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Regional Evaluation of Soil Erosion by Water: a Case Study on the Loess Plateau of China

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Abstract

This chapter discusses how spatial information techniques can be used to predict and evaluate regional soil erosion. The study, carried out in central China, identified sediment discharge, precipitation, soil composition, gully density and land use as the controlling factors of regional erosion. The authors found that soil erosion can be assessed and predicted quantitatively at a regional scale; that quantitative evaluation can be used to study and describe the soil erosion mechanism at the macro scale; and that soil erosion at the national or provincial scale can be rapidly surveyed using remote sensing, geographic information systems (GIS) and erosion modelling.

本研究以黄土高原为例，在分析了区域水土流失过程、类型和分布特点的基础上，拟订了区域水土流失评价指标体系，包括：沟壑密度、汛期降雨量、土壤团粒含量、植被盖度、坡地面积比等。根据遥感影像划分编制了评价单元图并在 GIS 环境下集成各评价因子建立了评价数据库。根据地理统计方法建立了评价模型。研究表明：区域水土流失宏观趋势的定量评价预测是可能的，基于水土保持类型区的定量评价，可以揭示区域水土流失的宏观规律，进而实现区域水土流失快速调查是可能的。最后对于模型进一步改进方法和途径进行了讨论。

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CHINA suffers severe soil erosion (Xianmo Zhu et al. 1999; Qinke Yang 1994). As the country's economy has developed, soil conservation and ecological rehabilitation have been increasingly taken into account and land-use policy has shifted its focus from small watersheds to large regions (China's Agenda 21 1994; Posen et al. 1996). As a result, policy makers and those responsible for planning soil conservation and environmental rehabilitation measures are demanding systematic information about the current situation and trend of soil erosion, and the benefits of soil conservation and ecological rehabilitation practices. This information is required urgently and will need to be continually updated.

Regional soil erosion and conservation are not just local effects; they also affect the surrounding region, including rivers downstream. Widespread events such as floods, sediment deposition in rivers and reservoirs, dust storms, land degradation and water shortages may result from localised erosion events. Consequently, we must quantify and predict the degree and effects of soil erosion at the regional, national and even global scales.

Spatial information sciences and techniques — including remote sensing, geographic information systems (GIS), global positioning systems (GPS) and related internet technology — have been widely applied to soil erosion monitoring and surveying since the 1980s. In China, the technology for modelling and predicting soil erosion has been developed and applied at the regional scale using GIS and remote sensing (Rui Li et al. 1998; Qinke Yang and Rui Li 1998; Feng Jiao et al. 1998). Usually the study area is divided into several integrated spatial units, so the heterogeneous characteristics or spatial differentiation of the units can be taken into account. Most research into erosion evaluation and prediction has been carried out at the scale of the slope or plot (Renard et al. 1997); there have been relatively few regional studies. Where studies have been carried out, they have usually been based on small areas, with scaling up and/or aggregation being used to extrapolate soil erosion data to a

regional or even global scale (Posen et al. 1996; Kirkby et al. 1996; Qinke Yang and Rui Li 1998).

China has been divided into eight soil erosion areas and the soil erosion trend in each has been predicted by relating sediment discharge to factors such as annual runoff, daily maximum runoff and control area (%) (Peihua Zhou 1988). Soil erosion data can also be obtained by the aggregation method using plot data from the United States Department of Agriculture (USDA) monitoring network (Rui Li et al. 1998). However, the problems of evaluating and predicting soil erosion regionally are not entirely solved.

Methodology

Study area

The study area was the 623,700 km² Loess Plateau, in central China. The plateau includes the southern part of Ningxia Autonomous Region, the whole of Shanxi Province, northern Shaanxi Province, the eastern and central parts of Gansu Province, the southern part of the Inner Mongolia Autonomous Region, and the western part of Henan Province. It borders the Riyue Mountains to the west and the Taihang Mountains to the east; and it extends from Qinling Mountains in the south to the Yingshan Mountains in the north. Figure 1 in the Overview shows the general location of the area.

The Loess Plateau is located in the second of the three grand relief landform terraces in China. The basic geomorphological types include loess hills, sand-loess hills and loess tableland; the gully density is 4–6 km/km² and 40–60% of the area has gullies. The climate is continental monsoonal, with mean annual temperature between 6.6 and 14.3°C and mean annual precipitation between 250 and 700 mm. Rain falls mainly in summer (50–70% of the annual total) and is most intense from July to October. The dominant soils are widely eroded, especially in northern Shaanxi Province, central eastern Gansu Province and western Shanxi Province. Secondary vegetation is limited to only a

few stony hills. For over 2000 years, crop growing has been the main form of land use in the area. The population density is 40–270/km². The relationship between the agricultural activities of people and the natural environment is not harmonious.

Figure 1 shows how erosion can be subdivided according to erosive intensity. According to this classification, the Loess Plateau has three erosion regions: the water erosion region, the wind–water erosion region and the wind erosion region.

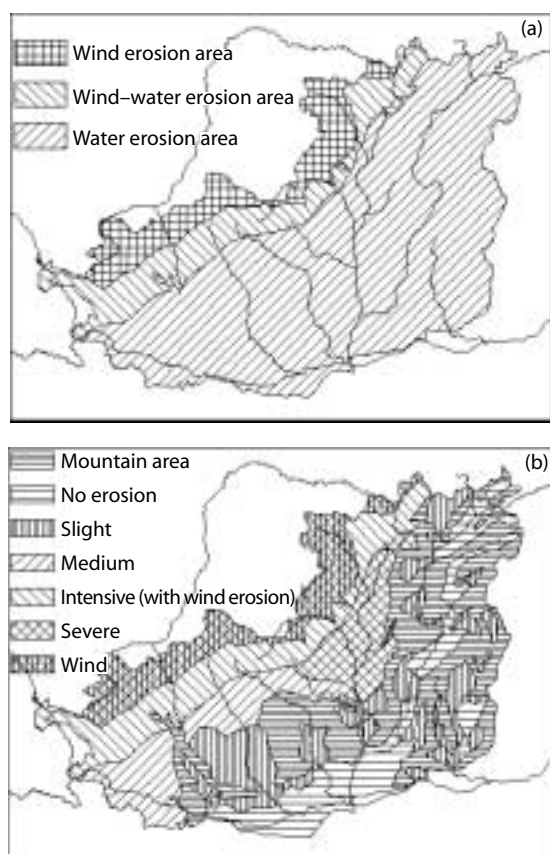


Figure 1. Soil erosion map of the Loess Plateau, showing (a) the types of erosion and (b) the major regions of erosion.

Data and materials

Field surveys and cartographic research by Xianmo Zhu (1981a, b; 1982a, b) show that regional soil erosion is a very complicated process that is affected

by many factors, including geomorphology, soil conditions, meteorology, hydrology, land use, vegetation coverage and soil conservation measures. By analysing these environmental factors and how they affect erosion, we describe the processes of regional erosion and quantitatively evaluate the interactions of the factors and the ability to semi-empirically model the spatial distributions of erosion intensity. In this study, we use the following data.

- **Sediment discharge data** were obtained from the records of 250 hydrological stations covering the period from 1959 to 1986.
- **Precipitation data** measured from 1955 to 1986 at 178 meteorology stations were used to calculate the mean rainfall in the rainy season (July to October).
- **Soil classification data** were obtained from the 1:2,000,000 Loess Plateau soil map produced in 1991 by the Institute of Soil and Water Conservation (ISWC), the Chinese Academy of Sciences and the Ministry of Water Resources. Soil organic matter content data were extracted from monographs that reported the results of the second national soil survey.
- **Gully density data** were determined from gully density annotation points from a 1:500,000 soil erosion map of the Loess Plateau that was produced in 1991.
- **Land-use data.** We estimated the ratio of cropland to forest/grassland from a 1:250,000 land-use map in ArcInfo format, produced by ISWC in 1993 based on the interpretation of Landsat Thematic mapper (TM) data (see Chapter 16 for further details).

Precipitation, sediment and gully density data were in coordinate format (x,y,z) and were spatially interpolated and contoured using ArcInfo. All data were transformed into the Albers projection.

Parameters and database

Table 1 shows the parameters selected for the evaluation. Their choice was dictated by what was needed for prediction and by what was available over the entire study area.

The characteristics of regional soil erosion vary over space and time. Consequently, multilevel areas and classes of erosion can be identified. The study of erosion on a regional scale is based on experimentation and observation at plot and watershed scales, but the data cannot simply be extrapolated from a slope surface or other small area to a larger area using spatiotemporal modelling of the environment (Burough 1998).

To adequately describe the study, the study area must be discretised in space and time. Conventionally, geonities in space are described by vector data such as points, lines and polygons and other common factors. We divided our study area into 3380 spatial units of uniform map area (UMA) according to Landsat TM imagery.

The parameters were processed into map format and integrated into each of the UMAs, based on the theory and method of the georelationship model. During the process of integration, the data for location and topology were based on the UMA map or base map. The number of data entities on the base map remained constant during data integration.

Results and Analysis

Modelling regional erosion

The general format of the model of regional erosion is:

$$A = f(Q, S, g, v, c) \quad (1)$$

Table 1. Parameters used in the evaluation.

Erosion factor	Soil erosion	Climate	Soil	Plant	Land use	Relief
Parameter	Sediment intensity	Rainfall in wet season	The fraction of soil (g/kg) with a diameter > 0.25 mm	Plant cover	Slope to area ratio	Gully density

where A is the erosion intensity, Q is a hydrological/climate factor, S is a soil factor, g is a landform factor, v is a vegetation factor, and c is a conservation measure factor.

There is an exponential correlation between the amount of erosion, the amount of rainfall in the rainy season, the gully density, the proportion of slope cropland, the coverage of vegetation and the content of aggregate (≥ 0.25 mm) (JunJie Ma 1990; JiYang Liang 1992; QiuSheng Wang 1991). The relationship can be expressed as:

$$L = 0.4735P^{0.9282} S^{-0.08855} \times G^{2.2666} M^{0.07254} e^{-0.00047C} \quad (2)$$

where L is the erosive intensity (tonnes/km²/year), P is the precipitation in the wet season (mm), S is aggregate content (g/kg), G is the gully density (km/km²), M is the ratio of slope cropland (%), and C is vegetation cover (%).

The highly significant regression result ($r = 0.937$, $F = 2984.64 \gg F_{0.05} = 2.21$ where F is the F -statistic, which is much higher than the level for 5%) indicates that the erosive intensity is positively correlated with rainfall quantity in the wet season, gully density, and the proportion of slope cropland. It is negatively correlated with the content of aggregate and vegetation cover. In other words, the higher the rainfall in the wet season, the greater the erosion intensity; the higher the aggregate content and vegetation covering, the lower the erosion intensity. This accords with general principles of soil erosion, and with other research in this field.

Evaluating the erosion factors

We have identified five variables controlling erosion regionally. These variables can be converted into

specific units and extracted from existing survey or remote sensing information. The variables are suitable for a macro study to evaluate trends, as in our study. Land-use data provide some indication of the extent to which soil and water conservation are practised in the region. For the purpose of analysing erosion potential, the landscape can be categorised into plains, terraces, hills and mountains. There are obvious differences between the categories in patterns of erosion, measures and patterns of soil conservation and types of reasonable land use. Topographic maps and TM imagery have made it possible to determine locations with a high degree of accuracy. As the UMA map has 2230 polygons and the 1:500,000 Loess Plateau erosion map has only 1100 polygons, each UMA can contain values derived from different thematic layers. Thus, erosion levels can differ within UMAs for the same landscape zone.

We applied several algorithms for attribute values from the maps (in digital format) to the databases. We used a flexible method to calculate the relationship between location and descriptive data. Consequently, all variables in the model can be integrated into the UMA map, and a database with multi-items can be built to satisfy the demands of multifactor evaluation (Qinke Yang 2001).

Figure 2 is a GIS map showing soil erosion calculated using Equation 2; it shows the relationships among the different factors affecting soil erosion and accords with the spatial differentiation pattern of soil erosion observed on the Loess Plateau. The result is useful in macro policy making.

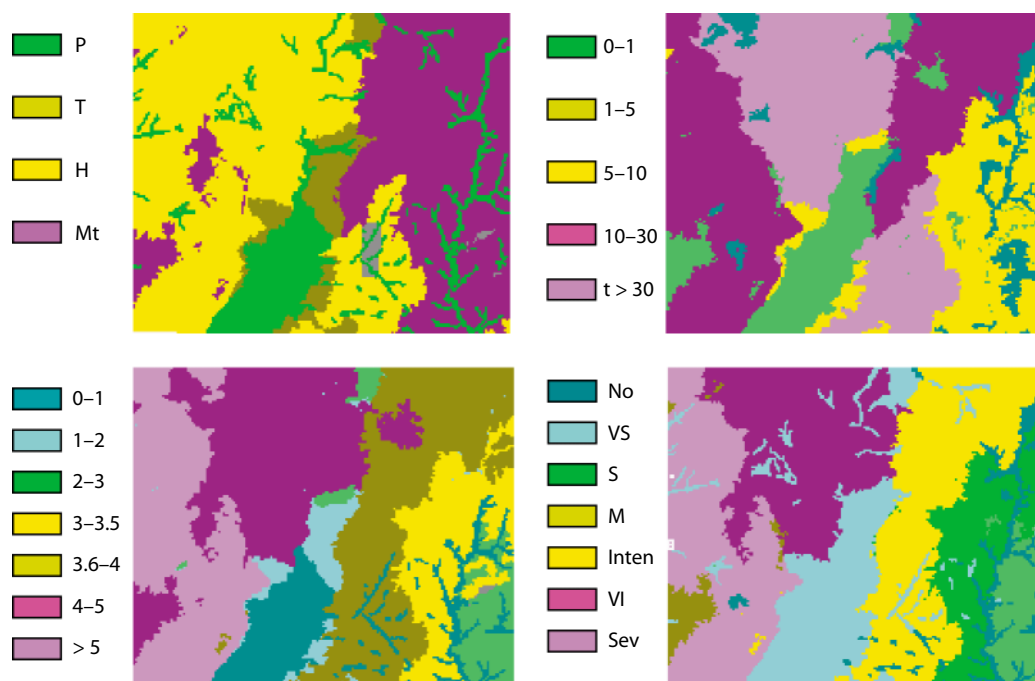


Figure 2. An example of factors influencing regional erosion modelling for a 127 km × 117 km portion of the Loess Plateau situated in Shaanxi Province. The top left image is of landform; P is plain; T is tableland; H is hill; and Mt is mountains. The top right image is the percentage slope of cropland for each polygon. The lower left image shows the density of gullies (km/km²). The lower right image illustrates erosion intensity (t/km²/year), which can be used for regional decision making on soil erosion control and ecorehabilitation; No is none, VS is very slight, S is slight, M is medium, Inten is intensive, VI is very intensive and Sev is severe.

Modelling regional soil erosion

Equation 1 allows runoff modulus ($\text{kL}/\text{km}^2/\text{year}$) to be used as a measure of relevant hydrology factors (Q) and soil antiscourability (kg/kL) as a measure of soil factors (S). Information for the landform factor (g) can be derived from regional DEMs, where the relative relief — the maximum elevation difference in a specified area — is used (Xinhua Liu et al. 2001). The remaining two factors, the vegetation index and soil conservation index, can be derived from advanced very high resolution radiometer (AVHRR) data (see Chapter 16 for further details) and soil conservation statistics, respectively.

Discussion

It is possible and practical to quantitatively assess and predict macro trends in soil erosion at the regional scale, using the theory and methodologies of regional soil conservation and GIS. The methodology involves:

- dividing the study area into discrete units in space and time with homogeneous factors and erosion types based on the analysis of processes and the spatial differentiation of soil erosion and related environmental factors at the regional scale;
- using research on the factors affecting regional erosion and the results of erosion evaluation studies, coordinated with the characters of GIS modelling methods, to identify the relevant parameters of the model;
- extracting the parameters one by one from many kinds of approaches, including field tests, thematic maps, descriptions of observed materials and remote sensing imagery/DEM analysis, and integrating all the parameters into the basic unit map to build up a parameter database; and
- establishing a statistical model for the sediment discharge (the sediment yield from erosion) and each relevant factor using geostatistical and correlative analysis methods.

Our study supports unpublished work of the national soil erosion survey that suggests that remote sensing, GIS and erosion modelling can be used to efficiently survey soil erosion at the national or provincial scale. In the 1980s, it took about 10 years to map soil erosion in China at the national scale using mainly manual methods; in 1998–2000, it took only two years to do the same using a combination of manual and computer methods. When we have all the basic information at the national scale, we will be able to survey erosion quantitatively and annually. The increased timeliness in providing a nationwide overview by performing this massive task in temporal GIS (TGIS, see Chapter 16) will allow cost–benefit analysis of soil conservation and ecological rehabilitation practices to feed back more quickly into policy decisions and directions. The development of this TGIS will not only allow monitoring of the environmental response, but also allow central government officials to determine the effectiveness of money spent in different regions.

Conclusions

This study has shown that soil erosion can be assessed and predicted quantitatively at a regional scale; and that soil erosion at the national or provincial scale can be rapidly surveyed using remote sensing, GIS and erosion modelling. The information so provided will assist macro policy making at the national and provincial levels. The accurate evaluation and prediction of regional soil erosion should be based on systematic research on the genesis and evolution of erosion at the macro scale, and on the factors that cause erosion. The current situation is far from perfect; we are doing more work on this topic.

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