Soil Erosion Information Entropy: A Comprehensive Measure Index and Simulation Tool for Land Surface Erodibility

Zhu Qijiang, Shuai Yanmin, Chen Xue and ***Gan Dayong***

Research Center for Remote Sensing Dept. Geography, and Beijing Key Laboratory for Remote Sensing of Environment and Digital Cities, Beijing Normal University, Beijing, 100875, China
E-mail: chxue@mail.bnu.edu.cn

Abstract: The author put forward the concept for soil erosion information entropy，and expressed by $H = -K\sum_{i=1}^{n}\sum_{j=1}^{m} \omega_{ji}a_{ij}\log(\omega_{ji}a_{ij})$ where K represents unit transform coefficient for information measurement, a_{ij} represents contribution of the jth type corresponding to the ith factor to soil erosion, ω_{ji} represents the weight of the jth type for the ith factor. Soil erosion information entropy, in essence, reflects synthetical information about internal aspect of the ground and also is a comprehensive measure index for erodibility, when related factors of soil erosion are divided into external factor such as precipitation and internal factors such as terrain, physical and chemical properties of soil, land use and land cover, crop, water and soil conservation factors, etc..

Human beings cannot control precipitation process so far, but they do have influences on soil erosion caused by precipitation through change of land surface. Soil erosion information entropy effectively simulates the process of land surface change and manifests its results directly. So it provides a quantative analysis tool for benefit estimation on water and soil conservation. The product of erosion information entropy and precipitation erodibility R(R=EI30), which is αHR (α is unit transform coefficient), can illustrate quantatively the amount of soil erosion and its spatial distribution. This paper also gave a case study at HongShuigou watershed located on tributary of SanChuan river in Shanxi province and gained fairly good results.

Keywords: soil erosion, erosion factor, erosion model, soil erosion entropy, remote sensing

One kernel problem in soil erosion is how to determine the amount of soil erosion in a given district. Several quantative analysis models have been set up for each single factor or multi-factors of soil erosion from different view of point. Universal Soil Loss Equation (1965) and Revised Universal Soil Loss Equation (1995) founded by Wischmeier H.H and Smith D.D are most widely used models in the world. CREAMS model (1980) used for controlling nonpoint source pollution in US and WEPP model (1995) used for replace USLE were developed. ANSWERS (1980) is a distributed event oriented watershed soil erosion model based on physical causes.

The integrating of geographic information system and soil erosion model is a new feature in the research of soil erosion. Remote sensing is a brand new method to obtain information of land surface soil erosion factor, but how to extract information from remote sensing data and how to use the information to proceed soil erosion quantative research is a new but momentous problem. This paper discussed the building-up, presentation and application of soil erosion model based on the integrating of remote sensing, geographic information system and soil erosion model.

1 Soil erosion model based on remote sensing information

(1) Soil erosion information extraction from remote sensing data

Precipitation, vegetation coverage degree, topography, soil erodibility and human activities that reflected by land use are all influential factors of soil erosion. Remote sensing image can be recognized as superpose of many erosion factors on record media though delivery. The frequency of information changes in the process of delivery by modulation of atmosphere, imaging system and record media, as a result of which, the borderline of target is not so clear as original signal and soil erosion information cannot be read directly from remote sensing images, but can be reflected by each erosion factor. Therefore, the first mission to set up remote sensing model of soil erosion is to extract status information of each erosion factor from remote sensing images. This work is coming through by interactive remote sensing image interpretation and produces a series of soil erosion factors images. One point needed to illustrate is that precipitation factor comes from meteorological observation not remote sensing image and topography factor is generated from DEM established by scanned topography map.

(2) Add mode of information entropy

Information that people have interested in is often implicit in uncertain thing or process. For instance, erosion information of a given pixel or watershed is uncertain. For a random variable X which has limited values:

$$X = \begin{pmatrix} x_1, x_2, ..., x_n \\ p_1, p_2, ...p_n \end{pmatrix}$$

Information Entropy $H(X) = -c\sum_{i=1}^{n} p_i \log p_i$,probability $p_i \geqslant 0$，$\sum_{i=1}^{n} p_i = 1$，c is a constant, which determined by information measure unit. When the base of the logarithm is 2, the unit of entropy $H(X)$ is bit, while the unit of entropy $H(X)$ is Hantley when the base of the logarithm is e.

The feature expressed by $H(X) = H(Y) + H(X/Y)$ is called add mode of information entropy. Where $Y = f(X)$, $H(X/Y)$ is conditional entropy of X, and is defined as:

$$H(X/Y) \equiv -\sum_{x,y} p(x,y) \log p(x/y)$$

where $p(x,y)$ and $p(x/y)$ are union distribution and condition distribution probability of X and Y respectively. The essence of soil erosion information entropy is on the basis of the add mode of information entropy.

Soil erosion in Entropy is the function for the status of soil erosion system; the increase of entropy symbolizes the dissipation of megascopic energy in the aspect of quality. The amount of entropy specifies the evolutional stage of the system.

(3) formation entropy model

Soil erosion information entropy is defined as following when the type of soil erosion is *j*(*j*=1,2,···,*m*):

$$H = -K\left[\sum_{i=1}^{n}\sum_{j=1}^{m} \omega_{ji} a_{ij} \log(\omega_{ji} a_{ij})\right] - e$$

where a_{ij} represents contribution of the jth type corresponding to the ith factor to soil erosion, ω_{ji} represents the weight of the jth type for the ith factor, and e is model adjustment parameter, representing effect of all non-considered factor to soil erosion.

Erosion entropy increases when soil erosion turns worse and decreases when it alleviates. The irreversible processes happening in the soil erosion system are always accompanied by the increase of entropy. The increase of entropy implies the quality of system energy becoming worse and worse and dissipating although the amount is conserved. The spatial representation of soil erosion information entropy requires the support of geographic information system.

2 Experiment data and results

(1) Experiment region and remote sensing data

Hongshuigou watershed, which is the first grade branch of Sanchuan River in Loess Plateau at west of Shanxi Province, is the research target of this paper, and it is located in 111º3'—111º8'E, 37º22'—37º29'N. The watershed is stripe shape, with 14.4km from north to south and 4.35km from east to west, covering an area of 36.34km^2. Its elevation is between 883 meter and 1,350 meter, and the average precipitation of multi-years is about 516.5mm. The watershed is situated in the mound gully region of Loess Plateau, the area of gullies and hill-land accounting for 44% and 51.8% respectively and the average gully density being 5.43km/km^2. It's a typical mound gully region in Loess Plateau, the slope of whose main trench is 2.34%, and 55.5% region's slope is more than 25º. The bedrock of the watershed is primarily arenaceous shale and limestone in partial, draping with the tertiary laterite and the quaternary loess. The area of soil erosion is highly as 95% and soil erosion modulus is 13,000 ton/km^2, so it is typical in the sandferous middle reaches of Yellow River.

A special designed large-scale aerial color infrared photograph in Hongshuigou watershed was taken in August 1990. The photographical scale is 1:14,000, then, the photos were made into 1:5000 orthorectified images after orthorectification. After those images interpreted, land cover map, vegetation cover map, lithology distribution map, landforms map and soil erosion map were generated. In addition, a SPOT-HRV image of 1988 and 1:5,000 black-white aerial color infrared photographs of September 1981 were available.

(2) Produce topography factor data

The 1:5,000 topography map was scanned into computer and digital elevation model was generated. Least square method was used to fit planarity

$$Z = ax + by + c$$

The angle of this planarity and planarity $Z = 0$, is slope angle

$$\theta = \arccos\left(\frac{1}{\sqrt{a^2 + b^2 + 1}}\right)$$

The direction of the slope is:

$$\alpha = \begin{cases} \operatorname{arc}\left(\frac{b}{\sqrt{a^2 + b^2}}\right) & when \quad a > 0 \\ \operatorname{arc}\left(\frac{b}{\sqrt{a^2 + b^2}}\right) + 180^\circ & when \quad a < 0 \end{cases}$$

(3) Category and weight of soil erosion factors

From the standpoint of erosion resistance, lithology is divided into 7 grades, landforms is divided into 8 grades, land cover type is divided into 13 grades and vegetation cover degree is divided into 6 grades (Table 1).

The maximum contribution weight of each erosion factor was set as 1, while the minimum was set as 0. The contribution value of each factor at different grade was come up (Table 2).

Table 1 Category of soil erosion factors

category / subcategory / Serial number	Slope	Land use	Lithology	Valleys and gullies distribution	Vegetation cover degree
1	≤ 3º	damland,gully land	Q_4	broken region	>70%
2	4º—8º	ridge land	Q_3	top of hill-land	70%—50%
3	9º—15º	terrace	Q_2	slope of hill-land	50%—30%
4	16º—25º	sloping cultivated land	N	valleys and gullies	30%—10%
5	26º—35º	sloping terrace	K	warping dam	<10%
6	≥ 36º	orchard	P	landslide	non forest or grassland
7		woodland	resident	slide cliff	
8		shrub		resident	
9		sparse forest			
10		non grown forest			
11		grassland			
12		resident			
13		bareland			

Table 2 Contribution value a_{ij} of each factor at different grade

category / grade / a_{ij}	1	2	3	4	5	6	7	8
slope	0.04	0.16	0.36	0.64	1	0.9		
land use	0.1	0.2	0.1	1	0.9			
lithology	0.1	1	0.85	0.55	0.15	0.1	0.1	
Valleys and gullies distribution	0.1	0.25	0.8	1	0.1	1	0.5	0.1
Vegetation cover degree	0.2	0.4	0.6	0.8	1			

Soil erosion requires to be treated diversely. Hongshuigou watershed can be divided into two groups: agricultural field and wood and grass field. As to agricultural field, lithology, land use, valleys and gullies distribution and slope factor are to be considered. For wood and grass field, lithology, vegetation cover degree, valleys and gullies distribution and slope factor are to be considered. Furthermore, wood and grass field are divided into four types, namely as low slope and high cover degree, low slope and low cover degree, high slope and high cover degree, and high slope and low cover degree.

Based on soil erosion intensity map and erosion factors distribution map of the watershed, 50 groups of ground data were used to simulate the linear equation of the above five situations:

$$S = aX + bY + cZ + dU + e$$

where: S is the amount of soil erosion, X, Y, Z, U are the value of each factor, a, b, c, d are the weight of each factor, e is the weight of all those unconsidered factors. Table 3 is the weight of each factor at five situations.

Table 3 Weight of each factor at five situations ω_i

category / ω_i / situatio		Slope	Valleys and gullies distribution	Land use	Vegetation cover degree	lithology	Other
agricultural field		0.33	0.21	0.24		0.12	0.10
wood and grass field	1	0.06	0.05		0.05	0.07	0.04
	2	0.17	0.06		0.21	0.15	0.06
	3	0.35	0.12		0.17	0.18	0.16
	4	0.22	0.18		0.24	0.19	0.17

(4) Computation of soil erosion information entropy

Since the data adopted grid structure, each pixel occurs at equivalent probability. If the proportional coefficient C=100/ln4, the value domain of erosion entropy is［0，100］.Theoretically, if the weight ω_i of each factor is equal, erosion entropy is 100; if one of the weights is 1 and others are 0, erosion entropy is 0. The virtual value domain of erosion entropy is [1， 86], and its statistical histogram is multi-peak.

3 Results analysis and prediction

The erosion entropy was spitted in the light of the distribution characteristics of the entropy histogram and referring to soil erosion distribution map (Figure 1) from experience interpretation, and then the erosion entropy distribution of the watershed (Figure 2) was created. The two figures presented striking correspondence. Table 4 compared the pixel of erosion entropy grading map with soil erosion intensity map. From this map, pixel statistic of erosion intensity is agree with that of erosion entropy. This is not coincidence but indicates the erosion entropy model contains abundant core information of soil erosion factors and is an objective measure of land surface erosion.

Table 4 Pixels of intensity of soil erosion and erosion entropy grading

Erosion intensity grading (m.m/a)	Grade of erosion entropy	pixels of erosion intensity grading	pixels of erosion entropy grading	pixels of erosion entropy grading of Figure 3	pixels of erosion entropy grading of Figure 4
Micro erosion <0.8	1—20	3,679	3,672	5,510	5,511
Light erosion0.8—2.0	21—57	970	998	850	1,547
Medium erosion 2—4	58—66	1,338	1,191	854	3,029
Intensity erosion 4—6	67—73	1,288	1,204	777	948
High tensile erosion 6—12	74—77	1,481	1,209	1,029	2,283
Violent erosion 12—20	78—79	2,309	3,063	2,317	970
Extreme violent erosion >20	80—86	3,229	2,957	2,957	0

Fig. 1 Distributio of soil erosion

Fig. 2 Present situation of erosion entropy

Fig. 3 Prediction 1 of erosion entropy

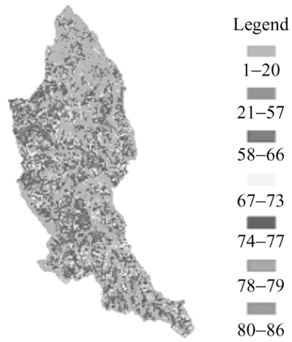

Fig. 4 Prediction 2 of erosion entropy

According to the USLE, determiners of land surface intensity can be divided into external factors and interior factors. Erodibility of rainfall R is external factor, while the remained factors for instance soil erosion resistance, land use, vegetation cover degree, topography, crop factor, etc, are all interior factors. External factors function though interior factors and erosion entropy is the comprehensive expression of those interior factors.

The principle of water and soil conservation is to control water and soil loss by changing interior factors. So, soil erosion entropy provides an effective tool for simulating soil erosion process and predicting soil erosion situation and can be used widely in water conservation plan. Figure 3 is erosion entropy distribution of the watershed under conditions of rebuilding the sloping field of 8º—25º to terrace while Figure 4 is rebuilding the sloping field of 8º—25º to terrace and planting trees in the sloping field of 26º—35º and vegetation cover degree reaches 50%—70% in ten years. The last two columns of table 4 is soil erosion entropy distribution change under two predictions. Figure 3 and Figure 4 shows visual prediction map of water and soil conservation effect, and the result is self-evident.

4 Conclusion and discussion

Soil erosion factors are divided into external factors and interior factors. External factor refers to precipitation factor and interior factors are topography, soil physical and chemical property, land use, vegetation cover degree, crop and water conservation measurements. Soil erosion entropy, in its essence, reflects comprehensive information of interior factors in eroded plot, and is a measure index of land surface erodibility. Though mankind is not able to control precipitation process at present, they do have effect on erosion by changing land surface situation. Soil erosion entropy is available to simulate the consequence of man's activities, present visually the effect, and so offer a tool for quantative analysis of water and soil conservation benefits.

The core of erosion entropy model is to determine erosion factors and their weights. This experiment did not use all factors, and needs further study. Moreover, the product of normalized erosion entropy and erodibility of rainfall R ($R=EI_{30}$) can be used to determine the real erosion intensity of each pixel, making into a soil erosion model which not only fit for slope but also suitable for watershed. The model uses grid-structured data, and is easily to realize the accommodating of remote sensing data and integrating with geographic information system, so it can become a multi-scale soil erosion model.