A STUDY ON QUANTITATIVE MONITORING OF SOIL LOSS IN SMALL WATERSHED BASED ON GIS

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ABSTRACT:

Soil erosion is a serious environmental and production problem in the Three Gorge Areas (TGA) of China. The objectives of the study were to develop and validate a soil erosion-predicting model based on the revised Universal Soil Loss Equation (RUSLE) in a geographic information systems (GIS) environment. The use of GIS to develop conservation-oriented watershed management strategies in the Taipingxi watershed is presented. The study showed that the serious eroded area (sediment is higher than 50 t/ha) is 10.62%, but contributes 61.55% sediments of all watershed, while no or slightly eroded area (sediment is lower than 10t/ha) is 62.18%, only contributes 3.49% sediments in the watershed. In the watershed, the annual average soil loss rate from relatively flat agricultural land was approximately 21 t/ha, whereas 48 t/ha was found on the cultivated sloping lands, which constitutes a large proportion of soil loss.

1. INTRODUCTION

The Three Gorge Project (TGP) of China necessitates the resettlement of over 1 million population (mostly farmers) to more rugged and isolated areas than their original settlements. It is probably the first time in Chinese history that so many people are relocated to marginal lands, which are mostly on steep slopes, with soil of poor structure. The climate is humid and subtropical. In general, high soil loss rates occur during intense storms. Moreover, intensive cultivation and socioeconomic pressure for more land have accelerated the rate of soil erosion on sloping lands. Soil erosion is a key factor determining the ecological sustainability of such a resettlement scheme. If this problem is not adequately addressed, not only will the well being of the resettled people suffer, but also the functionality of the Three-Gorge Dam.

To evaluate the soil erosion of the TGP, there is an increasing demand for a more cost-efficient and timely assimilation of tabular and spatial information for informed resource management planning. GIS is an integrated suite of computer-based tools that facilitates the input, processing, display, and output of spatially referenced data. Significant advancements in the application of GIS for solving soil erosion problems have taken place over the past several decades.

Models are needed to predict soil erosion rates under different resources and land use conditions. Unfortunately, reliable or financially viable means of measuring soil erosion is lacking in the Three Gorge Areas (TGA). Recently, many process-based and empirical models have become available for predicting soil erosion. Because of the fact that most process-based erosion prediction models, in general, are not well tested and require many input parameters, the empirical erosion prediction models continue to play an important role in soil conservation planning. The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978) is the most frequently used empirical soil erosion model worldwide. More recently, Renard et al. (1997) have modified the USLE into a revised Universal Soil Loss Equation (RUSLE) by introducing improved means of computing the soil erosion factors. The RUSLE is written as

$$A = R \times K \times L \times S \times C \times P \qquad (1)$$

where A is the soil loss in t/ha over a period selected for R, usually a yearly basis; R is the rainfall-runoff erosivity factor in MJ mm/ha h; K is the soil erodibility factor [t ha h/(ha MJ mm)] ; L is the slope length factor; S is the slope steepness factor; C is the cover and management factor; and P is the conservation support-practices factor. The L, S, C, and P values are dimensionless. Application of RUSLE in the TGA offers the following advantages: required data are readily available; it is fairly simple to apply; and it is compatible with a GIS. The objectives of the study were (1) to develop a method based on RUSLE and GIS technology to aid in soil loss at the watershed level.
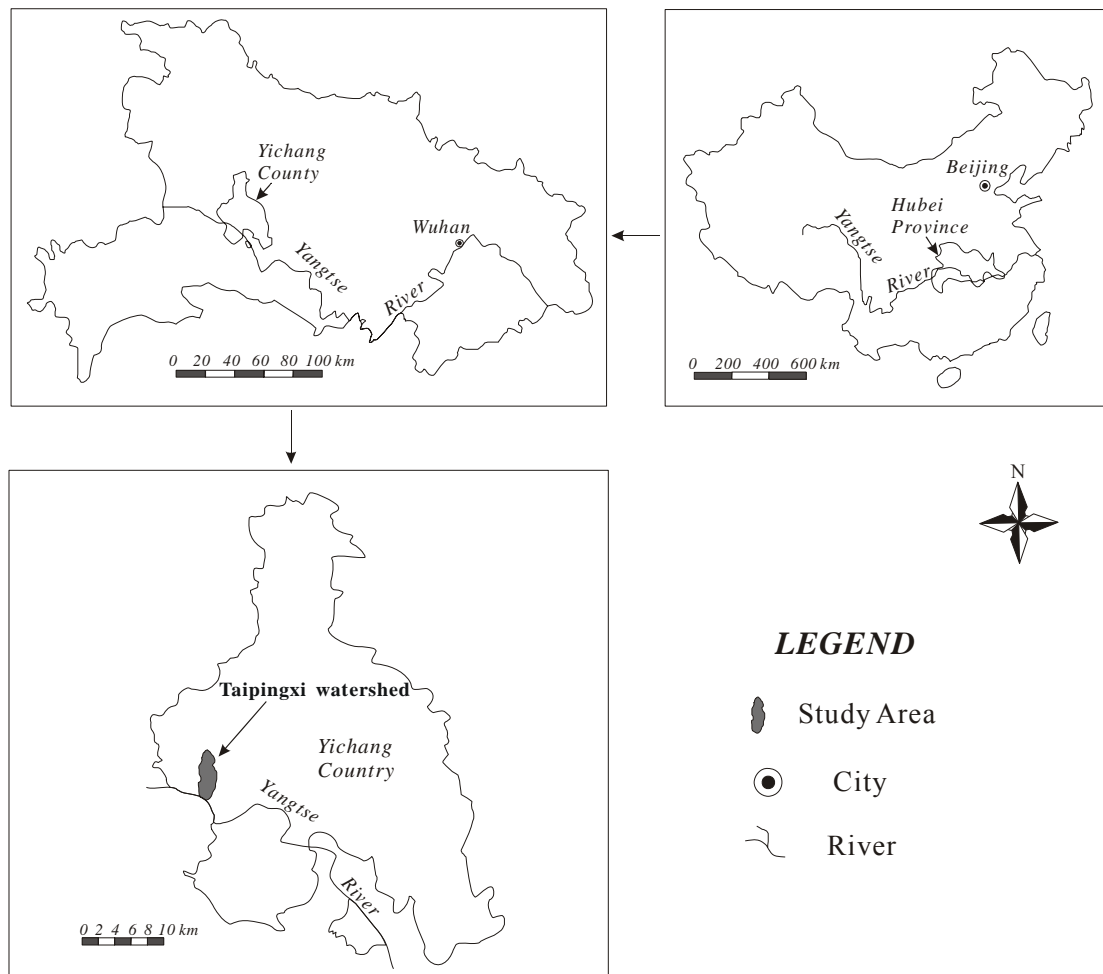
Figure 1. Geographical location of the study watershed in the TGA, China

2. DESCRIPTION OF STUDY AREA

The study was conducted in the Taipingxi watershed (30°52′~30°58′N， 109°57′~110°01′E) that lies in Yichang County of Hubei Province, China. It is about 5 km northwest of the Three-Gorge Dam and covers an area of 2614 ha (Figure 1). It is situated in a subtropical zone with a monsoonal climate and its altitude is between 80m and 1321m. Annual average temperature is 17℃, with an average summer high of 28℃ in July and an average winter low of 7℃ in January. Annual precipitation averages 1300 mm, of which 65% occurs between May and September. Two main soil great groups occur in the study watershed, namely, yellow-brow earths derived from granite and paddy soil developed from the yellow-brow earths.

3. METHODS AND CALCULATION

The overall methodology involved use of RUSLE in a GIS environment, with factors obtained from meteorological stations, reconnaissance soil surveys, topographic maps, land use map, and results of other relevant studies. Individual GIS files were built for each factor in the RUSLE and combined by cell-grid modeling procedures to predict soil loss in a spatial domain.

3.1 Field survey and GIS input

A reconnaissance field survey was carried out in the study area. Geological and topographic maps were used in combination with aerial photographs of appropriate scale. Land use units were delineated on the photographs and verified in the field. Land use classifications, soil conservation practices and other factors of each land use unit were recorded. Soils were mapped by delineating units on the aerial photographs and subsequently verified on the ground. Profile descriptions were recorded according to the description manual for soil profiles. A total of 32 soil samples were taken with at least one set of soil sample taken from each mapping unit. The physical and chemical properties were determined using standard laboratory procedures. Rainfall data from 1983 to 1996 were obtained from the one meteorological station located within the Taipingxi watershed (2614 ha). A 1:10,000 topographic map, including the Taipingxi watershed, was input to the GIS by manual digitization with TOSCA. An interpolation routine was employed to derive the elevation surface from the rasterized line data. The digital elevation map (DEM) was used as the base for other topographic-related analyses. The soil, land use, and other related attributes were input to the GIS by manual digitization and keyboard entry. The polygons and their attributes were connected with uniform code. These vector maps were also converted into raster, which had the same reference system and resolution as the DEM. The data sources were integrated in the GIS with grid-cell format. Each defined

cell (pixel) had an exact location in space, determined by the grid orientation and cell size and a list of assigned attributes.

3.2 Determining RUSLE factor values

Derivation of the factors required by the RUSLE is well documented in the literatures (Wischmeier and Smith, 1978; Renard et al., 1997). However, recent advancements in GIS technology have enabled more accurate estimation of some RUSLE factors, specifically those related to slope length and steepness (Renard et al., 1997; Nearing, 1997). Values assigned to the RUSLE factors are discussed below.

3.2.1 Rainfall-runoff erosivity factor (R)

Unlike thunderstorms, which occur as a result of local convective activities, and are characterized by very different spatial and temporal distributions, monsoon rains, which develop in response to annual variations in the temperature difference between oceans and continents over a large geographic area, are the prevailing rainfall in the Taipingxi watershed. The monsoonal rains are relatively uniform in both intensity and duration across large distances. With this in mind, it was felt that rainfall characteristics of the entire watershed (2614 ha) were adequately represented by data collected from the single weather station. Rainfall-runoff erosivity was determined by calculating the erosivity value for each storm using the method described by Wischmeier and Smith (1978). The storm erosivity of each storm was then accumulated to produce a yearly erosivity value (R factor). One value, R =4969 MJ mm/ha h year, obtained by averaging the yearly values from 1987 to 1996, was used for the entire watershed.

3.2.2 Soil erodibility factor (K)

The K values were estimated using the soil-erodibility nomograph method (Wischmeier and Smith, 1978; Renard et al., 1997). This method uses % silt plus very fine sand (0.002~0.1 mm), % sand (0.1~2 mm), % organic matter, and soil structure and permeability classes to calculate K. Basic data for estimating soil erodibility were obtained by collecting soil samples from 32 test sites, representative of the major soil-mapping units. With exception of the soil structure, which was interpreted from soil profile descriptions, other values were determined. After assigning appropriate permeability codes to each saturated hydraulic conductivity value, soil erodibility R factors were calculated for each soil-mapping unit.

3.2.3 Slope length and steepness factor (LS)

The LS factor was limited to slopes ⩽18% because data used to develop RUSLE involved slopes up to 18% only (McCool et al., 1987). However, the Taipingxi watershed has 68% of its area having slope gradient in excess of 30%. Most of this steeply sloping land is under forest cover or other non-agricultural use. Under these slope gradients, much of the sediment may move by gravity rather than shear force alone and new LS factors should be developed. Using equations proposed by McCool et al. (1987) for computing S in RUSLE, Nearing (1997) proposed a logistic equation expressed as a single continuous function of slope gradients for computing S:

$$s = -1.5 + 17 / [1 + \exp(2.3 - 6.1 \sin \theta)] \qquad (2)$$

where θ is the slope angle in degrees and s is the slope steepness factor. Eq. (2) closely follows the RUSLE S factor for slopes up to 22%, and also represents existing data for

slopes greater than those from which the RUSLE relationships were derived (Nearing, 1997). For this reason, Eq. (2) was adopted for computing S factors in this study.

In both USLE and RUSLE, slope length is defined as the horizontal distance from the origin of overland flow to the point where either the slope gradient decreases to a point where deposition begins, or runoff becomes concentrated in a defined channel (Renard et al., 1997). However, in a real two-dimensional landscape, overland flow and the resulting soil loss do not really depend upon the distance to the divide or upslope border of the field, rather on the area per unit of contour length contributing runoff to that point. For this reason, the slope length unit should be replaced by the unit-contributing area. To model upslope drainage area, the steepest descent algorithm, multiple flow algorithm and the flux decomposition method have been proposed for calculating the contributing area of each grid cell in a grid-based digital elevation map (DEM). The flux decomposition method is well suited to the Taipingxi watershed because it accounts for complicated flow divergence and convergence patterns that are common in highly mountainous terrain. Therefore, the flux decomposition method outlined by Desmet and Govers (1996b) was selected as the flow routing algorithm in this study.

A uniform slope rarely exists in any natural landscape. To accommodate conditions of the non-uniform slope, Foster and Wischmeier (1974) subdivided the slope into a number of segments with uniform slope gradient and developed an equation to calculate the LS factor of each segment. This equation was then expanded for two-dimensional topography by substituting the unit contributing area for the slope length as each grid cell may be considered as a slope segment having uniform slope. Replacing slope length with unit contributing areas at the inlet and outlet of a grid cell, the slope length factor L may be written as:

$$L_{i,j} = \frac{A_{i,j\text{-out}}^{m+1} + \lambda_{i,j\text{-in}}^{m+1}}{(A_{i,j-out} - A_{i,j-in}) \times (22.13)^{m}} \qquad (3)$$

where $L_{i,j}$ is the slope length factor for the grid cell with coordinates() (i, j) ; $A_{(i,j-out)}$ and $A_{(i,j-in)}$ are the unit contributing areas at the outlet and inlet, respectively, of a grid cell with coordinates (i, j) ; and m is the slope length exponent of the LS factor of the USLE. After determining the L for each grid cell, the LS factor was then determined by multiplying the L and S values and a map of the LS factors was produced.

3.2.4 Cover and management factor (C)

The cover and management factor (C) reflects the effect of cropping and management practices on soil erosion rates (Renard et al., 1997). Due to the completely different cropping practices in China as compared to that of North America, the direct application of the soil-loss ratio algorithm based on prior-land-use (PLU), canopy-cover (CC), surface-cover (SC), surface-roughness (SR), and soil-moisture (SM) subfactors is impractical. Because of severe land availability limitations, an average farmer has less than 0.1 ha of farmland. Soil and crop management is mostly by hand or small machinery with very little or no subsurface residue and therefore a value of 1 was assigned to PLU. In addition, most soil erosion occurs during the months from June to August, inclusive, which coincides

with relatively high soil moisture content resulting from monsoonal rains. For this reason, a value of 1 was also assigned to the SM subfactor. Using over 200 soil-loss ratios measured from 30 runoff-erosion plots under both natural and simulated rainfall events in the TGA, Du and Shi (1994) established relationships between soil-loss ratios and canopy-cover and surface-cover subfactors. The cover and management factor (C) of the RUSLE expressed as a function of canopy/surface-cover (c) in % is as follow:

For $0 < c < 78.3\%$ $C = 0.6508 - 0.3436 \lg c$ (4)

Where C equals 1 and 0 if c is equal to 0% and $\geq 78.3\%$, respectively. The C of any cover or cropping sequences was then calculated using Eq. (4) by substituting the monthly measured average c, and multiplying by the corresponding proportion of the rainfall runoff erosivity of the same period. Indeed, a land use map was used as the basis for determining the C factor values. And then average C factor values were then assigned as attributes in the land use map. In this study, the annual average value of C was calculated by average c and land use classifications. Tab. 1 lists the C factor values for various land use classifications in the study area.

Land use classification	C value
Water	0
Residential area	0.08
Paddy field	0.18
Dry land	0.46
Woodland	0.005
Nondense woodland	0.019
garden plot	0.10
Grassplot	0.21
Naked land	1.00

Table 1. The C values for various land use classifications in the study area

3.2.5 Conservation support-practice factor (P)

The support practice factor (P) is the soil-loss ratio with a specific support practice to the corresponding soil loss with up-and-down slope tillage (Renard et al., 1997). The major soil conservation techniques used in the TGA are contour tillage (CT), contour farming with a seasonal no-till ridge (CTN), and level terraces. The P values for common support practices used in the TGA were obtained from experimental data under runoff-erosion plots under different support practices using both natural and simulated rainfalls (Du and Shi, 1994) and are listed in Table 2. The P value for individual map units was determined according to the conversation practices obtained from the field survey. If a new conservation practice was recommended to the unit, a new P factor was assigned to the database accordingly.

Land slope (°)	Up-and-down slope tillage	CT	CTN	Level terrace
2.0～5.0	1.00	0.50	0.30	0.10
5.1～9.0	1.00	0.70	0.40	0.16
9.1～16.0	1.00	0.90	0.50	0.30
16.1～20.0	1.00	1.00	0.70	0.40
20.1～25.0	1.00	1.00	0.90	0.55

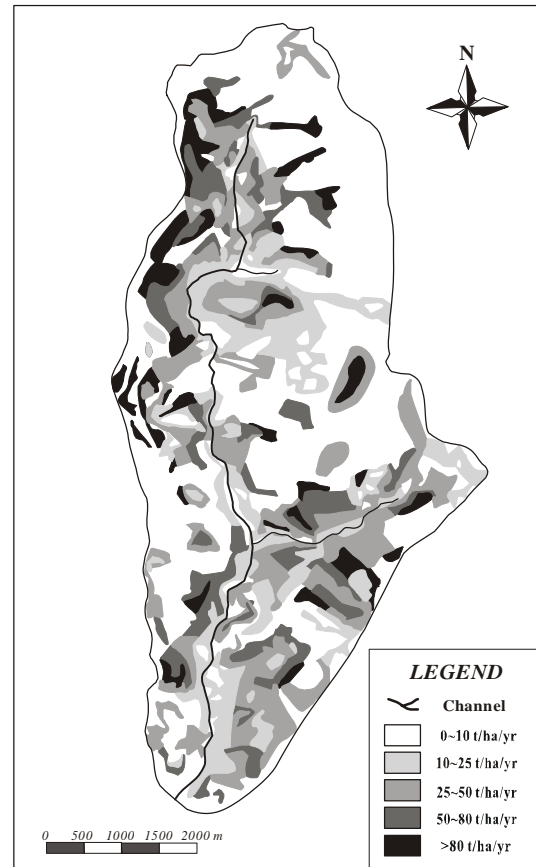Table 2. The P values for various support practice factors

Figure 2. Soil loss map showing general distribution of soil erosion in Taipingxi watershed

4. RESULTS AND DISCUSSION

The quantitative output of predicted soil loss rates for the Taipingxi watershed were computed and grouped into five ordinal classes and displayed on the map in Figure 2. Of the 2614 ha land, approximately 62.18% exhibits soil loss rates of ≤ 10 t/ha year. Of the remainder, approximately 20.12%, 7.08%, 4.79%, and 5.83% belong to the low (10~25 t/ha year), medium (25~50 t/ ha year), high (50~80 t/ ha year) and very high (> 80 t/ ha year) level classes, respectively. Average annual soil loss rate from relatively flat agricultural lands was 21 t/ha, whereas from cultivated sloping lands, it was 48 t/ha. These cultivated sloping lands were major contributors to sediment yield in the Taipingxi watershed. Due to these massive soil losses, soil conservation measures were urgently needed, especially on the cultivated sloping lands.

The major concern in this case is the accuracy of the estimated values for the factors used in the RUSLE. The C and P factors used in this study were mostly derived from runoff-erosion plots using either natural or simulated rainfalls. This further accentuates the uncertainty of the RUSLE factors. In addition, several algorithms were used when preparing data for the RUSLE and each step brings with it the possibility of accentuating errors. The RUSLE model requires six input data layers be multiplied, and the inherent errors in each layer when multiplied, contribute to an even greater uncertainty in the derived soil loss values. While these potential errors exist,

RUSLE generated estimates of soil loss appear to be reasonable. Considering possible yearly variations in R-values, differences in landscape features, and sediment deposition in depressions, the value estimated using the RUSLE and GIS compared favorably to that of the measured value. Most importantly, this study demonstrated that the RUSLE used with appropriate values for each factor is a useful tool, especially for identifying high-risk areas where soil conservation practices are needed. Various soil conservation-planning scenarios can be evaluated easily through database manipulations. This RUSLE-GIS model is a valuable tool for assessing various soil conservation techniques in soil conservation planning at different levels of scale by land managers.

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