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Original research

Predictive modeling in sediment transportation across multiple spatial scales in the Jialing River Basin of China

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ABSTRACT

This research models soil erosion and sediment transportation in the Jialing River Basin based on the Revised Universal Soil Loss Equation (RUSLE) with Geographic Information System (GIS) technology. Studies have shown that, the improved method based on the RUSLE model was effective in calculating and predicting the annual sediment transport rate in Jialing River Basin in consideration of the hydrological conditions causing the annual variability of soil loss and the changes in the underlying surface resulting from land management activities. Comparing the observed and simulated sediment loads in the period of 1989 and 1998, the simulation values showed a consistent trend with the observed values, and the relative errors were controlled at 20% or less. This shows that the model can be used to identify hot-spot watersheds with different degree of sediment yield and help to make corresponding land use planning and soil and water conservation strategy, and thus help to reduce soil erosion in areas surrounding the Three Gorges Project and other reservoirs in other rivers.

1. Introduction

Soil erosion due to the action of water or wind is a major environmental problem worldwide. About 85% of land and environmental degradation globally is associated with soil erosion. Global water erosion affects about 1094 Mha and wind erosion affects about 549 Mha (Lal, 2003). Additionally, soil erosion leads directly to high levels of stream sedimentation. Total sediment outflow from a watershed per unit time is called sediment yield. And sediment delivery ratio (ratio of yield to the total eroded material) refers to the transported portion of the eroded sediment (Aksoy & Kawas, 2005).

Water erosion is affected by climate, topography, soil, vegetation and human activities (Kuznetsov et al., 1998), which are considered in erosion prediction models. One of these is the Universal Soil Loss Equation (USLE- Wischmeier & Smith, 1978) and its revised version (RUSLE- Renard et al., 1997) which is widely used over much of the world—including China. Additionally, some powerful non-point source pollution load models, such as SWAT, AGNPS, LASCAM, EPIC and SWMM models, are also based on USLE or RUSLE.

RUSLE is an empirically based model, established on soil erosion theory and the statistical analysis of the observational data from tens of thousands of runoff and soil loss events from a large number of runoff plots at nearly 50 different locations in the United States that were used in the USLE development. Thus, RUSLE is designed to model and predict soil erosion at the runoff plot or single hillslope scales. Various factors that affect soil erosion including soil erosivity and erodibility are considered in the model, which provides a sophisticated infrastructure for remote sensing of soil erosion prediction. Both the USLE and the RUSLE model enable prediction of average annual erosion by multiplying several factors together: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management(C), and support practice (P).

The objective of this research is to test the annual sediment discharge estimates based on RUSLE soil erosion and the spatial distribution of sediment delivery ratio against measurements at the Beibei station on the Jialing River between 1989 and 1998.

2. Methods

RUSLE is an empirically based model founded on the USLE. It has the same model structure as does the USLE (Renard et al., 1997):

$$A = R \cdot K \cdot LS \cdot C \cdot P \tag{1}$$

where A is the computed spatial and temporal average soil loss per unit area (Mg/ha year^{-1}); R is the rainfall-runoff erosivity factor [MJ mm/(ha h year^{-1})]; K is the soil erodibility factor [Mg h/(MJ mm)];

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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 all dimensionless.

Sediment discharge is the soil erosion on the soil surface of the basin that is transported to the river and eventually reaches the basin outlet. It is calculated by the following equation (Novotny & Chesters, 1989):

$$Q_s = A \cdot X \cdot \lambda \tag{2}$$

where Q_s is the unit sediment discharge (Mg/year), A is given by Eq. (1), X the basin area (km^2), and λ is the sediment transport coefficient. Substituting Eq. (1) into Eq. (2) yields

$$Q_s = X \cdot K \cdot LS \cdot R \cdot M \cdot \lambda \tag{3}$$

2.1. *Rainfall erosivity factor (R)*

Rainfall erosivity is the potential of rainfall to cause runoff and soil erosion. The Rainfall Factor-R of the Universal Soil Loss Equation (USLE) and RUSLE is the most common expression of a storm's potential to cause runoff and soil erosion. The R-factor for a storm is the product of the kinetic energy of the storm and the maximum 30 min rainfall intensity within the storm. A period R-factor is the sum of the R factors for that period. Wang (1995) expressed the average annual R-factor as:

$$R = \sum_{j=1}^{12} 1.735 \times 10^{\left(1.5\,\lg\left(\frac{P_j^2}{P}\right) - 0.8188\right)} \tag{4}$$

where P is the yearly average rainfall (mm) and P_j is the monthly average rainfall (mm).

2.2. *Soil erodibility factor (K)*

The soil erodibility factor (K) is a quantitative description of the inherent erodibility of a given soil, indicating sensitivity of the soil to soil erosion and sediment transport. Soil texture is the main factor affecting soil erodibility with soil structure, permeability, particle composition also playing a role. Soil erodibility was estimated with the help of the soil map provided by the Soil Geographical Data Base and soil attribute data. The K-factor was calculated using the method in the Erosion Productivity Impact Calculator (EPIC) model (Sharply & Williams, 1990) and is given by the following equation:

$$K = \left\{0.2 + 0.3\exp\left[-0.256 S_d\left(1 - S_i/100\right)\right]\cdot\left[S_i/\left(C_i + S_i\right)\right]\right\}^{0.3} \left\{1.0 - 0.25 C_0/\left[C_0 + \exp\left(3.72 - 2.95 C_0\right)\right]\right\} \tag{5}$$

where S_d is sand content (0.05–2 mm), S_i is silt content (0.002–0.05 mm), C_i is clay content (<0.002 mm), and C_0 is soil organic carbon. Table. 1

Table 1
Soil types of the study basin and their K factor values.

Soil types	K-factor	Soil types	K-factor
Latosolic red soil	0.278	Red soil	0.299
Yellow brown soil	0.297	Yellow soil	0.300
Dark brown soil	0.286	Brown soil	0.291
Torrid red soil	0.283	Cinnamon soil	0.278
Alluvial soil	0.314	Lime soil	0.294
Purple soil	0.330	Fragmental soil	0.275
Fluvo-aquic soil	0.344	Boggy soil	0.306
Peat soil	0.324	Yellow cinnamon soil	0.323
Meadow soil	0.302	Mountain meadow soil	0.268
Alpine meadow soil	0.287	Subalpine meadow soil	0.288
Brown coniferous forest soil	0.295	Alpine cold desert soil	0.284

2.3. *Slope length and steepness factor (LS)*

The slope length and steepness factor (LS) is calculated based on a GIS spatial analysis module. Slope length is measured as a change in elevation over some distance in a raster-based DEM. If each grid in DEM is defined as a slope segment, then the L-factor is calculated using the following equation:

$$L_{i,j} = \left[\left(\sum_{1}^{i} \frac{D_{i,j}}{\cos\theta_{i,j}}\right)^{(1+m_{i,j})} - \left(\sum_{1}^{i-1} \frac{D_{i,j}}{\cos\theta_{i,j}}\right)^{(1+m_{i,j})}\right] \frac{\cos\theta_{i,j}}{22.13^{m_{i,j}} \times D_{i,j}} \tag{6}$$

where $L_{i,j}$ is the slope length factor for the grid cell with coordinates (i,j); D_{ij} is the horizontal projection distance of slope length along the runoff direction for the grid cell with coordinates (i,j); θ_{ij} is the slope for the grid cell with coordinates (i,j); m_{ij} is the slope length exponent for the grid cell with coordinates (i,j). When $\theta_{ij} \geq 5\%$, $m_{ij}=0.5$; $3\% \geq \theta_{ij} < 5\%$, $m_{ij}=0.4$; $1\% \geq \theta_{ij} < 3\%$, $m_{ij}=0.3$; $\theta_{ij} < 1\%$, $m_{ij}=0.2$.

The RUSLE model is mainly used in arable land where the slope is less than 20%, however, there are steeper slopes in the Jialing River Basin. Thus, referring to the study of soil erosion on steep slopes, the equations of steepness factor are described by Eq. (7) (Liu et al., 1994), where S is the steepness factor

$$S = \begin{cases} 10.8\sin\theta + 0.03 & \theta < 5^\circ \\ 16.8\sin\theta - 0.5 & 5^\circ \leq \theta < 10^\circ \\ 21.9\sin\theta - 0.96 & \theta \geq 10^\circ \end{cases} \tag{7}$$

Slope length and steepness factors are topographic factors that indicate the terrain impacts on soil erosion. The results showed that, the steepness is the most significant factor, which leads to the destruction by surface runoff and is the main factor deciding the soil resistance.

2.4. *Cover and management factor (C)*

The vegetation cover and management factor C reflects the integrated effect of cropping and management practices in agricultural management, and the natural vegetation covers on reducing soil loss in non-agricultural situation (Eldridge & Rothon, 2002). The vegetation cover is derived from the Normalized Difference Vegetation Index (NDVI). Considering that the extent of erosion is closely related to precipitation, the ratios of monthly rainfall to annual rainfall are taken as weighting factors to calculate annual average vegetation cover, reflecting the average effect of vegetation cover on reducing soil erosion (Zaimes et al., 2005). Annual averaged vegetation cover c and monthly averaged vegetation cover c_i are calculated as

$$\begin{aligned} c_i &= \left(\mathrm{NDVI} - \mathrm{NDVI}_{\mathrm{soil},i}\right)/\left(\mathrm{NDVI}_{\mathrm{veg},i} - \mathrm{NDVI}_{\mathrm{soil},i}\right) \\ c &= \sum_{i=1}^{12} \frac{P_i}{P} \times c_i \end{aligned} \tag{8}$$