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Development stage threshold of watershed landforms in Loess Plateau and separation of erosion mechanism

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Threshold is a limit and marginal point when a qualitative change takes place. Since threshold principle was firstly used in landform research by S.A.Schumm in the 1970s, the quantitative research on watershed landform development stage has come true. Davis proposed a three-stage model on landform evolution: young, mature and old stages. Thereafter Strahler quantified this model by hypsometric analysis method. The authors thought that the material movement stage cannot be expressed by hypsometric method in watershed landform at development stage, because of the uncertainty on stage delimitation. To meet this shortcoming, this paper presents an integral erosion value method. A clear delimitation on landform development stage in the Loess Plateau region has been tested by this method. The result shows that gullied loessial hilly area is at the mature stage, and gullied loessial tableland area is at the young stage. It is estimated that from the point of erosion related sediment yield, natural erosion accounts for 70% of the total erosion amount, and artificial accelerating erosion is 30%. Therefore soil and water conservation is very crucial for the Loess Plateau.

Development stage threshold of watershed landforms in Loess Plateau and separation of erosion mechanism LU Zhong-chen1, CHEN Shao-feng2, YUAN Bao-yin3, CHEN Hao4 (1. Eco-Environment Research Center, CAS, Beijing 100085, China; 2. Institute of Policy and Management Science, CAS, Beijing 100080, China; 3. Institute of Geology, CAS, Beijing 100029, China; 4. Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China) 1 The concept of threshold and its practical significance Threshold could be defined as the upper limit of some accumulative processes, a limit when qualitative change takes place (Donald et al., 1980). It can be a specific figure or a dividing point. The significance of threshold in geography was fully discussed by Brunet (1968) (Schumm, 1973). In the 1970s, threshold principle was first introduced into the study of geomorphic system by S A Schumm (1973; 1980). He put forward two geomorphic limits, namely, internal geomorphic limit and external geomorphic limit. The development of different parts of geomorphic system will always undergo gradual change and catastrophic change. In catastrophic change, a quantitative limit will be broken thoroughly; the threshold is the intrinsic attribute of the development of things, which is called internal threshold of geomorphic limit in the analysis of geomorphic development. On the other hand, external conditions are the basis for the change of things. The geomorphic system of watershed develops under the comprehensive actions of different factors of physical geography. The catastrophic change of landscape may be caused under certain external conditions. The natural condition threshold, which triggers out the catastrophic change of landscape, is called external geomorphic threshold (Schumm, 1977; Yin, 1986). Generally speaking, various classifications, stage delimitation, and establishment of periodic sequence are all based on catastrophic change point (threshold). Therefore, with study on regular pattern of threshold, it is able to delimit the stage of geomorphic development of a watershed and to predict the trend of its development, thus providing a scientific basis for soil and water conservation of watershed system. The theory on erosion cycle, i.e., a theory on stages of geomorphic development established by W M Davis views geomorphic form as the function of construction, stress and time. The division of geomorphic development into young, mature and old stages is a real reflection of threshold law. Later, Strahler advanced hypsometric analysis method, i.e., area-hypsometric analysis method, thus, quantifying Davis´ method of geomorphic development with the help of threshold value (Strahler, 1952). That is young stage when hypsometric integral value is over 60%, it is mature stage when the value is between 35% and 60%, and old stage below 35%. The so-called hypsometric analysis or area-hypsometric analysis refers to the study of the relationship between the area of horizontal section of a certain place (or a certain watershed) and hypsometry. The hypsometric curve is the curve that shows the relationship between the area of horizontal section of the watershed and relative height above the river mouth. The deficiency of hypsometric analysis lies in its failure to reflect the stage of matter migration and indefiniteness of stage division during the watershed development. From the aspect of study of soil erosion, Strahler curve provides us with information of integral erosion value used to delimit geomorphic development stages of watershed. 2 Integral erosion value Integral erosion value refers to the ratio between the matter volume eroded and that of the integrated part uncut or uneroded. The value not only quantifies erosion but also reflects the level and result of mutual efforts of internal and external stress of separation destruction and migration of the surface matters. It is the comprehensive index of various factors that affects erosion. With the help of integral erosion value, it is able to delimit geomorphic development stages with threshold value, thus quantifying geomorphic development stages. Meanwhile, it is able to analyze the size and intensity of natural erosion, which can lead to the erosion acceleration in size and intensity. This article will focus on the former point. It is well known that there are different rates of erosion at different development stages. If the existing shape of land surface is connected with the volume of matters eroded, we can get the quantitative relationship between geomorphic development stage of watershed and quantity of erosion. Matters eroded can be expressed as: If relative volume is used, after being divided by HA on both sides, erosion integral value Ei can be expressed as follows: where y=h/H is the ratio of relative height of contour line (h) and topographic difference (H), and x=a/A is the ratio of the horizontal area of tangent intersection (a) by contour line and total watershed area (A). If y serves as ordinates and x abscissa, there will be a hypsometric curve (Cheng et al., 1986), with the help of which integral erosion value will be obtained. Strahler believes that it can determine the topographic development stage of a specific watershed by studying the pattern of hypsometric curve of watershed landform. From the aspects of eroded matter, integral erosion value quantifies hypsometric curve, thus indicating topographic development stage with threshold value (Figure 1). It should be stressed that the development of all things always undergoes quantitative and qualitative changes: with the accumulation of quantitative changes reaching to certain threshold point, qualitative change will take place. Things develop by stages, so do the cases of development of watershed geomorphic system. Take the Loess Plateau for example, as an open system, the input, transformation and output of matter and energy led to a series of changes on the erosion and accumulation in watershed. However, the evolution of the system was determined by the size of eroded matters and the time lasted, i.e., the function of erosion process and time, which is the intension of integral erosion value. The problem lies in the determination of integral erosion value threshold which can quantify geomorphic development stage. 3 Determination of integral erosion value On the basis of a great deal of field investigations and close prospecting for typical small watersheds, hydrological networks of different ages and their geomorphic locations have been determined. With the help of stratigraphy and chronology, ages of gullies of different periods as well as their discriminant marks on topographic map are determined. Hydrographic networks of different periods are put into the map after indoor assessment. Then river network densities of different periods are obtained with the help of computer. Fitting equation is derived by relation curves among the river network density, the quantity of sediment produced and integral erosion value. (1) Fitting equation of relation between the river network density and quantity of erosion Gullied loessial hilly area: Fitting equation: Ws=3334.27ds0.945α r=0.95 (3) Gullied loessial tableland area: Fitting equation: Ws=59.84ds3.353α r=0.90 (4) where ds stands for river network density (km/km2), and Ws stands for erosion modulus (t/km2.yr). (2) Curve and fitting equation of relation between the river network density and integral erosion value Its fitting equation is: Ei=0.194ds0.697 r=0.90 (5) Since ages of several river network densities are known, through the relation between the river network density and integral erosion value, the connection between integral erosion value and sediment produced quantity and time could be established. A further mathematical analysis on the determination of integral erosion value Ei = f(T) is shown, where T stands for ages (10,000 years per unit). Firstly several known river network densities are put into the formula (5), with corresponding integral erosion value of different periods obtained from the formula, draw a curve, and then according to the variation character of the integral erosion value within the zone [0,1], the following fitting pattern is used. Then we put river network density of four different periods of gullied loessial hilly area and gullied loessial tableland area of the Loess Plateau into formula (5) and with formula (6), the process formulas of integral erosion value are determined as follows: Gullied loessial hilly area: Gullied loessial tableland area: With the analysis on the concept of integral erosion value, erosion modulus and integral erosion value are connected in this way: The function between erosion modulus and changing rate of integral erosion value are determined based on the following points: 1) erosion cycle of the watershed determines the changing process of erosion modulus being increase first and then decrease; 2) the ch aracters of erosion modulus are:; 3) put the several known river network densities into formulas (3) and (4) and then with formula (10), the changing rate of erosion modulus of corresponding periods is obtained. A line is formed after spotting into the logarithmic coordinate, which shows the logarithmic relation between erosion modulus and variation of integral erosion value, thus determining the function as follows: put formula (10) into formula (11) where A and B are coefficients obtained by statistical iteration. Put various known river network densities of the Loess Plateau into formulas (3) and (4), simultaneously obtaining changing rate of corresponding erosion modulus with formula (10), and with formula (11) to imitate it, an equation of natural sediment produced process is obtained. Gullied loessial hilly area: Gullied loessial tableland area: where T is time (10,000 years per unit). We put different time into formulas (7), (8), (13) and (14) to obtain the integral erosion value and natural sediment produced process curve in the gullied loessial hilly area and gullied loessial tableland area (Figures 3 and 4). In Figure 3, b is natural sediment produced process; b1 is artificial accelerating erosion--30% sediment produced process; b2 is artificial accelerating erosion--44% sediment produced process; b3 is geomorphic development process up to b1; b4 is geomorphic development process up to b2; a is integral erosion value up to b; a1 is integral erosion value up to b1; and a2 is integral erosion value up to b2. Variation rate equation of erosion modulus in different geomorphic areas can be obtained through deduction of formulas (13) and (14). Gullied loessial hilly area: Gullied loessial tableland area: where Ws is erosion modulus (t/km2), and T is time (10,000 years per unit). The process curve of variation rates of erosion modulus of gullied loessial hilly area and gullied loessial tableland area can be drawn by putting erosion modulus of different periods and time into formulas (15) and (16) (Figure 5). The process curve of the variation rates of erosion modulus shows clearly that there exists a variation threshold point of development stages of the watershed. The threshold point is the turning point of the curve of the natural sediment produced process. According to the definition of derivative, the two-step derivative of the natural sediment produced process against time is zero, and the corresponding integral erosion value which reflects geomorphic patterns is identical to threshold integral erosion value, i.e., the quantitative index of dividing development stages of watershed: which reflects the sediment produced characters of different stages of watershed. The solution found from formula (17) is Ti (i=1,2,...,n), if i = n, there exist n+1 development stages. But actually i = 2, i.e., there are three stages and two threshold values, which is the mathematical solution of the above threshold value. Substituting Ti into formulas (7) and (8), it can determine threshold integral erosion value. Threshold integral erosion value is a definite quantitative index to divide watershed development stages, thus avoiding the indefiniteness of hypsometric integral value in stage division and possibility of confusion of different stages. It includes two basic intensions in time and space, i.e., deciding on which development stage the watershed is at from the aspects of space, and deciding on the time of corresponding development stages. To be specific, in Figure 5, the process curve of the variation rates of erosion modulus, the threshold point on the curve is just threshold of integral erosion value of geomorphic development stages. In Figure 5, the threshold point on the left side of the curve is 60,000 years ago, then we find 60,000 years on the abscissa in Figure 3 is the process curve of integral erosion value, the corresponding integral erosion value is the geomorphic development threshold value. There are different erosion characters in different geomorphic development stages: at young stages, erosion modulus is relatively small and the variation rate of erosion modulus increases to the maximum; when it comes into mature stages, at a higher level, the erosion modulus continues to increase to the maximum, and then turns to decrease, as for the variation rate of erosion modulus, it continues to decrease, once it develops into old stages, the watershed begins to decline and fall, and its erosion modulus decreases but the variation rates of erosion modulus continue to increase progressively, from minus maximum value to near zero. Therefore threshold point of integral erosion value obtained in this way is definite. As for gullied loessial hilly area and gullied loessial tableland area of the Loess Plateau, the threshold relation between integral erosion value (Ei) and watershed development stages can be divided as follows: Gullied loessial hilly area: Gullied loessial tableland area: Ei<32% young stage Ei<39% young stage 3266% old stage Ei>61% old stage 4 Examination on watershed geomorphic development stages in the Loess Plateau The above discussion is focused on theoretical analysis of watershed geomorphic development stages. However, in practice, at present with integral erosion value, it is able to examine which stages that different landforms in the Loess Plateau have developed into. Therefore, 200 typical small watersheds in gullied loessial hilly area and gullied loessial tableland area of the Loess Plateau have been chosen and measured and hypsometric curves (Figures 6 and 7) have been drawn, after calculating the integral erosion value, it is found that the maximum integral erosion value of gullied loessial hilly area is 0.622, and most of them fall into 0.4-0.5, which indicates this area has developed into the second stage, i.e., the mature stage. At present it has been developing within the second stage. Figure 3 demonstrates that gullied loessial hilly area has reached its peak erosion value, and along with time elapsing, erosion modulus will decrea se gradually, i.e., without any soil and water conservation measures, through self-adjustment of geomorphy, soil erosion will be weakened gradually for the intensity of erosion is connected with geomorphic development stage (Cheng et al, 1986). The maximum integral erosion value in the gullied loessial tableland area is 0.389 and the average is 0.384, which shows that geomorphic development of this area has been in the first stage, the later young stage. In one word, different landforms have not developed into old stages and one of the main reasons lies in continuous rise of this area. As above mentioned, integral erosion value itself is affected by internal stress. In the definition of integral erosion value, relative erosion quantity, i.e., the amount of erosion in a watershed, is jointly affected by internal and external stress. At present, it is unable to distinguish the efforts of two stresses and further study is needed, but it is commonly believed that geomorphic development process is the result of the joint efforts of the two types of stress. The existence of geomorphic threshold reflects the catastrophic change of geomorphic process. Gradual change and catastrophic change of different parts of geomorphic system always occur alternately, and the geomorphic process always begins with gradual change and ends with catastrophic change (Yin, 1986). Therefore, studying the law of threshold is the only way to grasp the nature of stages in geomorphic development, thus predicting the future course and making the best use of it to remake nature. 5 Erosion related sediment production in watershed Another significance of studying integral erosion value is that it can be used in the study of erosion related sediment producion in the Loess Plateau region. To be specific, it can be used to distinguish natural erosion and artificial accelerating erosion in the Loess Plateau. Erosion is one of the factors of topographic model as well as an external cause of the migration of surface matters, i.e., external factor of geomorphy. With the efforts of erosion, soil (surface soil layer) and bed rock (lithosphere) are destroyed. Therefore it is an important link of the erosion, transportation and deposition process of matters in the watershed system. With the efforts of erosion, the Loess Plateau drops because of soil erosion and river bed in lower reaches rises due to deposition of sediment. Erosion can be divided into two types according to its meaning: one is natural erosion (geological erosion), and the other, artificial accelerating erosion. As the terms suggest, the former is a geological process on condition of physical balance of ecological environment without participation of human beings, which is dominated by the law of physical evolution. With influence of human activities, natural erosion process speeds up, having harmful impacts on land use and with deposition of sediment on the lower reaches, threatening the security of flood control. This is accelerating erosion based on natural erosion, accelerating erosion continues to develop with the participation of human activities. Sediment reduction benefits of soil and water conservation measures in the Loess Plateau region reflect people´s anti-disaster competence in the process of remaking nature. This anti-disaster competence is very effective in reducing accelerating erosion, but, ineffective to the physical law of development of the Loess Plateau. Therefore, in order to study soil and water conservation benefits and their effects on silt discharge into the Yellow River, it is necessary to distinguish natural erosion and artificial accelerating erosion. With some knowledge of natural erosion (background erosion - erosion background value), it is able to find out the amount of accelerating erosion, thus determining the maximum anti-calamity competence and estimating the tendency of sediment reduction quantity in the future. Furthermore, at present, there exist two conflicting points of view concerning the evolutionary problem of erosion environment in studying soil erosion of the Loess Plateau, i.e., controversy between those who consider that the severe soil and water loss results from human beings destroying vegetation, and those who believe that severe erosion of the Loess Plateau comes from geological period and is not completely the result of human beings´ destructive activities in recent years. The controversy is significant not only in theory, but also in practice. Which is correct? Only when natural erosion and artificial accelerating erosion are correctly distinguished and the quantitative relationship between them is made clearly, could a definite answer be given. 5.1 Natural erosion quantity On the basis of the above natural sediment production formulas (8), (10) and curve of natural sediment produced process, it is able to analyze natural erosion. The process curve of natural erosion in gullied loessial hilly area, shown in Figure 3, demonstrates that since geological period (310,000 ago) erosion modulus has increased progressively by 28 times from 350 t/km2.yr to 10,146 t/km2.yr. From early years of erosion period to middle period, quantity of erosion increased with the passage of time. If calculating the quantity of accelerating erosion respectively in accordance with geomorphic development stages, quantity of erosion increased by 18 times from 350 t/km2.yr in early stage to 6,665 t/km2.yr 75,000 years ago; from early time of middle period till present, the quantity of erosion has nearly been doubled, from 6,665 t/km2.yr to 10,146 t/km2.yr. In Figure 4, natural erosion in gullied loessial tableland area demonstrates that during geological period (90,000 years ago), erosion modulus has increased by 4.7 times from 350 t/km2.yr 70,000 years ago to 1,990 t/km2.yr. Therefore, in the long history of natural erosion, the increase rate of different natural erosion stages are quite different, and the main reason lies in the fact that they are different types of landforms and different development stages. 5.2 Accel

erating erosion Very limited study on accelerating erosion was undertaken as what has done to natural erosion of the Loess Plateau. The limited available data are derived from estimation, inference and comparison. Foreign scholars concerned have also tried to solve this problem. Take Douglas, British geomorphologist for example, he adopted a spatial contrasting method to distinguish accelerating erosion. This method is restricted by effectiveness for a given period of time and also limited by the control conditions of the watershed. We have obtained the quantity of accelerating erosion through theoretical analysis and calculation based on a great quantity of actual data from the Loess Plateau (including geological period), the solution of accelerating erosion can be found in the following process. Suppose total quantity of sediment produced is Ws, quantity of accelerating erosion is Ws´, and natural erosion Ws´´, then we obtain: The percentage of accelerating erosion to total quantity of erosion is as follows: Let α= Ws´´/Ws´, andαis the function of time and space, which is affected by human activities. It is generally believed that human activities began about 10,000 years ago, therefore the section curve from 10,000 years ago till today in Figures 3 and 4 can be taken out from the process curves of erosion modulus. After calculating and amplifying the curve with formulas (8) and (10), drawing the curve in Figures 8 and 9, which is the curve of natural sediment produced process from 10,000 years ago till now. In Figure 8 although curve of natural sediment produced process in gullied loessial hilly area increases progressively, the amount added is quite small, it increased by 19% from 10,036 t/km2.yr to 10,145 t/km2.yr, and the average annual increment rate is about 0.2%. The average annual increment rate of the curve of natural sediment produced process in gullied loessial tableland area (Figure 9) is 4.0%. With curve of natural sediment produced process, it is required to establish a curve of overall sediment produced process from 10,000 years ago to date (or years less than 10,000 years to date) including natural erosion and accelerating erosion. The recent data for the process curve can be obtained through two channels: 1) with topographic map of high precision, calculate the density of river networks of certain point, and then put the density value of river networks into formulas (3) and (4) to obtain erosion modulus of certain watershed; and 2) find erosion modulus directly from erosion modulus map of high precision and then put erosion modulus obtained into formula (19) to get the ratio taken up by the present maximum quantity of accelerating erosion. If human activities began 8,000 or 6,000 years ago instead of 10,000 years ago, erosion modulus (total quantity of sediment produced) of other periods can be put into the following formula based on the relation between the population of different periods of time and sediment produced quantity of the Loess Plateau: where Ws is sediment produced quantity (in 100 million tons), and Q is population (in 10,000 persons); The population was 8.85 million 2000 years ago, put it into formula (20) and then the sediment produced quantity could be 1.276 billion ton. It is the same to other times. With present sediment produced quantity, it is able to find the quantity of accelerating erosion in different periods of time since 10,000 ago and to establish a test equation for the quantity of accelerating erosion in different geomorphic areas of the Loess Plateau within 10,000 years. Gullied loessial hilly area: Ws ´= 6.42T2.83 (21) Gullied loessial tableland area: Ws´ =1.32 × 10-6 T0.84 (22) where T is time (10,000 years per unit), and Ws is quantity of accelerating erosion. With these formulas, it is able to draw a process curve of total sediment produced quantity (a line) in Figures 8 and 9, and with the curve of natural sediment produced process (b line), it is able to calculate the ratio taken up by accelerating erosion, i.e., line c in Figures 8 and 9. Percentage of accelerating erosion quantity in different periods is shown in Table 1. It is seen from Table 1 that artificial accelerating erosion of the Loess Plateau takes up 30%. This figure is reliable and accelerating erosion quantity of other times remains to be studied further. Thus it is clear that accelerating erosion of the Loess Plateau takes up 30% and natural erosion is dominant in the erosion of the Loess Plateau. Similar value is obtained in similar studies by other researchers with different approaches. For example, the research result of Chengdu Institute of Mountain Disasters and Environment, CAS, shows that valid sediment produced quantity caused by gravitational erosion is about 70%. Li Zhaoshu, with analysis on the landslide and mud-rock flows of five typical small watersheds, finds that the sediment produced quantity by mud-rock flows takes up 70% of the total sediment produced in the watershed. Zhang Pingcang, with grading analysis, determines that sediment produced quantity from basic rock takes up more than 69% of the total sediment produced. The above-mentioned researches, though different in methods, lead to such results that support each other. Hong Yetang also considers that "the Yellow River should not be viewed as the symbol of biological destruction" (Lu, 1991). This means that the great amount of silt in the Yellow River has not been resulted from human activities. Before loess vegetation was destroyed by human activities, gully system had already been developing. The phenomenon of soil erosion had existed earlier in the ecological environment of ancient vegetation of the Loess Plateau, and the Yellow River itself is a good proof. The intensity of soil erosion caused by human activities is much less than that of geological loess erosion.
关键词： landform development stage; hypsometric analysis method; integral erosion value; natural erosion; artificial

accelerating erosion