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DEM BASED RESEARCH ON TIME SERIES OF SLOPE SPECTRUM - A CASE STUDY WITH SIMULATED LOESS WATERSHED

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1. BACKGROUND AND OBJECTIVES

Slope spectrum, a more integrated terrain index which is not only simple and easy to extract, but also well capable to show the terrain feature as well as the development of the loess landform are proposed (Tang, 2003, 2008). Previous research in the Loess Plateau indicated a strong relationship between the slope spectrum and the loess landform types. A continuous change of slope spectrum from south to north in northern Shaanxi Loess Plateau shows an obvious spatial distribution of different loess landforms. However, if there existing a bound relationship between the time series of the slope spectrum and loess landform evolution? Does the slope spectrum potentially reflect the loess landform evolution? It is impossible to observe any long term evolution of any kind of loess landform and is difficult to give a convincible explanation because of endless evolution of loess landform. So a series of carefully-designed experiments were tested based on a simulated loess watershed which was designed by Cui et al (2002) in Artificial Rainfall Simulation Laboratory of the Institute of Soil and Water Conservation, Chinese Academy of Science. Purpose of this research is to probe the slope spectrums in different evolution stage of the simulated watershed.

To create a lab-based suitable simulated watershed in which the loess material and surface relief could correctly represent the true loess surface, a series of statistic analysis based on real loess surface and pre-experiments are carried out as a reference. Meanwhile, previous researches and many experts' experiential suggestions are considered. Simulated watershed developed with the force of artificial rainfall. The rain strength, duration and term in the experiment will be adjusted as much similar as the true rainfall of loess region. Close-range photogrammetry is applied at the stage of normal rainfall experiment. The interval between the neighboring two shoots is approximately a week and 2 to 5 times rainfalls were applied during the same time. 9 shoots are conducted in normal rainfall experiment.

2. DATA AND METHODS

High resolution digital elevation models (DEM) of different evolution stage of the simulated watershed are basic data sets of this research. As it said, all the DEMs are gained through the way of close-range photogrammetry. According to test planning, 9-stage DEMs were generated. A series of hillshade maps show gradually evolution of simulated watershed driving by artificial rainfall (Fig. 1).

Erosion amount can be calculated through subtraction of two close stages DEMs (table 1). Based on these DEMs, streams are extracted then the gully density of each stage can be calculated (table 3). At the same time, slope models in different stages are derived from the DEMs, and then the slope spectrum of each stage is established as the way designed by Tang and Li (2008).

Table 1 Gully density and erosion amount of the simulated watershed (from Cui, 2002)

Stage	1	2	3	4	5	6	7	8	9
Gully density (m/m^2)	0.5086	0.7404	0.8650	0.9640	1.1609	1.3551	1.8470	2.0437	1.9488
Erosion amount (kg)	1355.2	1461.3	1423.4	1881.7	979.7	1597.7	965.4		777.8

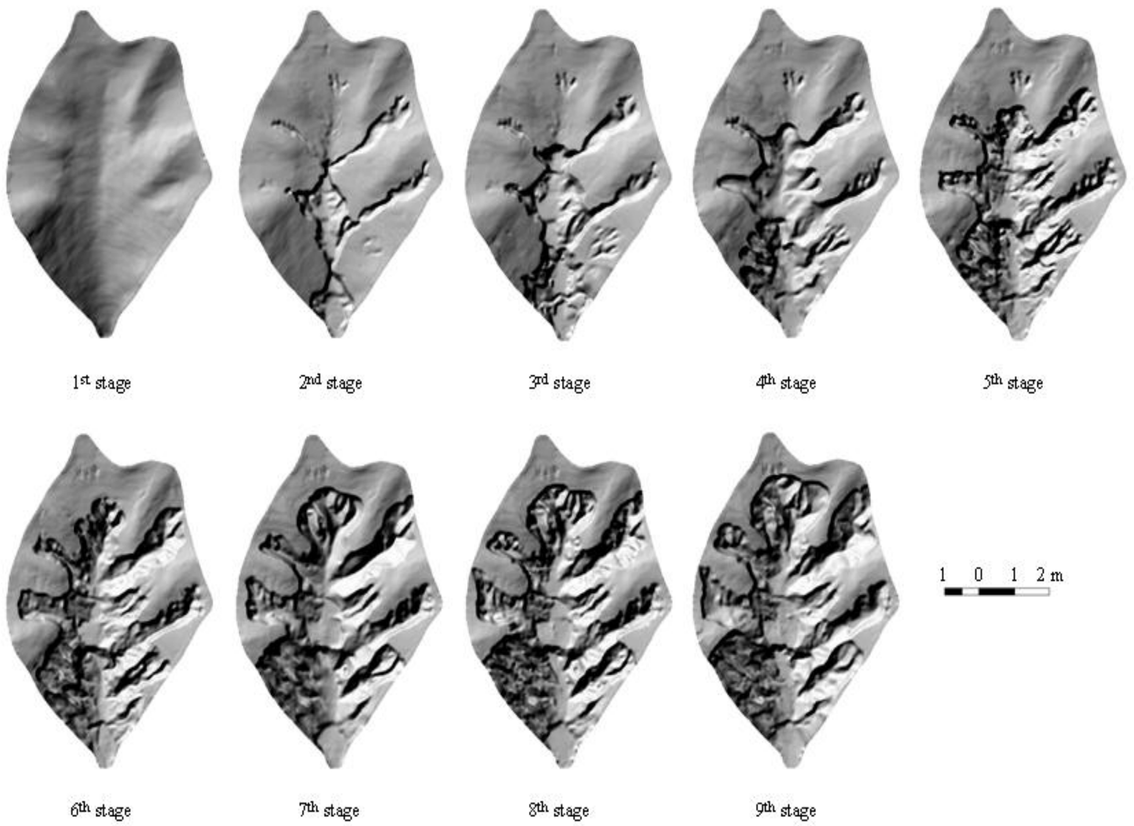

Figure 1 hillshade maps of stimulated watershed

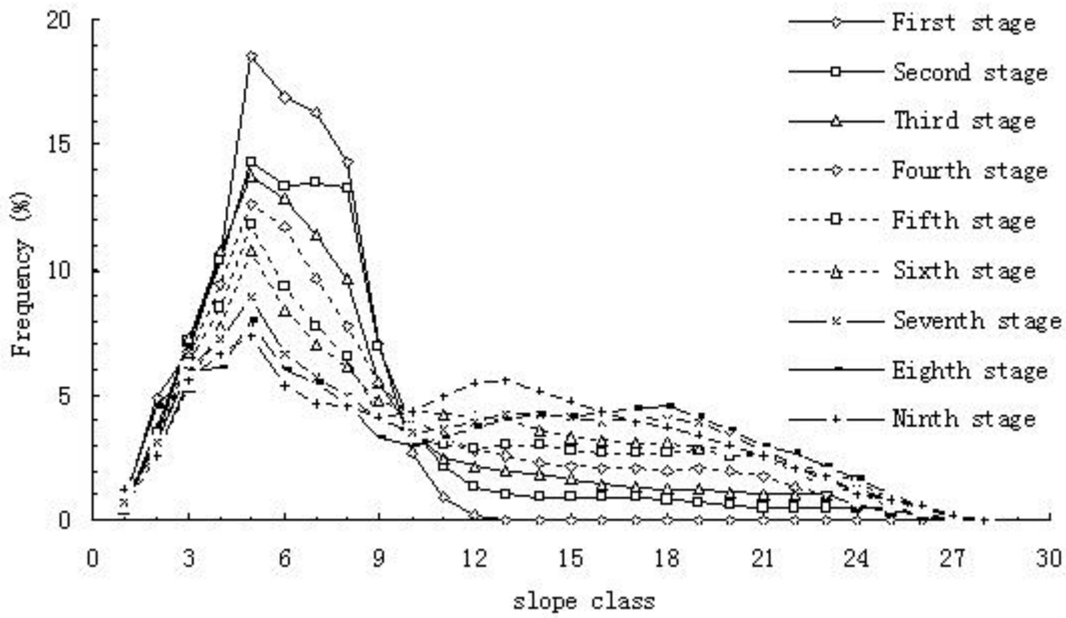

Figure 2 Slope spectrums of simulated watershed in different stage

Based on previous research, three factors are proposed to quantize the slope spectrum from different points of view, and five landscape indices are applied to quantize the slope-landscape TUPU (table 2).

Table 2 Algorithms for the calculation of slope spectrum indices

Quantitative index	Calculation	Remark
Slope spectrum Entropy (H)	$H = -\sum_{i=1}^{m} P_i \ln P_i$	m: number of slope class P_i: frequency of each slope class
Skewness of the slope spectrum (S)	$S = \sqrt{\frac{1}{6n}} \sum_{i=1}^{n} \left(\frac{P_i - \overline{P}}{\sigma} \right)^3$	$\overline{p}$: mean frequency σ: standard deviation
Terrain dynamic force (T_d)	$T_d = \sum_{i=1}^{m} \left(\left(\sum_{j=1}^{n} \sin \alpha_{ij} \right) / n \times P_i \right)$	i: number of slope class Pi: frequency of each slope class a_{ij}: slope gradient of grid ij j: number of grid for slope class i
Mean patch area ($AREA\_MN$)	$AREA\_MN = \sum_{j=1}^{n} a_{ij} / n_i$	a_{ij}: area (m^2) of slope patch ij n_i: patch number
Perimeter-Area Fractal Dimension ($PAFRAC$)	$PAFRAC = \frac{2}{\frac{\left[n_i \times \sum_{j=1}^{n} (\ln p_{ij} \times \ln a_{ij}) \right] - \left[(\sum_{j=1}^{n} \ln p_{ij}) \times (\sum_{j=1}^{n} \ln a_{ij}) \right]}{(n_i \times \sum_{j=1}^{n} \ln p_{ij}^2) - (\sum_{j=1}^{n} \ln p_{ij})^2}}$	p_{ij}: perimeter (m) of patch ij n_i: number of patches in the landscape of patch type (class) i
Contagion Index ($CONTAG$)	$CONTAG = \left[1 + \frac{\sum_{i=1}^{m} \sum_{k=1}^{m} \left[(P_i) \left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right) \right] \times \left[\ln (P_i) \left(\frac{g_{ik}}{\sum_{k=1}^{m} g_{ik}} \right) \right]}{2 \ln (m)} \right] \times 100$	P_i: proportion of the landscape occupied by patch type (class) i g_{ik}: number of adjacencies (joins) between pixels of patch types (classes) i and k based on the double-count method. M: number of patch types (classes) present in the landscape, including the landscape border if present.
Interspersion and Juxtaposition Index (IJI)	$IJI = \left[1 + \frac{- \sum_{k=1}^{m} \left[\left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}} \right) \ln \left(\frac{e_{ik}}{\sum_{k=1}^{m} e_{ik}} \right) \right]}{\ln (m - 1)} \right] \times 100$	e_{ik}: total length (m) of edge in landscape between patch types (classes) i and k m: number of patch types (classes)
Patch Cohesion Index ($COHESION$)	$COHESION = \left[1 - \frac{\sum_{j=1}^{n} p_{ij}}{\sum_{j=1}^{n} p_{ij} \sqrt{a_{ij}}} \right] \times \left[1 - \frac{1}{\sqrt{A}} \right]^{-1} \times 100$	p_{ij}: perimeter of patch ij a_{ij}: area of patch ij in terms of number of cells A: total number of cells in the landscape

3. RESULTS AND DISCUSSIONS

Figure 2 shows the temporal distribution of slope spectrum in different stage. Combined the research of Cui (2002), we can easily comprehend the meaning of it. Through long term carefully and thoroughly observation and analysis, Cui (2002) found that the average sediment transport ratio in every rainfall stage showed pretty obvious temporal distribution during the process of simulated watershed evolution. That is why he divided the simulated watershed evolution into three periods of time, i.e. early developing period (from the 1st rainfall to the 5th rainfall, with DEM stage 1-2), active developing period (from the 6th rainfall to the l8th rainfall, with DEM stage 3-6) and stable developing period (from the 19th rainfall to the 25th rainfall, with DEM stage 7-9). Erosion type of the watershed mainly showed surface erosion and gully headward erosion accompanied little gravitational erosion in hillslope area and accumulation in the channel. In early developing period, the sheet flow erosion is dominant, along with randomly downcutting in some gully bottom area; slope spectrums in this period present the frequency of low slope gradient rapidly decreasing as the frequency of high slope gradient increasing. In active developing period, downcutting in main branch gully is the most active, the gully bed gradually changes more undulate and many scarp are developing, meanwhile, an acceleration of gully headward erosion make quickly retreat of gully shoulder line; slope spectrums in this period present the frequency of low slope gradient gradually decreasing as the frequency of high slope gradient increasing equably. In stable developing period, gully headward erosion still is dominant, but the retreat of gully shoulder line obviously slow down, and gravitational erosion emerges in hillslope area accompanied local accumulation in some gully bottom area; slope spectrums in this period present the frequency of low slope gradient showing irregularly decreasing and increasing, meanwhile the frequency of high slope gradient maintaining increasing companied the emerging of second peak value, slope spectrums in this period also change from unimodal distribution into bimodal distribution.

Table 3 shows that in different stage of the simulated watershed, quantitative indices of slope spectrum maintaining continually changing. Mean slope, slope spectrum information entropy and terrain driving force keep increasing following the evolution of the simulated watershed, while skewness shows opposite changing. But there is one thing in common, i.e. all the indices keep changing actively in the periods of early developing period and active developing period, but slowly in stable developing period.

Table 3 Quantitative indices of slope spectrum in different stage

Stage	1	2	3	4	5	6	7	8	9
Mean slope	16.52°	20.76°	22.73°	25.30°	28.79°	29.67°	31.97°	33.24°	32.70°
Skewness(*S*)	1.563	1.411	1.419	1.356	1.339	0.875	0.313	-0.079	-0.231
Slope spectrum information entropy (*H*) (nat)	2.138	2.590	2.755	2.888	3.033	3.048	3.121	3.157	3.142
Terrain driving force (T_d)	0.283	0.342	0.369	0.406	0.451	0.468	0.498	0.514	0.511

Gully density is an overall comprehensive geomorphologic index, which can not only reveal degree of soil erosion, but also stage of landform evolution (Zhang et al, 1998; Lu et al, 2002). Gully densities of the simulated watershed are calculated respectively based on the DEMs (table 1). Correlation analysis of gully density and H, Td show positive correlation between them: gully density increase as *H*, Td increase (Figure 3-a、3-b). Integrated previous discussing, we think that in early developing period, gully density is small, so are the *H* and T_d; in active developing period following the strengthening of soil erosion, terrain relief become more stronger, especially in gully-hill region, gully density is big, so are the *H* and T_d. On the contrary, relations of S and gully density show negative correlation (Figure 2-c). It indicates that following the evolution of loess landform, slope distribution is more close to normal distribution, and the soil erosion intensifies gradually. Hence, it is toward of quantitatively depicting laws of landform evolution through slope spectrum based on detail research of slope spectrum, gully density and soil erosion.

Variation of *H* and T_d show quadratic function relationship with erosion amount (Figure 3-d、3-e). Which indicates in the process of simulated watershed evolution, the more intensive the rainfall erosion is, the more changefully the slope spectrum will be.

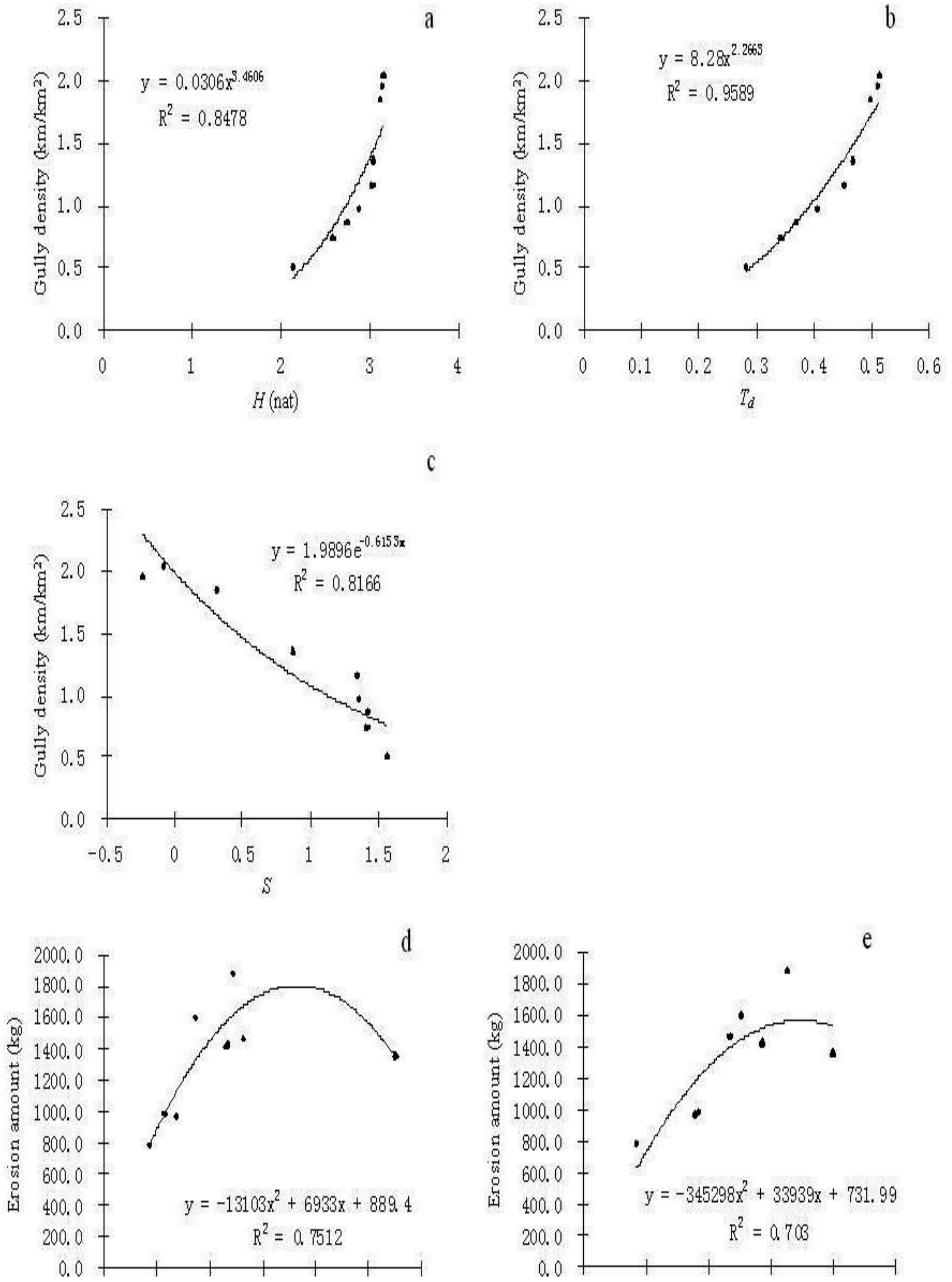

Figure 3 Scattergrams of quantitative indices of slope spectrum against gully density and erosion amount

Table 4 shows slope-landscape indices' structure of different loess landform at landscape lever. According it, the five indices show different changing ways and can be classified in two groups. One group includes *PAFRAC* and *IJI*, they keep decreasing following the evolution of the simulated watershed. The other group includes *AREA_MN*, *CONTAG* and *CONHESION*, they keep increasing following the evolution of the simulated watershed. The *PAFRAC* and *IJI* in early period are smaller than that in later period, whilst the *AREA_MN*, *CONTAG* and *CONENSION* in early period are bigger than that in later period. This suggests that, in the early period of simulated watershed, fragmentation of the patches of slope class is small, the patches distribute connectively, and the patch shape is regular than that in later period.

The loess surface in early period terrain are smooth relief, so the *AREA_MN* now is large than that in later stage. This also suggests that, in early period fragmentation of slope class patches is big, the patches distribute connectively, and the patch shape is regular than that in later stage. Actually, *PAFRAC* in different stages show little difference (change from 1.314-1.576), which indicates comparability of the patches shape in general.

Tab.4 Slope-landscape indices in different stage at landscape lever

Stage	1	2	3	4	5	6	7	8	9
AREA_MN (m^2)	1.982	0.218	0.184	0.166	0.103	0.121	0.116	0.091	0.109
PAFRAC	1.314	1.512	1.538	1.555	1.569	1.565	1.577	1.579	1.576
CONTAG (%)	55.217	49.865	45.676	42.402	37.325	37.324	35.598	34.26	34.220
IJI (%)	48.958	62.631	63.638	63.37	67.155	64.355	64.979	65.91	64.749
COHESION (%)	99.080	95.992	94.438	93.36	90.728	90.655	89.970	87.470	88.197

4. CONCLUSION

With the technology development of geomorphological experiment simulated, DEM data availability and GIS-assisted processing of DEM data, it became more and more easy to establish a loess watershed which the loess material and surface relief could correctly represent the true loess surface. And this offers us a better platform to investigate the micro processing of loess landform evolution driving by rainfall. It also makes it reality for validating some geographical phenomena in controllable period.

A series of carefully designed test with the loess simulated watershed proved that time series of slope spectrum show obvious temporal distribution following the evolution of the loess simulated watershed. Compared with the spatial distribution of slope spectrum in the Loess Plateau (Li, 2007), we could make the conclusion that both the spatial series and time series of slope spectrum show obvious spatial or temporal distribution. Following the loess landform changing from loess Yuan to loess ridge then to loess hill (or the gradually evolution of the simulated watershed) all the quantitative indices of slope spectrum show similar change rule.

So the slope spectrum is potentially capable of delineating the spatial or temporal distribution of loess landform. A continuous change of slope spectrum shows a strong relationship between slope spectrum and loess landform. Our research also suggests a relation between digital terrain analysis and landscape ecology. It will be beneficial to complete quantitatively research of loess landform, and to extend application of DEM and complete methodology of digital terrain analysis in the Loess Plateau.

Acknowledgement

Thanks for financially support from the Natural Science Foundation of China (Grant No. 40801148 and 40930531). We are very grateful to Prof. Dr. Josef Strobl for his constructive critique on the manuscript.

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