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A STUDY ON MODELING AND 3-D SIMULATION OF HILLSLOPE EROSION BY WATER

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ABSTRACT Based on analyzing strong points and weak points of previous modeling methods for hillslope erosion by water, this paper proves that mathematically dialectical logic is necessary for the modeling of soil erosion and chooses one model of mathematically dialectical logic --- Remote Sensing Information Model of Water Erosion on Hillslopes (RSIMWEH) combined with particle system and metaball technology to simulate the overland flow and the process of soil erosion on hillslopes. Furthermore, based on the platforms of PowerBuilder, VC and OpenGL, the computation and 3-D simulation system of hillslope erosion has been developed. The result is satisfying.

1. INTRODUCTION

1.1 Mathematical modeling of soil erosion by water on hillslopes

Water erosion on hillslopes refers to the whole process of destruction, denudation, transportation and deposition of soil, soil mother material and other components of the ground on the hillslopes, under the influence of the splash of raindrops, the washing of the surface runoff and seeping water [1]. Water erosion advancing hillslopes to evolve, this process is affected by many factors, including terrain, vegetation and the surface characteristics of soil.

In the process of the time-lapse measure of erosion, it is necessary to make a summing-up of the sediment's detachment from hillslopes, transportation and deposition. This process itself is complicated, and there is interaction between processes. The complicacy asks for erosion models as a tool in the resource management. The combination of erosion model and observation is better than pure observation, because the current technology cannot observe and measure all the processes controlling surface runoff and erosion at the same time. Moreover, observation and measure are very difficult, because during the period of one event of runoff and erosion, the required spatial-temporal scale is very small. Usually the observation after the occurrence is the best result, but usually these observations after the event can only expose a little real mechanism leading to erosion [2].

Existing models of erosion by water are generally formal logic computational models that can be further divided into four types—empirically based model, partially conceptually and partially empirically based model, partially physically based and partially empirically based model, and theoretically based model.

The strong points and weak points for each type are listed below [3]:

- empirically based model: based on fieldwork, modeling in the way of random statistics, with no need to simplify any factor or process. This type of model is relatively reliable when used in areas with similar natural conditions. But many model dimensions are inconsistent, and many conceptions and causes are not clear. In recent years, many researches have normalized the variables, but the variables are not similarity criteria, and still belong to lumped statistic model;

- partially conceptually based and partially empirically based model: this approach attempts to model logically and testify with measured data, based on the analysis of causes. It has absorbed the strong points of equation and statistics, but still belongs to lumped model;
- partially physically based and partially empirically based model: this approach summarizes the quantitative relations between the process of soil erosion and the factors that influence it, in the form of equation. Clear analysis is enabled as far as conceptions and causes are concerned, but it is often impossible to find the solutions to the complicated equations. As a result, simplification is necessary. Nevertheless, the solution to coefficient is often inconsistent with measured data. They need the researchers' readjustment and precision is also a problem. In recent years, computers have been used in calculating the numeric solution. The precision has been improved, but the majority still belongs to lumped physical models. Even if they can be built into distributed models, different regions have different models.

Theoretically based model will not be discussed in this paper because there is not any applicable one as yet.

1.2 3-D simulation of soil erosion by water on hillslopes

In the last decades, research papers relevant to simulation of water erosion by water on hillslopes mainly include [2][4][5][6][7][8][9][10][11][12][13][14][15][16][17][18][19][20][21][22]:

- 2-D simulation for slope and stream evolution;
- DEM grid size, landscape representation and hydrologic simulations;
- GIS-based simulation of erosion and deposition patterns;
- Multi-dimensional GIS environment for simulation and analysis of landscape processes;
- Process-based modeling of soil erosion by water;
- Distributed soil erosion simulation;
- Integrating a watershed simulation with a GIS.

In China, there are some researches relevant to 2-D simulation of the movement of sediment-laden flow [23][24].

Among those, what Helena Mitasova, Lubos Mitas, William M. Brown, Douglas M. Johnston and B. Saghafian etc. (from Geographic Modeling and Systems Laboratory, University of Illinois at Urbana-Champaign) did for U.S. Army Construction Engineering Research Laboratories from 1995 to 2000 has made a difference. They sampled rainfall excess, moving sediment and clay into particles. The method has strong points compared to traditional approaches because it can be easily extended into arbitrary dimensions and is suitable for multi-scale data. Their results of simulation are applied in GRASS GIS. But:

- differences in velocities and directions of water flow within a pixel can't be represented precisely. On the other hand, too many sampling points lead to a jammed visual effect;
- sampled points are ball-shaped; therefore, their velocities and directions can't be displayed intuitively;
- differences in the depth of runoff haven't been represented;
- the phenomena of soil separation and fusion during the process of soil erosion can't be represented [25].

2. THEORY AND METHODOLOGY

2.1 Mathematically dialectical logic is necessary for the modeling of soil erosion

Traditional water erosion models on hillslopes mainly belong to the computational model of classically mathematical logic that is based on functions of deductive logic, statistics of inductive logic and similarity criterions of analogous logic [26]. It plays a great role in the prediction of water erosion on hillslopes because it coincides with the traditional status --- lagging data-monitoring methods, slow data-update velocity and low data precision, and meets the requirements of application greatly.

With the rapid development of scientific techniques such as global positioning system, remote sensing, geographical information system and computer hardware, recognition methods of classically mathematical logic prove to have resulted in an unsatisfying forecasting precision because the system of soil erosion by water is a complex system that contains the essential factors such as continuum, infinity and indeterminacy, which form attributes and structures of the system, and the system itself. It is necessary to use recognition methods of connection, development and totality that are adopted by mathematically dialectical logic rather than classically mathematical logic to raise the model precision.

One significant merit of mathematically dialectical logic is that it is a powerful tool for effectively identifying and understanding a complex system. It mainly lies in [27]:

- mathematically dialectical logic provides an applied symbolic language to describe a complex system;
- it provides methods of continuum analysis while classically mathematic logic can only provide methods of discreteness analysis;
- it provides methods for analyzing multi-layer systems: mathematically dialectical logic explains that the attribute set of arbitrary layer in a complex system mutually complements with the attribute set of both its higher layer and its lower layer, i.e. on the one hand, they have differences and discreteness, on the other hand, they have connections and continuum;
- it provides applicable logically reasoning methods for predicting and demonstrating complex systems. For example, newly recognized phenomena of a complex system can be predicted through reasoning propositions based on mathematically dialectical logic.

2.2 RSIMWEH is a model of mathematically dialectical logic

The expression of RSIMWEH:

$$E_{sl} = a_0\left(\frac{I-I_0}{I}\right)^{a_1} h_{sl}\left(\frac{\delta_{st}}{d}\right)^{a_2}(\sin 2\alpha)^{a_3}\exp\left(-a_4 S_{vc}\right) \tag{1}$$

where E_{sl} (mm per year) is the intensity of soil erosion on hillslopes; I is the intensity of rainfall (mm/a); I_0 is the threshold value of the intensity of rainfall causing erosion; h_{sl} (mm per year) is the intensity of runoff on hillslopes;δ_{sl} (mm) is the effective thickness of soil, d(mm) is the average soil particle size; α is the gradient (radian); S_{vc} (%) is vegetation coverage; a_0 is geographical coefficient and a_1, a_2, a_3, a_4 are geographical indices.

It is a model of mathematically dialectical logic:

- its geographical coefficient and indices both depend on space and time, which do not change in a short period (the tolerance threshold is preset), and when the accumulated influence of model factors is beyond this threshold, geographical coefficient and indices accordingly change. The coefficient and indices in the classically mathematic logic model are both constant;

- its geographical coefficient can separate out a new similarity criterion of geography. On the other hand, it can fuse into any already known affecting factor that lacks of data. However, the coefficient of a classically mathematic logic model is constant.

The equation effectively represents continuum, multi-layer and newly recognized phenomena of a complex system because:

- geographical coefficient and indices of the model depend on space and time thus effectively represent continuum phenomena;
- geographic information coding models [28] can be used to express a multi-layer system;
- the geographic coefficient can separate out newly recognized phenomena.

2.3 3-D simulation of soil erosion by water on hillslopes

The factor of slope angle in RSIMWEH can be precisely represented by DEM, and the factor of vegetation coverage can be represented in detail by surface textures formed by aerial photographs. Other factors, e.g. soil, rainfall and runoff, can be vividly represented by particle systems and metaballs. In this paper, rainfall and sediment-laden flow are represented by streamline structures e.g. fine cylinder and sampled based on pixels. Where the length of the cylinder represents the velocity, the inclination of the cylinder represents the direction of movement, and the diameter of the cylinder is in direct proportion to the depth of runoff. Particle system is used to maintain a list of particles. On one hand, it will speed up scene rendering; on the other hand, it will be in favor of system optimization and function extension. A pixel-based metaball is formed when existing accuracy of data acquisition is considered. It represents the soil loss in the unit duration per pixel that is computed using RSIMSEH and serves as a time step of simulation and can effectively represent the phenomena of soil separation and fusion during the process of soil erosion [29].

3. SYSTEM AND APPLICATION

To better support the rehabilitation of water and soil loss using RSIMWEH and other erosion models, and to support the departments of management and decision with modern tools for analysis, the computation and 3-D simulation system of hillslope erosion has been developed.

3.1 Goals of the system

- data management: Measured data, RS imagery data, geographic base maps and statistical data etc. are integrated in the system and can be searched and queried to provide scientific information for the departments of management and research on soil and water loss;
- model computation and verification: It is based on source data to analyze the status and trend of soil erosion;
- 3-D simulation: 3-D dynamic scene is created to vividly reappear the process of soil erosion by water on hillslopes. It can provide perceptual knowledge, enhance visual effect and testify the result of model computation for research, management and decision.

3.2 Software and hardware configuration of the system

- basic hardware configuration: P□350 CPU, 196M memory, 20G hard drive space, AccelSTAR □ graphic accelerator, color jet printer, LG Studioworks 575N display, AGC-ViewG stereo observing system, infrared emitting controller, stereoscopes, scanner and digitizer;
- basic software configuration: Windows 98 operating system, Visual C++ 6.0, OpenGL 1.1, ENVI 3.0, Photoshop 6.0, Arc/info 8.01 and PowerBuilder 7.0.

The system is developed based on Powerbuilder, VC and OpenGL. Different language has different strong points. It raises operating efficiency for the system.

3.3 Function modules of the system

The system is composed of different modules that are linked by menus to carry man-machine interaction and the interface is friendly. The system contains three modules for DB management, model computation and verification, and 3-D simulation respectively. One module performs kinds of operations by calling function modules at lower levels thus leads to the layer structure of function modules of the system.

- module of DB management: this module includes the sub-module for data update and the sub-module for search and query. It is mainly used to input, modify, copy, search and query source data, model data and simulated data;
- module of model computation and verification: it is used to compute and verify models, and create simulated data. Fig. 1 shows the methodology of RSIMWEH that contains the process of model computation and verification;
- module of 3-D simulation: 3-D simulation is based on raster structure and vector structure to use their strong points.

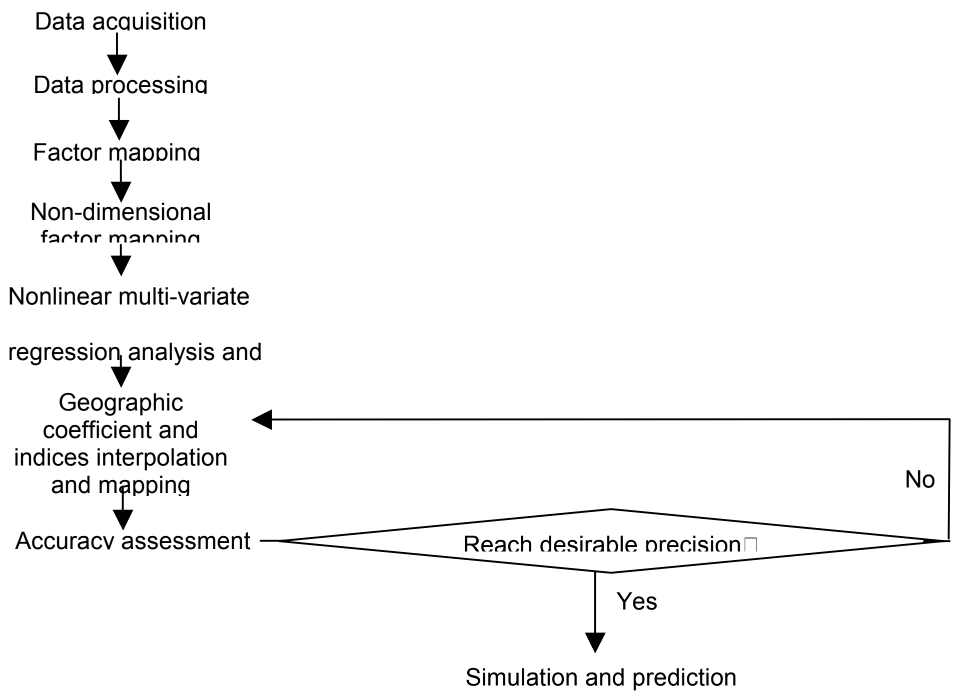

Fig. 1 RSIMWEH methodology.

Compared to raster data structure, strong points of vector data structure are high geometric precision, clear topologic structure among spatial objects, less storage memory, and simpler coordinates transformation and distance computation. In this work, vector data structure is used to locate rainfall, runoff and erosion units.

Compared to vector data structure, strong points of raster data structure are simpler grid unit addressing, easier computation of intersection, union and difference between objects. In this work, raster data structure is used to create DEM, texture and image DB.

Fig. 2 shows the system structure and flow chart.

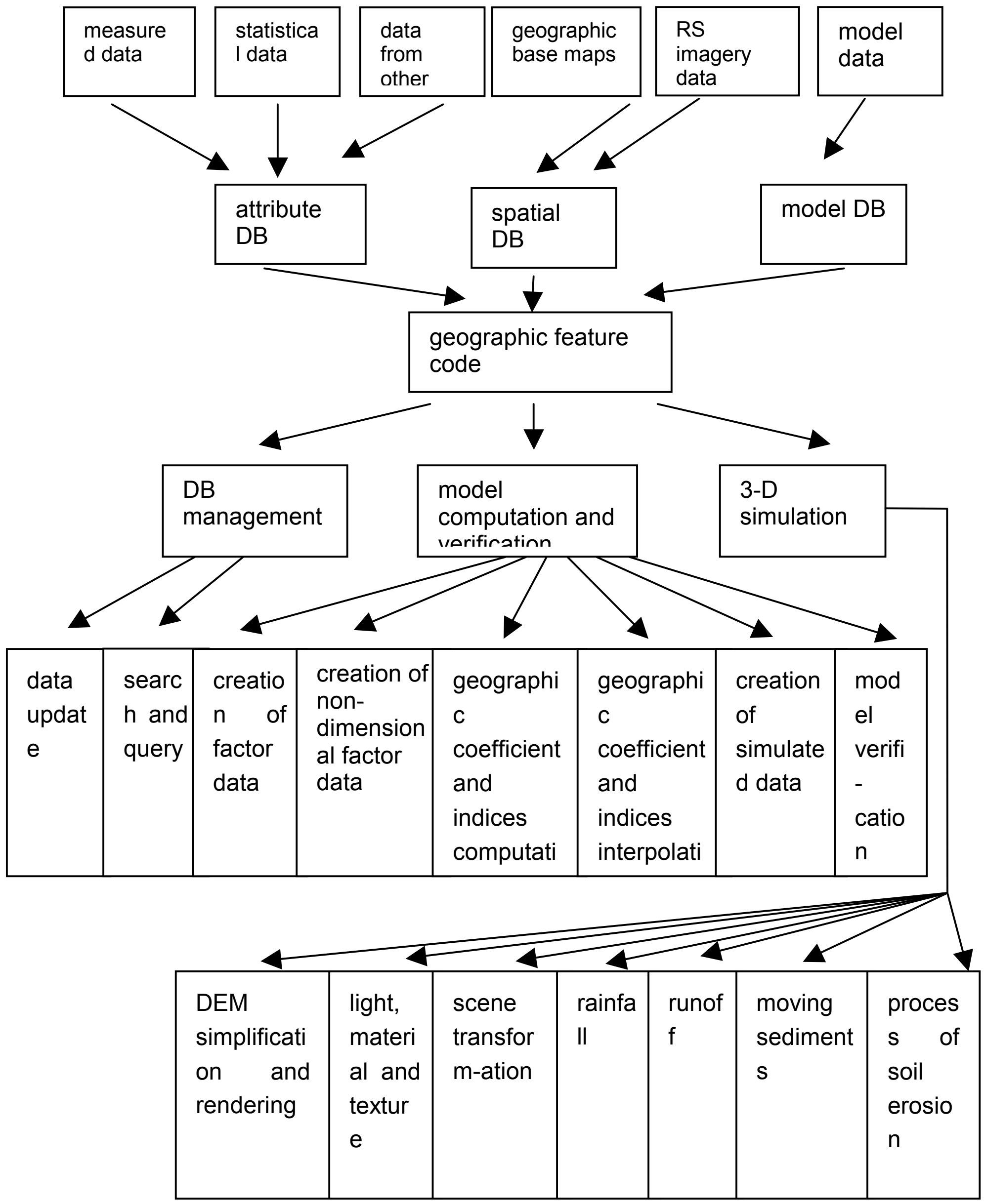

Fig.2 System structure and flow chart.

To test the performance of the system, Wufendigou sub-watershed is chosen as a large-scale object for research and the intensity of soil erosion during one rainfall process in the watershed has been simulated. Wufendigou sub-watershed is on the east bank of the middle reaches of Changchuan--- one branch of Huangfuchuan that is the first-class branch on the right bank of the middle reaches of the Yellow River. Its area is 3.85 km^2 and belongs to the experimental plot of Wufendigou. Because it is an area with severe water and soil loss, research on soil erosion in this watershed will absolutely better the understanding of the laws of dynamic changes of soil erosion by water in the region of Loess Plateau. Especially, the majority research content of the whole team of the project Experimental Investigation of Complete Development of Agriculture, Forestry and Husbandry by Comprehensive Treatment on Water and Soil Loss in Huangfuchuan Watershed during six-five and seven-five national plans of China is performed in this experimental plot, thus results in rich accumulation of resources [30][31][32].

The precision of simulated data using RSIMWEH is approximately 85% in this application [29] and fig. 3 shows the simulation of an erosion scene. It proves that the system has efficient algorithm, fine graphical display, realistic dynamic scene and good model precision. It also has strong extendibility and can run on PCs without high system configuration.

4. DISCUSSION AND CONCLUSIONS

From the application, following achievements have been acquired:

- models of soil erosion by water on hillslopes are classified as formal logic computational models and dialectical logic computational models (fig. 4);
- RSIMWEH is a dialectical logic computation model. The methodology of RSIMWEH is put forward and divided into 8 steps (fig. 1);
- RSIMWEH, particle system and metaballs are used together to simulate the process of soil erosion by water on hillslopes. Based on the platform of PowerBuilder, VC and OpenGL, the computation and 3-D simulation system of hillslope erosion has been developed. The system has the functions of data management, model computation, model verification, and 3-D simulation. With friendly interface based on man-machine interactive techniques, it has strong extendibility.

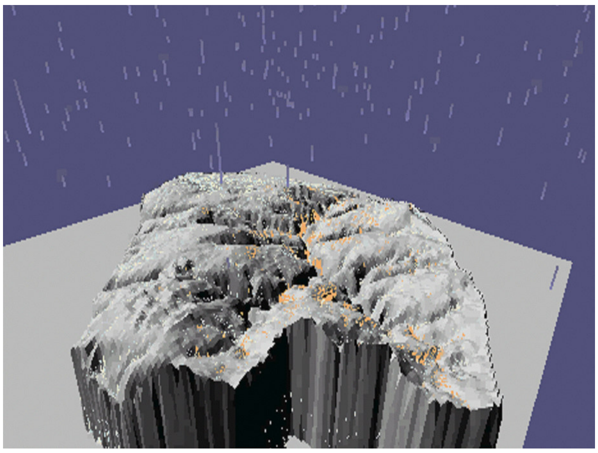

Fig. 3 Simulation of an erosion scene.

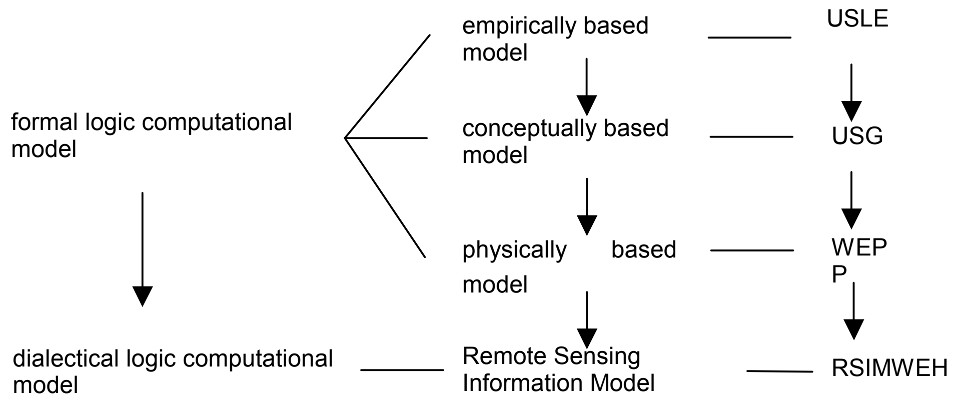

Fig. 4 Categories and development of the modeling of soil erosion by water on hillslopes.

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