

A SOIL EROSION MODEL BASED ON CELLULAR AUTOMATA

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ABSTRACT:

It is of great significance to dynamically simulate and forecast the development and evolutionary of soil erosion process. Traditionally, most of soil erosion models are essentially steady-state models. Thus, they have limitations at real-time simulation on the initiation and development of soil erosion process. Cellular Automata (CA), with a "from down to up" dynamic modeling framework, is capable to simulate the spatial-temporal evolutionary process of complex geographical system. So, the basic idea about how CA will be applied to simulate soil erosion process is put forward. In this paper, the process model of soil erosion in one small watershed at loess hilly gully region of the Chinese Loess Plateau is constructed based on CA principles. This research also provides us a new methodology for the simulating and modeling soil erosion process.

1. INTRODUCTION

Dynamically simulate and predict soil erosion process is being of great significance to the thorough understanding of soil erosion mechanism, quantitative evaluation of erosion intensity, forecast of future erosion trend, and optimization of soil and water conservation project. Though empirical models such as USLE (Wischmeier and Smith, 1978) are generally more user friendly because they need fewer parameters. Nevertheless, they are not able to model soil transport and deposition, and hard to simulate a real-time erosion process caused by rainfall and runoff due to the lack of considerations about erosion physical process, so the parameters in these models are limited by application, and accordingly the simulation accuracy is difficult to control. With the increasingly exposure of "birth" defect of traditional empirical statistic models, people are no longer only satisfied with the average erosion modulus estimates and calculation, their research interests gradually shifted to the modeling and prediction of soil erosion process. Based on the erosion mechanism, to calculate a given period of soil erosion modulus, through the evolution of topography and geomorphology under the rainfall and runoff, to simulate the pattern of erosion evolution, have become the new development trend of erosion.

Compared with empirical statistical models, physically based models provide a better quality of simulations based on interaction mechanism of rainfall, runoff and surface soil, due to their higher grade of accuracy and a relatively wide scope. Physical models take conservation of mass and energy law as the foundation, and differential method adopted to establish erosion and sediment yield equation. Actually, as for the existing physical knowledge, physical models need more parameters that are often very difficult to determine especially at describing the complex process of erosion and sediment yield. Therefore, they must be integrated with experience means to execute parameter calibration. The more real the simulation of these models is, the more input parameters they needed. For that reason, the current erosion models need innovation and breakthrough on research methods and modeling means.

Cellular Automata (CA), as a tool for space complexity studying, has the capacity of simulating complex spatio-temporal evolution of geographic system. Recently, it has been widely applied in the field of soil erosion. Smith (1991) designed a simple CA model to simulate terrain erosion process and this model has a powerful simulation function by using a simple rules definition. Chase (1992) developed another CA model to simulate splash erosion and slope rainfall-runoff erosion process. Murray and Paola (1994) established a CA model to simulate the convergence process, and the simulation of main characteristics of erosion phenomena was successful. Favis-Mortlock (1996) used CA method to simulate the initiation and development of slope rill, and showed the evolution of surface geometrical morphology form by inter-rill and rill erosion. These simulation processes avoided the limitation of parameters from traditional models. D.D. Ambrosio (2001) developed "SCAVATU" model to simulate the water-erosion process. The model was applied to the small catchment of the Fiumara Armaconi, Calabria, Southern Italy. Wei Lou (2001) developed "LANDSAP" software to simulate the topographic process of rainfall, infiltration, runoff and erosion based on CA method. Zhou (1999) presented the geographic cellular automata (GeoCA) model to promote the application of CA model in geography. Using GeoCA, Chen (2004) established a land desertification dynamic evolution model, and made a comparative analysis in Beijing region. Studies above promoted the application of CA model in the field of soil erosion.

In general, CA model applied to soil erosion in our country is just the beginning, and the application extent is also a little superficial. So the attention is needed to be paid necessarily, especially from experts at soil erosion disciplines. Based on CA theory and methods, this paper presented a basic thought of applying CA at small watershed of Loess Plateau to simulate soil erosion process. CASEM, a small watershed erosion and sediment yield model is developed.

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2. CONCEPTS AND PRINCIPLES OF CA

CA is a kind of dynamic system which is discrete in time, space, and status (Zhou et.al., 1999). Its basic component units include Cell, Lattice, Neighbor and Rule. So CA can be regarded as an organism integrated with lattice and transformation function. A standard CA is a tetrad which can be expressed as follows: $A = \{d, S, N, f\}$. Where, A represents a CA system; d is a positive integer which represents the dimension of CA; S is a limited set of discrete state of CA; N represents all neighbors of a cell, which is a space vector including different cellular state: $N = \{S_1, S_2, S_3, \dots, S_n\}$, there n is the number of neighbors, $S_i \in Z(\text{integer aggregate})$, $i \in (1, \dots, n)$; f means a partial transfer function from S_n to S. All cell are in d-dimensional space with their location been determined by an integer d-dimensional vector Z_d (Sun, 1999).

Using the parallel evolutionary algorithms of a large number of cells, the basic principle of CA is to simulate complex, rich macroscopic phenomenon under relatively simple rules. This thought rooted from an important viewpoint in the complexity science: local rules lead to changes in the macro system that is the appearance of ordering behavior and self-organization. Each cell spread in regular grid, when each limited discrete state selected, following the same rules, they would synchronization update based on determined local rules. Lots of cells formed evolution of dynamic system through simple interaction between each other.

3. SMALL WATERSHED SOIL EROSION PROCESSES CA MODEL

3.1 Modeling Ideas

Modeling ideas of distributed models been taken as guide, CA as the kernel, Watershed space can be divided into squares with regular cells. Each cell indicates its different special surface status which is supported by a group of parameters. At the same time a cell is used as the basic calculation modules for the computation of erosion and sediment yield. In generally, soil erosion process caused by rainfall can be divided into two parts: i) soil particles are separated from the surface soil; ii) the separated soil particles are washed away (Huang, 1988). Therefore, these two physical parts, separation and transport, are considered in the CA model. Processes of soil erosion and sediment transport occurred on each cells, and this abide by the rule which was mentioned by Wischmeier and Meyer (1969). That is, the output amount of soil erosion is equals to the total sediment caused by runoff and rainfall. While, the output amount of soil erosion shall not exceed the output total from transport capacity of runoff. Distribution of runoff, erosion and sediment transport processes are realized through inter-cellular exchange of water and sand. In each step, the erosion is deducted in the cell where the deposition is accumulated, thus cell space is continuously updating. As a result, watershed erosion process was dynamically simulated.

3.2 Model Assumptions

In the Loess Plateau region, due to its special soft texture, poor corrosion resistance, once the rainfall (rainfall ≥ 10 mm) can lead a lot of sediment runoff into the channel. Research shows [11]: soil erosion and sediment yield is mainly caused at the flood season (normally from Jul. to Sept.). At the same time the precipitation in a rainstorm can sometimes reach 70 per cent of

the annual rainfall. Simultaneously, Soil erosion and sediment yield in a rainstorm can sometimes reach 40% -60% of the annual Soil erosion and sediment yield. Therefore, in accordance with local rainfall and erosion and sediment characteristics, An assumption that vegetation interception, evapotranspiration and surface filled depression to the impact of the storm runoff is negligible is put forwarded, at the same time the impact of underground runoff is not taken into account.

3.3 Model Structure

In CASEM model, the valley discrete space is calculated by cell which is composed of square grid cell, its natural valley boundaries is defined as the model border (fixed-value type); the configuration of cell neighbors is defined by a standard neighbor-Moore; State variables of cell include core variables (flow and elevation) and auxiliary variables which include the various parameters related to the cellular evolution rules. In CASEM, cellular status will be defined in a continuous real-space, and its state variables are multidimensional and consecutive. A cellular evolution rule consists of two majorities: rainfall runoff rules, erosion and sediment yield rules. The structure framework of CASEM model is described as figure 1.

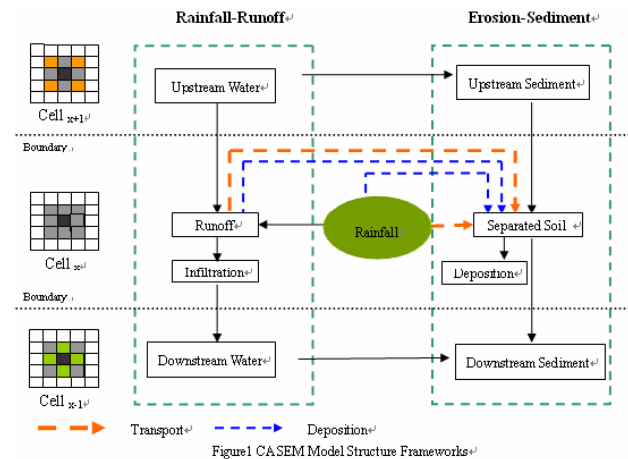


Figure1 CASEM Model Structure Frameworks

4. CASEM MODEL EVOLUTION RULES

Evolution rules is the core content of CASEM model, which is primarily composed by rainfall runoff rules and sediment yield rules. In rainfall runoff rules, the main purpose is to inquire into input calculation parameters during separation and transport in the process of surface runoff and sediment yield.

4.1 Rainfall-runoff rules

4.1.1 Runoff calculation:

Runoff Curve Number (CN) method proposed by Soil Conservation Service (SCS), U.S. Department of Agriculture (USDA) is used to calculate surface runoff. Its parameters are corrected and modified in order to fit the need for the calculation of surface runoff at the Loess Plateau region.

SCS CN method is set up based on the following assumptions: the ratio of the actual infiltration capacity to the actual runoff of the catchment is equal to the ratio of the greatest possible infiltration capacity (or potential income infiltration) and the

greatest possible runoff (or potential runoff) before this rainfall in the same area.

$$\frac{F}{Q} = \frac{S}{Q_m} \quad (1)$$

In this formula, F represents actual infiltration (mm); Q represents actual runoff (mm); S is a potential infiltration (mm); Qm is potential runoff (mm). Assuming that the potential runoff Qm is equal to the precipitation P minus the initial losses Ia (including depression ground water, plants withholding, evaporation and infiltration), that is,

$$Q_m = P - I_a \quad (2)$$

The actual infiltration is equal to precipitation minus early loss and runoff.

$$F = P - I_a - Q \quad (3)$$

By the formula (1) to (3), the following formula is conducted:

$$Q = \frac{(P - I_a)^2}{S + P - I_a} \quad (4)$$

Ia changes in height. According to lots of natural watershed information, Ia can determined approximately using the following empirical formula:

$$I_a = 0.2S \quad (5)$$

When formula (5) incorporated into the formula (4), Ia is eliminated as formula (6):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (P > 0.2S) \quad (6)$$

Where, if P less than 0.25S, then Q = 0. Parameters S establish correspondent relationship with soil and watershed coverage conditions through CN, which ranges from 30 to 100.

$$S = 254 \left[\frac{100}{CN} - 1 \right] \quad (7)$$

By the formula (7), the greater value of CN, the less S value, the more susceptible runoff occurs.

4.1.2 Surface convergence calculation

D8 algorithm is used to simulate flow direction during the calculation of surface convergence. Runoff follow water balance equation from each cell can be expressed as:

$$\frac{dQ}{dt} = Q_i - Q_o \quad (8)$$

Where Q represents the current cell of water; t represents time; Qi is water inflow to current cell; Qo is water outflow from current cell Qi is the total water capacity including rainfall at current cell and water inflow from neighbor Cells. Qi can be expressed as:

$$Q_i = Q_{center} + \sum_{n=1}^k Q_{up} \quad (9)$$

Where, Q_{center} is the rainfall runoff of current cell; k represents upstream neighbor cell numbers; $\sum_{n=1}^k Q_{up}$ is the inflow from adjacent cell to current cell. The outflow from cell element includes infiltration, and the inflow to downstream neighbor cell, it is

$$Q_o = F + \sum_{n=1}^k Q_{down} \quad (10)$$

Where, F is infiltration, $\sum_{n=1}^k Q_{down}$ is the inflow to downstream neighbor cell.

When the flow directions been determined, water balance principle mentioned above is adopted, through the recursive procedure, convergence number of each cell is worked out thoroughly, until all convergence cell number are calculated. According to convergence number and certain flow direction, the mainstream road figure of spatial cell can be produced then. Accordingly, cell unit network flow can automatically generated based on computer program, various cellular modules in a small watershed then become an organic system. Runoff from slope system and channel system are calculated in a valley by the generated networks, the discrete spatial cell convergence process can be identified.

4.1.3 Unit discharge rate calculation

The purpose of unit discharge rate calculation is mainly to support parameters for erosion and sediment yield. Unit discharge rate refers to the discharge rate through the unit width of the cross-sectional velocity. Due to the ground water flow at cell unit has a rectangle shape at the cross section; the unit discharge rate of cell unit is equal to the product of ground water flow velocity and the depth of water.

$$q = V \times h \quad (11)$$

Where q is unit discharge rate (m²/min), V is the runoff velocity (m/s), h is the water depth of each cell (mm). The factor V can be calculated by Manning formula.

$$V = \frac{1}{n} h^{2/3} S^{1/2} \quad (12)$$

Where, n is Manning roughness coefficient, its corresponding value varies according to the difference of underground and land use types, S is slope gradient, h is for water depth at cell unit, which is equals to the cell flow divided by the cell area.

4.2 Erosion and Sediment Yield rules

4.2.1 Surface Erosion and Sediment Yield

① Separation of erosion

As for the calculation of soil separation in CASEM model, raindrop splash separation and rainfall runoff that are no longer been separated. While RUSLE is directly used to calculate the erosion separation amount in each cell during a rainstorm. Basic form of RUSLE model is as follows:

$$A = R \bullet K \bullet LS \bullet C \bullet P \quad (13)$$

where, A is average soil loss per year, kg/(m²·a); R is rainfall-runoff erosivity factor; K is soil erodibility factor; L is slope length factor; S is slope steepness factor; C is cover-management factor; P is support practice factor.

② Sediment transport

Transport capacity mainly refers to the transmission capacity of flow to taken sediment downstream. In CASEM model, transport capacity is calculated according the following formula, which are derived from large amounts of data based on the improved Yalin formula (Beasley, etc., 1963) combined with Foster and Meyer formula.

$$T_{RF} = 161 \bullet S \bullet q^{0.5} \quad (q \leq 0.046 \text{ m}^2/\text{min}) \quad (14)$$

$$T_{RF} = 16320 \bullet S \bullet q^2 \quad (q > 0.046 \text{ m}^2/\text{min}) \quad (15)$$

Where, T_{RF} represents the transport capacity, S is slope gradient and q is unit discharge.

4.2.2 Sediment evolution

Eroded soil particles were taken by the water flow from the slope surface, channel, branch and mainstream till to the export section of this valley. There, the sediment yield constituted though it does not all the eroded soil particles can be transported to this export section. During the influx process, some even be the majority of the soil particles may deposited on toe-slope or valleys, thus these arrived sediment soil

particles at the export section is less than the erosion of the valley.

Sediment influx process is companied with the current flow campaign process. Similar to the flow influx process, the sediment of cell meets the material balance equation:

$$\frac{dW}{dt} = W_i - W_o \quad (16)$$

In CASEM model, due to erosion and sediment process occur on each cell, so it is easy to reflect dynamic sediment, and obtain sediment evolution path. Because the runoff sediment in each cell is from the dispersion of rainfall and runoff, as well as the uphill cell input sediment, when compared the sediment with its transport capacity in a cell, if the sediment is less than its transport capacity, then the available sediment would be the limiting factor, the sediment taken to the cell downhill would be the current sediment of this cell. Conversely, if the sediment yield is greater than the transport capacity, then the transport capacity would be the limiting factor and the sediment yield is just equal to the ability to transport, accompanied by intra-cell sedimentation. Based on this ideology, the sediment yield from upstream to downstream, from the top part of the slope to the lower part of the slope, till to the watershed exports, can be calculated, along with the evolution in the whole process.

5. CONCLUSIONS

Due to the characteristics of a great deal of uncertainty and chaos in the process of soil erosion, so it will be very difficult to predict the precise development and evolution process of soil erosion by mathematical models thoroughly. CA provides a powerful tool for this special phenomenon. In this study, the theory and method of CA is firstly applied at the loess hilly gully region of the Chinese Loess Plateau to simulate and model the soil erosion process. Based on the practical experiments, erosion and sediment yield process model – CASEM is proposed. The CASEM model has more advantages as: simple structure and simulation rules, clear dynamic mechanism, fewer input parameters required. This initiatory study at the next stage will be concentrated at: ① Model validation; ② Further integration with remote sensing and GIS technology, data mining, fuzzy logic, try to build an intelligent expert system of soil erosion and erosion process simulation evaluation; ③ Enable CA model adjust its parameters and rules automatically during the simulated erosion evolution process, and realize the conversion at random at spatial-temporal scale.

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