Estimation of soil erosion in some sections of Lower Jinsha River based on RUSLE

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Abstract Soil erosion increasingly poses a great threat to human food security and environmental quality. It is necessary to implement the assessment of soil erosion so as to provide precautionary measures and relevant suggestions for soil conservation. In this paper, the soil erosion model, revised universal soil loss equation (RUSLE), was used to quantify the soil loss in a large mountainous area of Lower Jinsha River Basin. The analysis of the datasets by means of geographic information systems (GIS) together with RUSLE led to the estimation of soil erosion. Results show that the average annual soil erosion was estimated at $52.1 \text{ t ha}^{-1} \text{ year}^{-1}$ and the total annual soil loss was $4.5 \times 10^8 \text{ t}$. The highest erosion was found along the main course of Jinsha River. Soil erosion was serious in the elevation zone between 1,675 and 2,153 m and slope zone with slopes between 15° and 35° . As for land use types, cropland and grassland contributed 84.1 % to total soil loss due to the large areas and higher erosion rates. The results can be used to advice the local government in prioritizing the areas of immediate conservation practices.

Keywords Soil erosion · Soil loss · RUSLE · Mountain region · Jinsha River

1 Introduction

Soil erosion has long been recognized as a very serious worldwide environmental problem (Saadat et al. 2014), especially in developing countries where economic development is

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pursued, while the protection of environment is disregarded. Soil erosion is a natural process of detachment of soil particles and has an irreversible effect on the environment. Soil particles detached from the soil surface carry nutrients, pesticides, and other harmful farm chemicals into rivers, streams, and groundwater resources (Pan and Wen 2014; Yang 2014), which not only causes damage to soil and agricultural production, but also affects water quality and hydrological systems (Lee 2004; Lu et al. 2004). What is more, erosion is increasingly being recognized as a hazard. Within an environmentally acceptable sustainable agricultural policy, the reduction in soil erosion must be a priority (Lee 2004).

Soil conservation planning often requires estimation of soil erosion at a catchment or regional scale. If the magnitude and features of spatial structure of soil erosion are clear, the conservation practices to alleviate the problem can be effectively carried out (Onyando et al. 2005). Predictive models are useful tools to generate the quantitative estimates necessary for designing sound conservation measures (De Asis and Omasa 2007). There are several models to estimate the soil loss, such as EUROSEM, WEPP, SHE, WaTEM/SEDEM, SEMMED and so on (Merritt et al. 2003). However, the most widely used model is an empirical model, the (revised) universal soil loss equation (RUSLE/USLE). The USLE and RUSLE have been applied at national level (Briggs et al. 1992; Van der Knijff et al. 2000), regional level (Ma et al. 2003; Xu et al. 2013) and basin level (Naqvi et al. 2013; Ozsoy et al. 2012) in different environments worldwide.

Soil erosion is a severe issue that poses great threats to the ecological environment and human living in the lower reaches of the Jinsha River, the upper reach of the Yangtze River. This area is dominated by mountain and plateau landforms, in which the ecosystem

Fig. 1 Location, boundary, and watershed of the Lower Jinsha River

is very fragile and susceptible to soil erosion due to deforestation, land reclamation, and other inappropriate land use (Long et al. 2006). In the 1970s and 1980s, there has been a rapid growth in population in the upper Yangtze River watershed. Thus, a large area of grassland and forest has been reclaimed to feed the population, thereby resulting in severe soil erosion and ecosystem damage (Ma et al. 2003). The soil loss in this region is a crucial issue for the government and has raised great public concern.

Estimation of soil erosion at a regional level poses a big challenge due to the different geographic features and the costly and time-consuming practical field methods which requires a lot of resources. However, the application of RUSLE is feasible and can be achieved because of the readily available data and its simplicity to apply with GIS and RS. The objective of this research is to quantify the magnitude and spatial distribution of soil erosion within the study area, in addition to yield an overall estimate of soil loss. The study results will provide useful information for soil conservation.

2 Study area

The study area is located in the lower reaches of Jinsha River basin which is the upper reach of Yangtze River, lying in the southwest part of China (Fig. 1). It lies between 100°50′–105° E and 24°25′–29° N stretching from southwest to northeast with an average elevation of 2,016 m a.s.l. The administrative region contains three provinces of Yunnan, Guizhou, and Sichuan under which there are 67 counties, covering a total area of approximately 8.7 million ha.

It represents diverse landscape types, including alpine valley, karst valley, lake, hill, etc. There are a variety of vegetation types in this area, which are dominated by alpine shrub, alpine meadow, farmland, and forest. This region belongs to the humid subtropics of south Asia, and the climate is mainly characterized by the southwest and southeast monsoons in wet season in addition to prevailing wind from the west in cold season (Fan et al. 2004; Shen et al. 2013; Zhuang and Ge 2012). Mean annual precipitation is 893 mm, and the rainy season occurs between May and October, accounting for 88.1 % of annual precipitation. Mean annual temperature is 15 °C. June, July, and August are the warmest months with temperatures over 20 °C. However, the precipitation and temperature are inhomogeneous due to the mountainous terrains.

3 Materials and methods

3.1 Materials

To achieve the objective, the following datasets are collected: (1) Monthly precipitation of 23 rain-gauge stations from 1955 to 2013, downloaded from China Meteorological Data Sharing Service System (<http://cdc.cma.gov.cn/home.do>). (2) Soil map at 1:1,000,000 scale of The Second Soil Survey Data of China, including subsoil sand fraction, silt fraction, clay fraction, and topsoil organic carbon, provided by Cold and Arid Regions Science Data Center at Lanzhou (<http://westdc.westgis.ac.cn/>). (3) An ASTER GDEM with a spatial resolution of 30 m of the area is obtained from Geospatial Data Cloud (<http://www.gscloud.cn/>). (4) SPOT VGT datasets with 1-km spatial resolution from April 1998 to July 2008 and August 2008 to December 2012 are acquired from the Cold and Arid Regions Science Data Center at Lanzhou (<http://westdc.westgis.ac.cn>) and the Vlaamse

Instelling Voor Technologisch Onderzoek (<http://www.vgt.vito.be/>), respectively. (5) Land cover dataset with 1-km spatial resolution is from Cold and Arid Regions Science Data Center at Lanzhou (<http://westdc.westgis.ac.cn>).

3.2 Model description

The soil erosion model used in this study is the RUSLE model taking the following form (Renard et al. 1997):

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the estimated average annual soil loss ($\text{t ha}^{-1} \text{ year}^{-1}$); R is the rainfall–runoff erosivity factor ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$); K is the soil erodibility factor ($\text{t ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$); LS is the topographic factor, derived from a combination of the slope steepness factor and slope length factor (dimensionless); C is the cover and management factor (dimensionless); P is the conservation support practice factor (dimensionless).

The RUSLE is a well-established empirical model and widely applied by many researchers. The combined use of RUSLE, GIS, and RS techniques makes it economical and feasible to estimate the soil erosion and its spatial distribution even for larger areas (Chatterjee et al. 2014). Under the ArcGIS 10.1 environment, all the factors of Eq. 1 are described as raster layers and a result layer of soil loss (A) is figured out through raster calculation function. All layers are unified to a 1 km^2 -cell basis resolution and so some layers are processed by upscaling techniques. The computations of the parameters are described in following sections, respectively.

Fig. 2 Location of rain-gauge stations used in this study

3.3 Spatial data process and parameter determination

3.3.1 Rainfall erosivity factor (R)

R factor is the long-term annual average of the product of events of rainfall kinetic energy, quantifying the effect of rainfall and associated runoff impact (Chatterjee et al. 2014; Onori et al. 2006). The original method to calculate the rainfall erosivity factor (R) requires pluviographical records and these data, however, are not always available. Furthermore, its preciseness depends on the temporal length and resolution of precipitation series (da Silva 2004; Onori et al. 2006). Given the restrictions, numerous alternative approaches have been developed to calculate R [e.g., (da Silva 2004; Diodato 1999; Kavian et al. 2011; Shamshad et al. 2008; Yu and Rosewell 1996a, b)]. In this study, we applied the formula developed by Wischmeier and Smith (1978) as follows:

$$R = \sum_{i=1}^{12} 1.735 \times 10^{(1.5 \times \log_{10}(P_i^2/P) - 0.08188)} \quad (2)$$

where R is the rainfall erosivity factor ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ year}^{-1}$); P_i is monthly rainfall (mm); and P is annual rainfall (mm).

To obtain a spatially explicit determination raster layer of R factor, we based our observation on the ANUSPLIN package which considers the elevation effect. ANUSPLIN package provides a facility for transparent analysis and interpolation of noisy multivariate data using thin plate smoothing splines (Hutchinson and Xu 2013). Precipitation data from ten rain-gauge stations located in the study area and 13 in the vicinity of the study area (Fig. 2) were collected to acquire an accurate R factor layer.

3.3.2 Soil erodibility factor (K)

The soil erodibility factor K is defined as the soil loss rate per rainfall erosion index unit for the specified soil under unit plot conditions, and it represents the effect of the inherent soil properties in soil erosion (Renard et al. 2011). The K factor is related to soil texture, grain size, organic matter content, and other factors, which are derived from the soil type. In the erosion–productivity impact calculator (EPIC) (Rahman et al. 2009; Sharpley and Williams 1990), soil organic carbon and soil particle size were used to calculate the K values. The formula was described as below:

$$K = \left\{ 0.2 + 0.3 \exp \left[-0.0256 \text{SAN} \left(1 - \frac{\text{SIL}}{100} \right) \right] \right\} \times \left(\frac{\text{SIL}}{\text{CLA} + \text{SIL}} \right)^{0.3} \left(1.0 - \frac{0.25C}{C + \exp(3.72 - 2.95C)} \right) \times \left(1.0 - \frac{0.7\text{SN1}}{\text{SN1} + \exp(-5.51 + 22.9\text{SN1})} \right) \quad (3)$$

where SAN, SIL, and CLA are, respectively, the sand fraction (%), 0.05–2.00-mm-diameter particles), silt fraction (%), 0.002–0.05-mm-diameter particles), and clay fraction (%), <0.002-mm-diameter particles); C is topsoil organic carbon content (%), and SN1 equals $1 - \text{SAN}/100$.

In this study, the factor K values were calculated using Eq. 3 and a soil map at 1:1,000,000 scale of The Second Soil Survey Data of China.

3.3.3 Topographic factor (*LS*)

The slope length factor (*L*) and slope steepness factor (*S*) mainly reflect the effect of topography on erosion (Yildirim 2012). Slope length is defined as the horizontal distance from the point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins, or runoff is concentrated in a defined channel (Renard et al. 1997; Wischmeier and Smith 1978). Slope steepness reflects the influence of slope gradient on erosion. In general, an increase in the *L* and/or *S* factor produces higher overland flow velocities and correspondingly greater erosion (Ozsoy et al. 2012). Generating the *L* and *S* values poses the largest problem (Moore and Wilson 1992). Several scientists have developed some algorithms to calculate the slope length and steepness (Liu et al. 1994; McCool et al. 1987, 1989; Mitasova et al. 1996; Moore and Wilson 1992; Renard et al. 1991; Wischmeier and Smith 1978). The basic input to generate the *L* and *S* factor grid layers in GIS software was DEM dataset. Given that, the slope steepness of this area mainly ranges from 5° to 40° (accounting for 85.5 %), and the combination of the equations below can calculate the steepness accurately. The calculation of *L* factor was calculated by the following formulas (McRoberts et al. 2002; Moore and Wilson 1992):

$$L = (\lambda/22.13)^m \quad (4)$$

$$m = \beta/(1 + \beta) \quad (5)$$

$$\beta = (\sin \theta/0.0896)/[3.0(\sin \theta)^{0.8} + 0.56] \quad (6)$$

where λ is the horizontal projection (m); 22.13 = the RUSLE unit plot length (m); *m* is a variable slope length exponent and θ is slope angle.

The *S* factor was calculated based on the relationship (Liu et al. 1994; McCool et al. 1987) below:

$$S = 10.8 \sin \theta + 0.03 \quad \theta < 5^\circ \quad (7)$$

$$S = 16.8 \sin \theta - 0.5 \quad 5^\circ \leq \theta < 10^\circ \quad (8)$$

$$S = 21.91 \sin \theta - 0.96 \quad \theta \geq 10^\circ \quad (9)$$

The *L* and *S* factors were calculated by Raster Calculator tool in ArcGIS. Then, the *LS* factor raster layer was further generated by multiplying *L* factor and *S* factor.

3.3.4 Cover management factor (*C*)

The cover management factor (*C*) is a crucial factor to the erosion because it is a readily managed condition to reduce erosion (Renard et al. 2011). Soil loss is very sensible to land cover in addition to relief (Chatterjee et al. 2014). Soil erosion decreases exponentially with increase in vegetation cover. Plant cover reduces soil erosion by intercepting raindrops, enhancing infiltration, slowing down the movement of runoff (Gyssels et al. 2005; Wang et al. 2013). The individual values of *C* factor vary from near zero for well-protected land cover to one for barren areas, reflecting abundance and type of the vegetation (Lee and Lee 2006). Higher values of *C* factor indicate no cover effect and high rate of soil loss, while lower values mean a very strong cover effect resulting in less erosion (Chatterjee et al. 2014).

There are several methods to get the *C* factor. Some studies determine *C* factor value using land cover classification map assuming that the same land covers have the same *C* factor values (Cebecauer and Hofierka 2008; Chatterjee et al. 2014; Lee 2004; Xu et al. 2011; Yang et al. 2012; Zhou et al. 2011), while some others use spectral mixture analysis (De Asis and Omasa 2007; Lu et al. 2004) or a regression analysis between *C* factor and spectral indices (e.g., NDVI, PVI) (Ma et al. 2003; Perovic et al. 2013; Tweddale et al. 2000; Xu et al. 2013; Zivotic et al. 2012). The regression analysis method was tested using NDVI data, but the result was not agreed well with other studies (Cai et al. 2000; Liu et al. 2009; Peng et al. 2007). To be specific, the values were overestimated, especially for forests. Taking into consideration the accuracy, in our study, *C* factor values were determined from land use classification according to relevant reports and local conditions.

The *C* value for forest land was 0.006, mixed forest 0.05, shrubland 0.02, woody savannas and forest 0.03, cropland 0.3, cropland/natural vegetation mosaics 0.1, water body and built-up 0, barren land 1 (Cai et al. 2000; Jiang et al. 2012; Liu et al. 2009; Peng et al. 2007).

3.3.5 Conservation support practice factor (*P*)

The *P* factor is defined as the ratio of soil loss with a specific support practice to the corresponding loss with upslope and downslope tillage (Renard et al. 1997). It is generally seen as reflecting the positive impact of management (Renard et al. 2011) that reduces the rate of water runoff. *P* factor values range from zero to one, representing good man-made erosion resistance facility and lack of such facility, respectively. *P* factor is usually estimated based on land use type. In this study, *P* factor values referred to previous research results (Naqvi et al. 2013; Xu et al. 2009, 2013; Zhao et al. 2007). Cropland was assigned with 0.4, barren land, water body and built-up with 0, and other land cover types were 1.

Fig. 3 Histogram of annual rainfall erosivity factor

3.4 Calculation of soil erosion

To estimate the soil loss, all model factors of the RUSLE were represented by raster layers. After preparation of R , K , LS , C , and P factor data layers, they were multiplied using ArcGIS to obtain erosion map. Average soil loss was calculated by multiplying each pixel value of the erosion map layer and pixel area then divided by total pixel area of the study area. The classifications of soil erosion under different slopes and elevations were operated with the raster calculation function of ArcGIS.

4 Results

4.1 RUSLE factors

Statistically, the annual rainfall erosivity factor data series show that the value of annual R factor for the years 1955–2013 ranges from 923.5 to 2,534.9 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{year}^{-1}$ (Fig. 3). The mean value of annual R factor is observed to be 1,558.4 $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{year}^{-1}$, and the standard deviation is 200.8 which implies that the rainfall in the study area was unstable and obviously fluctuated. The figure of R factor exhibits obvious spatial difference (Fig. 4). High values gather at the left bank of the main stream, while the low values are mainly clustered at the northeast part of the region. R values of any place in the study area for RUSLE can be obtained from R factor map in Fig. 4.

Fig. 4 Soil erosion modulus and factors of RUSLE model (Soil loss in $\text{t ha}^{-1} \text{year}^{-1}$; R factor in $\text{MJ mm ha}^{-1} \text{h}^{-1} \text{year}^{-1}$; K factor in $\text{t ha h ha}^{-1} \text{MJ}^{-1} \text{mm}^{-1}$; LS , C and P factors, dimensionless)

LS values are directly related to surface relief. The high values were along the river courses and in the mountainous areas (Fig. 4). The average value for this area was 30.6 with a large standard deviation of 42.6 which indicates the LS values were relatively unevenly distributed.

The high values of C factor were scattered on the low vegetation-covered area, such as lake, reservoir, river, cultivated land, and build-up. The average value was 0.1 with a standard deviation of 0.13. Owing large area of forest and grassland, the average value was lower.

K factor values were relatively discrete and unsteady due to the coarse resolution of available soil data. The values mainly ranged from 0.195 to 0.329 t ha h ha⁻¹ MJ⁻¹ mm⁻¹, and the mean value was 0.265 t ha h ha⁻¹ MJ⁻¹ mm⁻¹. The map of K values showed some clusters of lower value along river valleys (Fig. 4).

The P factor values were generally higher owing to the large area of forestland and grassland which lacked effective conservation practices.

4.2 Estimate of soil loss

The obtained results present the annual soil loss on a pixel by pixel basis (Fig. 4). Annual average soil erosion rate for the study area was estimated at 52.1 t ha⁻¹ year⁻¹, and annual soil loss was 4.5×10^8 t. The statistical result of annual soil erosion rate by category (Table 1) indicates that 14.7 % of the study area was under a slight erosion category, 35.3 % under a light soil erosion category, and 19.5 % under a moderate category of soil erosion. The severe to extreme erosion categories accounted for 30.5 % of the total area although the percentage of extreme erosion category was only 8.1 %. Regarding annual soil loss on a mass basis, 62.3 % of the total soil loss was derived from very severe and extreme erosion categories although their erosion areas only took up a small proportion less than 20 % of total area. And the rest was mainly from moderate and severe erosion categories with equally percentage. 9.8 % of soil loss was from light and slight erosion categories which were very low in comparison with their erosion area which accounted for 50 % of total area. On the whole, the study area belonged to severe erosion category considering the average erosion rate of 52.1 t ha⁻¹ year⁻¹.

Table 1 Statistics of soil erosion categories

Category	Criterion of erosion modulus ^{*, #}	Area percent (%)	Erosion area (10 ⁴ ha)	Avg. of erosion rate [#]	Soil loss percent (%)	Soil loss (10 ⁴ t year ⁻¹)
Slight	<5	14.7	127.2	2.3	0.6	285.8
Light	5–25	35.3	306.3	13.5	9.2	4,110.6
Moderate	25–50	19.5	169.5	36.0	13.5	6,048.3
Severe	50–80	11.9	103.4	63.3	14.5	6,492.0
Very severe	80–150	10.4	90.5	107.7	21.6	9,671.2
Extreme	>150	8.1	70.4	260.8	40.7	18,226.9

* SL190-2007 (Ministry of Water Resource of China, 2007)

[#] Unit: t ha⁻¹ year⁻¹

Fig. 5 Distribution of soil erosion intensity

As shown in Fig. 5, mountainous areas in the northwest and central part and river valleys had the severest soil erosion rate due to steep slopes, poor vegetation cover, and relatively heavy rain and runoff. The areas of low soil erosion rate were scattered in lake and lowland having a good ground cover, gentle slopes, and effective protection.

5 Discussions

5.1 Soil erosion on different elevations and slopes

The soil erosion category associated with different elevation zones is elaborated in Table 2. Around 96 % of the erosion area was in the elevation zone of 838–3,350 m. To be more specific, nearly 62 % of the erosion area occurred in the zone of 1,675–2,513 m and this zone was dominant no matter for any category. Therefore, it is essential to take conservation practices in the zone between 1,675 and 2,153 m to reduce soil loss. Meanwhile, the erosion in zone of 838–1,675 m cannot be ignored because severe to extreme categories in this zone took up a greater proportion.

While considering soil erosion on different slope zones (Table 3), around 95 % of erosion occurred in the zone with slopes less than 35° and excepting the less than 3° slopes the severe erosion category was overpowered by light, moderate, and slight categories of erosion. In particular, higher values are found in the zone with slopes between 8° and 25° , accounting for nearly 59 % of total erosion area. The very severe and extreme soil erosion

Table 2 Soil erosion category on elevation zones (percentage of area, %)

Elevation zone (m)	Slight	Light	Moderate	Severe	Very severe	Extreme	Total
<838	0.43	0.64	0.62	0.54	0.52	0.64	3.39
838–1,675	1.67	5.12	3.68	2.80	2.81	2.88	18.96
1,675–2,513	11.08	23.73	11.76	6.42	5.45	3.42	61.87
2,513–3,350	1.36	5.52	3.25	2.00	1.56	1.17	14.85
>3,350	0.13	0.31	0.23	0.16	0.08	0.02	0.93
Total	14.66	35.32	19.54	11.92	10.43	8.12	100.00

Table 3 Soil erosion category on different slope zones (percentage of area, %)

Slope	Slight	Light	Moderate	Severe	Very severe	Extreme	Total
<3°	2.00	1.92	0.73	0.38	0.29	0.19	5.52
3°–8°	3.16	5.95	2.73	1.38	1.17	0.73	15.13
8°–15°	4.62	11.11	5.46	2.84	2.46	1.83	28.32
15°–25°	3.44	10.52	6.49	3.85	3.24	2.84	30.38
25°–35°	1.14	4.36	3.03	2.37	2.13	1.79	14.83
>35°	0.30	1.42	1.11	1.10	1.15	0.75	5.83
Total	14.67	35.29	19.55	11.92	10.45	8.13	100.00

categories are seen in the zone with slopes between 8° and 25°, and the slight erosion category are mostly in the zone with slopes less than 15°.

5.2 Comparison of soil erosion in sub-basins

The spatial distribution characteristics of erosion are elaborated on a sub-basin level. The study area consists of 31 sub-basins which were generated from DEM using ArcSWAT. Average elevation, slope, and soil erosion rate of each sub-basin are presented on bar diagram in Fig. 6.

The top ten highest sub-basins with erosion rate more than 70 t ha⁻¹ year⁻¹ were mainly situated along the main course of Jinsha River where the slopes were steep, including sub-basin 17, 6, 20, 15, 18, 13, 30, 19, 25, and 5 (Fig. 6). Sub-basins situated along the left side of Jinsha River had higher erosion rate than those along the right side. For example, the erosion rates of basin 10, 12, 17, 22, 26, 27 were more than 59 t ha⁻¹ year⁻¹ which were higher than that of basin 1, 0, 3, 8, 16, 24, 28 with rates less than 55 t ha⁻¹ year⁻¹ (Fig. 6).

The correlation analysis of erosion rate with slope and elevation of these sub-basins revealed that the correlation between erosion and slope was very significant ($r = 0.86$, $P < 0.001$) while that between erosion and elevation was not significant ($r = 0.11$, $P = 0.541$). Therefore, it is essential to take conservation practices to reduce soil loss in steep slope areas, and specifically, as discussed above, areas with slopes between 15° and 35° should get key protection.

Fig. 6 Spatial distribution of annual soil loss in sub-basins **Table 4** Soil loss on different land use types

Land use type	Area percent (%)	Soil loss (10^4 t year $^{-1}$)	Soil loss percent (%)	Avg. erosion rate (t ha $^{-1}$ year $^{-1}$)
Forest	17.8	1,217.0	2.7	7.4
Mixed forest	3.0	1,687.6	3.8	66.9
Shrubland	17.6	4,019.8	9.0	25.5
Woody savannas	0.4	127.9	0.3	33.9
Grassland	35.6	11,383.6	25.4	38.0
Cropland	25.4	26,321.3	58.7	122.7
Cropland/Natural vegetation mosaics	0.2	77.1	0.2	39.3

5.3 Soil erosion on land use types

The soil loss and erosion category on different land use types were also assessed (Tables 4, 5). The analysis shows that the croplands contributed 58.7 % of total soil loss owing to its large erosion rate. The mean erosion rate of cropland was 122.7 t ha $^{-1}$ year $^{-1}$ and two-thirds of the cropland areas were under severe to extreme erosion categories. Therefore, soil conservation measures were urgently needed to control soil erosion of slope cultivated land, thereby reducing this massive soil loss. Grassland was the type of land cover that dominated the study area overwhelmingly (accounting for 35.6 %), from which the quantity of soil erosion made up a quarter of the total soil loss. Shrubland was the third

Table 5 Soil erosion category on land use types (percentage of area, %)

Land use type	Slight	Light	Moderate	Severe	Very severe	Extreme	Total
Forest	6.9	10.4	0.4	0.0	0.0	0.0	17.8
Mixed forest	0.1	0.6	0.7	0.6	0.7	0.2	3.0
Shrubland	1.8	8.2	5.1	2.0	0.5	0.0	17.6
Woody savannas	0.0	0.2	0.1	0.1	0.0	0.0	0.4
Grassland	3.1	12.8	9.8	5.9	3.7	0.3	35.6
Cropland	0.9	3.8	3.7	3.5	5.6	7.8	25.4
Cropland/natural vegetation mosaics	0.0	0.1	0.1	0.0	0.0	0.0	0.2

largest contributor due to its large area although the erosion rate of $25.5 \text{ t ha}^{-1} \text{ year}^{-1}$ was not very high. Comparatively, the mixed forest land had a high erosion rate of $66.9 \text{ t ha}^{-1} \text{ year}^{-1}$ and 76.7 % of this type had light to very severe erosion rate. Fortunately, this type has only 3 % of total area and the soil loss accounted for merely 3.8 %. Woody savannas and cropland/natural vegetation mosaics had moderate erosion rate and took up smaller proportion in either erosion area or amount of soil loss.

As regards to soil erosion on different land use types, most of the soil erosion occurred in cropland and grassland, accounting for about 84 % of the total soil loss, and the remained 16 % occurred in other land use types (Table 4). It should be noted that nearly all of severe to extreme erosion categories were from grassland and cropland (Table 5). The key work of conservation practices should put emphasis on these two land use types taking into consideration their large areas and mass soil loss. And it indicates that forests play an important role in soil conservation. Therefore, the Natural Forest Conservation Program and Grain-to-Green Program in this region is essential and should be implemented strictly.

5.4 Validation of the soil erosion estimation

In China, the upper reach of Yangtze River, namely Jinsha River, is known for soil erosion due to deforestation and slope farmland reclamation. As the study revealed, the annual average annual total soil loss was $4.5 \times 10^8 \text{ t}$ and soil erosion rate was estimated at $52.1 \text{ t ha}^{-1} \text{ year}^{-1}$. This is why government implemented the “Chang Zhi” Project, i.e., Major Control Engineering of Soil and Water Conservation in upper and middle Yangtze River. Apparently, our government has to take many effective measures to carry out the project according to the relatively high erosion.

As a whole, the result obtained in this work agrees well with the conclusions of other studies inside this region or in adjacent areas (Peng et al. 2007; Yang et al. 2004, 2005; Zhang et al. 2003). To be specific, the erosion rate in Yiliang County bordering Songming and Chenggong Counties which lie in our study area on the southeast side is $44.26 \text{ t ha}^{-1} \text{ year}^{-1}$ (Yang et al. 2005) or even higher ($85.43 \text{ t ha}^{-1} \text{ year}^{-1}$) (Zhang et al. 2003). The erosion rate in Binchuan County adjoining Dayao County which is located in our study area is $34.58 \text{ t ha}^{-1} \text{ year}^{-1}$ (Yang et al. 2004). And the erosion rate in Mouding County lying in our study area is $62.71 \text{ t ha}^{-1} \text{ year}^{-1}$ (Zhang et al. 2003). Besides, the erosion rate in Lijiang County which is next to our study area is $52.50 \text{ t ha}^{-1} \text{ year}^{-1}$

(Peng et al. 2007). These results indicate that our study result is reasonable and reliable. The methods and results described in this study are valuable for understanding the soil erosion in Jinsha River basin. And it is feasible to apply the RS, GIS, and the RUSLE model to assess soil erosion at a larger scale.

6 Conclusions

Soil erosion in Jinsha River basin is a serious problem, and assessment of soil erosion rate and soil loss is essential for water and soil conservation and sustainable development in this region. The application of RUSLE in GIS environment can be cost-saving and time-saving to estimate soil erosion over a large area. This study reveals that spatial annual average erosion rate was $52.1 \text{ t ha}^{-1} \text{ year}^{-1}$ classifying the area into severe soil erosion category. The annual soil loss was $4.5 \times 10^8 \text{ t}$ and 62.3 % of the total soil loss was derived from very severe and extreme erosion categories. Soil erosion is serious in the elevation zone between 1,675 and 2,153 m and slope zone with slopes between 15° and 35° . Correlation analysis indicated that slope was a very crucial factor affecting soil erosion. Soil erosion had been assessed also in sub-basins. The results show that the sub-basins of erosion rate more than $70 \text{ t ha}^{-1} \text{ year}^{-1}$ were mainly situated along the main course of Jinsha River. And spatially, sub-basins situated along the left side of Jinsha River had higher erosion rate than those along the right side. In terms of land use, grassland and cropland contributed mass majority to total soil loss. Thus, these areas need immediate attention from soil conservation point of view.

The RUSLE model and GIS techniques are very effective to estimate soil loss and erosion rate in this large area. The methods and results described in this study are valuable for understanding the situation of and relationship between soil erosion and environmental factors, which are useful to formulate and implement conservation program that will reduce soil erosion.

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