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RunCA: A cellular automata model for simulating surface runoff at different scales

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SUMMARY

The Runoff Model Based on Cellular Automata (RunCA) has been developed to simulate surface runoff at different scales by integrating basic cellular automata (CA) rules with fundamental measureable hydraulic properties. In this model, a two-dimensional lattice composed of a series of rectangular cells was employed to cover the study area. Runoff production within each cell was simulated by determining the cell state (height) that consists of both cell elevation and water depth. The distribution of water flow among cells was determined by applying CA transition rules based on the minimization-of-difference algorithm and the calculated spatially varied flow velocities. RunCA was verified and validated by three steps. Good agreement with the analytical solution was achieved under simplified conditions in the first step. Then, results from runoff experiments on small laboratory plots (2 m × 1 m) showed that the model was able to well predict the hydrographs, with the mean Nash–Sutcliffe efficiency greater than 0.90. RunCA was also applied to a large scale site (Pine Glen Basin, USA) with data taken from literature. The predicted hydrograph agreed well with the measured results. Simulated flow maps in this basin also demonstrated the model capability in capturing both the spatial and temporal variations in the runoff process. Model sensitivity analysis results showed that the calculated total runoff and total infiltration were most sensitive to the input parameters representing the final steady infiltration rate at both scales. The Manning's roughness coefficient and the setting of cell size did not affect the results much at the small plot scale, but had large influences at the large basin scale.

1. Introduction

Surface runoff and associated soil erosion are subjects of continuous concern around the world, as they may have serious environmental consequences, including flood, landform instability (e.g., landslide and debris flow), loss of top soil and fertilizer leading to plant death or crop failure, and the transport of pollutants to surrounding areas and water courses. A quantitative evaluation of the extent and magnitude of runoff problems is consequently required to find, implement or improve land management strategies. For this purpose, some lumped conceptual runoff models have been developed since the 1970s, typical examples being the SCS curve number (U.S. Department of Agriculture, 1972), USLE (Wischmeier and Smith, 1978), CREAMS (Knisel, 1980) and RUSLE (Renard et al., 1997). These models usually treat the study area as a spatially singular entity, use state variables that represent averages over the entire area, and produce outputs at a single point according to empirical relationships (Haan et al., 1982). These models are computationally very efficient in calculating runoff and have relatively few input parameters. However, they are not able to capture the spatial or temporal variations in hydrological processes, and require calibration if applied to regions different from the location of first development.

To better describe the extent of spatial and temporal variability of runoff processes, some distributed physically based hydrologic models have emerged. Some of these models, including KINEROS (Smith, 1981), WEPP (Laflen et al., 1991), EUROSEM (Morgan et al., 1998b) and HEC-1 (Feldman, 1995), partition the target area (e.g., a catchment) using a network of elemental sections, such as a cascade of planes and channels. These elements are always simplified geometries with large sizes, which can provide a representation of the gross topographic features but may lose some local topography details and complexities. With the development of remote sensing, digital elevation models (DEMs) and geographic information systems (GIS), grid structures are more frequently used in hydrologic models, with examples being ANSWERS

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(Beasley et al., 1980), AGNPS (Young et al., 1989), LISEM (De Roo et al., 1996) and SHE (Abbott et al., 1986). These grids usually have much smaller sizes than the geometric elements and provide an easier way to represent the study area.

Numerical techniques have been widely employed in these distributed models to simulate the runoff routing processes. Typically, the overland flow and channel flow are described by solving the Saint–Venant equations of continuity and momentum. To make these complex equations solvable, simplifying assumptions need to be made and different methods are produced by neglecting various terms of the momentum equation (Chaudhry, 1993; Swensson, 2003). The kinematic wave model is the simplest method that neglects both acceleration and pressure terms, while the diffusion wave model is a more complete form that includes the influence of the pressure force (Chow et al., 1988). Therefore, the diffusion wave method is expected to be more accurate under complex conditions but at the expense of the reduced efficiency in computation. These two models only simulate the one-dimensional flow, while the spatial variation in the direction perpendicular to the principle slope could not be captured (MacArthur and DeVries, 1993; Vieux, 1991). The more advanced 2-D diffusion wave method, such as that used in CASC2D (Rojas et al., 2003), could better describe the spatial variation of the flow behaviors, but this would further increase the complexity and hence may lead to low computational efficiency.

Alternatively, several simpler methods have been developed for determining the water flows based on the elevation differences of the elements. For example, in AGNPS flow directions are determined from the DEM. The DEM-based runoff routing algorithms include both single-direction algorithms (e.g., D8 (O'Callaghan and Mark, 1984) and ρ8 (Fairfield and Leymarie, 1991)) that transfer all flow from the center grid to one downslope neighbor, and multiple-direction algorithms (e.g., MFD (Quinn et al., 1991), DEMON (Costa-Cabral and Burges, 1994) and D∞ (Tarboton, 1997)) that partition flow to multiple downslope neighbors. These elevation-based methods are very straightforward and computationally efficient; however, a major limitation is that they tend to be oversimplified as the water component in the elements is not taken into account. In reality, the water does not always flow according to the elevation differences because of the different water depths among the elements. Moreover, flow directions derived from these methods are pre-determined and fixed, thus nor the dynamic flow behaviors or the interactions between elements can be captured.

Therefore, alternative methods that have both high reliability and reduced complexity are required for more efficient hydrologic modeling. Cellular Automata (CA), a discrete dynamic system composed of a set of cells in a regular spatial lattice, is one of such promising approach worthy of investigation. Since the states of each cell depend only on the states of its neighbors and the global behavior of the whole system is determined by the synchronous evolution of all the cells in discrete time steps, CA is very effective in simulating dynamic complex natural phenomena from local to global according to simple transition rules (Wolfram, 1984). Unlike some other disciplines where CA has been widely applied and accepted, CA was not introduced into hydrology until Murray and Paola (1994) developed the first cellular braided river model about 40 years after CA was first proposed in the 1950s (Von Neumann, 1966). Later it was successfully applied to other hydrological processes, such as water flow in unsaturated soil (Folino et al., 2006; Mendicino et al., 2006) and ground water modeling (Ravazzani et al., 2011). However, only in the recent decade a few studies have emerged to relate its application to surface runoff modeling. For example, Mendicino et al. (2013) added an overland flow module to their CA based ecohydrological model (Cervarolo et al., 2011). While their model takes the advantage of CA that is directly compatible with the efficient parallel computing, the runoff routing process is still determined by the diffusion wave model. Rinaldi et al. (2007) and Ma et al. (2009) also developed CA based algorithms for simulating runoff in large plains and on hill-slopes, respectively. Both models have shown the capacity of CA, however, a spatially uniform flow velocity was assumed and simply applied over the entire study area, leading them to be only used for simulating the steady flow conditions. Parsons and Fonstad (2007) developed a more complex CA model capable of simulating the unsteady flow conditions by delaying the water from one cell to the next until the correct timing is reached. Although this is a significant progress, unfortunately in their model the flow directions were restricted to only four cardinal directions due to the difficulties in producing accurate timed water flows. Uncertainty also existed in selecting an appropriate time step for simulation. In addition, calculation of the rainfall excess is rather simple and empirical in this model as it does not include any related hydrologic principles. Some other CA models, such as RillGrow (Favis-Mortlock, 1998), EROSION-3D (Schmidt et al., 1999), and CAESAR (Coulthard et al., 2000), incorporate a surface hydrology component, but it is usually simplified because these models were primarily developed to study soil erosion or landform evolution. Consequently, in this study a CA-based model, which integrates measurable hydrologic parameters, is developed for quantitatively predicting the dynamic surface runoff processes under complex conditions at different scales. The efficacy of this model is then validated by the analytical solution under simplified conditions, the laboratory experiments at small plot scale and the field measurements at large basin scale. Sensitivity analysis is also conducted to understand the model response to input parameters and model settings.

2. Model development

A typical CA based model A can be expressed as a quadruple (Gregorio and Serra, 1999):

$$A = (Z^d, X, S, \sigma) \tag{1}$$

where Z^d represents a lattice of cells covering the study area, X is the definition of the local neighborhood, S is the set of cell states, and σ is the transition rule determining the changes in cell properties. Based on this structure and integrated with the physical processes involved in runoff production and distribution, the RunCA (Runoff Model Based on Cellular Automata) has been developed and is described as follows.

2.1. Definition of lattice space and spatial cells: partition process

As illustrated in Fig. 1, in this model the study area is partitioned into small hydrologic elements by a two-dimensional lattice consisting of square cells. This discretization is selected for its simplicity, broad application and convenience of implementation in

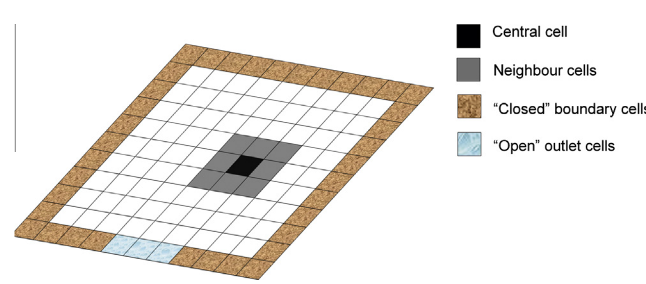

Fig. 1. Lattice space and spatial cells in the RunCA model.