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A Soil Erosion Assessment of the Upper Mekong River in Yunnan Province, China

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This study estimated average annual soil loss and clarified its spatial distribution and impact on reservoirs in the upper Mekong River basin in Yunnan Province, China. A quantitative grid-based estimation was made using a Universal Soil Loss Equation model in a geographic information system framework, along with remote sensing and other source data. The results suggest that the average annual soil loss in most of the area ranged from 0 to 2853 t/ha/y, with a mean value of 19.8 t/ha/y. We estimated that a little more than half (61.0%) of the study area undergoes minimal erosion; this was primarily observed in the south, and more particularly in the southeast portion of the study area. Almost one fifth (19.2%) of the study area was estimated to undergo low erosion; this was primarily found in the central and southwest portions of the study area. Moderate soil erosion was observed in 8.5% of the study area. We estimated 11.3% of the study area to undergo high or extreme erosion; these locations were concentrated in the northern part of the study area. Soil erosion appeared most frequently at the mean elevation and mean slope zone. Dams on the upper reaches were found to be threatened by the presence of sediment.

Keywords: *Soil erosion; USLE; GIS; Mekong River; China.*

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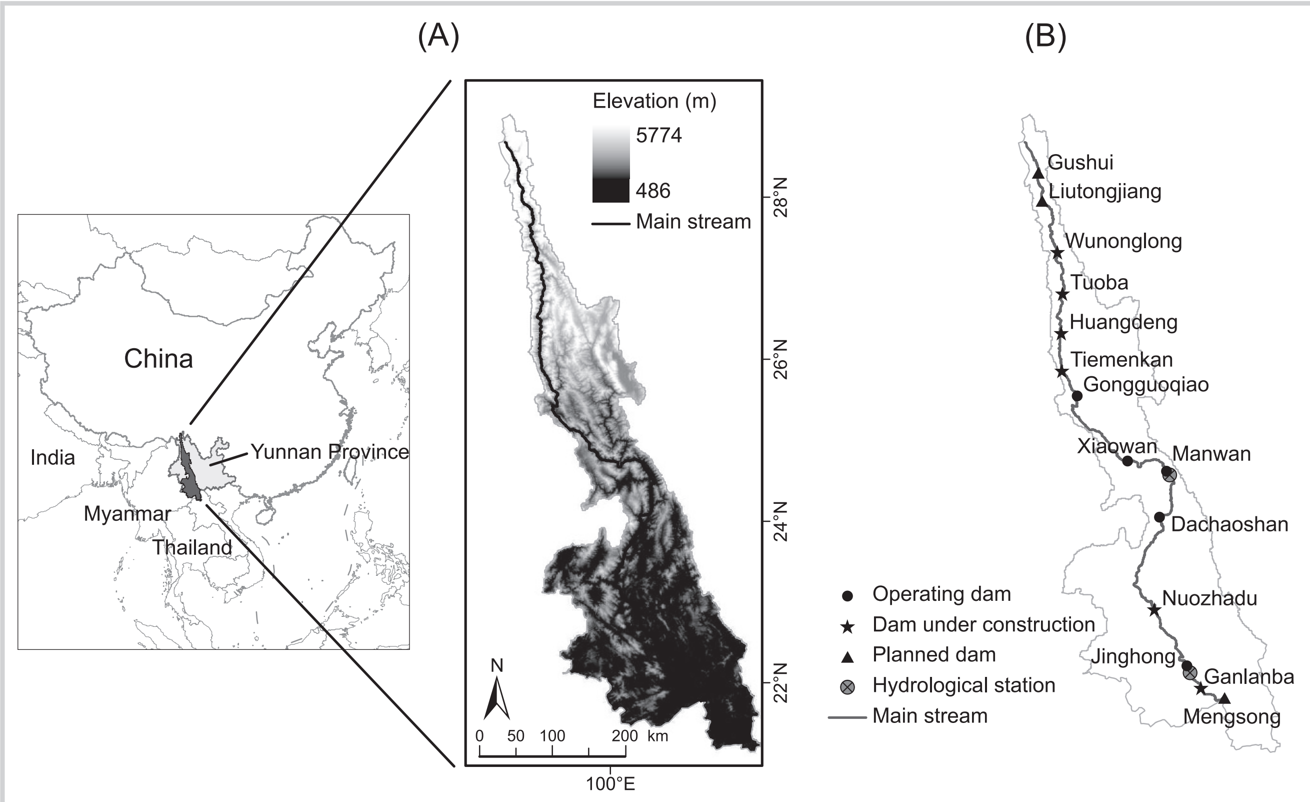
Introduction

Soil erosion has been described as one of the most critical environmental hazards in modern times (Bahadur 2009), because of its adverse economic and environmental impacts. These include diminished land resources and reduced land productivity, as well as sediment delivery, which reduces the storage capacity and life span of reservoirs (Eroglu et al 2010). The annual loss of storage capacity of the world's reservoirs due to sediment deposition is estimated at 0.5–1.0% (WCD 2000). For many reservoirs, annual depletion rates can reach 4% or 5%, which means that they lose most of their capacity after only 25–30 years (De Vente et al 2005). In large reservoirs with infrequent drawdowns, the majority of the deposited sediment load occupies parts of the usable storage capacity, whereas the dead storage capacity is almost free of sediment (Zarris et al 2002; Snyder et al 2004). (Usable storage capacity refers to when the reservoirs are full of water and maximum water volume can be released from the gate, whereas dead storage capacity refers to a volume where no release is possible.) This accumulation pattern in large reservoirs poses a serious threat to the sustainability of major hydraulic systems (Demetris et al 2011).

The Mekong River (known as the Lancang River in China) is an important transboundary river, flowing through China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. The China portion of the Mekong River is the site of 90% of the river's drop in elevation and provides a rich resource for hydropower development (Fu et al 2008). This hydropower potential has led to the construction of a number of dams (Li et al 2013). However, the upper reach of the Mekong River in China suffered large-scale deforestation for many years, exposing the soil to rain. This unprotected soil was easily carried into the river by the combined action of rain and the resulting flow. The dams themselves, regardless of their operation, construction, or stage of development, are now or soon will be threatened by the resulting soil erosion and sediment load.

In recent years, a considerable number of studies have been published concerning soil erosion and sediment in the upper Mekong River Basin. Kummu and Varis (2007) studied the sediment loads of the upper reaches of the Lower Mekong River at Chiang Saen (Thailand). Fu et al (2008) analyzed pre- and postdam sediment data for monitoring stations below the Manwan dam (China). Using annual data from 7 stations from 1965 to 2003, Liu et al (2013) analyzed the nature and magnitude of recent changes in the sediment load of the Lancang/Mekong River. Most of these studies concentrated on the sediment in reservoirs and river channels by applying observational sediment data. Some studies used spatially distributed

FIGURE 1 (A) Location and elevation of the study area; (B) existing and planned dams on the upper Mekong River. (Map by Qiuwen Zhou)



data to estimate regional soil erosion in study areas related to the upper Mekong River basin (Yu et al 2006; Peng et al 2007). Yao et al (2005, 2006) also estimated soil erosion in the upper Mekong River basin in Yunnan, China, and analyzed its spatial pattern and relationship to environmental factors.

Few of these studies analyzed the spatial pattern of soil erosion and its impact on reservoirs or dams in this area, however. Because soil erosion measures can effectively reduce sediment and thereby protect reservoirs from sediment accumulation, this information is of critical importance. It would, for example, allow the effective implementation of managerial practices that minimize soil erosion. Consequently, it would mitigate harm to the reservoirs from sediment deposition.

This article uses the upper Mekong River basin in Yunnan Province, China (hereafter referred to as the upper Mekong River basin) as a case study, focusing on the spatial pattern of soil erosion and its impact on reservoirs. Using remote sensing and other data sources, 5 soil-erosion impact factors were calculated and analyzed. Actual and potential soil loss in the river basin was then estimated, and actual soil erosion was classified into 5 categories. Finally, soil erosion and its impact on reservoirs were analyzed by dividing the catchment area of reservoirs and considering sediment delivery distance. Study results help to identify regions prone to erosion and allow the development of site-specific erosion management measures for high-erosion areas, thus enhancing the protection of reservoirs from sediment deposition.

Study area

The upper Mekong River (21°08′41″–29°14′04″N, 98°40′07″–102°20′51″E), located in southwest China, originates in the Tibetan highlands of China at an altitude of 4970 m above mean sea level. After leaving China, it is known as the Mekong River. The Chinese portion of the river is approximately 2160 km long, of which 1170 km is in Yunnan Province, where the river has a catchment area of 8.79 × 104 km^2. The annual maximum and minimum mean flow rates are 1590 and 923 m^3/s. The time of occurrence and duration of floods and the inundated area each year are relatively stable (Kite 2001; Fu et al 2008). The terrain of the basin is complex, with high hills and deep valleys. Because of this variance in elevation, the region's vertical distribution of plants differs according to climatic zones that range from tropical to temperate to cold. The complexity of the terrain and variance in elevation also generate copious hydropower potential; many dams have been built or are planned on the main stream (Figure 1).

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Material and methods

Universal Soil Loss Equation model

A range of models have been used to estimate soil erosion, including the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978), the Water Erosion Prediction Project (Flanagan and Nearing 1995), the Soil and Water Assessment Tool (Arnold et al 1998), and the European Soil Erosion Model (Morgan et al 1998). These can generally be divided into empirically and physically based models. Because the latter are not well verified or require many input parameters, empirically based models are more prevalent in soil erosion estimation (Shrestha et al 2006). Other constraints include the lack of a gauging station to observe soil erosion in the study area and the fact that conventional methods of soil erosion estimation are time consuming, costly, and biased, particularly in this mountainous region. Compared to other empirically based models, the USLE, and its revised version, RUSLE, are the most popular for estimating mean soil erosion by water (Ozcan et al 2008). The USLE/RUSLE can also be easily integrated with a geographic information system (GIS) and remote sensing (Fu et al 2005; Karaburun 2009), which means the input data are more accessible and the spatial distribution of soil erosion in a large basin can be vividly revealed. However, as RUSLE requires more sophisticated input parameters and such data were not all available in the study area, the USLE model was considered a better choice in the present case.

In the USLE model, mean annual soil loss is expressed as a function of 6 erosion factors:

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

where A is the computed amount of soil loss (t/ha/y), R is the rainfall erosivity factor (MJ mm/[ha h y]), K is the soil erodibility factor (t h/MJ/mm), L is the slope length factor, S is the slope steepness factor, C is the cover and management practices factor, and P is the soil erosion control practices factor. L, S, C, and P are dimensionless. Here, each cell is assumed to be a closed plot that cannot be entered by surface flow from another cell.

Improving the model was not the goal of this study; we simply selected the most suitable formulas to estimate the USLE model factors. We mainly considered data availability and feasibility when selecting the formulas for several reasons. First, the upper Mekong River basin is somewhat data scarce, and so observational data are often hard to obtain. In addition, the terrain of the river basin is complex, accessibility is poor, and it is impractical to carry out the large number of field experiments needed to obtain the model parameters.

Rainfall erosivity

The R factor was derived according to the modified Fournier index. This index is used widely to estimate the R factor from monthly rainfall data (Arnoldus 1980); it is determined by the ratio between monthly and annual precipitation.

Precipitation data were derived from WorldClim, which is a set of global climate data in layers or grids with a spatial resolution of about 1 km^2 (Hijmans et al 2005). This dataset was developed based on the ANUSPLIN software program (Hutchinson 2004) and meteorological data—including monthly precipitation and monthly mean, maximum, and minimum temperature—collected from 1950 to 2000 from 47,554 stations worldwide. Five meteorological stations in our study area are included in the dataset, with data collected for 1980–2000.

Soil erodibility

Several equations have been developed to estimate K (Wischmeier and Smith 1978; Foster et al 1991; Torri et al 1997). Williams and Renard (1983) developed an equation that uses only soil organic carbon and soil particle composition as input parameters, which is especially suited for a data-limited area like the upper Mekong River. We therefore chose this equation for our K value estimation.

Soil parameters used in this study were collected and derived from the Harmonized World Soil Database (FAO et al 2012). The database is a global 30–arc-second raster soil database. This database assimilated many existing soil maps and database worldwide (Batjes 2009), including the Soil and Terrain Database (UNEP et al 1995), the Soil Database for Europe (European Soil Bureau 2004), the Soil Map of China (Office for the Second National Soil Survey of China 1995), the World Inventory of Soil Emission Potential Database, and the Soil Map of the World (FAO and UNESCO 1981). The scale of the Soil Map of China is 1:1,000,000 (FAO et al 2012).

Topography

Traditionally, the best topographic (L and S factors) estimates were obtained from field measurements. However, field measurements in the upper Mekong River basin have not always been available or practical. Because of the significant variance in elevation, accessibility is limited, and obtaining enough sampling sites to estimate the L and S factors was not feasible. We therefore used digital elevation model (DEM) data to estimate it. The unit stream power algorithm developed by Moore and Burch (1986a, 1986b) makes use of the upslope drainage area, which is obtained by multiplying a flow accumulation grid with its cell area, allowing the algorithm to be easily integrated with raster DEM data and the GIS environment (Moore and Wilson 1992). This algorithm has been widely applied (Zhang et al 2009; Manoj and Debjyoti 2010; Prasannakumar et al 2011). Thus, the unit stream power algorithm (Moore and Burch 1986a, 1986b; Moore and Wilson 1992) was applied to estimate the L and S factors for the upper Mekong River basin. The empirical

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TABLE 1 DRs in similar regions of the upper Mekong River.

Region	DR	Reference
Eastern Yunan Province	0.40–0.41	Zhang and Chai 1996
Upper Jialingjiang River	0.61	
Lower Jinshajiang River	0.61	
Upper Yangtze River	0.70–0.80	Jing 2002
Upper Longchuanjiang River	0.42–0.80	Wen et al 2003

exponents in this algorithm adopted widely used values (Moore and Wilson 1992; Lopez-Vicente et al 2009; Ali and Ahmet 2012).

The DEM data are derived from ASTER GDEM, which is a satellite observed digital elevation dataset, with a cell size of 30 m (Abrams et al 2010). We calculated the *L* and *S* factors using the ArcGIS Spatial Analyst Plus and the Archydro extension.

Cover and management practices

Several methods have recently been developed to use the Normalized Difference Vegetation Index (NDVI) to estimate the *C* factor (Lin et al 2002; Wang et al 2002). Van der Knijff et al (2000) introduced a scaling approach to estimate the *C* value, which provides better results than assuming a linear relationship and does not require field measures. For these reasons, this method was selected to estimate the *C* value. Monthly NDVI data were derived from Moderate Resolution Imaging Spectroradiometer (MODIS) remote sensing data, with a cell size of 250 m (Zhan et al 2000). In order to accurately reflect the average vegetation cover in the study area, July and December data were selected for 2001–2010. The data were then calculated to generate 10 years of annual average NDVI.

Soil erosion control practices

Because the upper Mekong River basin covers a large area, the *P* factor varies and is difficult to summarize. Thus, this study determined the *P* value by land cover type, using the values suggested by Yang et al (2003).The land use and land cover data were derived from MODIS remote sensing data, with a cell size of 250 m. Because it is difficult to calculate the average land use pattern and because it is relatively stable in the study area, 2010 land use and land cover data were used to obtain the *P* factor.

Software

Applying the methods described above, all the data were calculated using the Raster Calculator tool in the ArcGIS 9.3 software. The spatial resolution and coordinate system of the parameter layers were consistent with the original data. After generating the 5-parameter layers, we converted them into a grid with 250 × 250-m cells in a uniform coordinate system, and the quantitative output of soil erosion for the study area was computed in an ArcGIS 9.3 environment. Potential soil erosion was computed by multiplying *R*, *K*, *L,* and *S*; all factors were included when computing actual soil erosion as in Equation 1. In this way, the average soil erosion and its spatial distribution pattern were obtained.

Results

Accuracy evaluation

The output of the USLE model included both actual and potential soil erosion. Because potential soil erosion and soil conservation capability are hypothetical, the accuracy is hard to evaluate, and we therefore evaluated only the accuracy of the data on actual soil erosion. By using mean annual sediment load data observed by the hydrological station, and multiplying the model output by the sedimentation delivery ratio (DR) as simulated data, we calculated the absolute error and relative error to evaluate the accuracy of actual soil erosion data. Here, DR is defined as the fraction of gross erosion that is transported from a given catchment in a given time interval (Lu et al 2006): it is the ratio of gross soil erosion and sediment yield.

Prior to 1987, there was no dam on the main stream of the upper Mekong River, and there were fewer dams on the tributaries. We therefore selected annual sediment load data observed from 1965 to 1987 to calculate the mean annual sediment load. Data were collected from Liu et al (2013). Two hydrological stations where data were observed, the Gajiu and Yunjinghong stations, were selected for the accuracy evaluation. We evaluated the DR in reference to research conducted in similar regions (Table 1), and then used 0.6 as the DR value.

The accuracy evaluation results showed that absolute error and relative error at Gajiu station were -3.52×10^6 t and -0.06, respectively, and at Yunjinghong station they were -25.6×10^6 t and -0.23. The mean annual soil erosion was thus properly simulated.

Soil erosion factors

Annual soil erosion was estimated by incorporating all the factors that determine its rate and amount.

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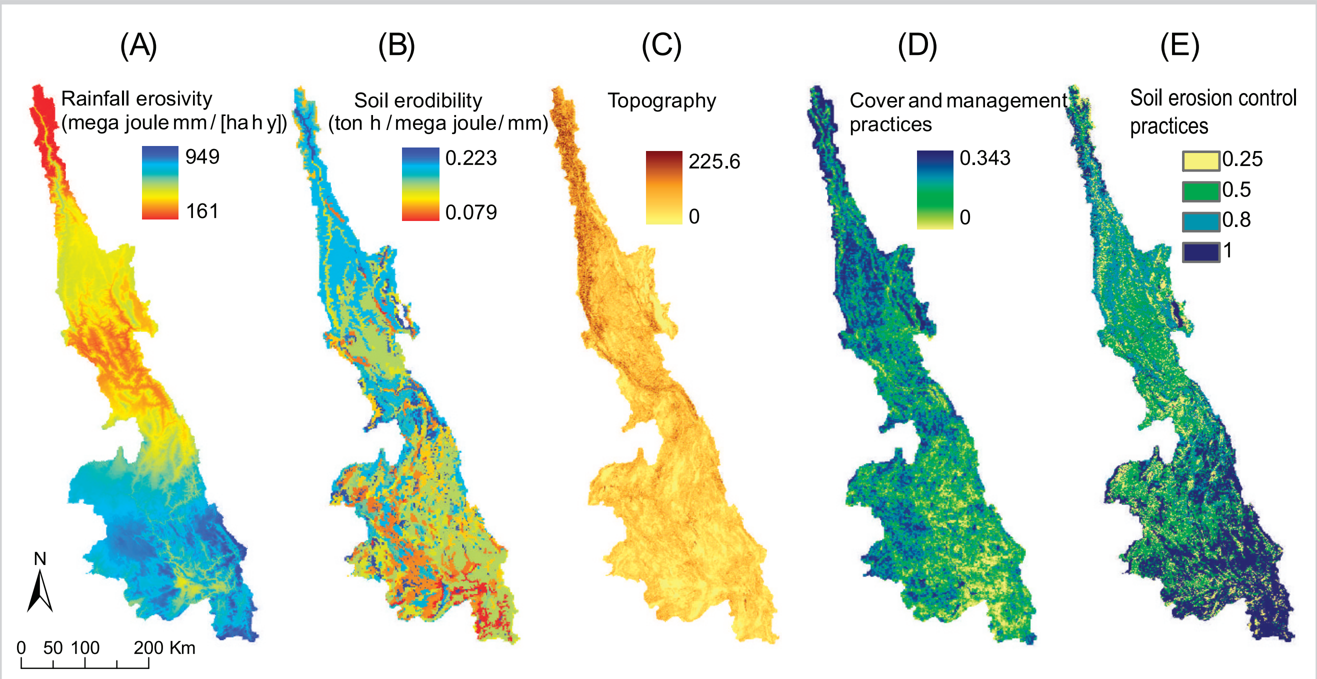
FIGURE 2 Factors considered in this study for the upper Mekong River. (A) *R*; (B) *K*; (C) *LS*; (D) *C*; (E) *P*.



Annual *R* values were found to range from 161 to 948 with an average of 584 MJ mm/(ha h y); the standard deviation was 143. The distribution of *R* values over the study area is shown in Figure 2A; *R* values generally increased from the lower basin to the upper basin. Lower *R* values were primarily distributed in the northern tip, and higher *R* values were primarily distributed in the southern portion of the study area. In comparison, mean *R* values were generally distributed in the central part of the study area. These trends were dependent on the distribution characteristics of precipitation.

Of the 102 soil groups that are found in the upper Mekong River Basin, 5 are major soil groups (FAO et al 1990). The largest is Eutric Gley, located in the central and southern portion of the study area, primarily on the east side of the Mekong River, and occupying 22% of the study area. Approximately 23% of the study area comprises 4 other soil groups: Calcic Luvisols, Gleyic Luvisols, Stagnic Luvisols, and Lithic Leptosols. The Gleyic Luvisols are mostly found in the upper reach of the basin and the Stagnic Luvisols and Lithic Leptosols are primarily found in the downstream portion, whereas the Calcic Luvisols are widely distributed in the study area. The *K* factor for each soil group in the study area was calculated using the soil properties obtained from the Harmonized World Soil Database. The *K* factor in the study area ranged from 0.08 to 0.22 t h/MJ/mm, with a mean of 0.16 t h/MJ/mm and a standard deviation of 0.027. Spatial distribution of *K* (Figure 2B) decreased from north to south. *K* value distribution was generally correlated with the variation of terrain, with the *K* value significantly lower in valleys than in mountain areas.

Figure 1A shows the elevation map of the study area. Elevation ranges from 486 to 5574 m, the average elevation is 1790 m, and the highest points are found in the north part of the study area. Approximately 76.5% of the study area has a slope of 10 to 40°; areas with steeper slope are mostly in the north and those with less steepness in the south. Only 2.6% of the area has a slope steepness under 2° (Table 2). As can be seen in Figure 2C, the *LS* factor value varies from 0 to 226, with a mean value of 7.71. The areas with higher *LS* factor values are generally located in the northern portion of the study area and the areas with lower *LS* factor values in the central and southern portions.

TABLE 2 Slope steepness categories for the study area.

Steepness (°)	Relief classification	Area (%)
0–2	Flat	2.6
2–5	Gently undulating	4.8
5–10	Moderately undulating	14.0
10–20	Undulating	39.7
20–40	Strongly undulating	36.8
>40	Mountainous	2.1

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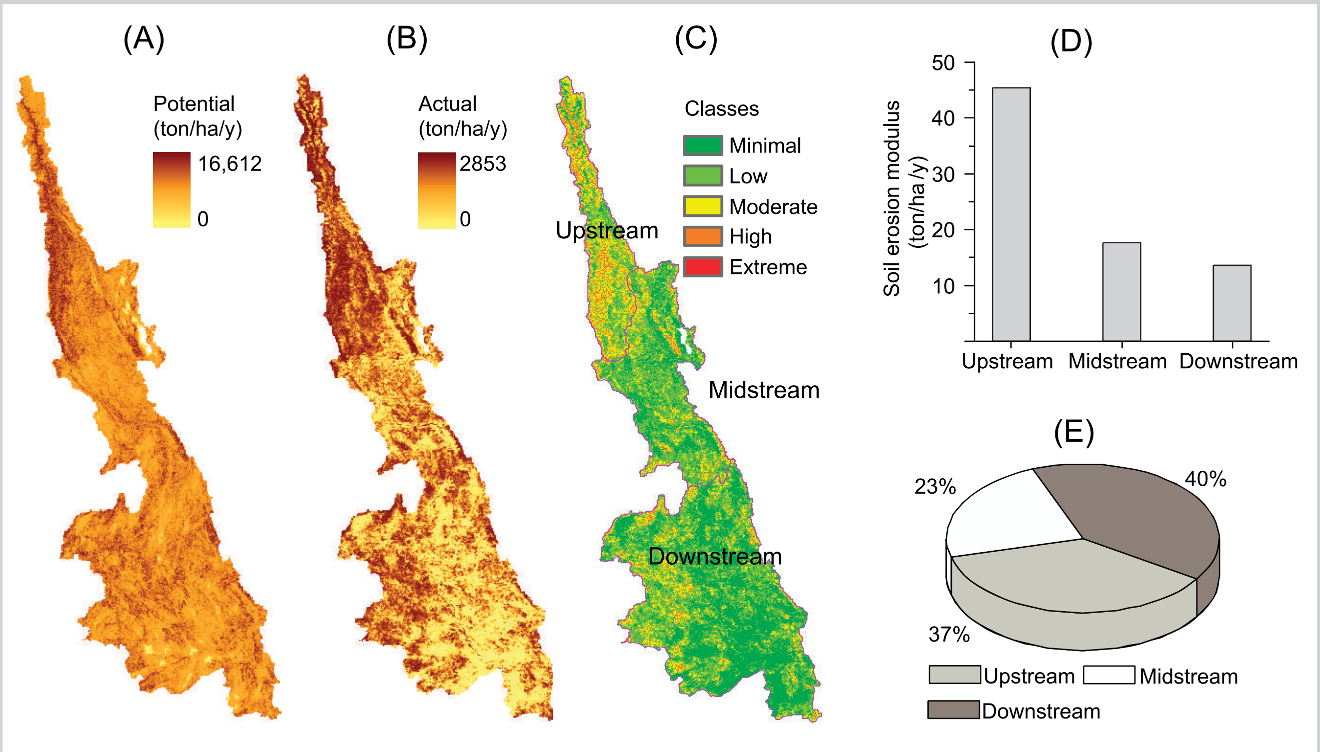
FIGURE 3 Soil loss in the upper Mekong River. (A) Potential annual loss; (B) actual annual loss; (C) classes of erosion and catchments over the study area; (D) soil erosion modulus for each catchment; (E) proportion of soil loss in each catchment.



The *C* factor value map (Figure 2D) was produced from NDVI data. The *C* factor value in the upper Mekong River basin varies from 0 to 0.34, with a mean and standard deviation of 0.049 and 0.067, respectively. The lower *C* factor values are found in most of the study area, where the majority of land is covered by forest. Higher *C* factor values are found only in the north and only in a small area.

The *P* factor value map (Figure 2E) was prepared from the land use and land cover data. The data were derived from MODIS remote sensing data (Zhan et al 2000). The *P* factor values inside the study area were found to be 0.25, 0.5, 0.8, and 1. The *P* value was 0.5 in the largest portion (36.2%) of the study area and 0.25 in the smallest portion (13.8%). A higher *P* factor value was generally found in the south and a moderate *P* factor value in the central and northern parts of the study area.

Potential and actual soil erosion

Potential erosion was computed based on just 4 factors—*R*, *K*, *L,* and *S*—which are considered naturally occurring factors in determining erosion processes. Potential soil loss was then obtained by overlaying the grid data of the 4 factors in the ArcGIS software (Figure 3A). The potential soil erosion rate ranged from 0 to more than 10,000 t/ha/y. Although a high potential soil erosion rate appears, this area accounts for only a small proportion of the study area. The mean potential annual soil loss was 683 t/ha/y with a standard deviation of 854. Despite the excessive disparity in potential average annual soil loss, the value for most of the area was between 190 and 1260 t/ha/y.

Because vegetation cover and support practice play an important role in the actual amount of soil loss and the rate of erosion, the *R*, *K*, *LS*, *C*, and *P* factors (see Figure 2) were taken into account in the actual soil loss estimate, which provides a better real-world picture of soil erosion (Figure 3B). Average annual soil loss in most of the area ranged from 0 to 2853 t/ha/y; the mean actual annual soil loss was 19.8 t/ha/y, with a standard deviation of 52. The most serious soil loss occurred primarily in the north; the farther south, the less the soil erosion.

Soil erosion and its relationship to slope steepness and elevation

Based on the estimated actual annual soil loss rates, the study area was classified into 5 erosion categories (Table 3; Figure 3C). The classification was based on the Soil Erosion Rate Standard, Technological Standard of Soil and Water Conservation SD238-87, issued by the Ministry of Water Resources of China (Ministry of Water Resources of China 1988). As seen in Table 3, more than half of the study area (61.0%) was estimated to have minimal erosion risk, which was mostly seen in the south, particularly in the southeast portion of the study area,

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TABLE 3 Levels of soil erosion in the study area.

Erosion class	Area affected (%)	Annual soil loss		
		Rate (t/ha)	Total (10^4 t)	%
Minimal	61.0	<5	292	1.7
Low	19.2	5–25	2146	12.3
Moderate	8.5	25–50	2624	15.1
High	4.6	50–80	2506	14.4
Extreme	6.7	>80	9823	56.5

where the annual soil loss was 292×10^4 t/y. An estimated 19.2% was in a low erosion risk category, primarily in the central and southwest portion of the study area, with annual soil loss of 2146×10^4 t/y. Moderate soil erosion was estimated for 8.5% of the study area, with annual soil loss of 2624×10^4 t/y. Approximately 11.3% of the study area was estimated to suffer from high or extreme erosion risk; this area accounted for 70.9% of the soil loss for the entire study area, which indicates that severe soil erosion had already taken place. High and extreme erosion risks were concentrated in the northern part of the study area.

Because of the significant variance of elevation and steepness, the topographic factor may have played a key role in soil erosion. Slope steepness and elevation effects on soil erosion are discussed below.

The highest elevation in the study area is 5774 m and the lowest is 486 m, with a mean elevation of 1800 m. The percentage of soil erosion at different elevation zones is shown in Table 4. About 80.4% of the soil erosion appears between 1000 and 3000 m, including most of the high and extreme erosion risk and most of the minimal erosion risk. In addition, 11.5% of the soil erosion occurred in an elevation zone lower than 1000 m, and most of this soil erosion represented minimal erosion risk. Just 8.1% of the soil erosion area was at elevations higher than 3000 m, and even less (1.5%) was at elevations higher than 4000 m. Most of the soil erosion occurred in the moderate elevation zone, particularly between 1000 and 2000 m.

The maximum slope in the upper Mekong River basin is 75°, and the mean slope is 18°. The percentages of the study area undergoing different soil erosion at different steepness categories are presented in Table 5. Fully 88.3% of the soil erosion was produced on land with a steepness between 0° and 30°, particularly between 10° and 20°, no matter how high or low the soil erosion. The soil erosion modulus (soil erosion amount in unit time and unit area) at different slope steepness rates generally increased with the steepening of slope. The average soil erosion modulus was 11.6 t/ha/y when the slope steepness was lower than 10°, but it reached 59.7 t/ha/y when the slope steepness was greater than 40°.

Impact of soil erosion on dams

Because soil erosion in the river basin has produced a large amount of sediment in the river channel, it threatens the operation of the dams. A total of 14 dams exist on or are planned for the main stream of the river (Figure 1B)—5 currently in operation, 6 under construction, and 3 planned. The operational dams—Gongguoqiao, Xiaowan, Manwan, Dachaoshan, and Jinghong—are mostly in the southern section of the Mekong, where soil erosion is relatively weak. However, these dams can be expected to receive sediment from the upper reaches, so until the dams on the upper reaches are completed, they will be negatively affected by sediment. Soil erosion in the northern portion of the basin is severe, and although few dams are currently operating in this area, there are still 4 dams under construction and 2 additional dams planned. Once these dams are completed, their operation will be threatened by the increasing amount of sediment.

In order to quantify the soil loss that threatens the dams, the study area was divided into 3 parts based on the reservoirs' water collecting areas—the upstream, midstream, and downstream catchments (Figure 3C). The upstream catchment—the smallest—covered 14,069 km^2, accounting for 16% of the study area. The midstream catchment covered 22,773 km^2 or 26% of the study area, and the downstream catchment covered 51,028 km^2 or 58% of the study area.

The soil erosion modulus for the study area decreased from the upstream catchment to the downstream catchment (Figure 3D). In the upstream catchment, it was 45.4 t/ha/y. Although the upstream catchment accounted for just a small proportion of the entire study area, 37% of the total soil loss was concentrated there. The soil erosion modulus in the midstream catchment was 17.7 t/ha/y, representing 23% (the smallest proportion) of the total soil loss. The soil erosion modulus in the downstream catchment was 13.7 t/ha/y. This value was the smallest even though the soil loss in this catchment was the largest, which can be attributed to the catchment's large area (Figure 3D, E). As a result of this analysis, dams located in the upstream catchment were found to be more

TABLE 4 Soil erosion at different elevations in the study area.

Elevation (m)	Area (%)					
	Minimal	Low	Moderate	High	Extreme	Sum of area per elevation class (%)
<1000	9.5	1.5	0.3	0.1	0.1	11.5
1000–2000	35.3	11.6	4.6	2.2	2.4	56.1
2000–3000	12.5	5.1	2.7	1.6	2.4	24.3
3000–4000	3.1	0.9	0.7	0.5	1.4	6.6
>4000	0.6	0.1	0.2	0.2	0.4	1.5
Sum of area per erosion class (%)	61.0	19.2	8.5	4.6	6.7	100.0

vulnerable to soil erosion and thereby to sediment. Dams located in the midstream catchment, including Xiaowan, Manwan, and Dachaoshan, were relatively safe. Soil erosion in this area was found to be light, and the area of this catchment is relatively small.

Sediment loads in the reservoirs

In order to analyze the possible sediment load of the reservoirs, we multiplied the mean annual soil erosion by DR to estimate the annual sediment yield. The DR value is the same as described above. In addition, we assumed almost all the sediment would be trapped by the reservoir, with little sediment moving downstream of it. We then divided the upper Mekong River basin area into several catchments according to the dominant sediment collecting area of each reservoir (Figure 4A–C).

There are 5 operating reservoirs on the upper Mekong River. As Figure 4D shows, Gongguoqiao has the most serious sediment load; both its sediment yield and soil erosion modulus are the highest among the 5 catchments. Sediment yield reached 39.2×10^4 t/y, and the soil erosion modulus is 46.9 t/ha/y.

When adding the dams under construction to the scenario, the results change significantly (Figure 4E). First, the mean and highest sediment loads decrease. Second, Gongguoqiao no longer has the heaviest sediment load. With the 4 dams upstream from Gongguoqiao completed, most sediment is trapped by their reservoirs. Of these 4 reservoirs, Huangdeng and Tiemenkan have a high soil erosion modulus, but Wunonglong has the highest sediment load, because it traps most of the sediment from upstream. Third, after the Nuozhadu dam is completed, the sediment load of Jinghong decreases.

In a scenario with all the dams complete (Figure 4F), the sediment loads at Manwan, Nuozhadu, and Jinghong are significantly higher than at other dams, although the soil erosion modulus in these areas is relatively low. The soil erosion modulus in the upstream areas is high, but the sediment load in these areas is low. This may be because the area is small, so gross sediment yield is low.

Generally speaking, with only 5 operating reservoirs on the upper Mekong River, the sediment load in each reservoir is high, especially in the upper reaches. As the number of reservoirs increases, the average reservoir

TABLE 5 Soil erosion at different steepness categories.

Steepness (°)	Area (%)					
	Minimal	Low	Moderate	High	Extreme	Sum of area per steepness class (%)
<10	15.3	3.6	1.2	0.5	0.5	21.1
10–20	24.8	8.0	3.4	1.7	1.9	39.8
20–30	15.3	5.4	2.7	1.6	2.4	27.4
30–40	4.7	1.7	1.0	0.7	1.4	9.5
>40	1.0	0.3	0.2	0.2	0.5	2.2
Sum of area per erosion class (%)	61.1	19.0	8.5	4.7	6.7	100.0

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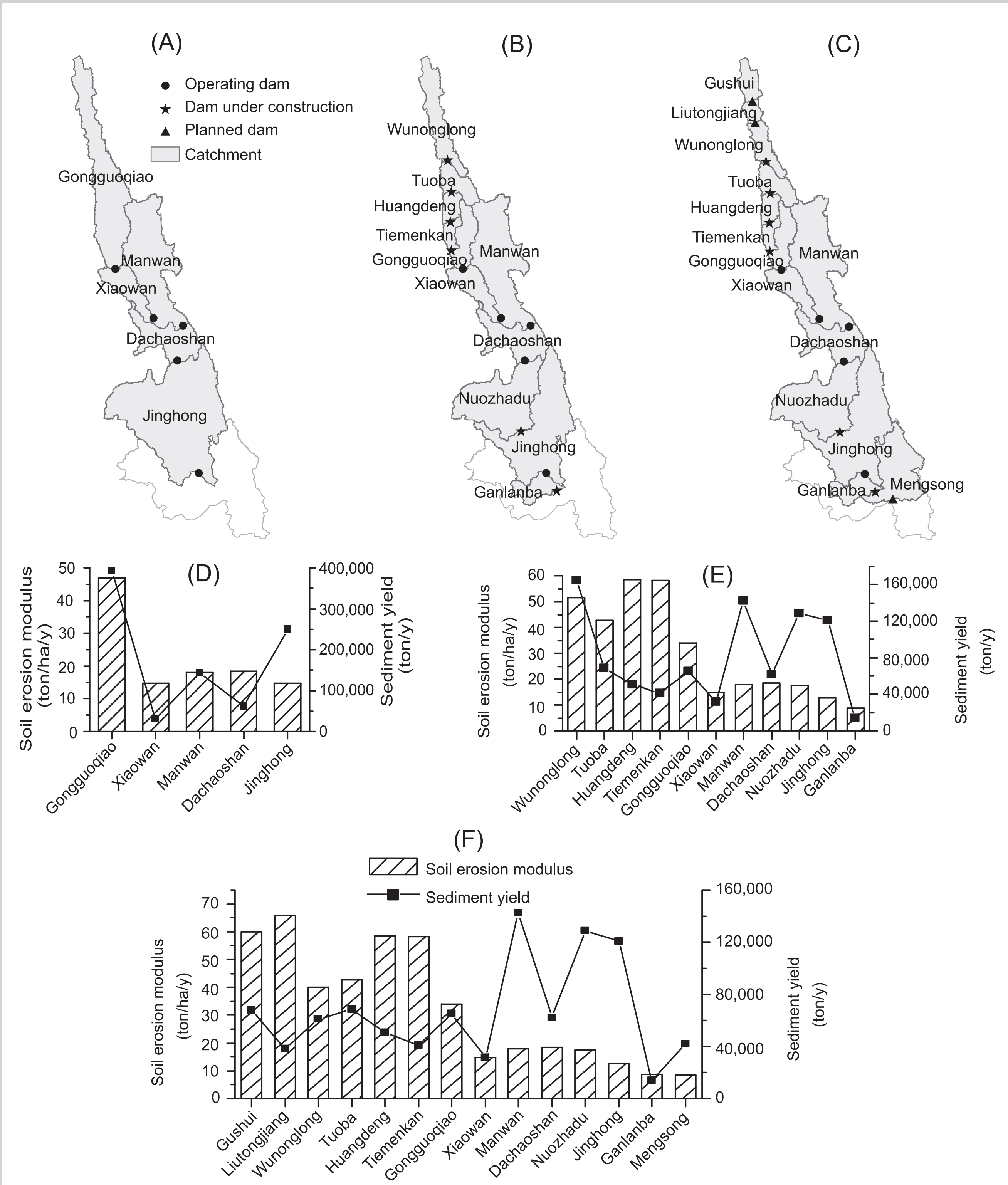
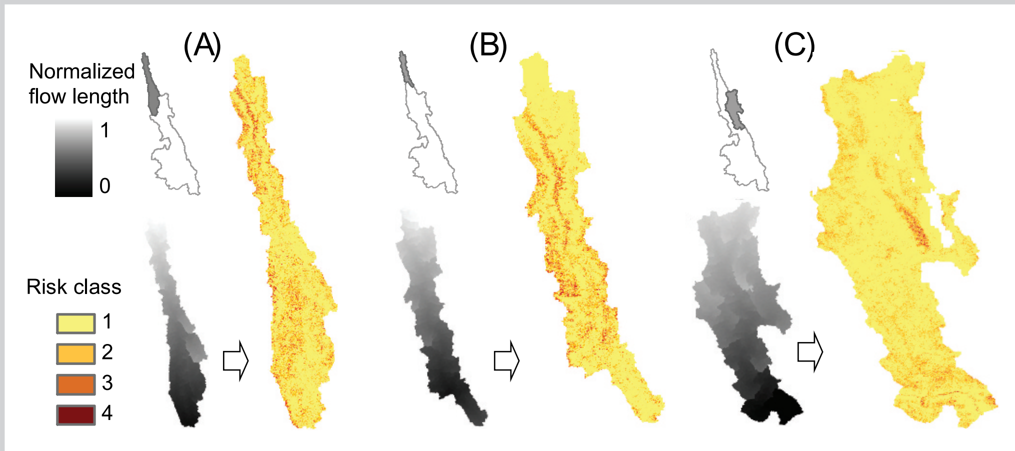
FIGURE 4 Dams on the upper Mekong River in 3 scenarios and the corresponding soil modulus and sediment yield. (A) Currently operating dams; (B) operating dams and dams under construction; (C) existing and planned dams; (D–F) soil moduli and sediment yields.



http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00027.1

FIGURE 5 Normalized flow length and soil erosion risk in 3 major catchments: (A) Gongguoqiao; (B) Wunonglong; (C) Manwan.



sediment load declines, and the relative sediment load of the reservoirs where it was originally the highest (Gongguoqiao and Wunonglong) becomes moderate, while the reservoirs that originally had moderate loads (Manwan, Nuozhadu, and Jinghong) receive higher loads.

Identification of the key area of soil erosion by considering sediment transport distance

In fact, not all the sediment yield is transported to the reservoir. Sediment transport is influenced by many factors, and we do not have the ability to precisely simulate the process. In this study, we instead identified the key area of soil erosion by considering sediment transport distance, as shown in Equation 2:

$$RKD_i = \left(1 - \frac{d_i - d_{min}}{d_{max} - d_{min}}\right) \times \left(\frac{M_i - M_{min}}{M_{max} - M_{min}}\right) \qquad (2)$$

where i is the serial number of calculation unit of the spatial data, RKD is soil erosion risk that considers sediment transport distance, d is sediment transport distance to the dam, M is the soil erosion modulus, and $_{min}$ and $_{max}$ represent minimum and maximum values. For our purposes, the sediment transport distance to the dam is similar to flow length, which is calculated by ArcGIS software (Figure 5A–C).

In this section, the 3 catchments most seriously affected by sediment load in different development periods for 3 dams were selected to evaluate the RKD using Equation 2. Each of the catchment's RKD maps was then reclassified into 4 grades based on the natural breaks (Jenks 1967; Jenks's natural breaks classification method is a data classification method designed to determine the best arrangement of values into different classes), based on the importance of soil and water conservation (Figure 5A–C). The area with a highest value was then identified as the key area of soil erosion at the reservoir.

As mentioned above, Gongguoqiao experienced the most serious sediment load among the 5 operating reservoirs. Key areas of soil erosion in the Gongguoqiao catchment (Figure 5A) were mostly found near the mainstream, especially in the northern part of the catchment. Although these areas are far from the dam, they were identified as the key soil erosion areas, primarily because their soil erosion modulus is high. Key areas of soil erosion at the Wunonglong catchment (Figure 5B) were mostly near the mainstream. This matches the pattern at the Gongguoqiao catchment. Key areas of soil erosion at the Manwan catchment (Figure 5C) showed no significant concentrations, confirming that the areas near the reservoir should be taken most seriously.

Discussion

This case study of the upper Mekong River evaluated mean annual soil erosion by applying a USLE equation with modules selected according to natural characteristics of the area. The sediment yield was also estimated by employing an empirical DR. Finally, the spatial pattern of soil erosion and its impact on reservoirs were analyzed, and the key areas of soil erosion were identified by considering sediment transport distance.

The study was largely based on earlier research on soil erosion in the upper Mekong River (Yao et al 2005, 2006; Yu et al 2006; Peng et al 2007; Liu et al 2013). The soil erosion and spatial pattern found in this study were generally consistent with the findings of Yao et al (2005, 2006). The mean soil erosion modulus was 19.8 t/ha/y, but it was higher in the northern portion of the study area. This result is also consistent with the results of other studies conducted in northwestern Yunnan Province (Yu et al 2006; Peng et al 2007). The earlier studies estimated spatial soil erosion in the upper Mekong River or another relevant region, as did this study. However, estimated soil erosion was only one aspect of this study; the ultimate goal was to analyze the impact of soil erosion on reservoirs. A number of studies have used observed

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sediment load data to analyze the impact of sediment on reservoirs in the upper Mekong River (Fu et al 2008; Kummu et al 2010; Liu et al 2013); their advantage is the accuracy of the data and their ability to analyze impact of sediment on reservoirs over a long period. This study is unique in that it analyzed not only the current spatial pattern of soil erosion and its impact on sediment deposition at reservoirs in the upper Mekong River, but also the way this relationship is likely to play out in the future when additional reservoirs come into operation. In addition, a spatial map of soil erosion and sediment yield was created that identified key areas of soil erosion at the reservoirs.

This study had some limitations. First, sediment transport is a very complex process affected by many factors. We estimated sediment yield by employing an empirical DR value, but this was clearly inaccurate. Second, we analyzed only sediment load in each reservoir and did not take into account the varied deposition capacity of the reservoirs. Third, there are many dams on tributaries of the upper Mekong River that play an important role in intercepting sediment, but this study did not take all of them into account. Finally, the region is experiencing serious landslides, but this study focused on regional-scale soil erosion, so the data and methods were not appropriate for the analysis of landslides. Although this study did not address landslides, future studies could do so.

Conclusions

The goal of this study was to analyze the spatial pattern of soil erosion and its impact on reservoirs in the upper Mekong River Basin in Yunnan Province, China. A quantitative estimation on a grid basis was made using the USLE model. The study found the following:

1. Soil erosion is a serious problem in the upper Mekong River basin in Yunnan Province, and a significant amount of soil has been eroded or will be eroded in the future by water every year.
2. The soil erosion did not show an even spatial distribution; the northern portion of the study area was found to have more serious soil erosion.
3. The dams on the upper reaches are more threatened by the problem of sediment.
4. As more reservoirs come into operation, the relative sediment load levels of the reservoirs where this load was originally highest (Gongguoqiao and Wunonglong) are likely to become moderate, and originally moderate load levels (at the Manwan, Nuozhadu, and Jinghong reservoirs) are likely to become high.
5. Most of the key area of soil erosion at the Gongguoqiao catchment was near the mainstream, as was the case for the Wunonglong catchment; however, soil erosion at the Manwan catchment showed no significant spatial concentration.

We can conclude that soil erosion is a serious problem in the upper Mekong River basin and that effective soil and water conservation measures should be adopted immediately. In addition, further research on this topic is important to decision-making and can provide critical information on the amount and spatial distribution of soil erosion.

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