomorphological evolution of catchments and river systems. The behaviour of the system can be simulated and compared for different scenarios of climate change and/or land use change. This is, in essence, another form of sensitivity analysis, not for initial conditions or parameter values, but rather for sensitivity to the external forcing conditions. "What-if" scenarios can also be used, in a similar manner, to investigate the theoretical implications of model equifinality. It is of particular interest to see if similar landscapes can evolve under different assumptions of process dominance, *i.e.* different sets of parameter values, and for which metrics this equifinality is expressed (Odoni and Darby, 2002; Bras *et al.*, 2003).

Non-linearity and self-organized criticality may appear to be major concerns in modelling the dynamics of fluvial landscapes. However, these can partially be addressed by using appropriate metrics for evaluating and interpreting the results, and by using ensemble predictions or probabilities of outcome instead of exact values, *i.e.* by incorporating uncertainty analyses.

4. Future prospects

Computational modelling of geomorphological evolution is a rapidly evolving discipline, as is evidenced by the progress made during the last two decades. Detailed prediction of what the future holds for the science is difficult, although some general trends can be identified. There are, essentially, three main ways to advance to state of computational modelling: conceptual, structural and technological. In many ways these apply to all modelling of spatially dynamic systems, but they will be discussed here with respect to the modelling of river system response to environmental change.

Conceptual advances arise from better process understanding, which would lead to improved representation of processes in the models. Often this equates to the reductionist approach to modelling, whereby it is assumed that more detailed representation of processes will result in better simulations. A pertinent example of this in the context of quaternary environmental modelling concerns vegetation dynamics, i.e. growth, succession and deterioration of vegetation as a response to climate change and geomorphological change, which currently are often ignored in computational geomorphology (but see Murray and Paola, 2003; Istanbulluoglu and Bras, 2005). Yet vegetation can have a major impact on the hydrology and geomorphology of fluvial systems (e.g. Trimble, 1990; Gray, 1995; Hupp and Osterkamp, 1996; Millar, 2000), and there have been several recent calls for better integration of ecological and geomorphological processes in studies of landscape evolution (Paola *et al*., 2005; Murray *et al*., 2008; Reinhardt *et al*., 2010). Of particular interest are the feedbacks of the vegetation dynamics on the subsequent morphological evolution of the catchment. Hence, modelling of vegetation dynamics, or other processes currently not included in landscape evolution models or any of the other model types, may increase the realism of the models, but will come at the cost of greater model complexity, higher computational demands, more parameters and more uncertainty. It is, therefore, unclear if this added realism in process representation will result in better simulation results. Nonetheless, conceptual advances in the understanding of processes, process interactions, and the overall dynamics will open new directions in computational modelling and will help to focus the development of new models.

In contrast, structural and technological advancements address the current limitations of modelling. Structural advances affect the algorithms underlying the models or the mathematics behind them. Many potential routes to follow are already indicated by other computational sciences. Current research on upscaling and downscaling in hydrological and climatological modelling (Blöschl and Sivapalan, 1995; Prudhomme *et al.*, 2002) could provide a mathematical basis for dealing with the scale and resolution related issues like heterogeneity and spatial variability of input data. Likewise, ongoing efforts in understanding, quantifying and managing model uncertainty and parameter sensitivity (e.g. Beven, 1996; 2002a; Odoni and Darby, 2002) might provide a means to improve assessment of the models' robustness. Indeed, the incorporation of uncertainty analyses will be a welcome advance to geomorphological modelling in general. The use of irregular meshes, as used in quadtree (e.g. Borthwick *et al.*, 2001; Greaves, 2004; Wang *et al.*, 2004) or finite element or finite volume fluid dynamics modelling (e.g. Bates *et al.*, 1997; 1998; Caleffi *et al.*, 2003), can decrease a model's computational requirements locally varying the spatial resolution according to the needs of the simulation (e.g. higher resolution in the alluvial valleys). However, these techniques require more complex algorithms adjust for the grid variability and are currently rarely used in landscape evolution modelling (but see Tucker *et al.*, 2001). For the special case of river system evolution modelling, an alternative approach consists of separating the simulation of small scale, high resolution alluvial reaches from the large scale, coarse resolution modelling of the upstream tributary catchments, where the output from the latter forms the input for the former (Van De Wiel *et al.*, 2005, 2007). Other advances in computational fluid dynamics over the last decade are slowly making their way in geomorphological modelling (e.g. Bates *et al.*, 1997; Nicholas *et al.*, 1999; Lane *et al.*, 2004), but have, as of yet, not been applied to landscape evolution modelling, due to their high computational demands. However, landscape evolution models would benefit from a more rigorous simulation of flow hydraulics, which is an essential component in calculating sediment fluxes.

Computational modelling has been greatly affected by technological advances over the last two decades. Not the least of these is the tremendous rate at which computer processing speed and storage capacity have been increasing. This trend is likely to continue for the foreseeable future, with obvious impacts on computation time. Of particular relevance is the increasing accessibility of parallel processing hardware, which is ideally suited for cellular models of landscape evolution, including recent advances in graphical processor unit computation (e.g. Komatitach *et al.*, 2009). Other recent technological advances affect data collection and data reliability. Remote sensing techniques like airborne LiDAR (Lane and Chandler, 2003; Lane *et al.*, 2003; Bellian *et al.*, 2005), ground penetrating radar (Neal, 2004) or X-ray tomography (Wildenschild, 2002) allow collection of surface and sub-surface data at ever increasing quantities and resolution. This not only benefits the availability and accuracy of input data, but can also provide more detailed data to calibrate and validate the models. Similarly, recent advances in dating techniques (see Lang, 2008), particularly radiocarbon dating (Lang, 2008; Guilderson *et al.*, 2005) and optical luminescence dating (Lang, 2008; Wallinga, 2002; Duller, 2004) can put temporal constraints on external forcing boundary conditions and input data, and can equally provide temporal benchmarks for model calibration and validation. A useful step in this direction is the development of databases of radiocarbon-dated alluvial sediments (e.g. Lewin *et al.*, 2005; Johnstone et al., 2006; Hoffmann *et al.*, 2008; Harden *et al.*, 2010), which can help identify episodes of intense alluvial activity during the Holocene for different regions.

It is likely that these conceptual, structural and technological advances will coevolve. Uncertainty analysis and sensitivity analyses can be very computationally intensive and will undoubtedly benefit from more efficient algorithms and technology. At the same time, expanding the range of simulated processes will always provide an incentive for advancing the state of the art of river system modelling, particularly when limitations like uncertainty, computation time and data collection become more manageable.

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Table captions

Table 1: Overview of properties and application domain of various model types.

Figure captions

Figure 1: Schematic view of different model types for simulating river systems. A: hydrological; B: floodplain inundation; C: channel evolution; D: alluvial stratigraphy; E: meandering; F: braiding; G: channel network; H: landscape evolution. See text for explanation.

Figure 2: Sample output from a hydrological model, showing observed (solid, bold) and modelled (thin, dashed) hydrographs for the Arno River in Firenze, Italy (from Liu and Todini, 2002).

Figure 3: Sample output from a flood inundation model, showing observed (outline) and predicted (shading) flood inundation for a reach of the River Meuse, the Netherlands (from Bates and De Roo, 2000).

Figure 4: Sample output from a channel evolution model, showing modelled flow depth (top) and changes in bed topography (expressed as changes in flow depth; bottom) for a reach of Goodwin Creek, Mississippi (after Van De Wiel and Darby, 2004).

Figure 5: Sample output from a alluvial architecture model, showing a perspective view (left) and planform view (right) of channel belt succession in an idealized valley subjected to baselevel fall (from Karssenberg and Bridge, 2008)

Figure 6: Sample output from a meander evolution model, showing sediment deposition patterns for a hypothetical meandering river (after Sun *et al.*, 2001b).

Figure 7: Sample output from a braided river model, showing discharge and planform channel configuration at two iterations of the simulation (after Murray and Paola, 2003).

Figure 8: Four sample outputs from a channel network model with different simulation parameters, for the Sarca Di Nambrone, Italy (from Rigon *et al.*, 1993).

Figure 9: Sample output from a landscape evolution model, showing channel incision in an idealized plateau in perspective (top), cross-section (lower left, showing maximum topography (upper line), mean topography (middle line) and minimum topography (lower line)) and planform (lower right; solid lines are elevation contours) (from Tucker, 2004).

Figure 1

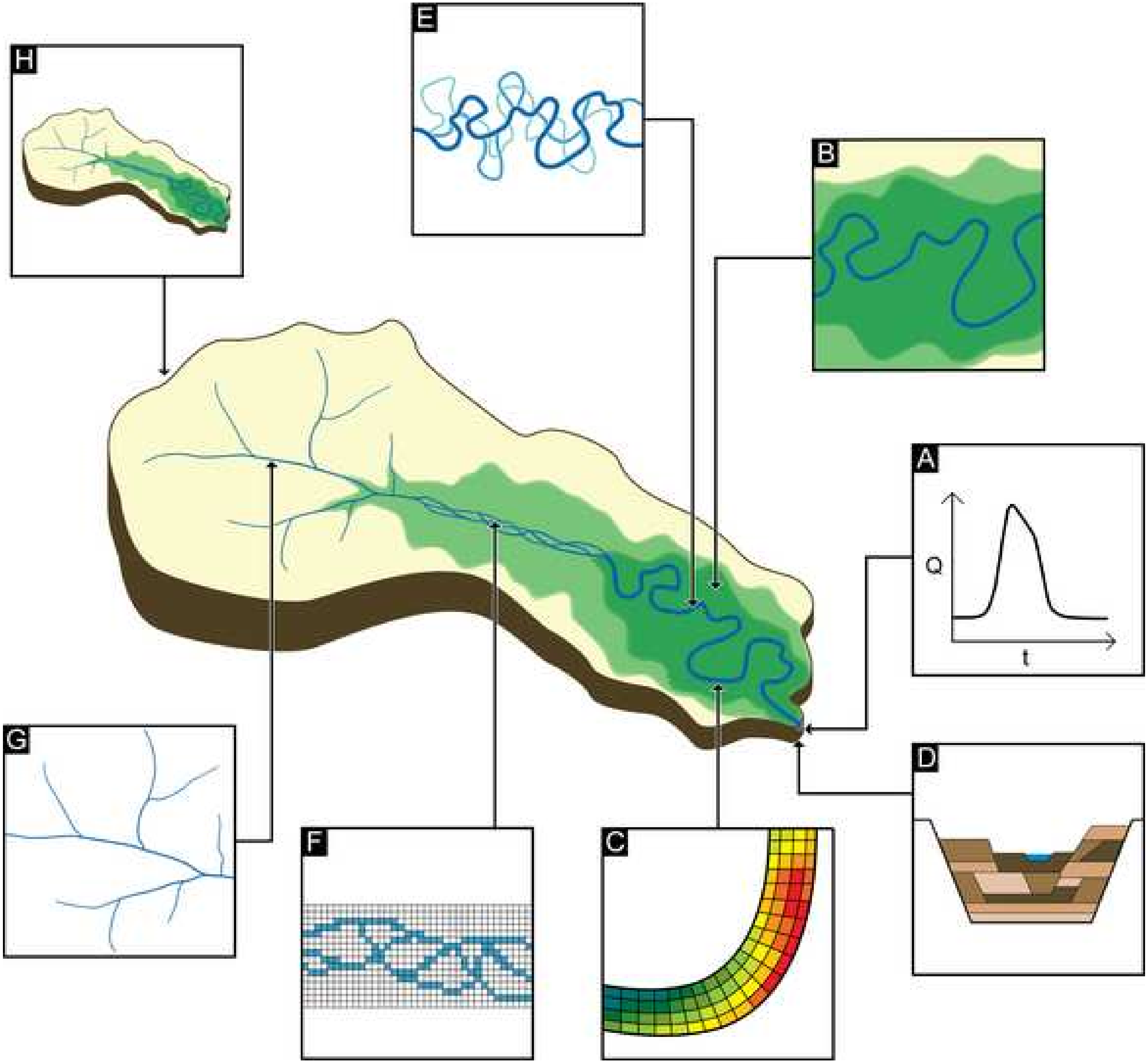
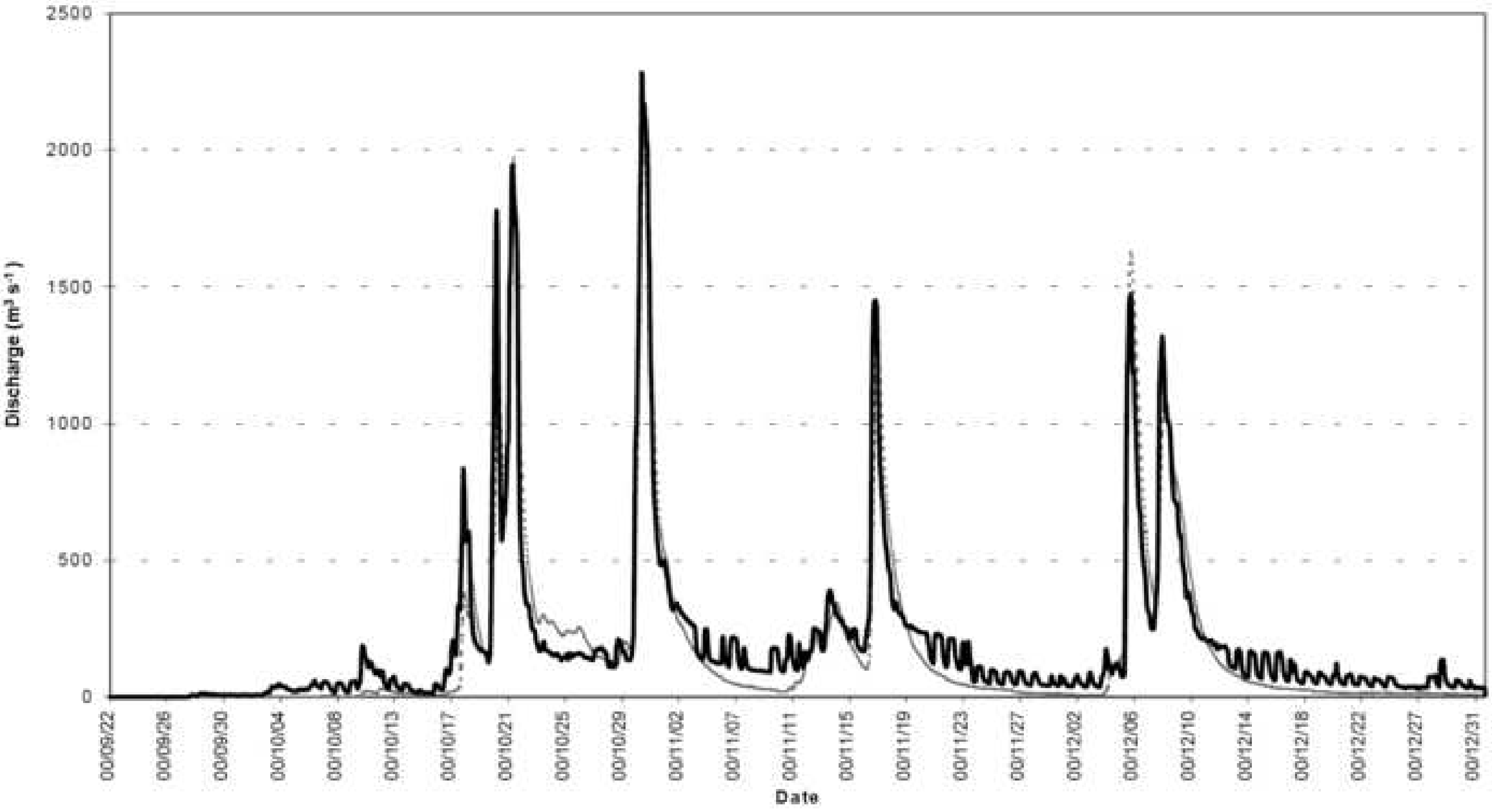


Figure 2


2500
2000
1500
1000
500
0
Discharge ($m^3 s^{-1}$)
00/09/22
00/09/26
00/09/30
00/10/04
00/10/08
00/10/13
00/10/17
00/10/21
00/10/25
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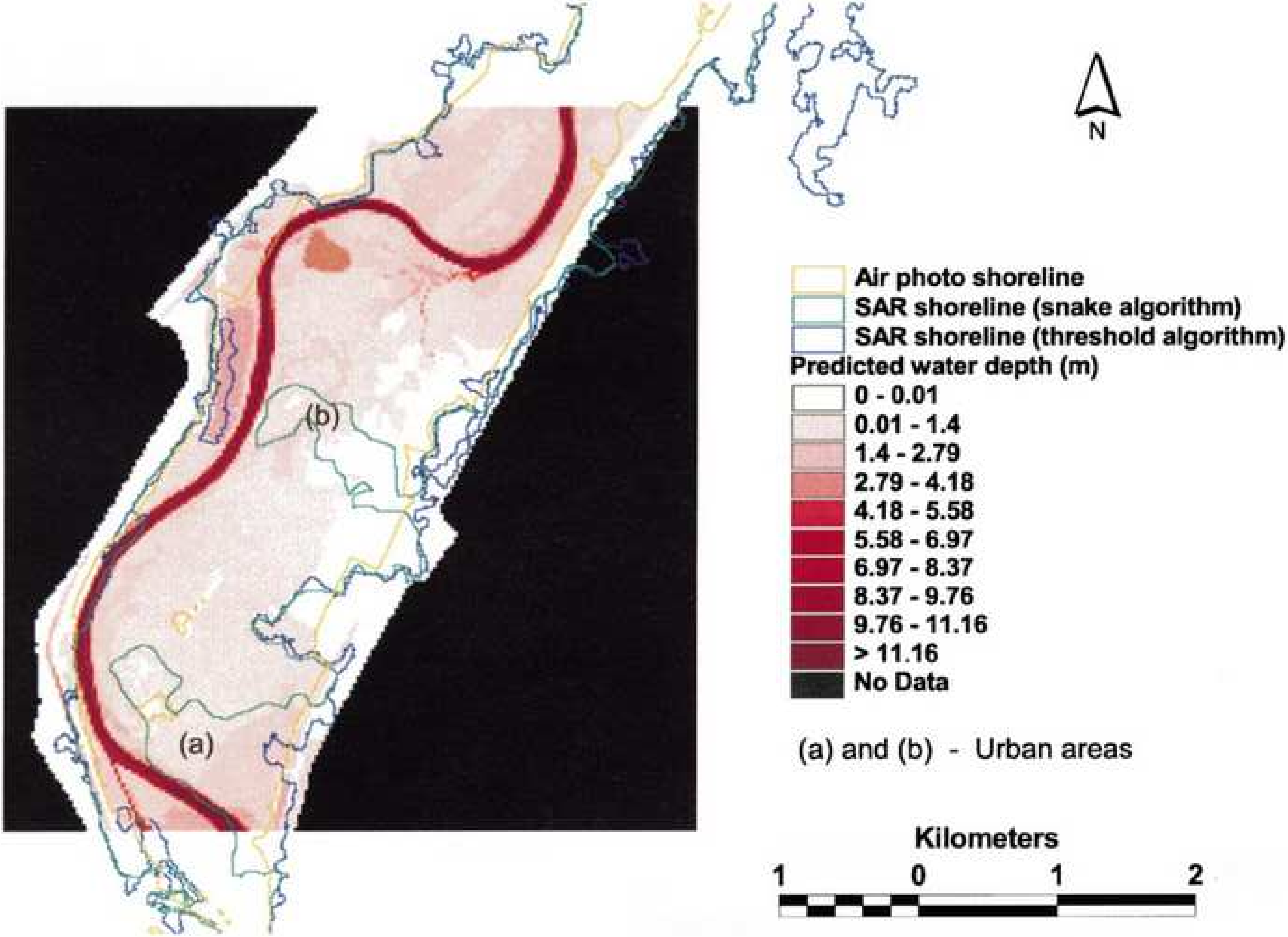
Date

Figure 3



N
Air photo shoreline
SAR shoreline (snake algorithm)
SAR shoreline (threshold algorithm)
Predicted water depth (m)
0 - 0.01
0.01 - 1.4
1.4 - 2.79
2.79 - 4.18
4.18 - 5.58
5.58 - 6.97
6.97 - 8.37
8.37 - 9.76
9.76 - 11.16
> 11.16
No Data
(a)
(b)
(a) and (b) - Urban areas
Kilometers
1
0
1
2

Figure 4

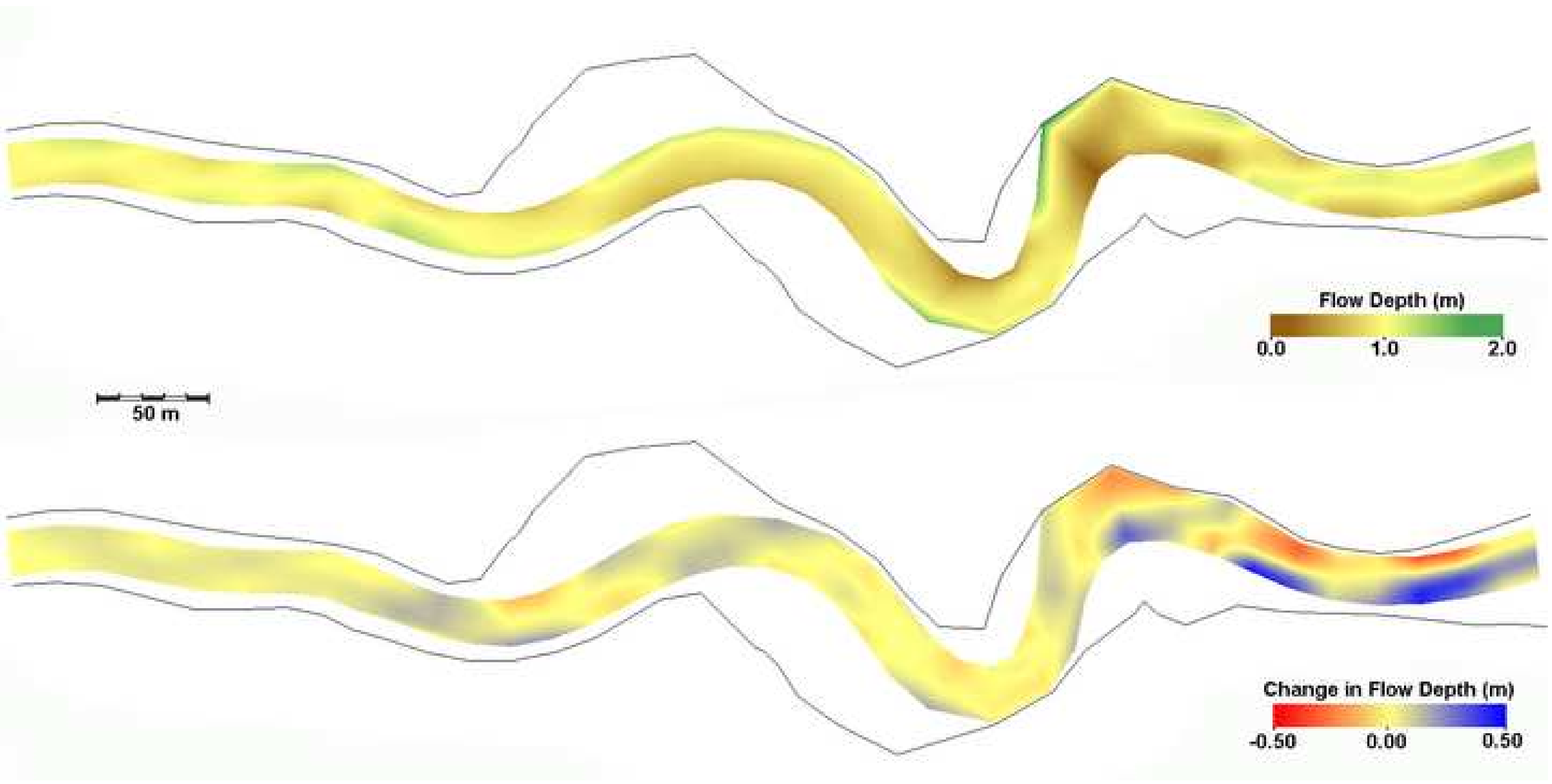


Figure 5

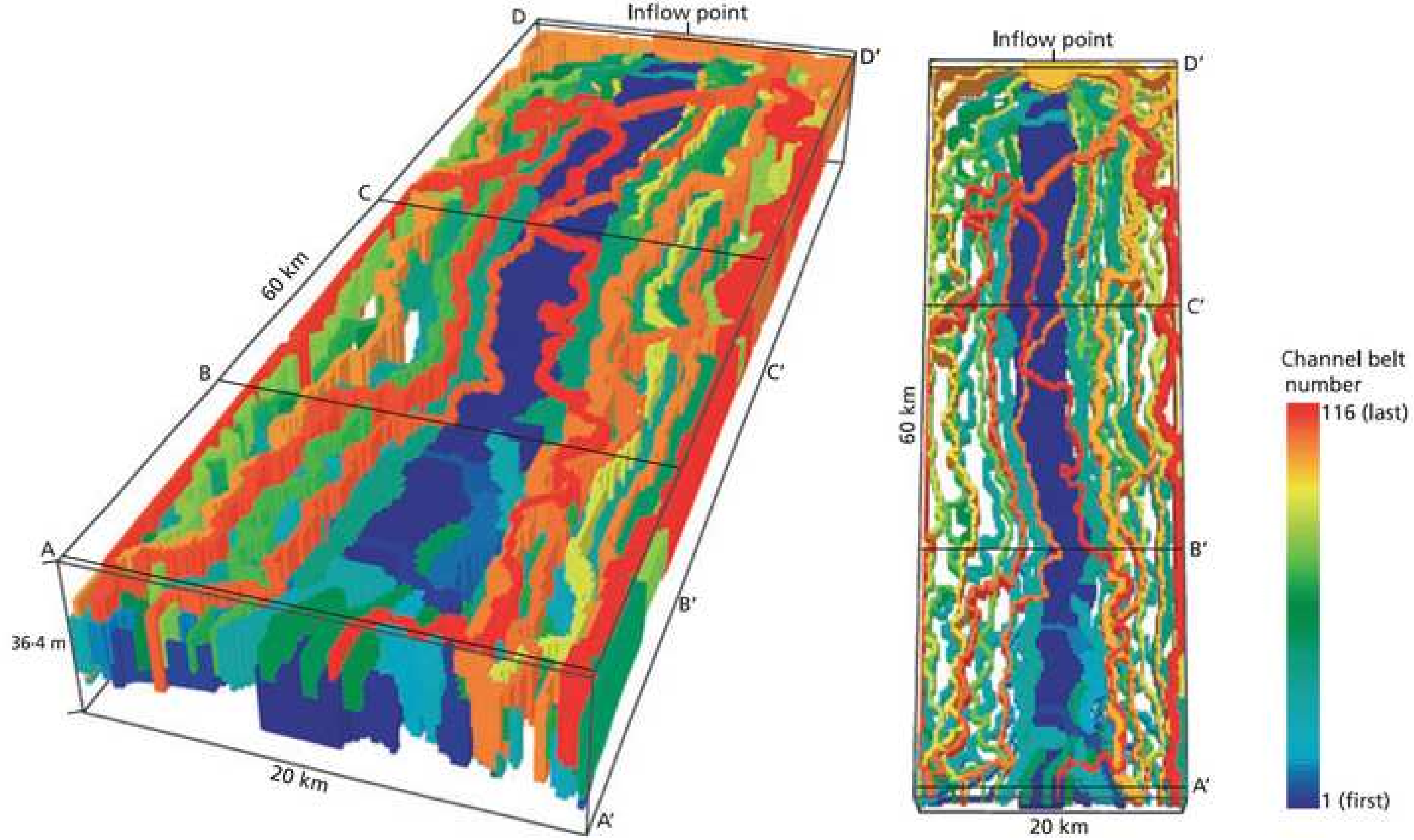

Inflow point
D
D'
C
C'
B
B'
A
A'
60 km
20 km
36·4 m
Inflow point
D'
C'
B'
A'
60 km
20 km
Channel belt number
116 (last)
1 (first)

Figure 6

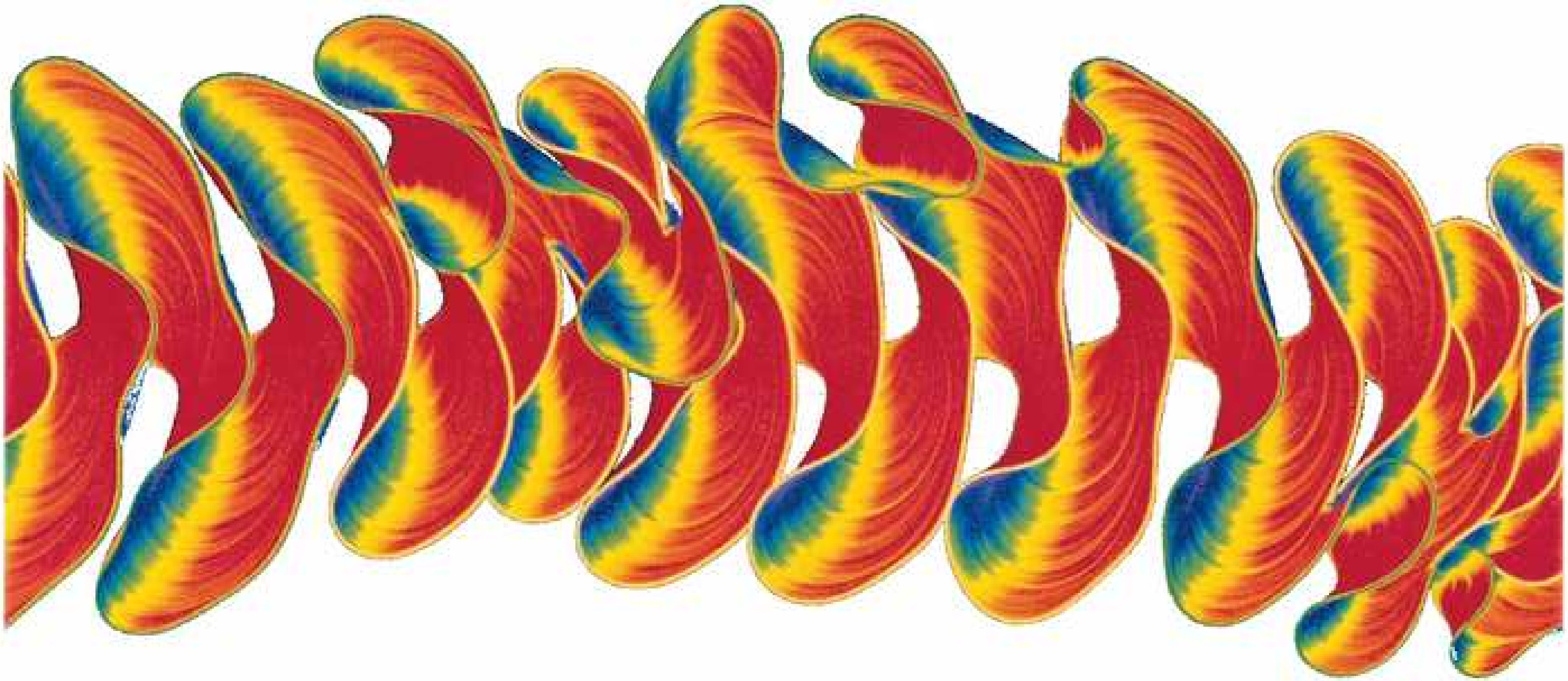


Figure 7

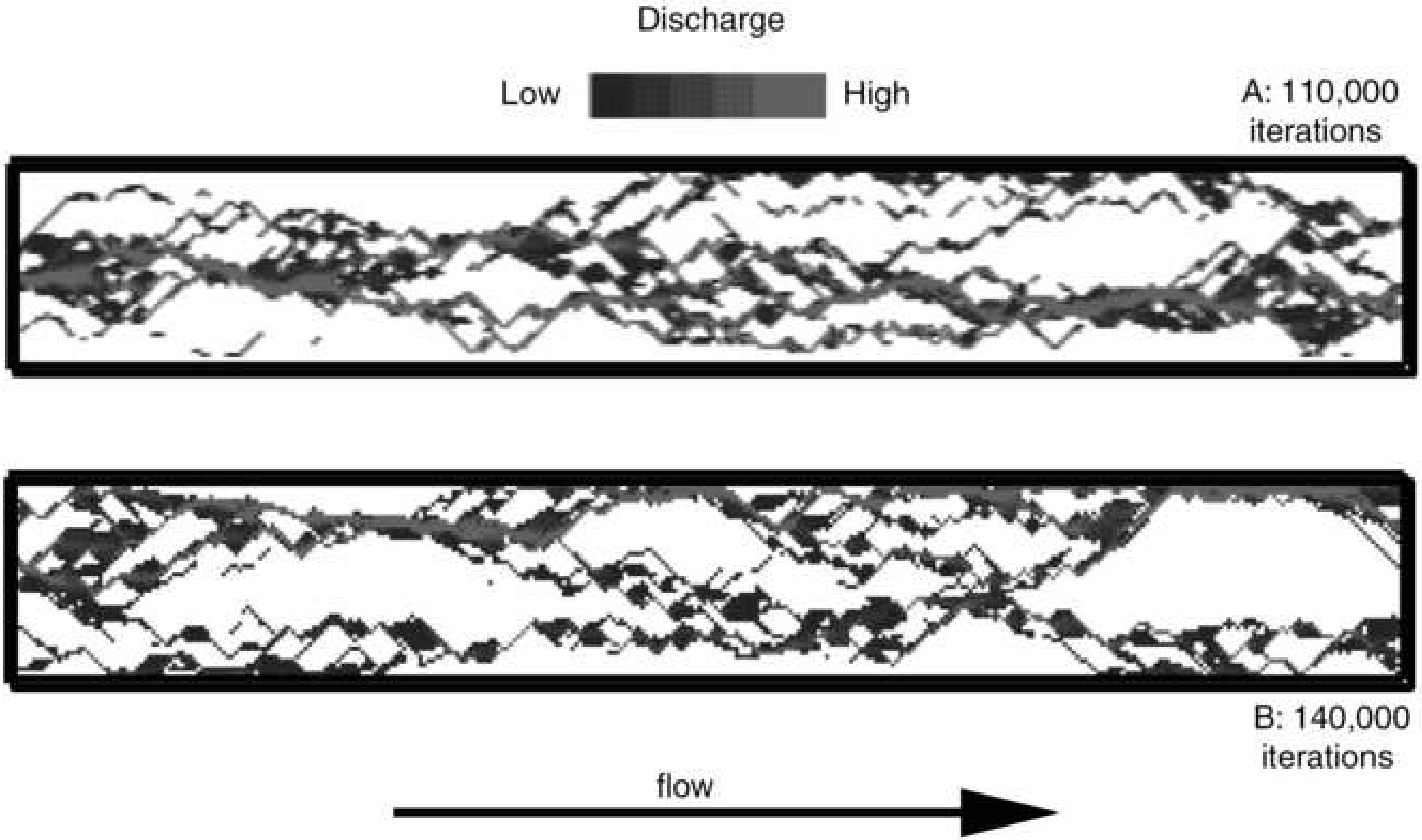

Discharge
Low
High
A: 110,000 iterations
B: 140,000 iterations
flow

Figure 8

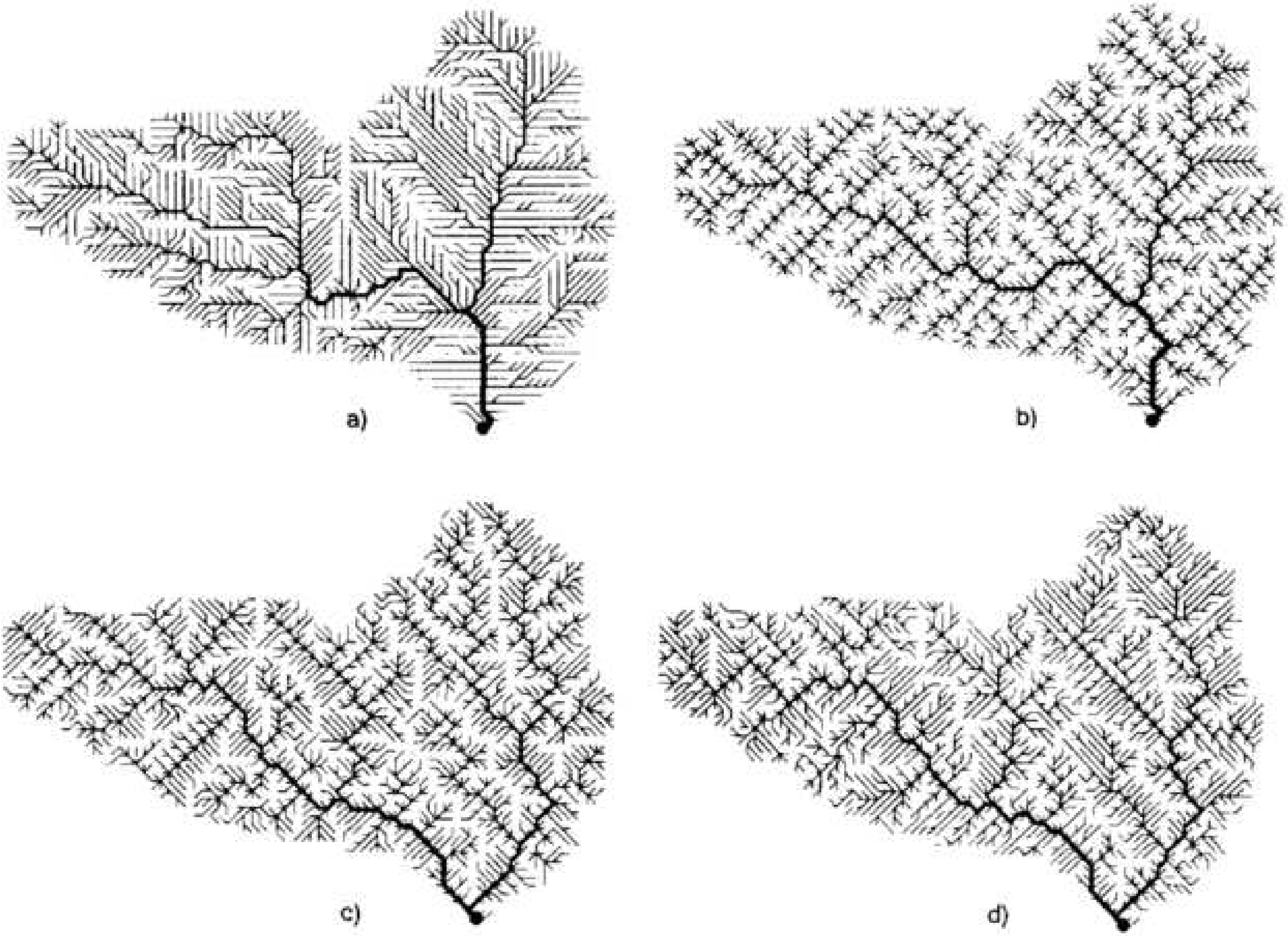


Figure 9

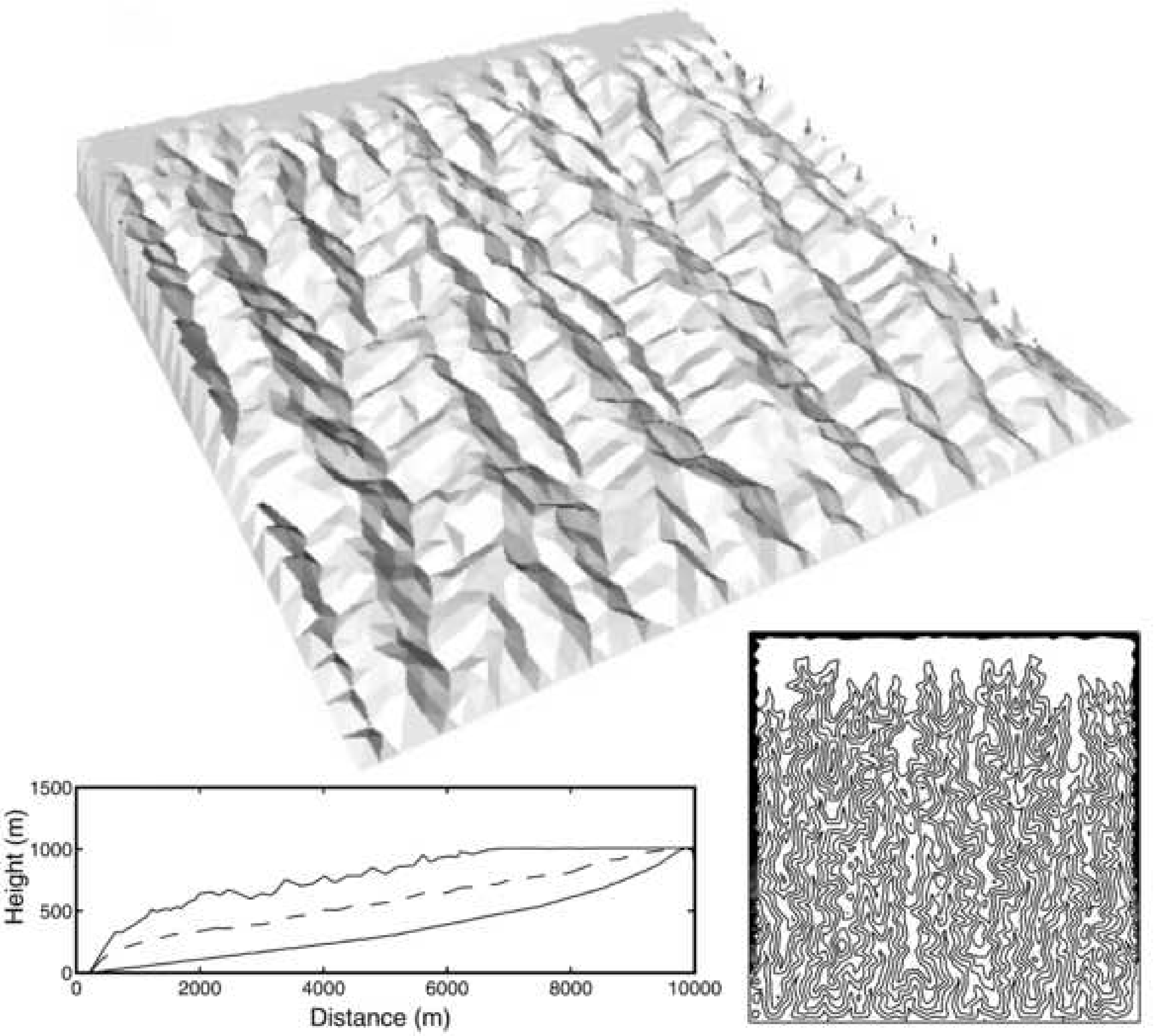

1500
1000
500
0
Height (m)
0
2000
4000
6000
8000
10000
Distance (m)

Table 1

Table 1: Overview of properties and application domain of various model types.

model type	operational domain				operational properties			application domain							
	spatial scale[a]	spatial resolution (m^2)	time scale[b]	time resolution (days)	processes[c]	data requirements[d]	computational requirements[d]	hydrology	inundation	flood frequency	channel change	floodplain evolution	terrace formation	drainage network	hill slope evolution
hydrological	sC,C	10^0 - 10^1	E,Y	10^{-2} - 10^{-1}	F	L,M	L	✓		✓					
flood inundation	R	10^0 - 10^2	E,Y	10^{-2} - 10^{-1}	F	L	M	✓	✓	✓					
channel evolution	sR,R	10^{-1} - 10^1	Y,D	10^{-3} - 10^{-2}	F,S	M,H	M,H		✓	✓	✓				
alluvial stratigraphy	R	10^1 - 10^3	D,C,M	10^0 - 10^2	S	L,M	M					✓	✓		
meandering	R	10^0 - 10^1	D,C,M	10^{-1} - 10^1	F,S	L	M				✓	✓	✓		
braiding	R	10^1 - 10^2	Y,D,C	10^{-2} - 10^0	F,S	L	L				✓	✓			
channel network	sC,C	10^1 - 10^2	C,M	n/a	F,S,H	L	L							✓	✓
landscape evolution	R,sC,C	10^1 - 10^2	E,Y,D,C,M	10^{-2} - 10^0	F,S,H	M,H	M,H	✓	✓	✓	✓	✓	✓	✓	✓

notes:
a: C = catchment; sC = sub-catchment; R = reach; sR = sub-reach
b: E = event; Y = year; D = decades; C= centuries; M = millennia
c: F = flow; S = sediment transport; H = hill slope
d: L = low; M = medium; H = high