Bright side? The impacts of Three Gorges Reservoir on local ecological service of soil conservation in southwestern China

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Abstract Three Gorges Reservoir in China was running since June 2003, and its impacts on soil erosion (SE) and soil conservation (SC) have attracted major public attentions. We quantified the soil conservation service of ecosystems in the Three Gorges Reservoir Area (TGRA) based on a GIS platform using the universal soil loss equation. We revealed the changes of spatial and temporal patterns of soil conservation (SC) and soil erosion (SE) after project construction as well as impact factors on local SE and SC. Results showed that the total amounts and mean capacity of soil conservation services in the TGRA were 15.38-billion $t\ a^{-1}$ and 2134.73 $t\ ha^{-1}\ a^{-1}$, respectively. Northeast reservoir area owned better services than the southwest, and the regions with a capacity of $>5000\ t\ ha^{-1}\ a^{-1}$ were primary located in mountain areas. An increasing trend in SC appeared in the TRGA and “with increasing SC” totaled 22690.5 km^2 (38.9%), while the areas “with decreasing SC” amounted to 3460.4 km^2 (5.9%) between 2000 and 2010. Moreover, the pattern of changing SC was continuous in this area. The spatial

characteristics of soil conservation service in the TGRA were primarily affected by slope, climate and terrain features. In addition, the reforestation and/or forest protection would contribute to soil erosion control in the TGRA. The results revealed a great spatial heterogeneity of soil conservation service in this region, which may provide useful suggestions for land management, soil erosion control and ecosystem protection in the TGRA in China.

Keywords The Three Gorges Reservoir · Soil conservation · Ecosystem service · Spatial and temporal pattern · Impact · Universal soil loss equation

Introduction

Ecosystem services are the foundation on which human welfare depends and ecological thresholds exist (Farley 2012). Soil conservation (SC), which is a fundamental regulating service, is defined as the ability of soil erosion reduction by ecosystems structure and processes (Ausseil et al. 2013). It is reported that ~62.5% (15 out of 24) of the ecosystem services evaluated worldwide were being degraded, including soil conservation (SC) (ME Assessment 2005), which will undoubtedly exacerbate the global soil erosion (SE).

China's territory covers one of the most important water assets in the world. However, over the past century, rivers have been increasingly impacted and fragmented by dams and irrigation projects that have led to significant environmental and ecological problems to rivers. Many large dams have already been constructed and more are under construction; however, the lack of long-term gauging data makes it difficult to document either reservoir SE or the shifting of SC in this reservoir. Moreover, river damming

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has serious negative impacts on the degradation of SC. Nearly one-third river basins of China are suffering from SE, leading to an economic loss equivalent to 3.5% of total gross domestic product (GDP) (Rao et al. 2014). In addition, SE can lead to land degradation and lake/reservoir siltation and then threaten ecological security, food security and flood protection (Cantón et al. 2011). It is imperative to enhance and assess SC services in the river basin in order to control SE and ensure ecological security. The impacts of Three Gorges Reservoir (TGR) on the Yangtze River have become the research hotspot for many scientists and engineers because its role as the world's largest hydropower project (Nilsson et al. 2005) with more than 450 million inhabitants (Yang et al. 2007). As the largest dam in the world with 2335 m length and 185 m height, TGD covers an area of 1080 km² (Chen et al. 2009). The TGD was closure of the reservoir and regulation of the water level started in 2003, and the normal sluicing water level was 175 m and the whole length of the reservoir is near 700 km with the backwater ending in Chongqing city by 2009 (Meng et al. 2001; Wang et al. 2009). However, the construction of TGR and its subsequent operations pose great challenges to the hydrological regime and ecosystem of the entire Yangtze River basin, especially to SC and SE in the Three Gorges Reservoir Area (TGRA) (Shen and Xie 2004). The changes in hydrological parameters, such as the slow-down of the water flow velocity, could reduce SE ability of water in the TGRA. Chen et al. (2009) found the TGD has greatly influenced the regional climate as decreasing trend of rainfall being revealed in the TGRA. Meanwhile, soils from the farmland accounted for 60% of the total soil erosion in this area (Yang et al. 2014). Change in land use pattern after water storage of TGR since 2003 elevated soil erosion rate (Meng et al. 2001). All these factors together are posing unpredictable changes in SE and SC of the TGRA after the construction of the TGD.

The universal soil loss equation (USLE) combined with GIS is used for evaluation of SC services (Pham et al. 2001; Yang et al. 2003; Rife 2010). The USLE is an empirical model established by the US Department of Agriculture for calculating the soil erosion rate on hill slopes (Wischmeier and Smith 1978). For the SE research, the USLE has been successfully embedded in ecosystem service models, such as InVEST (Tallis et al. 2008). The aim of this study was to quantify the SC service of the ecosystems in TGRA based on GIS platform using the USLE model, aiming at revealing the spatial and temporal pattern of SC and SE impacted by this project. This study would provide a clear understanding and information about land management, soil erosion control and ecosystem protection in the TGRA as well as other regions with large water project in the world.

Study area and methods

Describing the study area

The Three Gorges Reservoir Area (TGRA) (see Fig. 1) is located between 106°16'–111°28'E and 28°56'–31°44'N, covering the lower section of the upper reaches of the Yangtze River. It encompasses 26 cities or counties in Chongqing municipality and Hubei Province, covering a total area of 57,802 km² with a total population of 20.1 million. It has complicated geographic conditions with lower lands in the west and higher lands in the east, 74% of the region is mountainous, 4.3% is plain area and 21.7% hilly area. Studied area has variety of land cover types including forest, shrub, grassland, cropland, river, urban and bare soil and. The dominant soil types are purple, yellow and paddy soil (Xi et al. 1994). The climate of the TGRA is a subtropical monsoon climate, characterized by changeable weather in spring, humid and hot summers, dry autumns, dry and cold winters. According to the data from Chinese National Metrological Information Centers, the mean annual temperature is 17–19 °C, with mean minimum and maximum temperatures of 4–8 °C in January and 26–29 °C in July, respectively. The mean annual precipitation is approximately 1100 mm. Rainfall is variable in amount and timing, and 85% of the annual rain mainly falls in summer (6–9 months).

At present, the area is undergoing a rapid population growth and economic development, and the ecological environment in the TGRA has changed rapidly because of urban expansion, excessive cultivation and over-felling. Rivers are threatened by the discharging and leaching of urban domestic sewage, industrial waste, agricultural pesticides and fertilizers. Due to a combination of natural factors and recent anthropogenic activities, soil erosion in certain parts of the TGRA is becoming more serious.

Data sources

The meteorological data used in this study included precipitation and temperature on monthly scale from 2000 to 2010. The monthly based meteorological data (Table 1) from the station-based information was interpolated to the whole research area with a spatial resolution of 0.05° by using the kriging interpolation method, which has been widely used during regionalizing various variables at different scales (Piao et al. 2001; Zhu et al. 2006). In addition, the monthly temperature was calibrated using the digital elevation model (DEM), declining by 0.47°/100 m of increase in elevation. Those coefficients were derived from a linear regression between the elevation and temperature (Xu et al. 2011).

Fig. 1 Map of the Three Gorges Reservoir Area (TGRA)

Table 1 Sources of principal data

Data name	Data resolution	Data source
Precipitation, temperature	30 points	Chinese National Metrological Information Center/China Meteorological Administration (NMIC/CMA)
Soil map	1:1,000,000	Chinese Academy of Sciences
SRTM digital elevation model	90 m	International scientific data service platform
Land cover map	90 m	Chinese Academy of Sciences
MODIS NDVI (MOD13Q1)	250 m	Land Processes Distributed Active Archive Center (LP DAAC)
Urban population	Counties	Statistical Yearbook
GDP data	Counties	Statistical Yearbook
Conservation area	Counties	Chongqing Government
Validation data	Counties	Chongqing Government
Roads density	Counties	Chongqing Government
Arable area	Counties	Chongqing Government

Soil data were collected from the National Second Soil Survey. This statistics included soil types, soil particle size, soil organic matter content and soil depth, at the scale of 1:1000,000.

Topography data were gathered from SRTM digital elevation model data in 2008, with a resolution of 90 m. This information was used to compute slope gradient and slope length.

As NDVI is a good indicator of vegetation, the moderate resolution imaging spectroradiometer (MODIS) NDVI (MOD13Q1) dataset from 2000 to 2010 was used in this study as well. The spatial resolution was 250 m, and the time interval was 16 days. As these products could be affected by cloud, atmosphere or ice–snow cover, we first used the asymmetric Gaussian function (AG) filter to reconstruct the NDVI time-series dataset to reduce noise and improve data quality in the data preprocessing procedure based on the TIMESAT 2.3 program (Jonsson and Eklundh 2002; Jönsson and Eklundh 2004). Then, the 16-day MODIS NDVI was compiled into monthly NDVI data by applying maximum value compositing (MVC) to the two NDVI images of each month in order to further eliminate noise (Holben 1986).

The information on distribution of land cover types in the study area was generated and interpreted based on Landsat MSS and TM satellite remote sensing by Chinese Academy of Sciences. The precise diachronic classifications of these areas have been used as references for object-oriented classifications (Zhang et al. 2014) based on three sets of 30-m Landsat images acquired at the beginning of the dry season during the periods 1999–2001, 2004–2006 and 2009–2011 (Fig. 2). Comparing areas with ground-based data (387 samples), the overall accuracy of the land cover map was, respectively, 91.2, 90.4 and 89.1% for the three periods concerned.

Socioeconomic data including urban/village population density (UP/VP), gross domestic product proportion (GDP), GDP 1 proportion (agricultural GDP), GDP 2 proportion (industrial GDP) and GDP 3 proportion (service industry GDP) were collected from statistical yearbook and government sector.

In the present study, the soil erosion statistical data were originally from the past years soil erosion commune and water conservancy annals of Chongqing. All the data used in present study could be simply grouped into cartographic data and statistics. All cartographic raster data were

converted to the same UTM coordinate system and spatial resolution of 90 m. Some details concerning the datum are listed in Table 1.

Methods

Soil erosion removes nutrients and reduces fertility (DeFries et al. 2004) and lead to decreased hydropower output, structural damage to reservoirs and flooding. Dense vegetation areas have strong ability to retain soils and prevent damage from erosion through sedimentation and eutrophication of nearby rivers. As water erosion dominates in Chongqing, wind and other erosions were not considered in this assessment. The universal soil loss equation (USLE) is an empirical model that allows the prediction of average annual soil loss and spatial distribution (Wischmeier and Smith 1978; Lufafa et al. 2003; Irvem et al. 2007). According to Wischmeier and Smith (1965), the basic form of the USLE is as follows:

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

where SE stands for the amount of soil loss ($\text{t ha}^{-1} \text{ year}^{-1}$); R is rainfall 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 dimensionless topographic factor; C is dimensionless vegetation cover factor; and P is the dimensionless conservation practice factor. The fixed standard rainfall threshold to initiate the erosion for our study area was determined by referring to the research results of Xin et al. (2011).

Supported by remote sensing and GIS technologies, the USLE model has been used as a common methodology in estimating soil loss for many river basins and regions worldwide (Erdogan et al. 2007; Dabral et al. 2008). Ongoing improvement has been made for the calculation of various factors of USLE [e.g., (Lufafa et al. 2003; Vaezi et al. 2008)].

Fig. 2 The distribution of Land use and land cover (LULC) in TGRA

The SC of ecosystems can be described as soil erosion prevention (Ausseil et al. 2013), which is the difference among soil erosion without vegetation cover (potential soil erosion), soil erosion under the current land use/land cover pattern and soil erosion control practice (actual soil erosion). The soil retention is expressed as:

$$SC = SEp - SEa = R \times K \times LS \times (1 - C \times P) \quad (2)$$

where SC is the soil conservation capacity, which is a consequence of vegetation cover; SEp and SEa denote the potential and actual soil erosion rates.

Accuracy assessment has not been done in the study. They have taken from Chinese Academy of Sciences results (Ouyang et al. 2016).

Rainfall erosivity factor (*R*)

Rainfall erosivity, which reflects the potential capacity of rainfall to cause erosion, is determined by rainfall kinetic energy and rainfall intensity (Wischmeier and Smith 1978; Zheng et al. 2002; Xin et al. 2011). Based on the availability of rainfall data (Xin et al. 2011), we calculated the *R* factor from 2000 to 2010 using monthly average and an empirical equation proposed by Wischmeier and Smith (1978).

$$R = \sum_{i=1}^{12} 1.735 \times 10^{(1.5 \times \log_{10}(Pi^2/P) - 0.818)} \quad (3)$$

where *Pi* is total rainfall (mm) of *i*th month; and *P* is annual rainfall (mm).

Soil erodibility factor (*K*)

The factor *K* is defined as the amount of eroded soil per unit area cost by unit rainfall erosivity, which reflects different soils' erosion rates when other factors that influence erosion are constant (Zhang et al. 2008). The physical properties of soil, such as texture, particle size, stability of the structure, clay type, permeability, organic matter content and soil thickness, affect soil erosion rates (Zhang et al. 2007). In the present investigation, erosion/productivity impact calculator (EPIC) formula was used for the calculation and the research conducted by Zhang et al. (2008) for revision, making it applicable to the properties of soils in China.

$$K_{EPIC} = \{0.2 + 0.3 \exp[-0.0256m_s(1 - m_{silt}/100)]\} \\ \times [m_{silt}/(m_c + m_{silt})]^{0.3} \\ \times \{1 - 0.25orgC/[orgC + \exp(3.72 - 2.95orgC)]\} \\ \times \{1 - 0.7(1 - m_s/100)/\{(1 - m_s/100) \\ + \exp[-5.51 + 22.9(1 - m_s/100)]\}\} \quad (4)$$

$$K = (-0.01383 + 0.51575K_{EPIC}) \times 0.1317 \quad (5)$$

where *K* is the soil erodibility factor ($t\ ha^{-1}\ ha^{-1}\ MJ^{-1}\ mm^{-1}$), and *m_s*, *m_{silt}*, *m_c* and *orgC* are the percentages based on content of mass of sand, silt, clay and organic carbon, respectively.

Topographic factor (*LS*)

Topographical factors reflect the impact of slope length and steepness on soil erosion including *L* (slope length) and *S* (slope gradient) (McCool et al. 1987). Although the exact relationship remains uncertain, we assumed that a greater flow accumulation and a faster runoff velocity were associated with a longer slope length and steeper slope, respectively, and erosion rate would stop increasing when the slope reached a certain threshold. The *LS* factor was calculated with improved *L* factor and *S* factor based on the procedure proposed by Wischmeier and Smith (1978). In addition, some revisions in the calculation were based on Rao's studies, with gentle slopes and steep slopes being differentiated (Rao et al. 2014). The equation is as follows:

$$L = (\lambda/22.13)^m \\ m = \beta/(1 + \beta) \quad (6) \\ \beta = (\sin \theta/0.089)/[3.0 \times (\sin \theta)^{0.8} + 0.56]$$

$$S = \begin{cases} 10.8 \sin \theta + 0.03 & \theta < 5.14^\circ \\ 16.8 \sin \theta - 0.5 & 5.14^\circ \leq \theta < 10.20^\circ \\ 21.91 \sin \theta - 0.96 & 10.20^\circ \leq \theta < 28.81^\circ \\ 9.5988 & \theta > 28.81^\circ \end{cases} \quad (7)$$

where *L* is the slope length factor; *S* is the slope steepness factor; *m* is the slope length index; *θ* is the slope gradient (°); and *λ* is horizon slope length (m).

Vegetation cover factor (*C*)

Vegetation plays a significant part in controlling soil erosion (Collins et al. 2004; Zhou et al. 2006, 2008). The vegetation cover factor is critical to soil and water conservation, owing to its high sensitivity to natural and anthropogenic activities (Ma et al. 2012). The calculation of the *C* factor at the regional scale usually relies on a lookup table and is defined in terms of land use. This method, however, can not accommodate the difference in land use; neither can it reflect the differences such as vegetation condition or tillage measures brought by phenophase. In this study, *C* was determined using the form of NDVI proposed by Knijff et al. (2000) and Li et al. (2011).

The average *C* factor from 2000 to 2010 in the study area was calculated based on coarse resolution NDVI data.

$$Ci = \exp\left(-\alpha \times \frac{(ndvi)i}{\beta - (ndvi)i}\right) \quad (8)$$

where α and β are the parameters deciding the shape of the curve. Many applications suggest that the ideal results were acquired when $\alpha = 2$ and $\beta = 1$. Even though some questions exist in the C calculation with the vegetation index, this method is one of the simplest and most practical to obtain C at the regional scale.

Erosion control practice factor (P)

The P factor is defined as the ratio between the soil losses expected for a certain soil conservation practice and that of up-and-down slope plowing (Liu et al. 2001). In this study, the value of P was determined by referring to the research results of Cai et al. (2000) in combination with local land use and farming activities (Table 2).

Data analyses

Trend analysis and significance test

To detect the variation in trends of SC and SE during the study period (2000–2010), a least-squares linear regression model was used to obtain the trend change of every pixel by fitting a linear equation of SC and SE variables as a function of a time variable (year) in order to obtain an image of changing slope. The least-squares linear regression method, which is one of the commonly used methods in trend analysis of variation trends (Stöckli and Vidale 2004; González and Menenti 2008; Beck et al. 2011), was applied as follows:

$$y = a + b \times t + \varepsilon \quad (9)$$

where y represents SC or SE variables, t is year, a and b are fitted variables (b is the slope as a proxy of trend and a is the intercept), and ε is the residual error.

If $b > 0$, there is an increasing trend in SC or SE. Conversely, if $b < 0$, there is a reducing trend.

In addition, precipitation, temperature, urban population density (UP), gross domestic product proportion (GDP), GDP 1 proportion, GDP 2 proportion, GDP 3 proportion and NDVI trends were obtained by the least-square linear regression model.

A trend significance test (P value) was used to determine changes in significant areas. If the P value is smaller, the trend significance is greater. If the slope is below the significance level of 0.05 ($P < 0.05$), the trend decreases or increases significantly (Table 3).

The calculations and analyses were implemented using IDL 5.0.

Pearson correlation

For exploring the relationship among the trend in SC, climate and anthropogenic factors, Pearson correlation was performed as follows:

$$R = \frac{\text{cov}(x, y)}{\sqrt{\text{cov}(x, y)\text{cov}(x, y)}} = \frac{n \sum xy - \sum x \sum y}{\sqrt{(n \sum x^2 - (\sum x)^2)(n \sum y^2 - (\sum y)^2)}}$$

where R represents a linear correlation coefficient, cov represents covariance, x and y are the main variables (x is the SC and y is the climate or anthropogenic factors), and n is the number of variables.

The Pearson correlation was conducted with statistical units of province, city and county, respectively. The calculations and analyses were implemented using SPSS 17.0.

Redundancy analysis

To discuss the influence of climate and human activities on the SC and SE trend and reveal the relative contribution in influencing the spatial characteristics of the SC, we adopted a constrained ordination technique applied in CANOCO 4.5 (Ter Braak and Šmilauer 2002; Lepš and Šmilauer 2003). Compared to other methods (principal component analysis (PCA), correlation analysis, regression analysis, etc.), the advantage of redundancy analysis (RDA) is that it can independently maintain the contribution of each variable to the environment. It is a method of direct gradient analysis that does not merely focus on the analysis of variable groups but also on the integration of a virtual complex variable. Therefore, it can explore the demographic characteristics of a single variable, based on the different associations of variables, and then, the decisive variables can be selected.

RDA was performed using environmental variables as predictors (precipitation, temperature, UP, GDP, GDP 1 proportion, GDP 2 proportion, GDP 3 proportion, conservation project (CP), arable area, road density, NDVI, altitude and slope), ranked according to their quantitative importance by forward selection. As variables may exist in the high autocorrelation, multiple CCA (canonical correspondence analysis) selection for all variables was

Table 2 The P value for various land cover types

land cover types	Crop land	Forests	Shrubs	Grasslands	Water	Urban	Bare land
Value	0.4	1	1	1	0	0	0

Table 3 Evaluation standard of trend significance

Variation trend	<i>b</i> value range	<i>P</i> value range
Significant decrease	$b < 0$	$P \leq 0.05$
Significant increase	$b > 0$	$P \leq 0.05$
No significant change		$P > 0.05$

performed. Rests of the variables were used to analyze the influence of climate and human activities on the SC and SE trends. The results of RDA were presented graphically on biplots, where parameters were shown as arrows + their names. The significance of correlation between the NDVI trend (including NDVI slope and improvement area ratio) and anthropogenic factors depended on the length of the arrows: Long arrow indicated stronger correlation. If anthropogenic factors were closely located on the same side of the SC and SE trends, the association was positively correlated. If they were on the opposite side, then the correlation was negative. In our RDA calculation, the SC and SE trends meant the dependent variables, and those environmental variables were defined as the independent variables (county as a unit).

Results

Model validation

In this study, the actual soil erosion rate was calculated by using USLE. For verifying the reliability of the application of this model, we validated the model results based on statistical data (China Water and Soil Conservation Bulletin, 2012) by using the average annual estimates between 2000 and 2010. Moreover, observed and statistical data for model validation were collected from local government's soil conservation bulletin.

As shown in Fig. 3, the simulations (USLE) of the average annual soil erosion rates fitted well the observation-based data ($R^2 = 0.813$, $P = 0.000$), and the regression coefficient was close to 1 ($R = 0.902$, $P = 0.000$). The significant correlation was found between our simulated results and observation-based data. These results indicated that the simulated models were applicable to the modeling of the soil erosion across study area. Indirectly, the model of the overall SC service could also be considered reasonable.

Spatial and temporal characteristics of SC

Spatial distribution and change of SC

The SC service displayed great heterogeneity in terms of its spatial distribution, with northeast TGRA generally

Fig. 3 Validation of the USLE model. The simulations (USLE) and observations of mean annual soil erosion rates

performing much greater SC capacity than the southwest (Fig. 4a–c). Daba Mountains ecosystems had greater SC capacity ($>5000 \text{ t ha}^{-1} \text{ a}^{-1}$).

In our linear regression calculation, the SC represented the dependent variable *Y*, and time represented the independent variable *X*. The trend analysis showed the overall variation trends in our research area (Fig. 4d). In the present study, areas classified as “no change” are areas with SC change at the grid pixel varying between -50 and $50 \text{ t ha}^{-1} \text{ a}^{-1}$. Accordingly, the areas “with no change” in SC totaled $32,244.2 \text{ km}^2$ (or 55.2% of the total area) between 2000 and 2010. The areas “with increasing SC” totaled $22,690.5 \text{ km}^2$ (38.9%), while the areas “with decreasing SC” amounted to 3460.4 km^2 (5.9%).

Areas with increasing SC mainly appeared in the northeastern part of the reservoir area, involving counties stretching from Yunyang to Zigui (including Fengjie, Wuxi, Wushan, Xingshan and Badong). These areas accounted for 83.4% of the total areas where SC has increased. In these areas, the primary land cover type was forest (44.0%), followed by shrub and grassland (32.5%) and cropland (20.4%).

Areas “with declining SC” were mainly distributed in the southwestern part of the reservoir section, which were densely populated, stretching from Fengdu County to Jiangjin District along the Yangtze River. Figure 4e shows the significance of the variation trend found in the study area. As expected, areas showing negligible rising trends in NDVI coincide with insignificant results.

Temporal dynamic of SC

From 2000 to 2005, total amount of soil retained remained slowly increasing, increasing by just $5.3 \times 10^8 \text{ t}$ (3.6%)

Fig. 4 Spatial and temporal changes of SC in 2000–2010, slope trend and significance. *Note a* SC spatial distribution in 2000; *b* SC spatial distribution in 2005; *c* SC spatial distribution in 2010; *d* SC slope trend and *fork symbols* describe significance of trends in SC

(Fig. 5). Since 2005, total amount of soil retained has been sustainable increasing, rising by 31.8×10^8 t (4.8%) during the period (2005–2010). At the continental scale, the lowest amount of soil retained appeared in 2006, followed by the highest amount of soil retained in 2007 (Fig. 5). The annual average potential and actual annual soil erosion were calculated to be 16.21 and 0.83 billion t, respectively. Thus, the annual average amount of soil retained was 15.38 billion t a^{-1} , with a mean capacity of $2134.73 \text{ t ha}^{-1} \text{ a}^{-1}$.

Most SC was produced from slope zones with slope gradient more than 8° (Fig. 6), which occupied 75.6% of the total land area and accounted for more than 90.2% of the total SC.

The correlation between the amount of soil retained and precipitation was highly significant, with the coefficients of 0.85, at the one percent significance level. The precipitation in 2006 (572.9 mm) was lower (47.4%) in comparison with annual average between 2000 and 2010 periods. Consequently, it seemed that soil retained levels in 2006 were underestimated in the model.

Impact of influencing factors on SC change

For the analysis of multiple index variables for the multiple CCA selection, the factors (precipitation, temperature,

NDVI, GDP 1, UP, road density, arable area, conservation project and slope) were selected as the main driving factors for SC and SE change. The results showed that the precipitation and temperature variable explained 13% of the variation in SC and SE trends—climate factor relationship in the RDA model. The slope variable explained 63% of the variation—topography factor relationship in the RDA model. In addition, the rest environmental variables (NDVI, GDP 1, UP, road density, arable area and conservation project) explained 14% of the variation—anthropogenic factor relationships in the RDA model (Fig. 7). The unexplained residual 10% variation may be the result of the integrated effects of other factors including soil type, land cover change and the dynamic of the landscape structure.

Discussion

The USLE is an empirical water erosion model based on runoff plot experiments (Wischmeier and Smith 1978). In the process of parameter localization for the USLE, we analyzed relevant progress in domestic research first, and calculated SE rates as well as SC capacities by using recent achievements on the parameters. Compared with the

Fig. 5 Total SC in the study area from 2000 to 2010 **Fig. 6** Change of SC of slope zones from 2000 to 2010 **Fig. 7** Ordinate plot from RDA on SC and SE change trends (blue arrows) and their relationships with environmental variables (red arrows)

observation-based data in the TGR basin, the USLE model and the parameters used herein proved capable of realistically simulating in this soil erosion situation ($R^2 = 0.813$, $P = 0.000$), thus rendering a satisfactory accuracy to the assessment of SE and SC service in the TGRA (Fig. 3). Moreover, the spatial resolution of topographical data was

a key factor for estimating the soil erosion by the USLE. A spatial resolution of 90 m used in the present study was the highest by now for such a large scale to capture the spatial heterogeneity of environmental variables more effectively (Table 1).

In the present study, the actual annual average amount of soil erosion in the TGRA was estimated at 0.83 billion $t a^{-1}$ between 2000 and 2010 (Fig. 5). The total amount of SC, which describes the reduction in soil erosion by ecosystems, was estimated at 15.38 billion $t a^{-1}$, with a mean capacity of 2134.73 $t ha^{-1} a^{-1}$, far more above the SC capacity of forests and grasslands (118.61–445.92 $t ha^{-1} a^{-1}$) that was determined through surveys and syntheses (Ouyang et al. 1998). The ecosystems' SC service in the TGRA was spatially unevenly distributed; this may be due to the vast territory and enormous differences in environmental conditions (Fig. 4). Ecosystems with a great SC capacity ($>5000 t ha^{-1} a^{-1}$) were primarily located in mountain areas, such as the Daba Mountain which is in northeast TGRA, implying a potential influence of topography. Additionally, based on the positive correlation between SC service and SE risk, greater importance should be given to areas where suffer from high risk of erosion (Rahman et al. 2009), including

western parts of the TRGA, since ecosystems in these areas are critical to the actual situation of soil erosion.

Our results demonstrated an increasing trend in SC over the TRGA during 2000–2010. After 2000, with the implementation of a strict policy of the conversion of cropland to forest and grassland program, vegetations have been restored well in steep slope, which effectively control soil erosion in the region (Bennett et al. 2008). These were the reasons for the increase in SC in this area. SC depends on the potential soil loss in a large extent which is the assumed soil loss without vegetation coverage. Rainfall was deemed as the major variant driving force for potential soil loss changing, while the slope and soil erodibility can be considered constant in short term (Rao et al. 2014). Decrease in SC was primarily a result of decreasing precipitation in our study area. The annual change of SC mainly depends on the annual change of rainfall. The pattern of changing SC is continuous rather than patchy (Fig. 4). The places with increasing SC in decade mainly appear in the northeastern part of the reservoir area (i.e., Fengjie, Wuxi, Wushan, Xingshan and Badong). In these areas, the primary land cover type was forests improved by Chinese “grain for green” and other ecological projects (Li 2004), and these projects may result in increased SC (Fig. 6). In the areas of the southwestern part of the reservoir section, which were densely populated areas, SC presented a decrease in the decade. It was probably because anthropogenic activities such as population growth and land reclamation were the main drivers of decreasing SC (Zheng et al. 2002; Su et al. 2012). The population post pressures on land and ecosystems due to its large size and high density, and agricultural lands have been regarded as a major source of sediment (Pimentel et al. 1995; Meng et al. 2001). Both population density (UP) and area ratio of arable land, which were proxy for the intensity of agricultural activities, displayed a significant negative correlation with the SC capacity (Fig. 7), using the statistical unit of county. These findings indicated that human activities could impair the SC service through changing the ecosystem structure and processes in short period of time (Zheng et al. 2002).

RDA was employed to reveal the relationships between SC trends and environment variables in the TRGA in China during the periods of 2000–2010 (Fig. 7). The results showed that except precipitation, NDVI, conservation project and slope, all other variables including temperature, GDP 1, UP, road density and arable area showed significant downward trends during increase in SC trends. Stepwise regression further demonstrated that the spatial patterns of SC service in the TRGA were primarily controlled by slope, climate and terrain features, while the effects of temperature, GDP 1, UP, road density

and arable area were relatively small at this scale (Fig. 7). RDA showed that using the slope variable as topography factor and precipitation and temperature as climate factor could explain 63, 13% of the variance information, respectively. The fact that water induced potential soil loss was closely correlated with topographical factor, because the greater the slope gradient the higher the potential for runoff and soil loss by water (Kateb et al. 2013). For example, plains in the southwest, despite large rainfall, suffer from light potential soil loss due to flat landform. The intense water erosion of the TGRA mainly occurred in the hilly and mountain areas located in the northeast part (Fig. 4). Additionally, the SC capacity showed a significant positive correlation ($R = 0.998$, $P = 0.000$) with the potential soil erosion rate, which was determined by climate and terrain, suggesting that a higher soil erosion risk was associated with greater importance of the ecosystem's SC service (Fig. 7). Furthermore, a positive correlation was found between SC and CP (Fig. 7). This showed that conservation projects could decrease soil erosion through changing ecosystem structures and processes in the TRGA in short period (Zheng et al. 2002). A reforestation or protection of forest would be very helpful in soil erosion control in the TRGA (Meng et al. 2001), which is the principal motivation for the conversion of degraded farmland into forest and grass land, protection of natural forest and similar projects (Li 2004).

Conclusions

The TRGA ecosystems annually reduced a huge amount of soil erosion, with a total of 15.38 billion t during 2000–2010. Soil conservation service displayed a great spatial heterogeneity, with northeast reservoir area performing much better than the southwest, and regions with a great capacity primarily located in mountain areas. The spatial characteristics of soil conservation service in the TRGA in China were primarily dominated by slope, climate and terrain. An increasing trend in SC appeared in the TRGA and “with increasing SC” totaled 22,690.5 km² (38.9%), while the areas “with decreasing SC” amounted to 3460.4 km² (5.9%) between 2000 and 2010. The pattern of changing SC was continuous rather than patchy in this area. The result suggested reforestation or protection of forest would be very helpful in soil erosion control in the TRGA in the future.

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