Estimation of the spatial distribution of soil erosion in the hilly area of Sichuan, China

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Abstract The hilly area of Sichuan (China) has suffered from soil erosion as a result of the intensive agriculture and steep topography. Many different methods have been used for the estimation of soil erosion and no clear consensus about erosion rates and subsequent sediment delivery ratios (SDR) has been reached. In this study, the Universal Soil Loss Equation (USLE) with different parameter estimation methods was applied to two river basins (i.e. Weichenghe (WCH) and Lizixi (LZX)) with the help of GIS techniques. The results were compared with those of previous studies based on remote sensing, erosion plots or the ^{137}Cs technique. The main results can be summarized as: (1) different rainfall erosivity estimation methods generate vastly different results; (2) using two-dimensional slope length produces higher soil erosion rate estimates and lower SDRs than the conventional approach in USLE; (3) the average annual soil erosion rates for WCH and LZX were estimated at 706 t km^{-2} year^{-1} and 3040 t km^{-2} year^{-1}, respectively, and the corresponding sediment delivery ratios at 0.27 and 0.38; and (4) the high erosion rates reflect the high altitude and intensive agricultural land use.

Key words USLE; rainfall erosivity; soil erosion rate; spatial distribution

INTRODUCTION

Effective control of soil loss in catchments requires the implementation of best management practices (BMP). Quantifying sediment budgets is essential in understanding the processes of catchment sediment transfer, including soil erosion, and in implementing appropriate mitigation practices for reducing stream sediment transport and associated pollutant loads. However, field measurements, especially in larger catchments, face important constraints due to the costs of data collection and problems with assembling temporally and spatially representative records (Oeurng, 2011).

Appropriate techniques are needed for better assessment of long-term soil erosion patterns as well as decision support tools for planning and implementing appropriate conservation measures. Available tools include various soil erosion models and GIS (Oeurng, 2011). A variety of soil erosion models, varying from empirical to physically-based, have been developed since the 1970s. Among these, the Universal Soil Loss Equation (USLE, Wischmeier & Smith, 1978), owing to its simplicity and parameterization is probably the most widely used model of overland flow erosion in the world. This approach does, however, have several limitations, one being that it is less effective for applications outside the range of conditions for which it was originally developed (Nearing *et al*., 1994). An alternative, the Water Erosion Prediction Project (WEPP) model is representative of physically-based models and contains nine key components such as surface hydrology as well as rill and interrill erosion. Such models, however, are not extensively applied worldwide due to their high data demands and difficulties associated with parameter estimation. Furthermore, some work suggests that physically-based models do not perform better than locally-adapted more simple empirical approaches (e.g. Renard *et al*., 1991; De Roo, 1998).

Many methods have been reported for estimating and localizing each USLE-factor. Martinez & Begueria (2009) reviewed and compared several approaches for estimating rainfall erosivity (*R*) from daily precipitation records. Wang *et al*. (1995, 1996) analysed the relationships between conventional rainfall indices and rainfall erosivity in different regions of China, and proposed some simple models to calculate *R*. There are also various methods for determining the soil erodibility factor (*K*) (Hou, 2001). In the standard USLE model, slope and slope length (*LS*) were calculated for a single plot or segment. However, when the USLE is combined with gridded data from a GIS, predictive power is improved (Jain & Kothyari, 2000). Foster & Wischmeier (1974) and Desmet & Govers (1996) proposed different equations to deal with complex heterogeneous slopes which can be used in conjunction with a grid-based USLE. In comparison, the crop management (*C*) and conservation practice (*P*) factors are more difficult to determine and less widely investigated.

China experiences serious soil loss. According to the second national remote sensing survey, an estimated 3.56×10^6 km^2 of land, constituting about 37.5% of the total geographical area, suffers from soil erosion and other forms of land degradation. An example of a severely eroded area is the catchment of the Jialingjiang River, in Sichuan, where erosion rates of 500 to 5000 t km^{-2} year^{-1} and corresponding SDRs of 0.1–0.31 have been reported (Fan *et al*., 2003; Zhang *et al*., 2004; Fu *et al*., 2005; Jing *et al*., 2010).

Given the context above, the specific objectives of this paper were: (1) to compare different methods for estimating the USLE *R* and *L* factors, (2) to examine the spatial distribution of soil loss and SDR, and (3) to discuss the differences in the results of the modelling in the context of previous studies.

STUDY AREA AND DATA

The Weichenghe (WCH; 249 km^2) and Lizixi (LZX; 437 km^2) are two typical small catchments located in the central portions of the Jialingjiang River basin, in Sichuan province, China (Fig. 1). Altitudes range from 250 to 700m (Fig. 2). The soil is typical purple soil, with a silt content of 34% and a sand content of 38%, and land use is dominated by arable land, with paddy, wheat and corn dominating the crop rotation. More than 80% of rainfall occurs between May to October, and the catchments are prone to heavy summer storms in July. Average annual (1974–1991) runoff and suspended sediment yields in WCH and LZX have been estimated at 85×10^6 m^3 and 130×10^6 m^3, and 268 t km^{-2} year^{-1} and 971 t km^{-2} year^{-1}, respectively. Monthly precipitation, discharge and suspended sediment concentration (SSC) data for the period January 1980 to December 1987 were used as model input. A pre-processed DEM as well as land use (1986) with a 100-m resolution were used in this study.

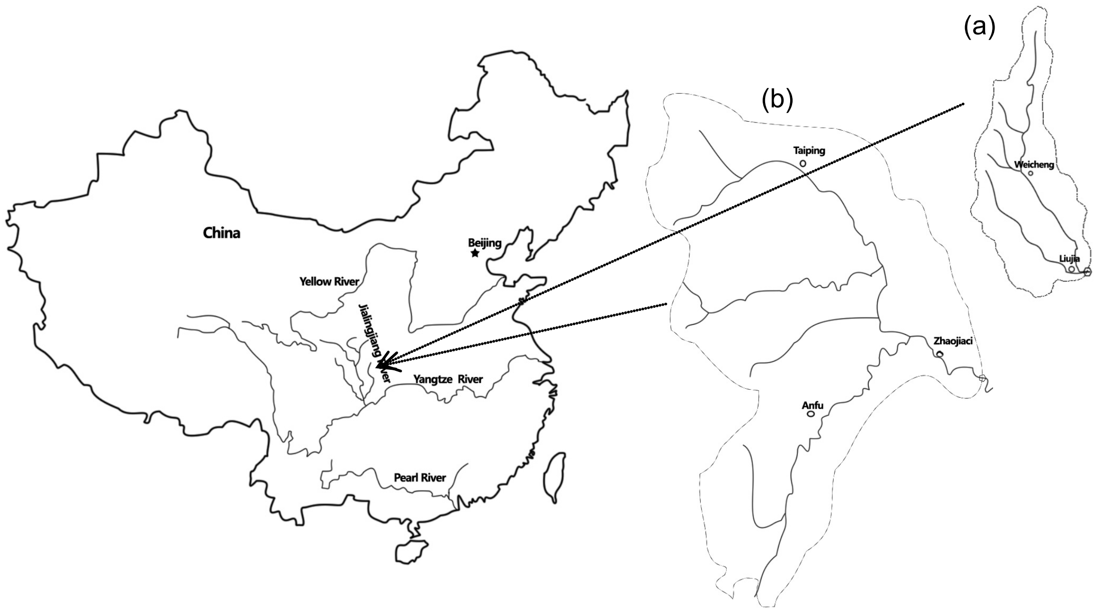

Fig. 1 Location, main rivers, precipitation gauges (circles) and the outlets (hexagons) of WCH (a) and LZX (b) catchments.

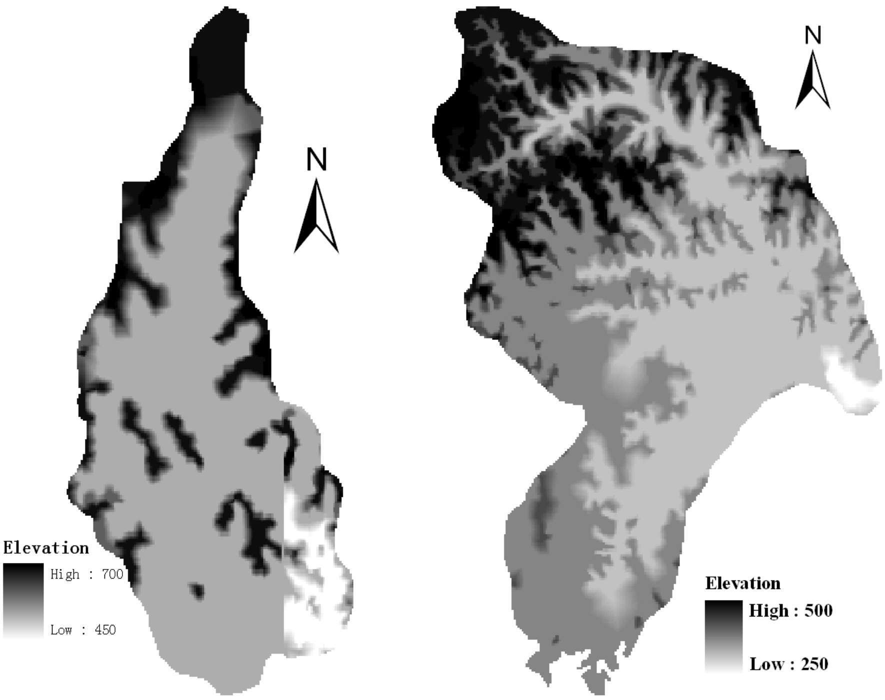

Fig. 2 Digital elevation maps for WCH (left) and LZX (right).

MODEL DESCRIPTION AND PARAMETER INPUT

The USLE has a very simple basis:

$$E = R \times K \times LS \times C \times P \qquad (1)$$

where E is the potential mean annual soil loss (t ha^{-1} year^{-1}), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K is the soil erodibility factor (t h ha MJ^{-1} mm^{-1} ha^{-1}), LS is the slope and slope length factor, C the crop management factor and P is the erosion control practice factor.

The USLE performance relies on the determination of these key controlling factors. Rainfall erosivity values are usually well fitted to the precipitation amount by an exponential relationship (Richardson *et al*., 1983). Lu (2006) proposed a simple equation for rainfall erosivity estimation for the hilly area with purple soil:

$$R_d = (2.2944P_d + 0.066\, P_d^2) \times 0.6 \qquad (2)$$

where R_d is daily rainfall erosivity (MJ mm ha^{-1} h^{-1} d^{-1}), P_d is the daily erosive rain (daily rain amount more than or equal to 10 mm). Another simple method reported by Zhang *et al*. (2002) has also been widely used in China (Ye *et al*., 2003; Wei, 2008; Tian *et al*., 2010):

$$R_m = \alpha \sum_{j=1}^{k} (P_j)^{\beta} \qquad (3)$$

where $\beta = 0.8363 + 18.177/P_{ad} + 24.455/P_{ay}$ and $\alpha = 21.586\beta^{-7.1891}$; where R_m is half-month rainfall erosivity, k is the number of days of the half-month being evaluated, P_j is the erosive rainfall amount for j-th day, P_{ad} is the average daily rain and P_{ay} is the average annual rain for only erosive rainfall. In this case, the threshold for erosive rainfall is 12 mm.

The original means of calculating the L factor is:

$$L = (D/22.13)^m \qquad (4)$$

where D is grid cell size (m), and m is the length exponent (equivalent to 0.5 for slope $s > 5\%$, 0.4 for $3\% < s \leq 5\%$, 0.3 for $1\% < s \leq 3\%$, 0.2 for $s \leq 1\%$). The two-dimensional slope length factor

L_{2D} was proposed by Desmet & Govers (1996) and uses the upslope unit contributing area to account for the effect of concentrated flow on soil erosion:

$$L_{2\mathrm{D}} = \frac{(A + D^2)^{m+1} - A^{m+1}}{D^{m+2}.(\sin\theta + \cos\theta)^m.(22.13)^m} \quad (5)$$

where θ is slope angle, A is upslope contributing area. The S factor is given by:

$$S = 10.8 \times \sin\theta + 0.03 \quad s < 9\% \quad (6)$$

$$S = 16.8 \times \sin\theta - 0.50 \quad s \geq 9\% \quad (7)$$

Values of the soil erodibility factor were derived from Lv & Shen (1992). Cai *et al*. (2000) and Yang (1999) reported the annual C values and P values for several kinds of land use and crop rotation in the Three Gorges area and Yunnan province. Since no detailed information about monthly variation in vegetation cover was available, homogenous C and P values were deployed over the entire estimation period for each land use type.

RESULTS AND DISCUSSION

Soil erosion estimates based on the different equations

For WCH, the values of the average annual rainfall erosivity were 2456 MJ mm ha^{-1} h^{-1} year^{-1} using equation (2) and 6077 MJ mm ha^{-1} h^{-1} year^{-1} using equation (3. For LZX, the corresponding values were 2058 MJ mm ha^{-1} h^{-1} year^{-1} using equation (2) and 4755 MJ mm ha^{-1} h^{-1} year^{-1} using equation (3). The two different rainfall erosivity and slope length factor equations generated four permutations. We used these four combinations to calculate the average annual soil erosion rates and SDRs for the two study catchments (Table 1). In comparison, Jing *et al*. (2010) reported a soil erosion rate of 539 t km^{-2} year^{-1} and a SDR of 0.36 for WCH, while Fan *et al.* (2003) reported a soil erosion rate of 4032 t km^{-2} year^{-1} and a SDR of 0.27 in LZX. This implies that the parameters in equation (3) need to be recalibrated for the study area. When compared to equation (5), equation (4) estimates lower soil erosion rates and a higher SDR because it discounts

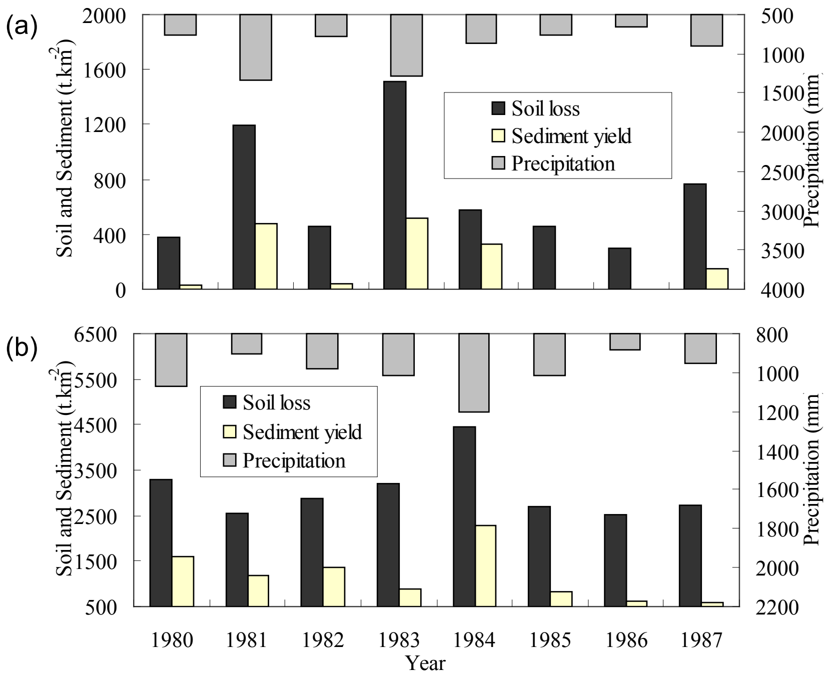

Fig. 3 Annual simulated soil loss, observed sediment yield and precipitation for WCH (a) and LZX (b) for the period 1980 to 1987.

Table 1 Soil erosion rates and sediment delivery ratios for WCH and LZX using four combinations of equations (2)–(5).

	WCH basin		LZX basin	
	E (t km^{-2} year^{-1})	SDR	*E* (t km^{-2} year^{-1})	SDR
Eq.(2) and Eq. (4)	491	0.34	2611	0.45
Eq.(3) and Eq. (4)	1216	0.16	6034	0.19
Eq.(2) and Eq. (5)	706	0.27	3040	0.38
Eq.(3) and Eq. (5)	1747	0.11	7024	0.17

E: erosion rate; SDR: sediment delivery ratio.

Table 2 Soil erosion grades for WCH and LZX.

		Mild <500	Slight 500–2500	Medium 2500–5000	Intensive 5000–8000	Extreme intensive >8000	Total
WCH	Area (km^2)	165	59	20	4	1	249
	Percent (%)	66	24	8	2	1	100
LZX	Area (km^2)	246	46	42	32	71	437
	Percent (%)	56	10	10	7	16	100
LZX (Fan)	Area (km^2)	158	20	80	132	47	437
	Percent (%)	36	5	18	30	11	100

* Soil erosion grade ranges are expressed in t km^{-2} year^{-1}. The last two rows show the results from Fan *et al.* (2003).

the location of the slopes and the impact of runoff convergence on soil erosion. Overall, a combination of equation (2) and equation (5) is most appropriate for estimating soil erosion in the study area.

The temporal and spatial distribution of soil erosion

The average annual (1980–1987) predicted soil erosion for WCH and LZX was estimated at 706 and 3040 t km^{-2} year^{-1}, respectively, compared to respective observed sediment yields of 194 and 1169 t km^{-2} year^{-1}. On this basis, the corresponding SDRs were estimated at 0.27 for WCH and 0.38 for LZX. Figure 3(a) and (b) presents these estimates together with precipitation. Table 2 provides Chinese soil erosion grade (SL 190-2007) summary statistics for the study catchments. The spatial distribution of the predicted soil erosion rates are illustrated in Fig. 4(a) and (b). In comparison with the DEMs, nearly all intensive erosion is simulated at high altitudes, suggesting that mitigation practices should target highland dry farming.

CONCLUSION

This paper has reported different parameter estimation methods for applying the USLE in two typical catchments of the hilly area of Sichuan, making comparisons with previous studies using remote sensing, experimental plots or the ^{137}Cs approach. Further research on the relationship between soil loss at the plot and basin scale is needed to facilitate the accurate prediction of landscape scale soil erosion rates.

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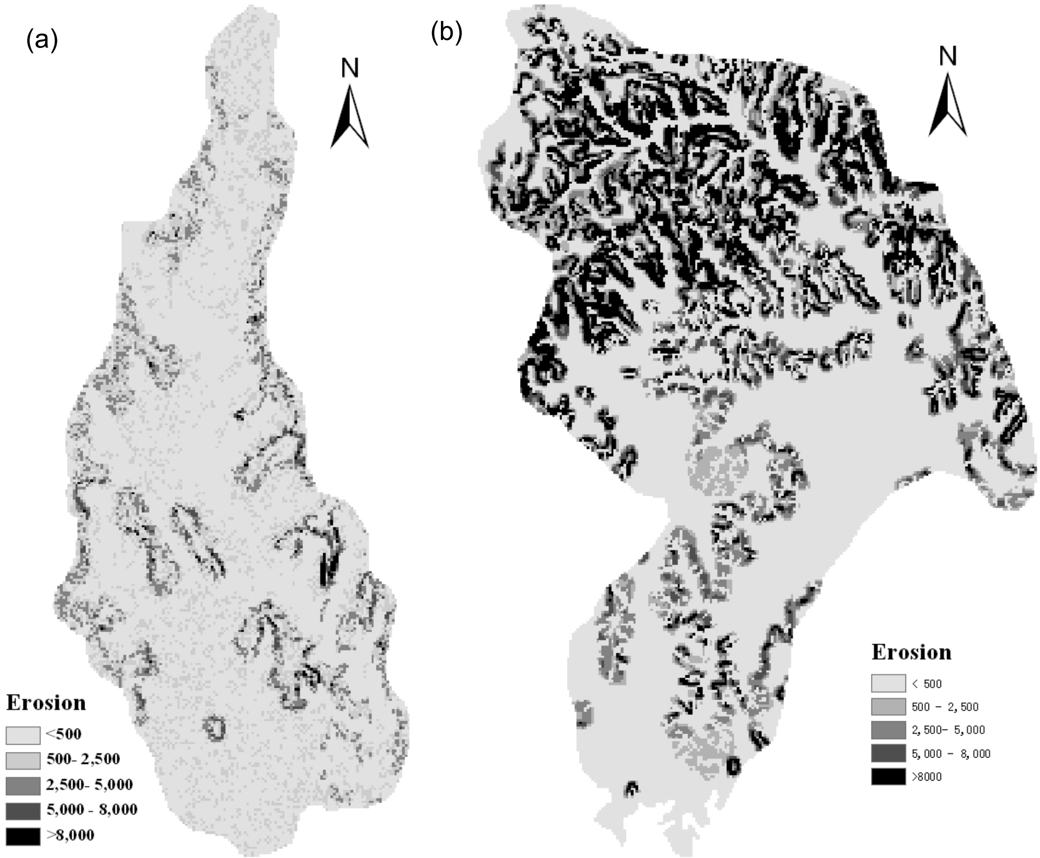

Fig. 4 Predicted soil erosion rates (t km^{-2} year^{-1}) for WCH (a) and LZX (b).

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