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Research Article

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Study on the cell size in the simulation of a cellular automaton model for hillslope rill erosion

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ABSTRACT

The erosion of The Loess Plateau could be regarded as one kind of representations of the huge complex system, which is the landform of topography. The complexity of the process is well reflected in an idealized nonlinear system called Cellular Automaton (CA) which is quite sensitive of the initialization and it may lead to an inestimable result just because of tiny differences of the initial sets. In this paper we produce a Hillslope Rill Erosion Cellular Automaton Model to find a better set of its cell size of the initial setting and implement it by a multi-agent programmable modeling environment called Netlogo. The result of this paper shows that the applicability of a certain range of cell size in Cellular Automata requires some degree of attention in the study of this area.

Keywords: Cellular Automaton, Soil Erosion, HRECA Model, Netlogo.

INTRODUCTION

Soil erosion is one of the most important reasons of soil and water loss as well as land resources degradation. To study the characteristics and influencing factors of soil erosion is of great imprtance for protecting the landform in land utilization and social development. The investigation to dynamically simulate and forecast the evolvement of soil erosion process could help control the effect with hazard assesment or some other government plicies.

Since computer simulation is an ideal tool, soil erosion is a complex phenonena, the behavior of which can be described in terms of local interactions of their consituent part, can be frequently modelled efficiently by cellular automata. Celullar automata are discrete (dynamical) systems whose behaviour is completely specified in terms of a local relation[1]. The cells change themselves according to a commom transition rule at discrete time steps, this kind of local interactions in microscosmic domains could emerge complex phenomenon in macroscopic level.

So far, several models for simulating the erosion process have been proposed, for example Pilotti and Menduni used LGA (Lattice Gas Automata) to simulate the sediment erosion, transition and deposition[2]. D. D'Ambrosio developed a CA model called SCAVATU (Simulation by Cellular Automata for the Erosion of VAst Territorial Units) and applied the model to the Armaconi basin.[3] Lifeng Yuan designed a model named CASEM and simulated the evolvement of rillslope within a virtual computer environment[4]. Min Cao and Guoan Tang used Fisher discriminant to get the transition rule automatically for the loess watershed cellular automata model and demonstrated that the simulation of terrain evolution could dig out the evolution mecanism of loess terrain within a small loess watershed[5]. Complex nonlinear systems like cellular automata are quite sensitive of the initialization and may lead to an inestimable result just because of tiny differences of the initial sets.

The sensity to initial conditions of cellular automata should be condidered carefully, but there is few discussed the initial set of cell size which may impact the result voilently because of the characteristics of complexity in those systems. Aiming at the problem we've found, this paper will disguss the initial condition of cellular space in the cellular automata system for hillslope rill erosion.

EXPERIMENTAL SECTION

HRECA model

This is the Hillslope Rill Erosion Callular automaton (HRECA) model:

$$HRECA = \{R, X, S, \gamma, \delta\} \tag{1}$$

Where:

- $R = \{(x, y) \mid x, y \in N, 0 \le x \le l_x, 0 \le y \le l_y\}$ is the set of integer co-ordinates in the finite space, where the phenomenon evolves.
- The set $X = \{(0,0),(0,-1),(0,1),(1,0),(1,-1),(1,1),(-1,0),(-1,-1),(-1,1)\}$ identifies the moore neighborhood, which influences the change in state of the central cell.
- S is the finite set of states of each cell, main states are described in Table 1.
- The finite set P is the global parameters of the cellular automaton model, decribed in Table 2.

Table 1 States of the HRECA model

State	Description
S_Z	altitude
S_Q	Run-off
S_i	infiltration
S_D	Erosion rate
S_τ	Hydrodynamic shear stress
S_q	Unit width discharge
S_C	Sediment concentration
S_{TC}	Sediment carrying capacity
S_ω	Steam power
S_{target}	Target cell

Table 2 Parameters of the HRECA model

Parameter	Description
P_S	Side size of the CA cell
P_T	Time step
P_R	Rainfall intensity
P_{RC}	Rainfall intensity per cell
P_τ	Sediment carrying capacity
P_J	slope
α	Empirical constant
β	Empirical constant
ε	Empirical constant
θ	Empirical constant

- Transition rule γ specifies the variation of water depth in cell due to rain at each CA step. The variation is based on the balance of the total amount of water causes by the rainfall and the water flow from upsteam and the totality of infiltration and water flow to downsteam in a cell:

$$S_{Q(t)} + \sum_{i=1}^{k} S_{Qin} + P_{RC} = S_{Q(t+1)} + S_{Qout} + S_i \tag{2}$$

$S_{Q(t)}$ and $S_{Q(t+1)}$ indicate the current run-off of the cell and that in the next time step, each cell gives its outlet S_{Qout} to its target cell when recieves the inlet $\sum S_{Qin}$ from other cells.

Single flow direction algorithm called D8(Deterministic eight-node) appoints the outflow towards neighboring cell. The cell chooses the minimum water head of its moore neighbors to flow. As is shown in Fig 1, the centre cell chooses its neighbor on the bottom left as its target cell and flow S_{Qout} to it:

$$S_{Qout} = \min\left[S_Q, \left(S_Z(self) + S_Q(self)\right) - \left(S_Z(target) + S_Q(target)\right)\right] \tag{3}$$

S_Z(self) and S_Q(self) indicate the altitude and water depth of the cell, S_Z(target) and S_Q(target) are that in the target cell.

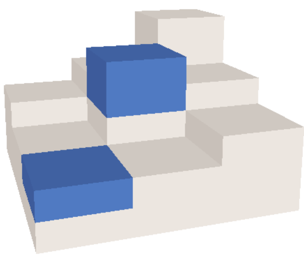


Fig.1 Single flow direction algorithm

- Base on the balance of sediment, δ is the transition rule of the sediment transpotation. The total amount of the sediment from upsteam and eroded from the land equals the totality of the sediment to downsteam and deposition:

$$S_C(t) + S_{Cin} + S_{ERO} = S_C(t+1) + S_{Cout} + S_{DEP} \tag{4}$$

$S_C(t)$ and $S_C(t+1)$ represent the sediment in the water of a cell, and the model regards it well-distributed in the water to calculate S_{cin} and S_{cout}.

To get the sediment amount, the model use the result of Jiongxin Xu[6]:

$$S_C = 11.89 S_Q^{\ 0.0129} S_J^{\ 1.137} \tag{5}$$

The sediment deposite when the amount of sediment is greater than the carrying capacity[7]:

$$\log S_{TC} = \frac{\alpha + \beta e^{\varepsilon + \theta \log S_\omega}}{1 + \beta e^{\varepsilon + \theta \log S_\omega}} \tag{6}$$

Where:
α, β, ε,θ are empirical constants, and the steam power S_ω is calculated as follows:

$$S_\omega = \rho g S_q S_S \tag{7}$$

The model uses fomula (8) to get the erosion rate (S_D, g/min) of the rills:

$$S_D = P_k\left(S_\tau - P_\tau\right)\left[1 - \frac{S_q S_C}{S_{TC}}\right] \tag{8}$$

Where:

P_K is an empirical constant, S_τ indicates the hydrodynamic shear stress and P_τ indicates the criticality.

Simlation Environment and Indoor percitipate experiment
A multi-agent progammable modelling environment called Netlogo was used to implement the model using Logo programming language. An indoor artificial rainfall experiment held in Xi'an University of Tecnology was for the verification on the accuracy of simulation results. The type of Leica HDS 6100 laser scanning was used for obtainint the original point cloud, intergratin current device was set at the bottom end of the soil tank to collect runoff and sediment. Sample every minute to get the runoff sediment concentration by oven drying method.

RESULTS AND DISCUSSION

To find the influence of different cell space resolution, we produce 6 simulations, the cell size of which is 15,20,30,40,50 and 60 milimeters. Compares the evolved slope in the indoor rainfall experiment and the six simulated result. The simulated rill shapes of different cell size are shown in Fig. 2. The numbers indicate the cell size in milimeters.

The smallest resolution, HRECA15 produces 9 little rill channels so that the slope is extremely fragmented, and the system runs extremly huge times. With greater cell size, HRECA40, HRECA50, and HRECA60, the slope is so simple that only one rill channel emerges after the evolvement. However, HRECA20 and HRECA30 shows a better estimation of the erosion process.

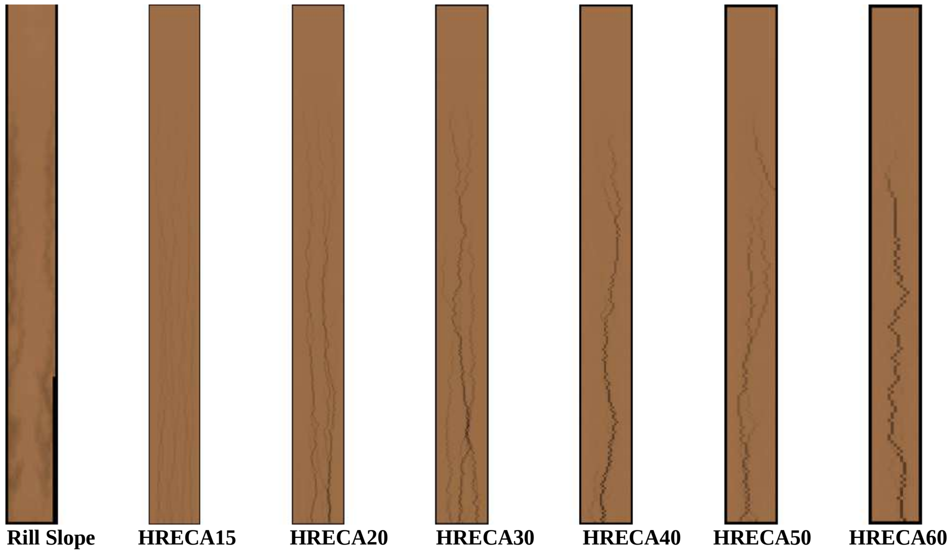


Fig. 2 Experimental slope feature and simulation slope feature

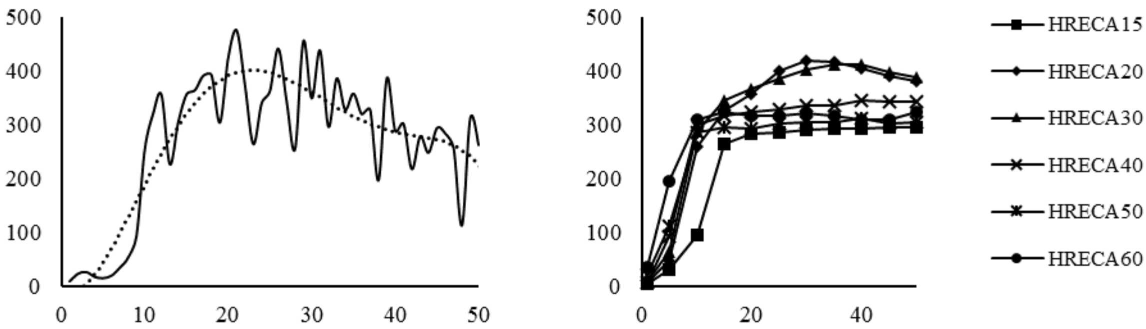
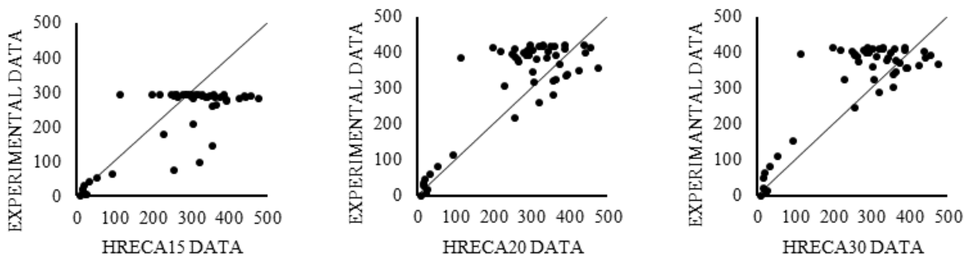


Fig. 3 Experimental erosion rate and simulation erosion rate

All the predicted soil erosion amounts are in permit value range even though the extremely uncertainty of soil erosion, but the dynamic erosion rates of each minute reflect the changing erode intensity shown as curves in Fig. 3 embodies a difference. The curves reflect the erosion rates of these simulations rapid change at first and then become stable guadually after several evlovements. After the sharpe change, HRECA15, HRECA20, HRECA30 and HRECA40 steadly rising, reflect the increasing erosion in the process of soil erosion due to the evolvement of the rills, but HRECA15 and HRECA40 rise quite slowly. Trends to stability in HRECA50 and HRECA60 cannot be found in the curves. However, the curves of HRECA20 and HRECA30 start to decrease after several mimutes, shows the increase of sedimentation to make it steady and accord with the observation in the indoor rainfall experiment and exhibits the system organizes itself to produce a set of definite localized structures.

We analyze the comarision between prediction curve and experimental curve, the coefficient of determination (r^2) sets is 0.6225, 0.6721, 0.6735, 0.6467, 0.5872, 0.5452. Because of the uncertain factors in the process of soil erosion, the determination coefficient values are not very high but in some extent reflect the features of the evlovement. The points distribute around the line of 45°equalbly in the 20 and 30 model but assemble nearly on a plane parallel to the x-coordinate in the others. The correlative analysis between experimental result and simulation result (Fig. 4) explains the proper cell size is 20mm and 30mm.



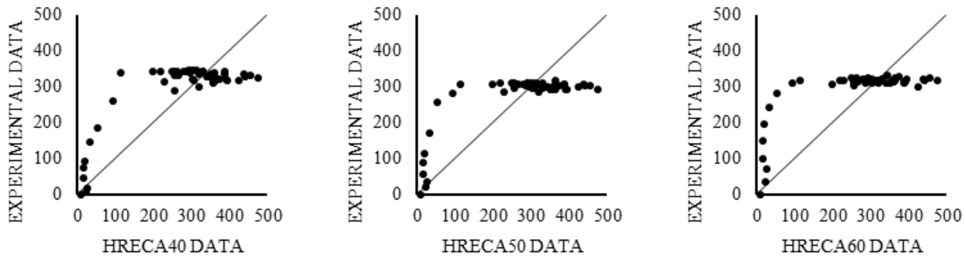


Fig. 4 Corralation Analysis

CONCLUSION

The simulation results of the cellular automata model and the analyses of the settings of the cell size indicate that different initial contiditons lead to unreal erosion process and the model is not applicatble at all scales. The resolution of the cellular space has an effect on the result of the simulation. High-resolution causes inaccurate predict result of the feature of the rill bank, which would be eroded to fragments and the eroded sediments increase slowly but cannot decrease to reach a stable localized structure. However, under the setting of low-resolution, the eroded rill channel shows its simple shape and the dynamic erosion rate cannot suit the observation value as well.

During the simulation process of soil erosion, the only appropriate resolution should be at the range of 20 to 30 milimetres which shows the process of increasing sediment erosion and decrease due to the rise of deposition obviously.

The determination coefficient values of models in proper resolution seems to be satisfying, though HRECA model still needs improving. Single flow direction algoritm (D8) diminishes the rills widen extent and langen the depth extent needs to be substituted for multiple flow direction algorithm.

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