地理学报(英文版) 2001年第11卷第3期

Material component to non-linear relation between sediment yield and drainage network development: an flume experimental study

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Abstract: This paper examines the experimental study on influence of material component to non-linear relation between sediment yield and drainage network development completed in the Lab. The area of flume drainage system is 81.2 m2, the longitudinal gradient and cross section slope are from 0.0348 to 0.0775 and from 0.0115 to 0.038, respectively. Different model materials with a medium diameter of 0.021 mm, 0.076 mm and 0.066 mm cover three experiments each. An artificial rainfall equipment is a sprinkler-system composed of 7 downward nozzles, distributed by hexagon type and a given rainfall intensity is 35.56 mm/hr.cm2. Three experiments are designed by process-response principle at the beginning the (shaped small network is dug in the flume. Running time spans are 720 m, 1440 minutes and 540 minutes for Runs I, IV and VI, respectively. Three experiments show that the sediment yield processes are characterized by delaying with a vibration. During network development the energy of a drainage system is dissipated by two ways, of which one is increasing the number of channels (rill and gully), and the other one is enlarging the channel length. The fractal dimension of a drainage network is exactly an index of energy dissipation of a drainage morphological system. Change of this index with time is an unsymmetrical concave curve. Comparison of three experiments explains that the vibration and the delaying ratio of sediment yield processes increase with material coarsening, while the number of channel decreases. The length of channel enlarges with material fining. There exists non-linear relationship between fractal dimension and sediment yield with an unsymmetrical hyperbolic curve. The absolute value of delaying ratio of the curve reduces with time running and material fining. It is characterized by substitution of situation to time.

Material component to non-linear relation between sediment yield and drainage network development: an flume experimental study JIN De-sheng, CHEN Hao, GUO Qing-wu (Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China) 1 Introduction The drainage network is one of the important components in a fluvial system, as Schumm[1] pointed out that three zones compose a typical fluvial system. As early as in the mid 20th century, Horton[2] made a significant quantitative explanation to hydro-geomorphology in a drainage network system. Since the 1960s, Leopold and Langbein have studied the network structure with random walk and entropy, and Shreve, Smart and Scheideger have topologically studied network structure[3-11]. Since the 1980s studies of fractal and fractional dimension in a drainage network system and its development have been carried out, because the stream length, network density and structure have their own fractal characteristics. Based on a great number of field data, Barbara et al.[12] derived fractal dimension between 1.5 and 2.2 with mean value of 1.6 to 1.7 for drainage network system. Gupta et al.[13] researched statistical self-infinity in a stream network and its relations to the other geomorphic features. Robert, Mesa et al., Ross et al., Tanzhou Luo and Nikora gave a fractal relation of channel length to drainage area and concluded the fractal structure of river platform at a given scale[14-18]. In addition, Feng[19] introduced a method to calculate fractional dimension of river forms and Jin et al., with measured data of the Lower Yellow River and the Middle and Lower Yangtze River, calculated and interpreted the value of fractional dimensions of longitudinal profiles in the two rivers, which can be taken as energy dissipate index in another way. Tarboton et al., Li et al., Fun et al., Chen, Mousa, Feng, Wang and Wei et al. discussed the fractional characteristics related to evolution of fluvial geomorphology and their hydraulic relations, etc[21-30]. Up to now, the fractal study in a drainage network has focused on analysis of its features and structures, and fractional dimension calculation, among which the spatial fractal is more than the temporal one, and less attention is given to fractal geomorphic development, hydrologic dynamics, sedime nt yield and transportation as well as and their relations. Experimental data that can reveal the relation between drainage network development and sediment yield have not been found yet[31]. Therefore the purpose of this paper is to detect the influence of material component on non-linear relation between sediment yield and drainage network development focusing on fractal characteristics in network processes modeling. 2 Modelling principle, experimental procedure and facilities 2.1 Experimental design and principle of the model For physical model of drainage morphology some researchers, for example, Strahler[32] applied a scale model to test drainage geomorphic system and network. On the other hand, many scientists studied fluvial geomorphic system with analogue approaches[33]. Jin et al.[34,35] produced a process-response model to study channel pattern development. The drainage geomorphic system belongs to a complex open system with complexity and randomness. Therefore, the similarity of a model process-response system to prototype can be treated as principles of model designing and drainage system simulating. They are (1) statistical similarity in drainage geomorphology; (2) similarity in material composition and structure; (3) similarity in geomorphic process; (4) similarity in energy dissipation; and (5) accordance of causality[36]. Figure 1 Platform of model drainage basin 2.2 Facilities and initial conditions This experiment was done at a given rainfall intensity of 35.56 mm/h with the coefficient of uniformity about 0.87. It used different materials, in which runoff and sediment yield could be produced, and network development and drainage geomorphic evolution could be observed. The rainfall-erosion facility is divided into two parts, i.e., water supplied system and erosion facility. The former is composed of a high pressure pump to supply water source, a controller to stabilize water pressure, and 7 downward nozzles, distributed with hexagonal type, which is 5.5 m high above the center of model catchment. The latter includes a concrete container which is 8 m wide, 11.3 m long in center line, and 9.6 m long to each side (Figure 1). A triangular weir is located at the outlet of the model catchment area. Elevation of the weir bottom is 16.25 cm high, which is regarded as local base order in the model drainage system. The container was covered by uniformed and pressured materials with different medium diameters of 0.021mm, 0.076mm and 0.066mm, which are finer, coarse and coarser for the Runs I-0, IV-0, and VI-0, respectively (Table 1). Table 1 Initial conditions of experiments 2.3 Data collection The experiment is divided into 3 groups including 18 runs (Runs I-1-I-6, Runs IV-1-IV-6 and Runs VI-1-VI-6). Each run lasted 2 hours except Runs IV-1-IV-6 for 4 hours, the total lasted 48 hours. For every run of rainfall, both runoff current time and cutoff time were observed. During the experiment, the water samples were collected every ten minutes and the coming water discharge was calculated with volumetric method. At the same time, sediment was also sampled and sediment load was measured with light turbidity-meter, or drying and weight method. At the end of each run, photographs of the whole drainage area were taken and elevation was surveyed with order of X-Y-Z coordinates of any points within the model drainage. Using Strahler´s method the channel number, length and grade of model network are obtained[37]. 3 Experiments of sediment yield processes 3.1 Drainage network composed of fine material The materials of experimental group I is composed of uniform loess material with a D50 of 0.021 mm, a sorting index of 2.48 and 92% silt-clay. It runs totally 12 hours. The group is divided into 6 runs (Runs I-1-I-6). The sediment yield process indicates that each run has sediment yield peak. With runs increasing, the time of peak occurrence is kept being ahead and its value decreases. Except Run I-1, the double peaks always exist and show randomness and complexity in the sediment yield processes (Figure 2). Based upon collected data, the relationship between sediment yield for super-infiltration and running time can be fit to negative exponential function as follows: where Qs-1 is sediment yield (kg/10min), and T is running time (in unit min). Figure 2 Sediment yield process of the drainage composed of fine materials Figure 3 Curves fit with drainage sediment yield composed of different materials 3.2 Drainage network composed of coarse material The materials of experimental group IV is composed of non-uniform loess material with D50 - 0.076 mm, a sorting index of 1.67 and 48.7% silt-clay. They are mixed by the loess with D50 - 0.066 mm, a sorting index of 1.53 and 62% silt-clay and gray fine sand with D50 - 0.095 mm, a sorting index of 1.86 and 22% silt-clay. The mixture ratio is 2 to 1. This group runs 24 hours in total, and is also divided into 6 runs (Runs IV-1-IV-6). In this experimental group the sediment yield process can be distinguished into three parts: at the beginning 4 hours (Run IV-1) sediment yield reaches maximum value with many peaks and valleys, during the second time span (Run IV-2) sediment yield reduces jumpily and goes lower and lower (Figure 4). From Run IV-4, the sediment yield processes have a stable tendency. However, the whole processes in the group have an alternation between peaks and valleys, of which the amplitude is decreased with time. The relationship between sediment yield for super-infiltration and running time can be fit to negative exponential function as follows: where Qs-4 is sediment yield (kg/10min), and T is running time (in unit min). 3.3 Drainage network composed of coarser material The materials of experimental group VI is composed of uniform loess material with a D50 of 0.066 mm, a sorting index of 1.53 and 62% silt-clay. It runs totally 12 hours with 6 runs (Runs VI-1-VI-6). At the beginning 3 hours from Run VI-1 to the first half of Run VI-2, the sediment yield process has great vibration of peak and valley. After t hat, sediment yield reduces very quickly. During the time span from Run VI-4 to Run VI-6, the curve of sediment yield processes seems to be gentle with some lower values for each run (Figure 5). The relationship between sediment yield for super-infiltration and running time can be fit to negative exponential function as follows: where Qs-6 is sediment yield (kg/10min), and T is running time (in unit min). Figure 4 Sediment yield process of the drainage composed of coarse material Figure 5 Sediment yield process of the drainage composed of coarser material 3.4 Comparison analyses The sediment yield processes of three groups described above have the same forms, i.e., the value of sediment yield decreases at different rates with time while the amplitudes of sediment peak and valley also decrease with time. The relationships between sediment load and running time can be illustrated by negative exponential curves. In the meanwhile the differences exist. Firstly, each curve is characterized by its own intersect on the vertical coordinate axis. The experimental group with coarse material has maximum intersects, which indicates the largest sediment load under the initial super-infiltration runoff production. The one with fine material has minimum intersects, which means the lowest sediment load under the initial super-infiltration runoff production. Secondly, the model with coarser covered material has the fastest decreasing rate of sediment yield, then the fine covered one and at last the coarse material covered one. Thirdly, the coarser the material in model drainage, the bigger the amplitude of the sediment yield vibration is. Finally, the vibration of peaks and valleys for the sediment yield processes curves occur during different time spans. To the model with coarse material covered, it exists at the beginning stage of the drainage network developing, in the coarser material model drainage it also occurs at the former stage of drainage network development with more peak values than valley and at the latter stage just more valley values could be found. For the fine material drainage, the alternation between peak and valley is more uniformly distributed during the whole sediment yield processes. 4 Experiments of drainage network development 4.1 Quantitative index of drainage network 4.1.1 Statistical calculation in spatial distribution Habitually, the laws of channel number and length are used to describe numbers and average length of different order streams and their relations to describe spatial distribution of a drainage network. Sometimes topological characteristics of a drainage network are revealed by means of topological method. However, those methods only indicate average spatial distribution situation for drainage network development, it is difficult for them to reflect temporal features and change laws of different order streams. The fractal method is expected to meet this gap. 4.1.2 Fractal value and calculation The fractional dimensions of model network for every run were calculated with the Wang´s method1. Based upon Horton´s stream number law and channel length law, he derived fractional dimension D of drainage network as follows: where K1 and K2 are coefficients for Horton´s stream number law Nu=K1(s-u) and channel length law lu = l1K2(u-1), respectively. From Horton´s stream-number law lnNu = slnK1 - ulnK1 suppose a1 = slnK1, b1 = -lnK1 Then lnNu = a1+b1u (5) From Horton´s channel-length law ln(lu/l1) = ulnK2 - lnK2 suppose a2 = -lnK2, b2 = lnK2 Then ln (lu/l1) = a2+b2u (6) Obviously, based on regression method using measured data of number and length of different order streams from model drainage network or field catchment, lnK1 = -b1 and lnK2 = b2 are easily obtained, and the fractal dimensions of network may be calculated (Table 2). Table 2a Characteristics values of networks of model drainage development processes and some field gullies 4.1.3 Physical significance of fractal dimension for drainage network Zhang[38] elucidated the significance of fractal in the fluvial geomorphic system. He and Barbara et al.[39-40] pointed out that fractal demention could (1) simulate the shape of a drainage network, (2) study the relation between stream length and drainage area, and (3) detect correlation of drainage hydraulics and its scale, etc. It is recognized that in the fractal value D=b1/b2 in a drainage network derived by Wang et al.2, b1 means an increment rate of stream number for a stream order and b2 is an increment rate of average channel length for a stream order. With the length increasing, a channel should become sinuous and the longitudinal gradient decrease, which is a way to tend to minimum energy dissipation. On the other hand, the increasing of the stream channel number is another way to tend to minimum energy dissipation. Therefore, the fractal value (D) could be interpreted as a relative increment ratio of stream number to channel average length, and it can be regarded as another index to calculate the energy dissipation in a drainage network. The variation of D value is a scale to assess temporal series processes for drainage network development. Table 2b Fractal value calculations of networks of model drainage development processes and some field gullies To compare geometrical characteristics of three groups, the data from experiments are analyzed with extreme values (Table 3) and the typical situation of model drainage network development for each group is drawn with a scale in Figure 6. The Tables 2 and 3 indicate that the lower the stream order develops in a model drainage network, the more the channel number is, and the larger the variation of channel number is. The lower the stream order develops, the shorter the channel average length is, and the smaller the variation of channel average length is. These situations are rather similar to the prototype in the field. However, due to the model area limit, the fifth order and some fourth order channels are shorter in the model drainage network. Figure 6 Sketch of typical drainage network d evelopment model Table 3 Number and average length of channel for each grade in model drainage systems The materials in the model have obvious influences on the number and average channel length. As a whole, the finer the material in a model drainage geomorphic system, the bigger the channel number and the shorter the channel average length, especially during the drainage network development for the second and third order channels (Table 2). As indicated that during the network development its fractional dimensions at first increased and reached the maximum value in the middle stage and then in the end became a stable value. It varied with network development and completion. 4.2 Non-linear character of drainage network development Data obtained from three groups indicate that the fractal (D) for each group has its own minimum value and it is fitted with time by an unasymmetrical concave hyperbola. At the beginning stage of drainage network development, the fractal value is medium, then appears a minimum threshold, and reaches the maximum value at last (Figure 7). The difference between the two fractal values of peak and valley is about 2. It is also found that the coarser the material in model drainage, the larger, the fractal value is, and the finer the material in the model, the smaller it is (Figure 8). Figure 7 Change of fractal value for Runs 1, 4 and 6 Figure 8 The relationship and fractal value for Runs 1, 4 and 6 5 Non-linear relation of sediment yield to network developing Jin et al. (1999) studied the relationship between sediment yield and network development during a model drainage geomorphic system evolution. It is recognized that the component of drainage system may have an influence on its fractal dimension [31]. We plot the erosion modulus data for each run as vertical coordinate value and the fractal data as horizontal one in Figure 8. The relation of them appears a clear non-linear character. As in detail, different development stage of network provides its own relationship between erosion modulus and fractal value. At the early stage of network development the fractal value decreases with increasing of erosion modulus, in the middle stage it reaches the minimum value, and at the later stage the fractal value increases with decreasing of erosion modulus. The curves illustrate that in the first half of time span the absolute decrement rate of fractal value is much smaller than that increment rate in the second half of time span. It seems that the coarser the composed material, the sharper the case is, and the finer the model material, the more gentle it is (Figure 8). 6 Conclusions and discussion Experiments show that under a given rainfall intensity and a given slope, the different material covered model clearly influences the sediment yield processes, drainage network development, and the relationship of them. 1) For coarse, coarser or fine materials, the sediment yield is characterized by a fluctuatedly decrease. The coarser the material, the larger the reduction rate and the amplitude of wave-vibration are. 2) The material in the model also has impacts on the number and average channel length of different order streams. The coarser the model material is, the more the channel number and the longer the average channel length are. 3) Though the model drainages are covered with different materials, the processes of sediment yield and drainage network development have non-linear characters. The fractal value of network development is a kind of measure to energy dissipation, because the increasing of channel number and the changing of channel shape slope stepping are the two ways of minimum energy dissipation. The fractal value D changes in time passing with a form of an asymmetrical concave curve and there exists a minimum threshold in the middle stage of network development. The minimum value falls with model material fining. 4) There exists a clear non-linear relation between sediment yield and the fractal value of a drainage network. It seems also to be described by an unasymmetrical concave hyperbola. As time passes, the absolute value of variation rate decreases. This tendency is intensified with material being coarse and is gentler with material fining, and thus, that is a suitable example substituted situation condition for temporal processes. These situations are mainly related to the coarser material with cohesive and stranger capability protected from erosion. The coarser the material, the easier the erosion and the less lower order channel forms, and the wider, shallower and straighter the channel is. The finer and the more concessive the material, the more difficult the erosion and the lower the order channel develops, and the more sinuous and extended the higher order stream is. References

关键词： material component; network; sediment yield; nonlinear relation; experiment