Scale-effect of Hypsometric Integral in Loess Plateau

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Abstract—**The Loess Plateau is gully and hilly with serious soil erosion and thus a thorough study on the landscape development and erosion process with the scope of small watershed is of vital importance for ecological restoration of this region. As a macroscopic landscape analyzing method, hypsometric integral could be used for a comprehensive analysis on the development stages and process of small watersheds. Nevertheless, this method could produce distinct scale-effect and consequently an in-depth recognition on the finest analysis scale is a basis for properly understanding the characteristics and development of the watershed. This paper, with small watershed in Loess Plateau as the object of study, elaborately analyzes the scale-effect of hypsometric integral from the perspectives of analysis scale, statistical scale and regional scale based on 5-meter-resolution DEMs. The results show that, with the increase of hypsometric series under analytical scale, the integral value decreases sharply to close to the true value, yet the decreasing range narrows greatly and finally hypsometric curve becomes more accurate. As DEM resolution in statistical scale rises, hypsometric integral value basically remains unchanged, and this value is closely related to the other two land surface parameters, depth of surface cutting and relief height of landscape. Moreover, when considering regional scale in the same landscape, the smaller the analytical area is, the greater the integral value difference will present. At last, the integral value tends to remain steady when analytical area reaches a certain degree. This paper lays a foundation for further analysis of watershed characteristics.**

Ⅰ. INTRODUCTION

Hypsometric integral is a terrain analysis factor with apparent physical and geomorphologic meanings which could reflect the landform erode stage and evolution process. As a macroscopic parameter and method in terrain analysis, the applications of hypsometric integral could reveal the quantitative characteristic of landform evolution in watershed scale. However, it still needs to be improved and enriched of the hypsometric integral analysis method, particularly in the little progress has been made of hypsometric integrals in the applications of watershed evolution and geomorphologic pattern from previous literatures.

Horton firstly put forward quantitative indicators to describe watershed morphology in 1932, followed by Strahler (1952, 1963) and other geomorphologists who constantly improved and complemented the quantitative description indicator system of the watershed (Schumm, 1956; Morisawa, 1964; Lu, 1991). Chen and Jiang (1986) summerized quantitative interrelations between watershed quantitative description indicator system and factors involved in their book Watershed Geomorphologic Mathematic Model. Hypsometric integral, initiated by American geomorphologist Strahler as early in 1952, mainly studied the relationship between regional horizontal section area and hypsometry, which contributes a great deal to the quantitative Davis Theory of Geomorphological Cycle. And later, scholars at home and abroad made further studies on it. Willgoose (1998) analyzed how the watershed morphology and drainage density influenced hypsometric integral. Moreover, Masek (1994) and Montgomery (2001) concluded that different sediments and runoffs had a great impact on hypsometric integral. Chen (2005) analyzed the variations of hypsometric integral from the aspect of drainage area and spatial distribution. Walcott (2008) illustrated specifically the spatial distribution of hypsometric integral in different scales with watershed in southeastern Africa as study object. With respect to the application of losses geomorphy, Wu (1965) comprehensively explained hypsometric integral's application in geography and pointed out its insufficiency mainly related to the conceptual feature of the curve. He held that it could only be used to summarize the characteristics of landform morphology. Besides, Ai (1987, 1988) proposed the comentropy of the watershed erosion system based on hypsometric integral and introduced the concept of linear unbalanced comentropy into the study of watershed system. Li and Lu (1990) developed erosion integral on the basis of hypsometric integral and analyzed the characteristics of watershed development stages from the angle of erosion. In addition, Xin (2008) made a spatial chart of hypsometric integral in losses plateau and drew the conclusion that with the variance of digital resolution, HI value, short for hypsometric integral, remained steady (100m as a starting point), while as analytical window increases gradually, HI value decreases by power function. Liao (2008) held that hypsometric integral could reflect present landform status and erosive tendency of the watershed, and the size and changing trend were closely related to whether watershed bottom reached basement.

As scale-effect widely existing in geo-analysis, therefore, a good comprehension on it is the key to providing the basis for thorough understanding of geographical characteristics and geographical phenomenon process. DEM itself depends so heavily on scale that scale-effect is absolutely inevitable while using DEM to calculate hypsometric integral value. Liu (2007) summarized the scale-effect of DEM, analyzed DEM scale conceptual model and scale system, and argued that scale could be classified into two groups, namely, geographical scale and representation scale with the latter including analytical scale, structural scale and sampling scale. This paper, with typical small watershed in loess plateau as a study case and DEM data as basic data source, analyzes basic characteristics of hypsometric integral within small watershed and explores the influence on hypsometric integral posed by analytical scale, digital scale and regional scale contained in application of hypsometric integral.

II. Data and Methods

A. Sample Region and Data

The Loess Plateau is covered with gully and hilly areas and soil erosion is serious. This paper concentrates on severely erosive area in loess plateau and selects typical types of loess landforms with three regions respectively loess tableland, loess ridge and loess hill (Fig.1). Then, based on watershed completeness and data accessibility, taking 1:10000 DEM of national fundamental geographic data as basic data, it extracts three small watersheds and analyzes integrated characteristics and scale-effect of its hypsometric integral.

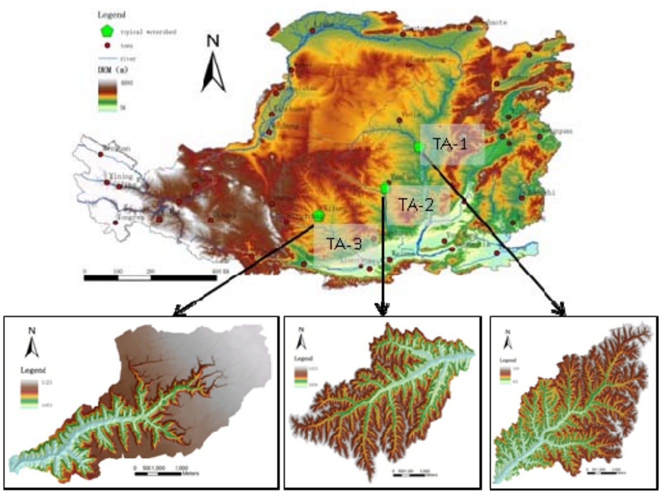

Figure 1. Distribution of test areas on the Loess Plateau

B. Method

The paper takes ArcGIS9.3 as a processing platform for sub-catchment division and DEM re-sampling and programs with MatLab software to calculate hypsometric integral. Firstly, it analyzes the influence produced by hypsometric classification in hypsometric integral calculation and curve plotting, namely analytical scale. Then, with respect to DEM resolution, a discussion is made here on variance of hypsometric integral value with different resolution. Finally, it works out hypsometric integral of sub-catchments differing in watershed area within the small watershed and discusses the issues on regional scale of hypsometric integral.

III. Scale-effect Analysis

A. Classification Effect

Hypsometric integral mainly comprises two parts, namely, the integral value itself embodies and the hypsometric curve plotted according to elevation cumulative frequency. While plotting the curve, one should find out a series of points based on which pattern of the curve will be drafted. The classification series equals to curve points. Specifically speaking, it means the number of elevation classification of the studying area, that is to say, suppose regional elevation difference is Δh, classification series is n and then elevation in each level is $\Delta h/n$. The number of frequency value we can get from elevation frequency histogram is n. Based on corresponding frequency value and cumulative area; the hypsometric curve can be drawn. While calculating, we set aside classification series-an input parameter, for different series could show how classification affects plotting of the curve and calculating of integral value.

According to the method used to calculate hypsometric integral, the factor that mainly influences its integral value and hypsometric curve is the percentage each elevation accounts in all classification of elevation. From definition of hypsometric integral, integral value can only be true when classification series is infinite. While in practice, we can only calculate percentage of area of each level and plot the curve by fixing a certain classification number. The more it classifies, the more precise the integral value is, thus bringing a more close-to-reality curve. However, when classification series increases, efficiency of calculation decreases straightly (Fig.2). In this case, a balance is needed which can ensure both accuracy of integral value and efficiency of curve-plotting. It's shown by difference in adjacent integral value, known as its decreasing range. As classification number increases, the decreasing scope of integral value narrows accordingly. And when it reaches 100-level, the value decreases is smaller than 0.0005. Taken overall consideration of integral value and curve, the classification series set in this paper is 100.

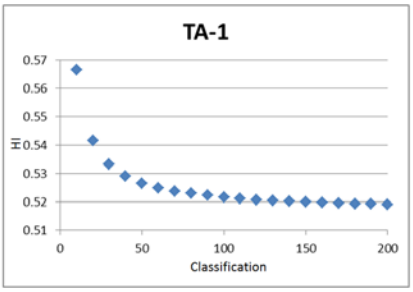

Figure 2. HI against the number of classification

B. Resolution Effect

Analysis on resolution dependence mainly focuses on its analytical characteristics of hypsometric integral under different resolution DEM data so as to explore the resolution sensitivity. Taken 5-meter resolution and scale of 1:10000 DEM as basic data source, resample the three small watersheds by using quadratic linear interpolation algorithm with ReSample tool in ArcToolBox, and set resolution interval as 10, and then we can get 19 resolution data ranging from 5 to 195m respectively. Next, we could explore its resolution dependence by calculating hypsometric integral of each watershed in different series of resolution scale (Fig.3). As a smaller resolution can reflect relief characteristics of landforms better, therefore, this paper supposes the 5-meter DEM data closes to real landform data.

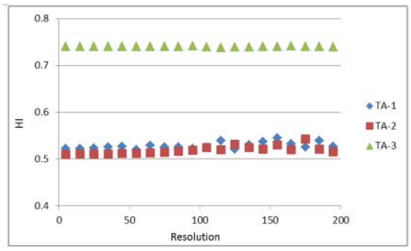

Figure 3. HI against Resolutions

Calculate respectively the hypsometric integral of different resolution in the three watersheds, as shown in the figure, hypsometric integral value of each watershed remains steady basically, and maintains constant with resolution changing. From the definition of hypsometric integral, physically it represents, compared with erosion basis, the ratio of potential erosive amount of the remaining watershed development erosion area.

$$HI = \frac{Vr}{Va}$$

Vr represents the volume of remained materials beyond erosion basis within watershed, while Va indicates the volume of all materials above erosion basis with no matter run off.

Taken DEM volume calculation as an example,

$$Vr = h\_meam \times g^2 * n - h\_min \times g^2 \times n = (h\_meam - h\_min) \times g^2 \times n$$

$$Va = h\_max \times g^2 * n - h\_min \times g^2 \times n = (h\_max - h\_min) \times g^2 \times n$$

Where, g is grid length, g^2 means grid area, and n shows the number of grids the watershed occupies.

Dividing one by the other results in:

$$HI = \frac{(h\_meam - h\_min) \times g^2 \times n}{(h\_max - h\_min) \times g^2 \times n} = \frac{h\_meam - h\_min}{h\_max - h\_min}$$

The numerator is cutting depth of surface and denominator is relief amplitude. Pike (1971) confirmed in his essay the correctness of the formula from angle of infinitesimal calculus. In this regard, the variance of hypsometric integral value is determined mainly by elevation extremum and average elevation in the area analyzed.

C. Watershed Size Effect

Hypsometric integral is a regional macro-statistical indicator analyzing landform characteristics within the region. Obviously, analysis results are inevitably diverse with different regions. How to ensure the stability of hypsometric integral under various landforms is a problem we must deal with. Meanwhile, hypsometric integral also serves as an indicator to show development stage of watershed and rectangular window analysis method by no means can summarize its basic characteristics completely. Therefore, the paper, in analysis of integral dependence, calculates integral value by using watershed analysis window with whole watershed as its object. The details are as follows: first, divide small watershed into several sub-watersheds by threshold value, and grant such sub-watersheds corresponding classification according to Strahler's classification and level of catchment network. Then, draw complete sub-watershed in accordance with classification and calculate hypsometric integral value. At the same time, in sub-watershed division, certain inter-areas exist which have a water inlet thus differing from complete watershed. The boundaries of such inter-areas aren't watershed in strict sense due to the existence of the inlet. The inter-areas lie in middle and lower reaches of gully that are traversing across. Compared with higher reaches of the gully, that is gully head areas, the erosion here is relatively weaker and the integral value is lower accordingly, which to some extent shows this type of watersheds maintain stable and stay in their later stage of erosion. Thus, same as the watershed classification, this type of sub-watershed is not considered here.

Three levels of several sub-watersheds can be gained by dividing three small watersheds, hypsometric integral value can thus be figured out. The scatter diagram on the integral value and sub-watershed is as follows (Fig. 4), from which we can see that the range of integral value is wide while the area of sub-watershed is small. With the increasing area of sub-watersheds, its integral value has a trend of convergence. The terrain feature can be displayed by a series of the combination of landform characteristic, which absolutely occupy some space. When its area is smaller than a certain value (stable area), the geomorphologic feature of the landform types cannot be completely displayed, which will increase the uncertainty of the indicators reflecting the terrain feature. Just like the stability of the slope spectrum (Tang, 2008), the hypsometric integral, as a statistical indicator, also has the inner characteristic of area stability.

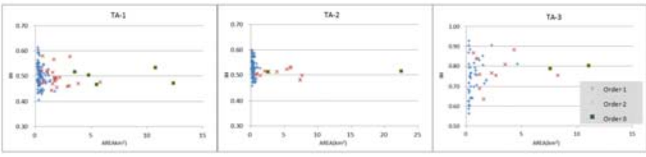

Figure 4. HI against the Watershed Size

Ⅳ CONCLUSION

The hypsometric integral value represents a function related to surface cutting depth and relief amplitude, but it is unrelated to its own classification series and DEM resolution. However, it is essential to choose the classification series in drawing the hypsometric curve. With the increase of classification, the integral value figured out on the basis of different levels has a trend of gradual decrease with sharp amplitude. That is, when the classification reaches a certain level, the magnitude is less than five ten thousandth as the integral value only changed very slightly. As a result, the influence on the integral value can be ignored. Similarly, due to the characteristic of hypsometric integral, basically it has the trend of constant arrangement in the calculation of its value with different DEM resolution. However, it also has a certain fluctuation, which is much consistent to the maximum or minimum fluctuations of DEM resolution. This is mainly because the re-sampling method, which, to some extent, has changed the hypsometric extreme value of DEM. When the precision of hypsometric integral is guaranteed, it is reliable to determine the value based on coarse DEM resolution. When the areas of sub-watersheds are small, the differences among the hypsometric integral values are very large in the same type of landforms, mainly because the local area of sub-watersheds is too small to represent and completely reflect the terrain feature of its landform. Consequently, it is necessary to consider its area dependence in order to reveal the development laws of characteristics of watersheds in the analysis of regional difference of landforms using the hypsometric integral method.

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