Modelling river history and evolution

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Over the last few decades, a suite of numerical models has been developed for studying river history and evolution that is almost as diverse as the subject of river history itself. A distinction can be made between landscape evolution models (LEMs), alluvial architecture models, meander models, cellular models and computational fluid dynamics models. Although these models share some similarities, there also are notable differences between them, which make them more or less suitable for simulating particular aspects of river history and evolution. LEMs embrace entire drainage basins at the price of detail; alluvial architecture models simulate sedimentary facies but oversimplify flow characteristics; and computational fluid dynamics models have to assume a fixed channel form. While all these models have helped us to predict erosion and depositional processes as well as fluvial landscape evolution, some areas of prediction are likely to remain limited and short-term owing to the often nonlinear response of fluvial systems. Nevertheless, progress in model algorithms, computing and field data capture will lead to greater integration between these approaches and thus the ability to interpret river history more comprehensively.

Keywords: numerical models; landscape evolution; alluvial architecture; computational fluid dynamics

1. Introduction

Models, in the context of river evolution, are simplified abstractions of river systems that aim to represent the salient processes and properties that affect changes in river form and dynamics. They provide a controlled environment in which river evolution can be studied.

Traditionally, the study of fluvial geomorphology has been observation based, either in the field or in laboratories. Indeed, many of the important advances of the discipline are based on these approaches. However, some questions cannot be answered in this way, for several reasons. First, there is a discontinuity between temporal scale of observation and temporal scale of change, particularly for long-term river evolution. Rivers evolve over centuries or millennia. Direct observation is limited to years or decades. This limitation can be partially overcome through the use of archived observations from the past such as historical data, maps and

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One contribution of 10 to a Theme Issue ‘River history’.
aerial photographs [1] or by inferring past environments from palaeochannels and sedimentary ‘archives’ in the landscape [2,3]. However, such archives are often incomplete and can only give a partial picture of the river’s evolution, especially temporally, often providing only time slices or glimpses of a river’s history. Second, the diversity of river systems, in terms of their geomorphology, geology, climate, soil development, vegetation cover, land use and anthropogenic impacts, both hinders generalization of observations between different systems and prohibits assumptions of homogeneity within one system. Finally, even with short-term changes, where the scales of observation and scales of change do overlap, it might not be feasible to obtain empirical data for all events, particularly for high-magnitude events.

Modelling can allow us to address some of these issues and thus provides a complementary way of gaining insights into river history and evolution. Modelling provides an environment, whether virtual (as is the case with numerical models) or physical (as is the case with laboratory models), wherein controllable and repeatable analyses and experiments can be conducted. In the context of river evolution, this offers two main advantages. First, it permits one to simulate and observe past events in the modelling environment, so that observations and measurements can be made to analyse past events for which limited direct observations are available. Second, it enables one to investigate how environmental conditions (e.g. climate, vegetation and geology) and internal processes (e.g. erosion, sediment transport and channel width adjustment) influence the morphological evolution of the river system. Through systematic variation of the controlling variables, the sensitivity of river systems to external factors or the nature of interactions between form and process can be investigated. These two modes are commonly referred to as applied modelling and theoretical modelling, respectively. They are often presented as distinct in nature, although in practice there often is a direct connection between them [4,5].

Geomorphological modelling is a rapidly growing discipline. Many models have been developed over the last two decades or so, both as academic tools and as commercial products, which are often quite different in their aims, assumptions and abilities (figure 1). Over the last few years, several reviews have appeared to summarize this diversity in models and modelling approaches [6–8]. Here, we build upon these reviews in the context of river history.

2. Numerical modelling

(a) Concepts

Numerical models can be broadly categorized into three groups. First, black box models are so named because they do not show the processes by which model outputs are linked to inputs, i.e. the model has no prior knowledge of how the system operates or what it is. The numerical mechanics of what occurs within the ‘black box’ model is not necessarily representative of what occurs in nature, but the response of model outputs to inputs is the same as or similar to that observed. Examples of black box models include statistical models and regression models and thus bear on many empirical relationships. Second, stochastic models may include a random element often in an attempt to reproduce the natural variability or chaos found in natural systems. Examples of this include models where the
results are sampled from a probability distribution. Third, process-based models attempt to simulate the physical processes occurring within the system to be simulated. The system (e.g. a river) may be split into components (e.g. flow and sediment transport), and interactions between these two component processes may then be modelled.

There are advantages and disadvantages associated with all of these approaches. Black box models are parsimonious and may perform well on the basis of the data from which they were developed, but they may not perform so well in different circumstances and tell us little about how a system may operate. Process-based models may provide us with insights into how the components of a dynamic natural system (such as a river) interact and behave but, owing to their relative complexity, may be hard to validate and thus can play more of a qualitative than a quantitative role. However, these are sweeping generalizations and many models, especially of river evolution, contain combinations of process, black box and stochastic elements. Even at the heart of the most physically based computational fluid dynamics (CFD) models of flow, there are empirical relations that describe turbulent flow (see §2f).

In order to model river histories and evolution, numerical models have to represent (or discretize) fluvial processes in time and space. For the spatial component, using the example of modelling a river channel, a series of cross sections may be used, water depth across this section calculated, and erosion and

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**Phil. Trans. R. Soc. A (2012)**
deposition allowed to raise or lower parts of the cross section. Or, as in the case of some meander and early braided river models [9,10], a simple line may be used to show channel location as it moves. Increasing the detail or spatial representation, a two-dimensional regular mesh of grid cells may be used to depict a surface or the river bed, where cell elevations rise or fall in response to erosion or deposition. Alternatively, an irregular mesh or triangular irregular network (TIN) of links and nodes can allow more topographic detail to be represented in certain parts of a modelled domain. Finally, a three-dimensional mesh of cells can allow flow of water and sediment in all directions. All of these methods are perfectly valid, but as the dimensions represented increase so does the complexity of the calculations required and the volume of data stored by the model.

Within this spatial domain (whether one-, two- or three-dimensional), the facets or components of the system to be modelled are represented by variables, i.e. values that can change throughout a simulation (e.g. flow depth, velocity and volume of sediment), and these are then altered by equations/rules containing parameters, i.e. values that are kept constant for a given simulation but which can change between simulations (e.g. Manning’s $n$, settling velocities, critical shear stresses). These alterations or changes occur at time steps within the model’s operation, which is how a model may discretize time. The time steps are typically fixed (e.g. every minute, hour or day), but some models use variable time steps to allow the model to operate faster at some times (e.g. during low river flows) and then slower during more complex periods (e.g. during a flood event).

(b) Landscape evolution models

From the late 1970s, researchers started using computer-based numerical models to simulate how rivers and landscapes interacted over large time scales. Now called landscape evolution models (LEMs), they simulated the development of drainage basins by guiding water across a mesh of cells (representing the landscape) according to the steepest slope, and eroding and depositing sediment according to the amount of water in a cell, which in turn was determined by the area draining into it [11]. Through the 1980s and 1990s, these models developed significantly. Cheaper, more powerful computers allowed far more sophisticated and realistic representations of fluvial and slope processes. Examples include the work of Kirkby [12], Howard [13], the SIBERIA model of Willgoose et al. [14] and the GOLEM model of Tucker & Slingerland [15].

It is important to note that LEMs were built to study river network and catchment evolution over long time scales (thousands of years) and over large areas. Therefore, the inclusion of slope processes was important as it allowed sediment from hill slopes to be introduced into the fluvial system by modelled processes, including creep, wash and mass movement. These models have been used to explore fundamental questions in long-term landscape development, such as how hydrology, fluvial erosion, slope processes, tectonic changes, climate and lithology combine to influence the drainage density and the shape/characteristics of the drainage basin. Although these models do not focus solely on fluvial geomorphology, fluvial action is at the heart of all of them, and their importance lies in their ability to take a holistic view and link together hydrological, slope and fluvial processes. As Willgoose et al. [16] stated, the hydrology will alter the catchment form; yet, the catchment form will in turn alter the hydrology.
However, owing to the complexities of integrating all the geomorphic processes operating within a drainage basin and the long time scales over which these models operate (1 K to ≥1000 K years), significant simplifications are required. In most cases, fluvial flow processes are represented by routing water only to the lowest neighbouring grid cell, which rules out the divergent flow patterns required by analysis of alluvial fans and braided rivers. Erosion processes are applied over coarse grid cells (50–100 m diameter), which results in a loss of detail: thus a river channel represented by a 100 m grid cell may in reality be only 10 m wide. Furthermore, processes may be time-averaged whereupon an individual flood event may be lost within a value for mean discharge. Owing to these simplifications, their application generally has been theoretical and often to abstract artificial catchments.

Recent work has addressed several of these issues. Multiple flow routing was added by Pelletier [17], who importantly showed that this enabled drainage networks to migrate over long time scales, whereas single direction routing led to static drainage networks. Multiple flow routing is also an important feature of the CAESAR model and allows the simulation of alluvial fans [18]. To address issues with spatial resolution (e.g. the need to reduce grid cell size), two methods have been adopted. The CHILD model, developed by Tucker et al. [19], replaced regular square grid cells by an irregular mesh or TIN. This allowed areas where greater spatial resolution was needed (e.g. channels) to have an increased density of grid points or cells than areas such as hillslopes, where less detail was required (figure 2). Alternatively, Coulthard et al. [18] used a larger number of much smaller regular grid cells (2–5 m as opposed to 25–50 m), but focused most of the model operation time on cells close to river channels where there is more geomorphic activity. The sophistication and variety of processes incorporated in LEMs has also increased as the models have developed. Examples include representations of bedrock erosion, multiple grain sizes [21,22] as well as the influence of vegetation on landscape evolution [23,24].

Possibly the most important development is that LEMs have made the transition from simulating the abstract to modelling real landscapes and examining their geomorphic response to forcings, such as changes in climate, tectonics and land use. The SIBERIA model has been used extensively to forecast the erosion of proposed landforms for mine rehabilitation in the Northern Territories of Australia [25]. The CAESAR model has been used to simulate the last 9000 years of catchment evolution of the River Swale in the UK, comparing the outputs with the sedimentary record [26]. More recently, Welsh et al. [27] used the CAESAR model to investigate the impact of centennial climate and land cover changes on an Alpine catchment, and found a good correlation between the model results and a lake sediment record. Clevis et al. [28] used the CHILD LEM to examine the preservation of archaeological sites within a meander belt system (figure 2).

Given the current state of the art, LEMs, or variants thereof, could provide one of the most appropriate ways for modelling river histories and especially for analysing how river systems interact with their wider environment. There is great potential for simulating how river systems have responded to past environmental changes—and for using the outcome as a form of palaeovalidation by comparing it with present-day topography or sedimentary records or both. By modelling the whole catchment and integrating hydrological, fluvial and slope processes, they
Figure 2. Section of the upper Thames valley, modelled over the Holocene, revealing the ages of sediments deposited (after [20]). Simulations made using the CHILD model. (Online version in colour.)

negate many of the difficulties imposed by other approaches we discuss in this paper (e.g. boundary conditions, slope/channel coupling). Importantly, they model all parts of the catchment all of the time. Nonetheless, many aspects of fluvial geomorphology, with respect to both form and process, are notably lacking from these models (for example, the formation and evolution of in-channel bars, pools and riffles). It is not clear, however, whether the addition of these smaller scale features and processes would significantly affect the results of the larger scale landscape evolution. Perhaps, as computational power grows ever exponentially and as our understanding of processes increases, the next generation of LEMs will incorporate such levels of detail.
(c) Alluvial architecture models

Still on the subject of long time scales, there is a group of models designed to simulate the vertical and horizontal development of basin stratigraphy. These alluvial architecture models have been developed mainly to simulate sub-surface heterogeneity of facies for natural resource exploitation, but they can also be very useful in the context of palaeogeomorphology. Some of them look at individual bends [29], extensive channel reaches [30–36] and entire basins [37–40].

These models can be split into structure-imitating and process-imitating models, depending on how the stratigraphic units are generated within the model [37,41,42]. Structure-imitating models [34,35,43–45] consider depositional structures (e.g. point bars, overbank deposits and crevasse splays) as individual units. The development of a floodplain is then simulated by the random placement of multiple units on the floodplain, where timing, the spatial location, geometry and size of each unit is determined stochastically. Process-imitating models [30–33,36,42,46,47] explicitly model the key physical processes that build the depositional structures (such as sediment fluxes and channel avulsion). This method results in more realistic simulated sedimentary architecture, although it retains a stochastic component (e.g. temporal and spatial occurrence of avulsion). Recently, attempts have been made to combine the advantageous properties of both structure-imitating and process-imitating models in a hybrid form [47–49].

For simulating river histories, process-imitating stratigraphic models could be used to investigate how environmental changes may impact on the construction and preservation of alluvial structures. For example, a set of exploratory scenarios could be run to evaluate the sensitivity of the simulated alluvial landscape to a range of specified climatic or environmental settings. Unfortunately, the often highly simplified process representation in stratigraphic models could limit their capacity to investigate such river responses in sufficient detail. Furthermore, the stochastic nature of most alluvial stratigraphic models prevents reproducibility and may complicate the interpretation of the results, as these could simply be a facet of the model’s random components.

(d) Meander models

Moving now to shorter time scales, meander evolution models simulate the development of channel planform in single-thread meandering rivers over time scales typically up to several millennia (figure 3). In their simplest form, they simulate channel flow to obtain a measure of hydraulic bank erosion from which channel migration rates are derived and the channel’s position migrates [51–53]. Usually, these meander models use a one-dimensional flow model with adaptations to account for secondary flow effects [54–56], although alternative flow models based on topographic steering have also been used [53]. Bank erosion is normally calculated as a function of flow velocity and channel curvature with an empirical erodibility coefficient. At present, all meander evolution models assume uniform channel width, so that the simulated development on a point bar along the inside bend matches simulated bank erosion on the outside bend. This assumption allows lateral channel migration to be directly equated with outer bank erosion but also leads to outputs that are almost geometric. More complex models [57–62]
Figure 3. Sample output of a meander evolution model. Visualization of a meander belt after 300 time steps (left) and 12,490 time steps. The current channel is shown in blue. Cut-offs are shown from light brown (recent and low elevation) to dark green (old, and higher elevation; adapted from Lancaster [50]). (Online version in colour.)

simulate channel migration in a similar manner, but also allow the channel to adjust vertically, and new point bar deposits and abandoned meander cut-offs to be preserved. In addition, these models simulate overbank deposition.

The more complex of these meander models have good potential for investigating river histories, especially where planform change is a key part of the river’s response. Importantly, they allow the generation of palaeochannels and meander belts—features that are often readily recognizable in the field as evidence of previous river history. This also allows straightforward comparison with channel patterns and meander locations from historic maps and aerial photographs—one of the most accessible metrics for river change [1]. But these schemes have some limitations. First, they generally simulate meandering channels that are single-threaded with a single width line, whereas rivers may contain islands or fluctuate between being braided and meandering. Second, and linked to the previous point, the fixed channel width reduces their capacity to change channel dimensions in response to changes in flow or sediment inputs. Third, and important from a geomorphic perspective, 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 as it is being eroded along the outside bank. This is rarely the case in reality, as the different elevation of point bars and outer bend cut banks means more sediment is eroded at the outside edge than can be deposited on the inside [63]. Some of these issues have been addressed by the inclusion of lateral erosion in cellular models [64] as we shall discuss later.

(e) Reach-based cellular models

More recently, cellular models have been used to study the fluvial geomorphology of river reaches. They have also been termed ‘reduced complexity models’ [65]. The first, a cellular model of a braided river, was developed by
Murray & Paola [66,67]. Representing a braided reach by a grid of cells (22 × 200) textured with a random ‘roughness’, they routed water downstream by allowing water to ‘flow’ to lower neighbouring cells. Cell elevations were then changed according to simple erosion and deposition rules based on the volume of flow between cells and a lateral erosion term. While simple in concept, this model simulated the multi-channel form of braided rivers and, for the first time, the dynamics of channel shifting, migration and avulsion. A key difference from the LEMs discussed earlier is that Murray & Paola [66] represented the channel by one or more cells across its width, as opposed to one cell for the channel, regardless of width. Murray & Paola’s model was deliberately parsimonious and the outputs compared well qualitatively with braided patterns and dynamics but less so with the results of flume studies [68]. However, this exploratory model significantly increased our understanding of braided river systems, indicating that all that was required for rivers to braid was sediment transport, and the unhindered ability to erode laterally.

Following Murray & Paola’s work, other researchers have adopted and modified this cellular approach. Thomas & Nicholas [69] developed a physically more detailed braided river model that allowed flow to more than the three downstream cells, demonstrating that results from their flow model were very similar to those from a two-dimensional depth-averaged flow model. Further work by Thomas et al. [70] also integrated sediment transport to interpret the historic evolution of a braided river. The CAESAR model [18,22,71] also develops the ideas of Murray & Paola [66]. Their model incorporates a more sophisticated flow routing algorithm than Murray & Paola’s work (figure 4), by calculating a flow depth (allowing flow over obstacles), and also allows flow in any direction (instead of just downstream). Coupled with a multiple grain size sediment transport model, the CAESAR model has been applied to river catchments and reaches to establish how climate and land cover impact upon river systems [26] and has also been used to identify nonlinear fluvial responses and the possible presence of self-organized criticality in fluvial systems [64,72]. Recent developments include the integration of meandering and lateral erosion (figure 5), giving CAESAR the potential to model braided to meandering transitions [71]. Crave & Davy [73] have developed a novel method for reproducing braided river patterns and dynamics using a particle modelling approach and creating different braiding intensities based on the probabilities of erosion and transport distances.

The key step taken by Murray & Paola, and followed by other researchers, was to simplify complex flow equations by using empirical relationships, often based on the Manning equation. Compared with the more complex CFD models described in the next section, this simplification of the flow model considerably releases computational time to allow them to simulate erosion and deposition over years to centuries.

Therefore, for exploratory modelling, investigating how geomorphic processes interact and why certain phenomena occur, these cellular models have proved insightful. But they have proved difficult to validate quantitatively and for this reason may be unsuitable for engineering predictions. In this manner, they are at present more akin to experimental physical models than to calibrated flume experiments. However, there are still many fundamental questions in fluvial geomorphology and river history that these models may address in a more qualitative than quantitative manner.
(f) **Computational fluid dynamics models**

CFD models rely on solving the basic conservation laws governing the motion of fluids, namely ‘conservation of mass’ (which states that no water is created or destroyed while it is flowing) and ‘conservation of momentum’ (which states that any change in the flow velocity is the result of the forces acting upon the flow—e.g. pressure, shear and friction, gravity). Mathematically, these laws are expressed by a set of differential equations known as the Navier–Stokes equations. In a Cartesian coordinate system, these equations are written as

\[
\frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} + \frac{\partial U_z}{\partial z} = 0, \\
\rho \left( \frac{\partial U_x}{\partial t} + U_x \frac{\partial U_x}{\partial x} + U_y \frac{\partial U_x}{\partial y} + U_z \frac{\partial U_x}{\partial z} \right) \\
= -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x, \\
\rho \left( \frac{\partial U_y}{\partial t} + U_x \frac{\partial U_y}{\partial x} + U_y \frac{\partial U_y}{\partial y} + U_z \frac{\partial U_y}{\partial z} \right) \\
= -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y \\
\text{and} \\
\rho \left( \frac{\partial U_z}{\partial t} + U_x \frac{\partial U_z}{\partial x} + U_y \frac{\partial U_z}{\partial y} + U_z \frac{\partial U_z}{\partial z} \right) \\
= -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} - \rho g + F_z,
\]
Figure 5. Images of different edition Ordnance Survey maps and corresponding CAESAR simulations of the River Swale near Reeth, UK, in AD 1857, AD 1956, AD 1982 and AD 2006. The model simulations were started with a DEM derived from the 1857 map and run forward to present day, using the sequential map editions to check that the model is performing correctly. (Online version in colour.)

where $U$ denotes flow velocity, $x$, $y$, $z$ denote the three Cartesian dimensions, $\rho$, $\tau$, $p$, $g$ and $F$, respectively, denote fluid density, shear stress, pressure, gravity and additional external forces.

These equations provide, in theory, an exact description of the motion of fluids (any fluid, not just water). Unfortunately, they are too complex to be solved analytically. Instead, numerical algorithms are used to find approximate solutions,

*Phil. Trans. R. Soc. A* (2012)
and even then assumptions and simplifications have to be introduced. For many applications in fluvial geomorphology, the vertical flow can be ignored, reducing the Navier–Stokes equations to a depth-averaged two-dimensional form known as the shallow water equations or Saint–Venant equations. Many river models (e.g. HEC-RAS) go even further, and reduce the equations to a one-dimensional form, effectively assuming that rivers are linear features in the landscape. The benefit of these simplifications is that solving the flow equations becomes easier and faster, albeit at the cost of ignoring secondary flows. Other simplifications relate to the turbulence closure, i.e. the algorithmic representation of the diffusion of momentum through flow turbulence. The most common turbulence closures are Reynolds averaging, which assumes a normal distribution of flow velocities around the mean flow velocity, and large eddy simulation, which assumes self-similarity of turbulence at the sub-grid scale. A final consideration is the method for evaluating the equations (finite difference, finite element and finite volume are the most common) and the resolution of the spatial discretization, i.e. how many points are used to represent the river and floodplain topography. An in-depth analysis of the computational implementation of CFD algorithms, turbulence closures, as well as other assumptions and simplifications is beyond the scope of this study. The reader is referred to Lane [74] and Bates et al. [75] for more extensive discussions of these technical aspects of CFD in the context of fluvial geomorphology.

Applications of CFD models can be broadly divided into two categories: those with sediment transport modelling and those without. The latter rely on the CFD equations alone, and can be used to investigate hydraulic flow properties over an unchanging topography, notably the simulation of flood propagation and inundation extent [76–79] and studies of habitat suitability for aquatic species [80,81]. These types of applications are mainly used in planning or river engineering studies, but they can also be used to gain insight into specific historic events [82]. Although useful, these models cannot simulate river evolution, because the morphology of their river never changes.

This shortcoming is addressed by incorporating a sediment transport algorithm in the model [83,84]. The model simulations are then iterated over time. The CFD part of the model is used to calculate the flow field that drives sediment entrainment and sediment transport. The channel and floodplain topography is adjusted in accordance with the calculated erosion and deposition. This may affect the flow field and thus requires the flow field to be recalculated after each change of the topography (figure 6). The models are, therefore, computationally very demanding and their applications are typically constrained to relatively small spatial and temporal scales. These models thus mainly focus on relatively small river sections or river reaches rather than entire river systems [85–88]. Although most models address in-channel sediment transport only, they can also be expanded to model the wider fluvial context, for example, by modelling the morphological changes of the floodplain through overbank sediment routing and deposition [89–91] or by modelling planform channel changes due to bank erosion or width adjustment [92,93].

CFD models are suitable for simulating changes over relatively short time periods, i.e. years to decades, notably for specific floods or specific short periods of high fluvial change [82,94]. They are less useful for long-term simulations—centuries to millennia—partly because of the computational problem noted earlier.
Figure 6. Sample output of a CFD model, showing computed bed elevation changes that occurred during a flood in 2002 in a 6 km reach of the Danube River (a–d). Also shown are the measured water depths. (Online version in colour.)

(although this may be overcome with future technologies) and partly because the accumulation of uncertainties over many iterations of the model simulation would make the predictions unreliable [95].

3. Reliability, value and meaning of models

In order for a model to represent reality, it must have some meaningful output. At its most basic, this may be predicting a correct value for a simulated outcome. However, when modelling river histories, this can be far from straightforward—and this can be partly attributed to history itself. Geomorphology has been described as physics with history, and in order to model how a river changes or has changed, we need to know the river’s initial state. In many cases, this may appear straightforward, as historical maps, for example, can provide excellent data on the dimensions and location of where a river channel was located. Furthermore, sedimentological evidence, or geomorphic mapping of palaeochannels on a floodplain, may give a longer term record of past river conditions. However, these data provide only a snapshot of the starting morphology, and ideally a history of water and sediment inputs is required as well. This is far harder—if not impossible—to establish and thus modellers have to simulate input values through using other models or on the basis of statistical representations of existing data on water and sediment inputs.

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A further limit on quantitative prediction may also be attributed to the nonlinear and/or chaotic nature of river systems. From the entrainment of individual pebbles, to the development of meander belts across a floodplain, up to the formation of large-scale sedimentary basins, river systems exhibit unpredictable, nonlinear and chaotic behaviour [96]. The extent of this is such that recent studies question whether or not it is possible to establish a response to external forcings within river systems [95]. Jerolmack & Paola [97] suggested that a river catchment may act as a giant filter, shredding input signals (e.g. climate change) through the storage and re-mobilization of sediment. That is to say, the ‘noise’ of the natural autogenic processes operating may be greater than or as great as that generated by changes in inputs. Similar results were found by Van De Wiel & Coulthard [72], who postulated that the sedimentary response of small river catchments may exhibit self-organized criticality, which effectively renders the system unpredictable.

For modelling past changes in river systems, this could have major ramifications. Unpredictability, chaos and nonlinearity present many issues for a science where things are far more readily explained if they are linear and follow a straightforward path of development. But, if we accept that river systems are nonlinear, what is required is a different, less deterministic approach to modelling and to processing or interpreting model results. Using the example of climate modellers, we need to present results as probabilities and likelihoods from ensembles of multiple runs. Even if a system is chaotic, often it will have a general behaviour (as would be hoped given that water and sediment generally move down hill!) and this can be gained by running multiple repeats of numerical simulations with fractionally different starting conditions and looking at the means, standard deviations and distributions of the outcomes.

Associated with these arguments are the difficulties in validating and calibrating numerical models of river history. Much of this stems from problems with measuring rivers and river systems; establishing metrics to describe a river’s geomorphology is notoriously difficult. Taking braided rivers as an example, do we measure the length of islands, the width of islands, width–depth ratios or braid indexes? None of these captures the dynamic nature that is so important for braided channels. Most river measurements are relatively basic, often descriptive and may change with stage, for example width, depth, bankfull discharge, sinuosity and planform. Measurements of sediment discharge are often cross-section averaged, temporally disparate and sadly lacking at peak flows, when arguably they are the most important. A further issue is that numerical models can generate far more data than we have available in the field. For example, Coulthard & Macklin [26] simulated a 9000 year hourly history of flow and sediment yield (in nine grain sizes) for a river catchment in the UK. The only way this could be compared with field data was by lumping the (highly variable) sediment yield data into 50 year sections and comparing them with dated Holocene sedimentary units found across the northern UK [26].

However, the ‘data revolution’ provided by rapid progress in surveying through laser scanning [98] and airborne LiDAR [99] provides ideal datasets to drive numerical models and also against which to compare and validate them. In the coming years, this situation will only improve, as areas surveyed by early LiDAR flights (in about the year 2000) will be repeatedly resurveyed, providing geomorphologists with highly detailed, unbiased, wide coverage of topographic...
changes. This progress is also augmented by the increased resolution and free availability of aerial and satellite photography through services such as Google Earth, which often allows a virtual river history to be established.

In this section, we have focused on some of the limitations and difficulties in modelling river history, but it is worth remembering that these models have advantages as well as limitations. It is, therefore, essential to note the intended scope of a model and what it was designed to do or discover. River history is a complex, multi-faceted subject and we should not expect there to be a ubiquitous one-size-fits-all model.

4. Conclusions and future directions

Numerical modelling of river history has developed significantly over the last 40 years since the first models were formulated. Modelling has an important place in the study of river history, as it provides a framework within which we can analyse and test how river history develops over periods and spaces we could not observe in the field. It provides us with a means of evaluating hypotheses, predicting change, learning how fluvial systems change over time, and, most importantly, challenging current ideas and raising new and important questions about the behaviour of rivers. In this review, we have shown that there is a wide range of models that can be used to address key issues when the focus is on river history.

Looking to the future, the integration of more detailed flow models (§2f) is inevitable as computer speed increases and new numerical solutions are developed. Recent advances have led to a major increase in the speed of simple two-dimensional flow algorithms [100], and the integration of these within landscape development models is probably the first step in the next phase of model development. However, a far better representation of flow (two or three dimensions) bizarrely raises more problems than it solves.

Translating flow into erosion and deposition requires the use of shear stress or stream power calculations, along with sediment transport laws of which there are many [101]. Unfortunately, most of our existing sediment transport formulae are based on cross-section measurements, whereas these new models will provide depths and velocities in two/three dimensions. Aside from cross-sectional averages, or very detailed grain-by-grain accounts, we have very little knowledge of how sediment transport operates at the scales required by future models. How does cohesive sediment influence this process? How does vegetation affect all of the above? Our past generations of numerical models of fluvial geomorphology have simply not required these levels of detail, nor have our field-based studies. There is a rich future ahead in both field and modelling studies in acquiring such data and understanding how sediment transport operates in greater detail.

Finally, it is important to temper the expectation of what researchers may get from numerical models. Instead of precise predictions, perhaps the true value of numerical models may be more nuanced, aligned instead with more qualitative outcomes: for example, predicting what is likely to happen or to have happened, or what direction a river system may take after a given external change. Thus, instead of simulating exactly where a river channel may be positioned in 50 or 500 years’ time, the model would be used to predict broader aspects of the river system’s dynamics (such as a classification of planform pattern, trends

*Phil. Trans. R. Soc. A* (2012)
of aggradation or incision, or long-term patterns in sediment yield). Weather predictions can be reliable up to 48 h in advance, but are nonsensical for 50 years in the future; yet, predictions of overall climatic patterns 50 years ahead may be reasonable. Given the complexity and chaotic nature of rivers, we cannot hope to simulate the position, size and grain size of a river channel in 50 years’ time, but we may be able to predict reasonably whether or not it will be braided or single-threaded or whether it will be incising rather depositing. Simulating past fluvial behaviour can be just as problematic, but here at least the outcome can be checked against the geological, photographic or cartographic record. Even if we have to adjust model parameter outcomes by this palaeovalidation, we can learn a good deal about what controls fluvial systems and thus river history.

References


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