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

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Abstract

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

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

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

1. Introduction

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

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1.1. Sediment transport integration

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

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

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

1.2. Scale issues

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