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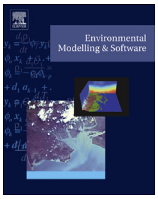

Simulating the influences of groundwater on regional geomorphology using a distributed, dynamic, landscape evolution modelling platform

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ABSTRACT

A dynamic landscape evolution modelling platform (CLiDE) is presented that allows a variety of Earth system interactions to be explored under differing environmental forcing factors. Representation of distributed surface and subsurface hydrology within CLiDE is suited to simulation at sub-annual to centennial time-scales. In this study the hydrological components of CLiDE are evaluated against analytical solutions and recorded datasets. The impact of differing groundwater regimes on sediment discharge is examined for a simple, idealised catchment, Sediment discharge is found to be a function of the evolving catchment morphology. Application of CLiDE to the upper Eden Valley catchment, UK, suggests the addition of baseflow-return from groundwater into the fluvial system modifies the total catchment sediment discharge and the spatio-temporal distribution of sediment fluxes during storm events. The occurrence of a storm following a period of appreciable antecedent rainfall is found to increase simulated sediment fluxes.

Software availability

Name of software: CLiDE
Developer: Andrew Barkwith
Contact address: British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, NG12 5GG, UK. E-mail: andr3@bgs.ac.uk
Year first available: 2013
Required software: Windows
Program Language: C#
Availability and cost: GNU licensed freeware

1. Introduction

1.1. Cellular automata

Simulation of distributed dynamic environmental systems is often based on the solution of differential equations that can be difficult to solve without simplification (Toffoli, 1984) or large computational resources. Cellular automata (CA), first developed by von Neumann (1951, 1966) to investigate self replication, provided an alternative to solving the governing equations, allowing a fast, exact numerical simulation of a physical system. Since their inception CA have been applied to a host of physical research areas focussed around fluid dynamics and natural systems (see for example, Margolus et al., 1986; Somers, 1993; Chen and Doolen, 1998; Chopard and Masselot, 1999). CA discretises space into regular two- or three-dimensional cells, each of which contain physical property information for that region of space. Each cell is able to pass and gather information about neighbouring cells and subsequently modify its contents based on a transfer function. Interaction with neighbouring cells for two-dimensional cases usually consists of either a Moore-type method, where all surrounding cells interact with the central node, or a von Neumann (Manhattan) neighbour-type method where interaction is solely with adjacent cells (Fig. 1). Initial cell states are user defined, and with each time step states are simultaneously updated based on the transfer function and states of neighbouring cells.

1.2. Groundwater and geomorphology

The impacts of surface hydrological processes on geomorphology, and thus topography, have been studied using

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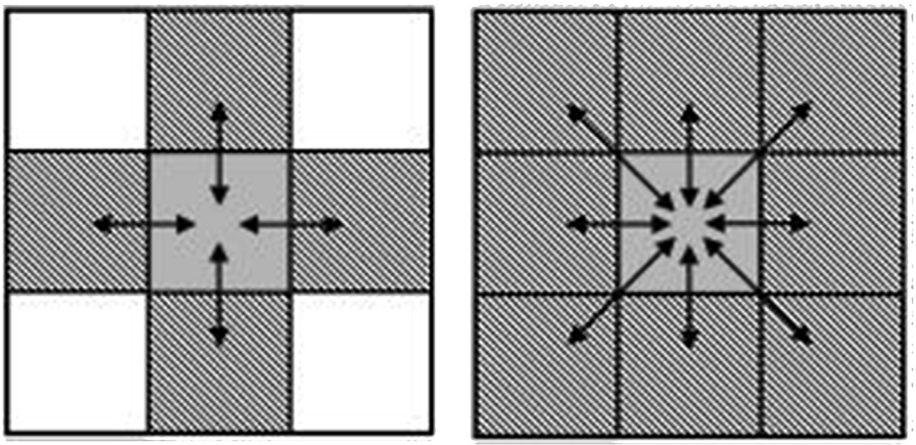

Fig. 1. CA neighbourhoods; the von Neumann neighbourhood (left) considers cells in the cardinal directions and the Moore neighbourhood (right) allows interactions with all immediate cells. Arrows represent cell neighbourhood interaction with a central node.

numerical methods for a number of years. With advances in computer processing power available to researchers, the development of landscape evolution models (LEMs) has progressed from simulating water routing effects on nodal elevation (Ahnert, 1976), to representing detailed fluvial and hillslope processes (for a full review see Tucker and Hancock, 2010). Recent advances in this field have seen increases in domain sizes and resolution, irregular gridding techniques, and the move from hypothetical to real catchments becoming common place (e.g., Pazzaglia, 2003; Coulthard et al., 2012). Currently, LEMs based on regular, square, gridded digital elevation models (DEM) are popular as slope attribution does not need to be determined manually. These DEM-based models also have the advantage of allowing run-time landscape adjustment in response to runoff, erosion and deposition (Hancock et al., 2011). Current models contain representations of surface hydrology but they all either use highly simplified representations of groundwater influx to rivers (as a constant baseflow) or ignore groundwater processes entirely (Huang and Niemann, 2006). An exception to this is Keesstra et al. (2014), who capture the transient nature of baseflow in an LEM environment suitable for simulating relatively small catchments.

There are a number of mechanisms by which groundwater can have an impact on erosional processes. Within cohesive soils or sediments, in a process similar to overland flow, the formation of subsurface channels from groundwater scour can cause near-surface fractures or cracks in the overlying surface (Dunne, 1988). These pipes can collapse, leading to the formation of extensive gully networks. This process tends to occur in shale-dominated, arid or semi-arid regions (Howard and McLane, 1988). The seepage of groundwater to the surface can locally enhance the erodibility of cohesive soils or sediments by increasing their susceptibility to a range of physical and chemical weathering processes (Laity and Malin, 1985). Chemical weathering at depth, which subsequently leads to enhanced erosion when a unit is exposed, can also be attributed to groundwater processes (Kelly, 2012). In less cohesive sediments the seepage of groundwater to the surface can provide buoyancy to particles, reducing the flow velocities required to entrain them and increasing the development of channel features (Fox et al., 2007). Groundwater flow operates on longer temporal scales than direct surface runoff and, in its simplest form, introduces a mechanism to lag surface water flow and impart a smoothing effect on surface fluvial systems (Changnon et al., 1988). Through this process, the fluvial flow velocities that drive sediment flux can be modified at multiple spatio-temporal scales.

Due to the limited extent of tunnel-scour erosion and long timescales associated with physical and chemical weathering, these processes are not considered in this study, which focusses on sub-annual to centennial geomorphological evolution. Although the groundwater seepage buoyancy process is known to be important locally, the impact on differing sediment classes and under differing groundwater regimes is not well constrained. Due to its conceptual simplicity and potential applications, it is the representation of baseflow-return to the fluvial system and the impacts that this can have on catchment morphology and sediment transport that forms the basis of this study.

1.3. Baseflow

The time taken for water to enter the groundwater system through recharge, until its contribution to a surface water body as baseflow, is influenced significantly by topography, geology, vegetation, land use and climate factors. Aquifer recharge through channel infiltration during storm events can be large enough to modify the commonly observed power law relationship between discharge and basin area (Goodrich et al., 1997), although many LEMs assume this relationship to be linear. If the return of this water to the surface as baseflow coincides with future rainfall events, the increase in storm flow can be significant (Sklash and Farvolden, 1979; Buttle, 1994; Kirchner et al., 2000). Spatial variability of baseflow is generally highly heterogeneous across a catchment, often increasing surface river flows in the lower reaches. The combination of these spatial and temporal groundwater influences on surface water dynamics can create a highly complex system. Modelling surface water flow dynamics accurately under these complex hydrological conditions without a groundwater component is often not possible. The characteristics of catchments with greatest susceptibility to complex hydrological interactions are: those with large ranges between topographic highs and lows, creating a strong subsurface hydraulic flow gradient; those with highly heterogeneous hydraulic conductivity and specific yield, formed for example by changes in geology; those where groundwater exhibits a strong seasonal signal and hence a variable baseflow-return to rivers, for example sandstone aquifers; and those that are unconfined, allowing the return of water to the surface.

1.4. Application

Depending on the baseflow contribution to surface flow components, groundwater process could have major impacts on the