Catena 160 (2018) 394–402

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of topographic factors on runoff and soil loss in Southwest China

Xingqi Zhang[a,*], Maochuan Hu[b,*], Xinya Guo[c], Hong Yang[d,e], Zhenke Zhang[a], Keli Zhang[f]

[a] School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210023, China
[b] Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto 611-0011, Japan
[c] Research Center For Eco-Environment Sciences in Shanxi, Taiyuan 030000, China
[d] Department of Geography and Environmental Science, University of Reading, Reading RG6 6AB, UK
[e] Chongqing Key Laboratory of Karst Environment, School of Geographical Sciences, Southwest University, Chongqing 400715, China
[f] School of Geography, Beijing Normal University, Beijing 100875, China

ARTICLE INFO

Keywords:
Soil erosion
Slope gradient
Slope length
Field plot
Karst

ABSTRACT

Soil erosion is a threat to sustainable agricultural and regional development in karst regions. In this study, field plot observation method was used to estimate the effects of slope gradient and length on runoff and soil loss in Guizhou, Southwest China. The results showed that runoff and soil loss is nonlinearly related to slope gradient. The increasing trends of runoff and soil loss declined after the slope gradient of 15°. This turning point was affected by both slope gradient and rock outcrops on the 20°–25° slopes, hence it is still unknown whether the slope gradient of 15° is a critical value. Runoff showed a trend of decrease-increase-decrease as slope length increased, and soil loss rate showed an increasing trend as slope length increased. There is a significantly positive linear relationship between soil loss and slope length ($P < 0.01$). Runoff and soil loss were significantly correlated with rainfall amount (P) and the maximum 30 or 60 min rainfall intensity (I_{30} or I_{60}), which had power function with PI_{30} on gradient-changed slopes and PI_{60} on length-changed slopes. Moreover, soil loss has a power function relationship with slope gradient/length and runoff depth. This study is helpful to elucidate the effect of topographic factors on soil erosion and to take effective soil conservation measures in karst regions.

1. Introduction

Soil erosion is a worldwide challenge to achieve a sustainable development (Pimental, 2006). Soil erosion is driven by the interactions between climate, soils, topography, land use and socio-economic factors. The consequences of soil erosion are both on-site including soil degradation, soil fertility decreasing, desertification, and reduce in infiltration and water storage capacities, and off-site including siltation of dams, reservoirs and rivers, water pollution, destruction of wildlife habitats, and increase in floods.

Slope gradient and length are main topographic factors affecting soil erosion (Liu et al., 1994; Liu et al., 2000). The effects of slope gradient and length on soil loss have been evaluated by different methods, for example the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) (Hickey, 2000; Kinnell, 2001). Several studies found runoff/soil loss increased with the growing slope gradient (Fox and Bryan, 2000; Nord and Esteves, 2010). However, runoff/soil loss is not always linearly positively related to slope gradient. Other studies showed that soil erosion started to decline when slope reached a critical gradient (Jin, 1995; Liu and Singh, 2004). In addition, many studies on the relationship between runoff/soil loss and slope length found runoff and soil loss are complicatedly affected by slope length. With the increasing slope length, there are three changes of soil erosion. 1) decrease (Joel et al., 2002; Yair and Raz-Yassif, 2004; Laws and Parsons, 1943; Stomph et al., 2002; Giesen et al., 2005; Xu et al., 2009; Kara et al., 2010); 2) increase (Zingg, 1940; Wischmeier et al., 1958; Rejman and Brodowski, 2005); 3) and no remarkable change (Wischmeier et al., 1958). Furthermore, rainfall characteristics play important roles in the effects of slope gradient and length on runoff and soil loss (Assouline and Ben-Hur, 2006; Liu et al., 2000).

Due to the extensive karst landscape, around 73% of the land area, Southwest China is one of the most severely eroded regions in the country (Guo et al., 2015; M.X. Liu et al., 2014; Y. Liu et al., 2014; Jiang et al., 2014). It has a subtropical monsoon climate, characterized by strong spatiotemporal variability of precipitation. Due to the high population density and the variable terrain conditions, the cropland parcels are characterized by steep slopes, short slope lengths and thin topsoil. More than 80% of its farmland is on slopes over 6°. Soil profiles in this mountainous karst area are generally undeveloped. Usually without the C-horizon, both adhesion and affinity between the topsoil and bedrock are substantially decreased. And therefore heavy rainstorm can easily cause soil erosion and exacerbate the rocky desertification

* Corresponding authors.
E-mail addresses: zxqrh@nju.edu.cn (X. Zhang), maochuanhu@gmail.com (M. Hu).

http://dx.doi.org/10.1016/j.catena.2017.10.013
Received 10 March 2017; Received in revised form 26 September 2017; Accepted 7 October 2017
Available online 13 October 2017

(Yuan, 1993).

As a kind of serious land degradation, karst rocky desertification heavily constrains the sustainable development in this region and it has received increasing attentions from both the governments and academic community (Wang et al., 2004; Yan and Cai, 2015). Several studies have researched the relationship between topographic factors and soil erosion in this region. For example, Xu et al. (2008, 2011) applied RUSLE model and GIS/RS techniques to research the relationship between land use and soil erosion. They found that dry farmlands with a slope from 6° to 25° were most seriously impacted and they were the key contributor to soil erosion in Maotiao river watershed in Guizhou. In addition, some studies used large runoff plot method to evaluate the effects of land use and land cover change, and rainfall regimes on the runoff and soil erosion on karst slopes (*e.g.* Peng and Wang, 2012). With more frequently extreme weather (M.X. Liu et al., 2014), there is an increasing demand for researches on soil erosion in this karst area. However, to the best of our knowledge, there is a lack of field observation in the effects of topographic factors on surface runoff generation and soil loss; and the understanding of the relationship between topographic factors and soil erosion is also far from satisfactory.

The current study was carried out on experimental field plots in Guizhou Province, a karst mountainous region in Southwest China. The objectives of this study were 1) to evaluate the effects of slope gradient and length on runoff generation and soil loss rate; and 2) to expand our understanding of the soil erosion mechanism on hillslope in subtropical monsoon climate. The findings are helpful to make policies for sustainable land use management and soil conservation in the similar karst areas.

2. Material and methods

2.1. Study area

The study was carried out in the Shiqiao watershed located in Bijie City, Guizhou Province, China (Fig. 1). The watershed, with the area of 8.19 km^2, is a tributary of the Wujiang River basin belonging to the Yangtze River basin. The altitude of the study area ranges from 1400 to 1743 m asl. The watershed has a subtropical humid monsoon climate. The annual temperature is 14 °C and average annual rainfall is 863 mm. About 80% of annual rainfall is concentrated from May to September (rainy season). Due to low cover of vegetation and the wide distribution of limestone, the study area presents typical rocky desertification and severe soil erosion area in Guizhou Province. Soils are composed of different particle sizes: 32.7% of size < 0.002 mm, 56.3% of size 0.002–0.05 mm, and 11% of size > 0.05 mm. The main land use types include forest, farmland, and grass land. The representative crops are maize, beans, potatoes, rapes, and peppers. Around 16.3%, 38.9%, 28.8% and 16% of farmlands are on slopes of < 6°, 6–15°, 15–25°, and > 25°, respectively.

2.2. Plots layout

Experiment was set up in the study area. Two set of plots were used to analyze the effects of slope gradient and slope length on runoff and soil loss (Fig. 2 and Table 1). Slope gradient-changed plots include 5°, 10°, 15°, 20° and 25° with the same slope length of 10 m. Slope length-changed plots include 5, 10, 15, 20 and 25 m with the same slope gradient of 15°. Soils have a thickness of 0.21–0.30 m. To minimize the effects of vegetation coverage on runoff generation and soil loss on plots, the vegetation coverage rate on plots was controlled to < 5% by weeding the plots properly during the observation periods. In addition, there are rock outcrops on 20° and 25° slopes (Fig. 2).

2.3. Data collection and analyses

Rainfall, runoff and soil losses data were obtained from field observation during the period of 2012–2014. Rainfall was recorded by an auto-recording rainfall gauge at 5-min intervals. Runoff and soil losses data were obtained from the field plots experiments.

Runoff and sediment were collected using collecting tanks installed in the outlet of each plot. Each collecting tank was connected to a diversion tank which accounted for one-ninth of the total runoff generated on a plot in the heavy rainfalls. The depth of the runoff water in the collecting tanks was measured after each rainfall. When the rainfalls

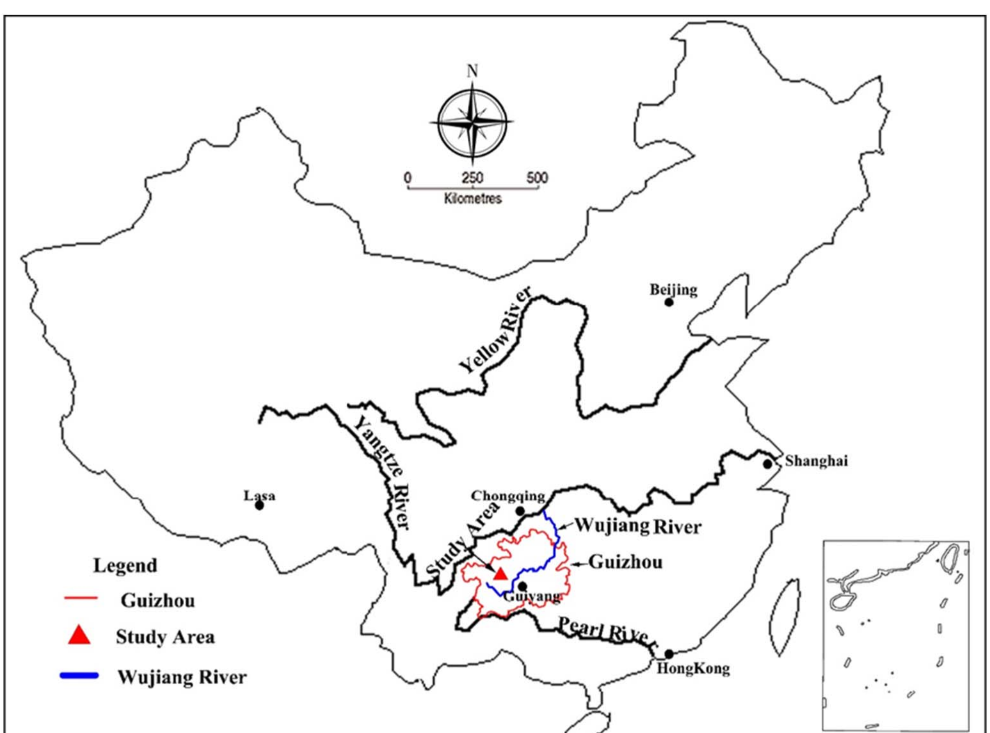

Fig. 1. Location of the study area in Guizhou Province, Southwest China.

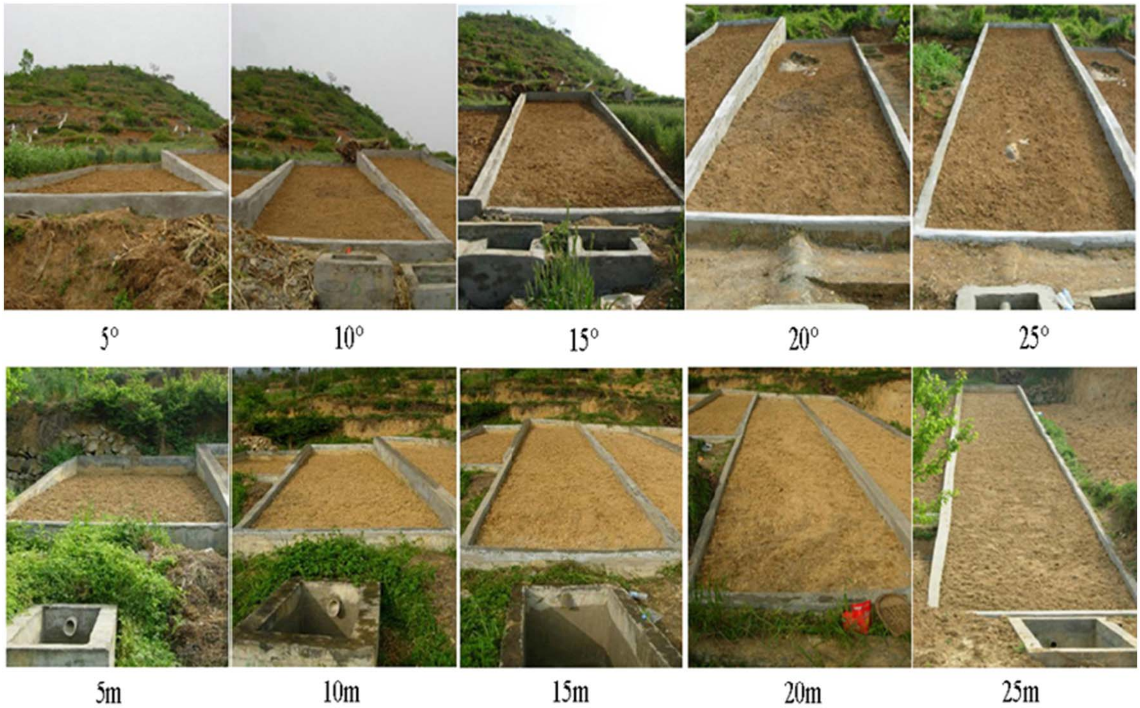

Fig. 2. Slope gradient-changed plots (5°, 10°, 15°, 20°, and 25°) and slope length-changed plots (5 m, 10 m, 15 m, 20 m, and 25 m).

Table 1
The basic situation of runoff plots.

Slope length (m)	Slope gradient (°)	Soil type	Thickness of soil layer (m)	Bedrock type	Vegetation coverage rate (%)	Notes
10	5	Yellow soil	0.25	Limestone	5	
10	10	Yellow soil	0.30	Limestone	5	
10	15	Yellow soil	0.28	Limestone	5	
10	20	Yellow soil	0.23	Limestone	5	Rock outcrops on the upper left part
10	25	Yellow soil	0.23	Limestone	5	Rock outcrops on the lower part
5	15	Yellow soil	0.21	Limestone	5	
10	15	Yellow soil	0.21	Limestone	5	
15	15	Yellow soil	0.21	Limestone	5	
20	15	Yellow soil	0.21	Limestone	5	
25	15	Yellow soil	0.21	Limestone	5	

stopped, runoff water was well mixed and sampled from the tanks.

The runoff volume was calculated after each rainfall through multiplying the depth of collected runoff water, measured using a ruler, by floor area of the collecting tank. Runoff samples collected in the tanks were filtered and dried to measure the suspended sediment concentration. Suspended sediment loss was calculated by the suspended sediment concentration multiplied by the corresponding runoff volume.

During the study period (2012–2014), we observed 53 erosive rainfalls with precipitation amount (P) of 4.8–87 mm. In order to evaluate the contributions of rainfall characteristics to runoff and soil loss, the erosive rainfall events were divided into light rain ($P < 10$ mm), moderate rain ($10 \le P < 25$ mm), heavy rain ($25 \le P < 50$ mm), and rainstorm ($50 \le P < 100$ mm). Based on the maximum 30 min rainfall intensity (I_{30}), the erosive rainfall events were also divided into low rainfall intensity ($I_{30} \le 10$ mm/h), moderate rainfall intensity ($10 < I_{30} < 30$ mm/h), and high rainfall intensity ($I_{30} \ge 30$ mm/h).

Correlation analysis was conducted using SPSS Statistics (V22.0, IBM Corp, New Orchard Road, Armonk, New York) to explore the relationship between runoff/soil loss and rainfall characteristics, the relationship between soil loss and slope length, and the relationship between soil loss and runoff generation.

3. Results

3.1. The effect of slope gradient on runoff and soil loss

3.1.1. The relationship between runoff/soil loss and slope gradient

Runoff and soil loss showed the same variation patterns of increase-decrease-increase with increasing slope gradient (Fig. 3). Runoff and soil loss increased with increasing slope gradient within 15°. However, runoff and soil loss turned to decrease when slope gradient increased from 15° to 20°.

Surface micro-topography strongly affects the spatial-temporal distribution of overland flow at the plot scale. There is a nonlinearly relationship between runoff and soil loss with slope gradient. This related to the rock outcrops (Fig. 4) which can affect overland flow's continuity and reduce the runoff velocity, which resulted in an increase of soil infiltration in the upslope area of the rock outcrops. The rock outcrops also affected the soil erosion process. In particular, rill erosion took place on the left upper part of the plot, but it did not take place on the right part of the plot (Fig. 4).

3.1.2. The impacts of rainfall characteristics on runoff and soil loss as slope gradient increase

Runoff and soil loss were almost unchanged when slope gradient

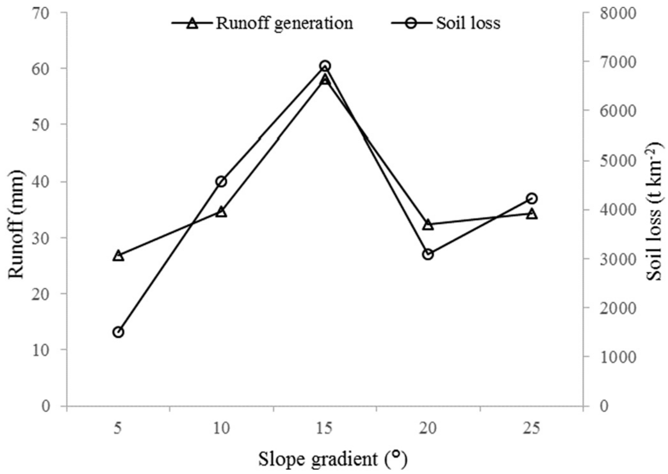

Fig. 3. The relationship between runoff/soil loss "(average of annual values for 2012-2014)" and slope gradient.

Fig. 4. Exposed rock outcrops on 20° plot
Note: The photograph was taken in June 2012

increased under light rainfall (Fig. 5). Under moderate rainfall and heavy rainfall, runoff showed a slight increase-decrease-increase trend with increasing slope gradient, but soil loss showed an increasing trend under moderate rainfall and an increase-decrease change under heavy rainfall as slope gradient increases. Under rainstorm, runoff and soil loss showed similar variations of significant increase-sharp decrease-slight increase with increasing slope gradient.

Under low and high rainfall intensity, there is no clear pattern between runoff generation and slope gradient (Fig. 6). Under moderate rainfall intensity, runoff showed a variation of sharp increase-sharp decrease-slight increase as slope gradient increases.

Under low rainfall intensity, soil erosion is dominated by sheet erosion and slightly affected by the rock outcrops. Soil loss slightly increased on the slopes of 5°–15° and obviously increases on the slopes of 15°–25°. However, under moderate and high rainfall intensity, soil loss showed a variation of increase-decrease-increase with increasing slope gradient. Soil loss was heavier than that under low rainfall intensity. This is due to that the rock outcrops on slopes affected rill formation and the scouring capability of surface runoff was enhanced by rill erosion.

Runoff and soil loss were significantly positively correlated with rainfall amount (P), maximum 30 min rainfall intensity (I_{30}), and maximum 60 min rainfall intensity (I_{60}) ($P < 0.01$) (Table 2). Especially, runoff was significantly correlated with rainfall amounts.

In order to evaluate the effect of rainfall characteristics on runoff and soil loss, mathematical relationships between runoff/soil loss and rainfall amount (P), maximum 30 min rainfall intensity (I_{30}), and maximum 60 min rainfall intensity (I_{60}) were analyzed. The relationships are expressed as $H = AP^{a}I_{30}{}^{b}$ and $M = AP^{a}I_{30}{}^{b}$, where H is runoff depth (mm); M is sediment modulus (t km^{-2}); and A, a, and b are statistical parameters. As shown in Table 3, the coefficients of determination (R^2) indicated that runoff and soil loss have power function with PI_{30} on slope gradient plots.

3.2. The effect of slope length on runoff and soil loss

3.2.1. The relationship between runoff/soil loss and slope length

Runoff showed a variation of sharp decrease-increase-decrease as slope length increases (Fig. 7). Field observations of runoff generation on different length plots showed the following situation. Runoff depth on 5 m long slope was larger than that on 10 m long slope, because of the bigger infiltration rates on the 10 m long slope than those on the 5 m long slope. When slope length was 15 m long, effective rainfall was greater than cumulative infiltration and flow continuity kept a longer period, resulting in the maximal runoff generation at the experimental

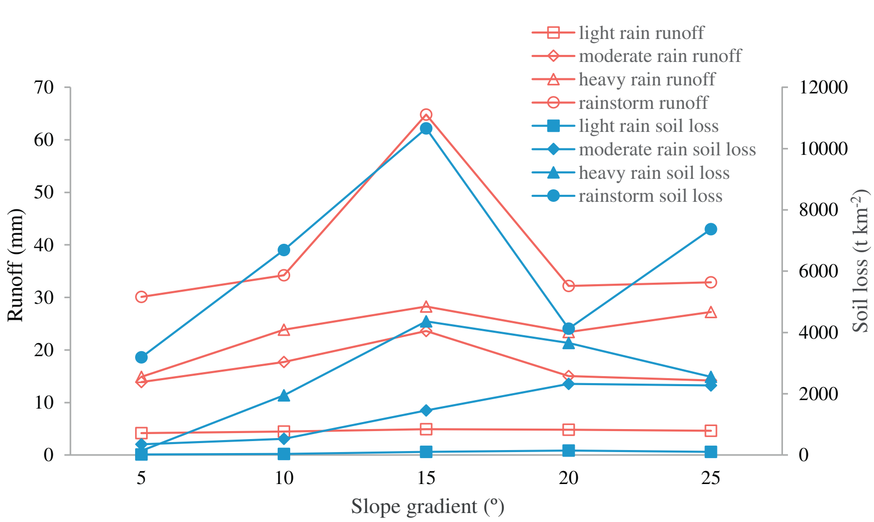

Fig. 5. The relationship between runoff/soil loss and rainfall amount.

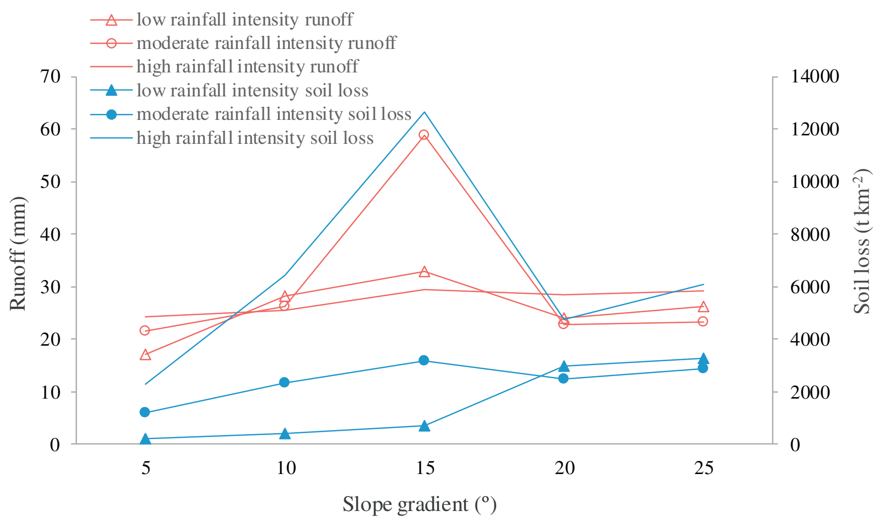

Fig. 6. Runoff on slope gradient plots in different rainfall intensities.

plot scale. When slope length increased to be longer than 15 m, flow continuity was destroyed, due to sediment deposit on the lower slope surfaces, and infiltration capacity increased with the increasing concentration time. Consequently, runoff depth decreased on 20 and 25 m long slopes.

Soil loss over the study period (2012–2014) showed a growing trend as slope length increased, namely the longer the slope length was, the more the soil loss was produced. According to field observation, rill erosion was a main factor affecting soil loss and it can enhance scouring capability of runoff and erosion intensity. Rills were easily formed on longer slopes and changed into small channels to carry sediment from upslope to downslope. On 5 and 10 m long slopes, the increment of soil loss was small, due to that erosion dynamic mainly came from rainfall erosivity, and the relative small upslope catchment area had limited effect. On 10–20 m long slopes, erosion came from both rainfall and runoff concentrated from larger upslope areas, leading to large increment of soil loss. On the 20–25 m long slopes, the amount of sediment in the surface runoff increased, but the scouring capacity decreased. Consequently, the increase in sediment yield slowed down.

3.2.2. *The impacts of rainfall characteristics on runoff and soil loss as slope length increase*

Under light rainfall, runoff and soil loss were almost unchanged with increasing slope length (Fig. 8). Under moderate rainfall and heavy rainfall, runoff showed a variation of slight decreasing-increasing-decreasing, whereas soil loss has no clear pattern with increasing slope length. Under rainstorm, runoff showed a variation of sharp decrease-sharp increase-light decrease, while soil loss showed a pattern of slight decreasing-significant increasing with increasing slope length. The relationship between soil loss and slope length under rainstorm was expressed as $M = 160.388\,L + 613.707$, where M is sediment modulus (t km^{-2}) and L is slope length (m). The determination coefficient (R^2) is 0.935, indicating a well fitted linearly relationship.

Under low and high rainfall intensity, runoff showed a variation of substantial decreasing-increasing-decreasing with increasing slope length (Fig. 9). Under moderate rainfall intensity, runoff showed a variation of decreasing-increasing-decreasing with increasing slope length. Runoff was significantly correlated to moderate rainfall intensity.

Sheet erosion made limited differences of soil loss under low rainfall intensity on different length slopes. Soil loss did not show much difference under moderate and high rainfall intensity within the 15 m long slope, however, soil loss became heavier under high rainfall intensity than that under moderate rainfall intensity within > 15 m long slopes. Under moderate and high rainfall intensity, the relationships between soil loss and slope length were expressed as $M = 126.736\,L + 212.400$ ($R^2 = 0.945$) and $M = 65.063\,L + 609.365$ ($R^2 = 0.811$), indicating the well fitted relationships.

Runoff and soil loss rate were significantly positively correlated with precipitation (P), maximum 30 min rainfall intensity (I_{30}), and maximum 60 min rainfall intensity (I_{60}) ($P < 0.01$) (Table 4).

The relationships between runoff/soil loss and rainfall amount (P), I_{30}, and I_{60} were expressed as $H = AP^{a}I_{60}{}^{b}$ and $M = AP^{a}I_{60}{}^{b}$ on different length slopes, where H is runoff depth (mm), M is sediment modulus (t km^{-2}), and A, a, and b are statistical parameters (Table 5). The high coefficients of determination (R^2) indicated that runoff and soil loss had power functions with PI_{60} on different length slopes.

3.3. *The relationship between soil loss and runoff*

There is a significant relationship between soil loss and runoff generation. Generally, the larger the runoff volume is, the more the soil loss will be. Analysis showed that the power function relationships are well fitted (Table 6).

Soil loss showed significant power function relationship with slope gradient and runoff on slopes, which can be expressed as $M = 0.405(SH)^{1.371}$ ($R^2 = 0.644$) under low, moderate and high rainfall intensity, where M is sediment modulus (t km^{-2}), S is slope gradient (m), and H is runoff depth (m). The relationship can also be

Table 2
Correlation coefficients between runoff/soil loss and rainfall characteristics (All correlations are significant at 0.01 level).

Rainfall characteristics	Runoff					Soil loss				
	5°	10°	15°	20°	25°	5°	10°	15°	20°	25°
P	0.818	0.821	0.671	0.751	0.704	0.685	0.652	0.648	0.649	0.622
I_{30}	0.599	0.484	0.426	0.520	0.462	0.441	0.551	0.647	0.481	0.393
I_{60}	0.653	0.563	0.376	0.571	0.519	0.730	0.743	0.846	0.600	0.690

Table 3
The relationship between runoff generation and rainfall characteristics.

Slope gradient (°)	Regression equation for runoff	R^2	Slope gradient (°)	Regression equation for soil loss	R^2
5	$H = 0.10466P^{1.048}I_{30}{}^{1.048}$	0.688	5	$M = 0.09623P^{1.074}I_{30}{}^{1.134}$	0.552
10	$H = 0.14128P^{1.054}I_{30}{}^{1.028}$	0.617	10	$M = 0.32046P^{1.077}I_{30}{}^{1.119}$	0.662
15	$H = 0.14185P^{1.055}I_{30}{}^{1.044}$	0.623	15	$M = 0.45886P^{1.065}I_{30}{}^{1.169}$	0.707
20	$H = 0.13656P^{1.047}I_{30}{}^{1.042}$	0.697	20	$M = 0.68045P^{1.065}I_{30}{}^{1.122}$	0.551
25	$H = 0.12481P^{1.051}I_{30}{}^{1.038}$	0.648	25	$M = 0.77414P^{1.069}I_{30}{}^{1.111}$	0.560

expressed as $M = 0.410(SH)^{1.537}$ ($R^2 = 0.763$) under moderate and high rainfall intensity.

Moreover, the relationship between soil loss and runoff on different length slopes can be expressed as $M = 0.176(LH)^{1.261}$ ($R^2 = 0.629$) under low, moderate and high rainfall intensity, where M is sediment modulus (t km^{-2}), L is slope length (m), and H is runoff depth (m). The relationship can also be expressed as $M = 0.144(LH)^{1.478}$ ($R^2 = 0.715$) under moderate and high rainfall intensity.

4. Discussion

Karst areas suffer from serious soil erosion in the world. The situation is much worse in Southwest China, for example Guizhou Province where thin and sloping farmland takes a substantial proportion. High-quality farmland resource is scarce and precious. Unfortunately, farmland has been threatened by the increasing land use and land cover change (Zhang et al., 2015; Lai et al., 2016) and soil pollution, particularly from urbanization and industrialization (Yang et al., 2014). The conflict between increasing population and decreasing land area and quality is being exacerbated. Therefore, it is important to formulate the effective land resource protection policy (Yang, 2014) and adopt conservative tillage measures to protect farmland and achieve sustainable development (Kong, 2014; Yang, 2016).

4.1. The effect of slope gradient on runoff and soil loss

In the current study, we researched the effects of slope gradient on runoff and soil loss in Guizhou Province. The results showed that runoff and soil loss were not linearly related to slope gradient (Fig. 3). The complicated relationship between runoff and slope gradients is due to the overall effects of several factors including rainfall regime, surface roughness, overland flow continuity, sealing layer on topsoil, soil particles and infiltration capacity (Lavee and Poesen, 1991; Cerdà, 2001; Chen et al., 2013). These factors have different effects on the runoff generation. For example, the rainfall intensity affected sealing layer formation which can markedly reduce infiltration rates (Assouline and Ben-Hur, 2006). During the soil erosion process, rill erosion is more active on steep sloping lands (Kimaro et al., 2008). When the sealing layers in rill areas were destructed, soil loss rate in rill areas was higher than that in inter-rill areas.

In addition, soil infiltration is affected by many factors including soil moisture, porosity, surface roughness, and rainfall characteristics. All these factors are interactive and the overall effects of them are far from perfectly understood. Similarly, Sadeghi et al. (2013) emphasized the complex circumstances which govern the interaction between runoff and soil loss. As shown in Fig. 4, the effects of the rock outcrops on runoff generation and soil loss are noteworthy, because the rock outcrops can further complicate the impact of slope gradient on runoff and soil loss. Namely, soil erosion is affected by slope gradient changes and rock outcrops, which is a character of soil erosion in the karst area.

4.2. The effect of slope length on runoff and soil loss

In the field observation in this study, we found that runoff had a decrease-increase-decrease pattern when slope length increased from 5 to 25 m (Fig. 7). The differences in slope length can affect the generation and spatial distribution of surface runoff. It is well known that runoff generation decreases with increasing area and this phenomenon is commonly called the scale effect (Delmas et al., 2012). Hydrological monitoring in humid regions indicated the remarkably spatial changes of runoff, even in small catchments with congeneric lithology (Leys et al., 2010). The low efficiency of runoff generation on long slopes is because of the difference between concentration time and the duration of effective rainfalls. When rainfall duration is equal to or longer than the concentration time, overland flow continuity occurs (Yair and Raz-Yassif, 2004).

With increasing slope length, soil loss showed an increasing trend in this study, this finding agrees with the results found in other areas (Zingg, 1940; Wischmeier et al., 1958; Rejman and Brodowski, 2005). As mentioned above, runoff did not show a positive relationship with slope length. It is obvious that the effects of slope length on runoff and soil loss were different. The positive relationship between the soil loss

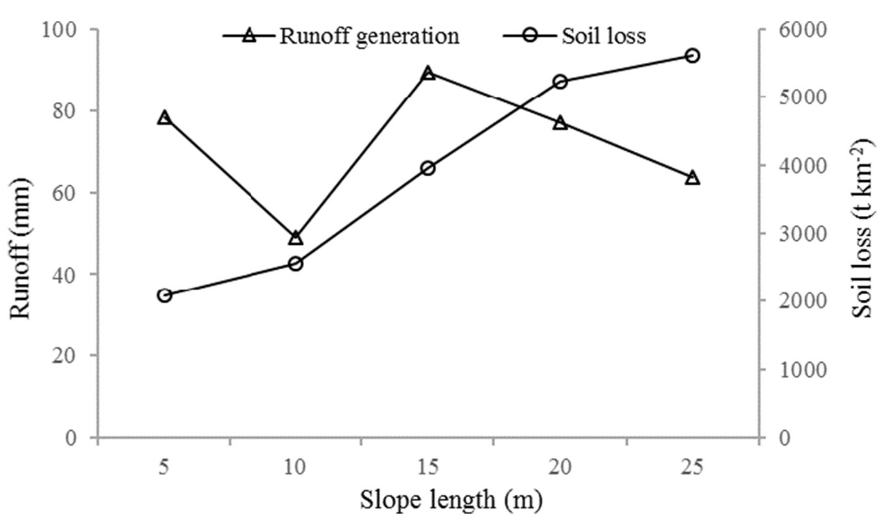

Fig. 7. The relationship between runoff/soil loss and slope length.

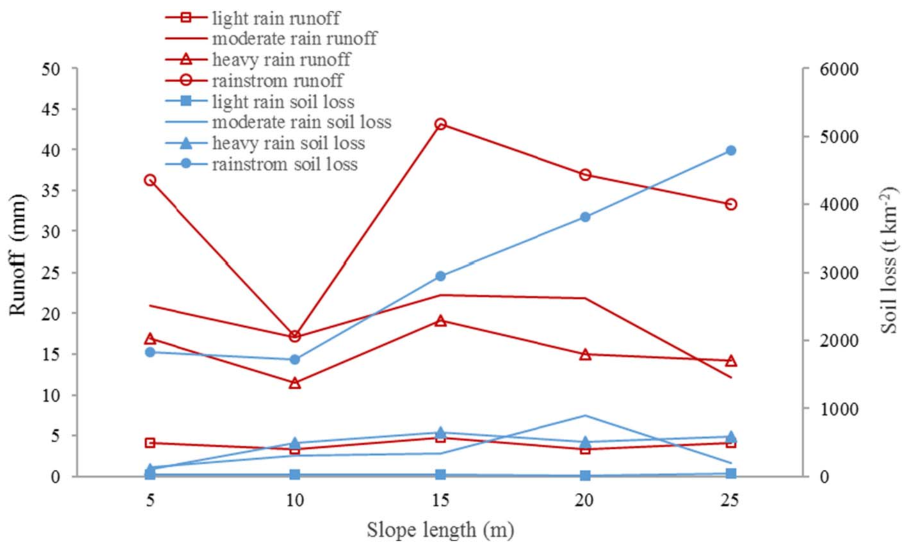

Fig. 8. The relationship between runoff/soil loss and rainfall characteristics.

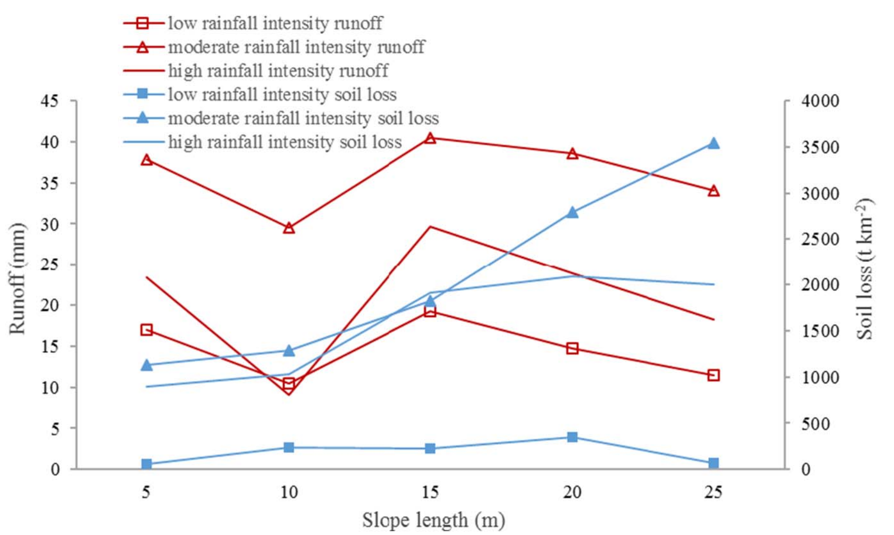

Fig. 9. Soil loss on slope length plots in different rainfall intensities.

Table 4
Correlation coefficients between runoff generation and rainfall characteristics (All correlations are significant at 0.01 level).

Rainfall characteristics	Runoff					Soil loss				
	5 m	10 m	15 m	20 m	25 m	5 m	10 m	15 m	20 m	25 m
P	0.841	0.707	0.868	0.824	0.863	0.665	0.662	0.675	0.621	0.611
I_{30}	0.646	0.476	0.689	0.664	0.645	0.580	0.593	0.641	0.554	0.521
I_{60}	0.706	0.582	0.763	0.734	0.724	0.710	0.733	0.776	0.660	0.644

Table 5
The relationship between runoff/soil loss and rainfall characteristics.

Slope length (m)	Regression equation for runoff	R^2	Slope length (m)	Regression equation for soil loss	R^2
5	$H = 0.0247P^{1.456}I_{60}{}^{0.153}$	0.561	5	$M = 0.0243P^{1.351}I_{60}{}^{1.002}$	0.560
10	$H = 0.0385P^{0.964}I_{60}{}^{0.402}$	0.579	10	$M = 0.0099P^{1.591}I_{60}{}^{1.133}$	0.626
15	$H = 0.0331P^{1.190}I_{60}{}^{0.426}$	0.693	15	$M = 0.0150P^{1.796}I_{60}{}^{0.861}$	0.599
20	$H = 0.0237P^{1.097}I_{60}{}^{0.585}$	0.685	20	$M = 0.0122P^{1.532}I_{60}{}^{1.309}$	0.609
25	$H = 0.0231P^{1.132}I_{60}{}^{0.484}$	0.674	25	$M = 0.0196P^{1.503}I_{60}{}^{1.165}$	0.630

and slope length possibly intensify the active rill erosion on longer slopes, even though runoff did not increase on longer slopes. Regarding the different increment of soil loss with increasing slope length, it mainly depended on the interaction of two factors: 1) the erosion dynamic, including rainfall erosivity and the upslope catchment area; and 2) the erosion resistance, which affects the sediment transporting capacity of surface runoff (Morgan, 2009). A possible explanation of the observed variation in soil loss is the continuous flow and efficient

Table 6
The relationship between soil loss and runoff generation.

Slope gradient (°)	Regression equation	R^2	Slope length (m)	Regression equation	R^2
5	$M = 6.201H^{1.487}$	0.684	5	$M = 3.680H^{1.112}$	0.580
10	$M = 11.039H^{1.426}$	0.652	10	$M = 5.180H^{1.545}$	0.641
15	$M = 15.174H^{1.263}$	0.576	15	$M = 3.797H^{1.531}$	0.748
20	$M = 23.465H^{1.626}$	0.671	20	$M = 5.536H^{1.551}$	0.760
25	$M = 25.678H^{1.469}$	0.664	25	$M = 7.485H^{1.493}$	0.750

sediment removal along the shorter slopes but a high frequency of flow discontinuity on the longer slopes.

4.3. The effect of rock outcrops on soil erosion

There is a negative relationship between erosion rates and rock outcrops cover in this study (Fig. 3), and this is in accord with the results found in other karst areas, for example the Mediterranean (Cerdan et al., 2010). The existence of rock fragments in the topsoil can substantially reduce sheet and rill erosions. The rock fragment cover in stony soils in karst area was found to be positively correlated with slope gradient. The high proportion of rock fragment content in Mediterranean soils is regarded as the main reason for the low erosion rates there (Poesen and Lavee, 1994; Poesen et al., 1994; Govers et al., 2006).

The karst area in southwest China is characterized by thin soils, rock fragments in stony soils, steep hillslope and short slope, and a humid climate with plenty of precipitation and frequent but high-intensity rainfalls in rainy seasons. All the factors cause severe soil erosion and rocky desertification. Slope gradient can also interact with soil texture, in other words, an interaction between soil properties and topography (Cerdan et al., 2010; Peñuela et al., 2015). In addition to topographic factors, the intensity of water-induced erosion is strongly related to the proportion of rock fragments and/or vegetation.

The positive relationship between erosion rates and slope length in this study is as expected, however, there is no positive relationship between erosion rates and slope gradient (Fig. 3). As demonstrated in Fig. 4 that surface roughness on the slopes is a key factor affecting runoff generation and soil loss rate, and it resulted in relatively lower runoff and soil loss on the slopes. Similar results are found in the karst areas in the Mediterranean zone (Cerdan et al., 2010). These results indicated the importance to integrate infiltration and rock fragment into the assessment of soil erosion in karst landscapes.

4.4. Limitation and future research

Similar to many studies, there are several limitations of the current study and therefore future studies are still needed. Rainfall processes were automatically recorded in detail and the impacts of rainfall characteristics on runoff and soil loss on slopes were evaluated in the current study. In the future researches, runoff generation and concentration process and the sheet/rill erosion process on hillslopes are needed to be observed and analyzed. More studies on the effects of rock outcrops on slope runoff and soil loss are needed, including evaluating the effects of coverage rate, the shape and the position of the rock outcrops on soil erosion (Calvo-Cases et al., 2003). In the design for field observation of soil erosion in the karst areas in future research, in addition to considering topographic factors, including slope gradient, length, shape and slope aspect, more attentions are needed to the surface configuration of hillslopes, especially the impacts of rock outcrops on soil erosion.

5. Conclusions

The karst mountainous area in Southwest China is vulnerable to soil erosion due to its rugged topography and subtropical monsoon climate. A sound understanding of the effects of topographic factors on soil erosion is crucial to effectively mitigate soil and water losses in this region. The current study examined the effects of slope gradient and length on runoff and soil loss using *in situ* plot data.

When slope gradient increases, runoff and soil loss on slopes showed a pattern of increasing-decreasing-increasing. The increasing trends of runoff and soil loss turned to slow down after the slope gradient of 15°. Nonetheless, it is still unknown whether the slope gradient of 15° is a critical value in the study area, due to that the turning point was affected simultaneously by slope gradient and rock outcrops on the 20°–25° slopes.

When slope length increases, runoff on the slopes showed a pattern of decreasing-increasing-decreasing. This is due to the effect of infiltration losses or transmission losses on runoff generation. Similar as in non-karst areas, soil loss rate increased nearly linearly with slope length. The positive relationship between soil loss and slope length is due to the active rill erosion on longer slopes.

When slope gradient and length increase, runoff and soil loss were positively related to rainfall amounts; and runoff was positively correlated with moderate rainfall intensity. When slope gradient increased, soil loss was positively correlated with high rainfall intensity. When slope length increased, soil loss was positively correlated with moderate rainfall intensity. In addition, soil loss had a power function relationship with slope gradient/length and runoff depth on slopes.

The current study provides valuable results for improving the design of field studies on soil erosion in karst areas. Our results highlight the necessity of considering the differences in climate conditions when comparing the soil erosion characteristics.

Acknowledgments

This work was supported by Guizhou Provincial Water Resources Department's project "Soil erosion mechanism and soil erosion prediction research in karst area of Southwest China" (No. 2006200) and partially supported by National Natural Science Funds of China (No. 41371045) and Open Project Program of Chongqing Key Laboratory of Karst Environment.

Author contributions

X. Zhang and M. Hu motivated and contributed equally to the study. H. Yang extensively revised the draft. All authors contributed to the writing and revising of the article.

References

Assouline, S., Ben-Hur, M., 2006. Effects of rainfall intensity and slope gradient on the dynamics of interrill erosion during soil surface sealing. Catena 66, 211–220.
Calvo-Cases, A., Boix-Fayos, C., Imeson, A.C., 2003. Runoff generation, sediment movement and soil water behaviour on calcareous (limestone) slopes of some Mediterranean environments in southeast Spain. Geomorphology 50, 269–291.
Cerdà, A., 2001. Effects of rock fragment cover on soil infiltration, interrill runoff and erosion. Eur. J. Soil Sci. 52, 59–68.
Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Gobin, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.J.P.M., Raclot, D., Ionita, I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M.J., Dostal, T., 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology 122, 167–177.
Chen, L., Sela, S., Svoray, T., Assouline, S., 2013. The role of soil-surface sealing, microtopography, and vegetation patches in rainfall-runoff processes in semiarid areas. Water Resour. Res. 49, 5585–5599.
Delmas, M., Pak, L.T., Cerdan, O., Souchère, V., Le Bissonnais, Y., Couturier, A., Sorel, L., 2012. Erosion and sediment budget across scale: a case study in a catchment of the European loess belt. J. Hydrol. 420, 255–263.
Fox, D.M., Bryan, R.B., 2000. The relationship of soil loss by interrill erosion to slope gradient. Catena 38, 211–222.
Giesen, N.C., Stomph, T.J., Ridder, N.D., 2005. Surface runoff scale effects in West African watersheds: modeling and management options. Agric. Water Manag. 72, 109–130.
Govers, G., Van Oost, K., Poesen, J., 2006. Responses of a semi-arid landscape to human disturbance: a simulation study of the interaction between rock fragment cover, soil

erosion and land use change. Geoderma 133, 19–31.
Guo, Q.K., Hao, Y.F., Liu, B.Y., 2015. Rates of soil erosion in China: a study based on runoff plot data. Catena 124, 68–76.
Hickey, R., 2000. Slope angle and slope length solutions for GIS. Cartography 29, 1–8.
Jiang, Z.C., Lian, Y.Q., Qin, X.Q., 2014. Rocky desertification in Southwest China: impacts, causes, and restoration. Earth Sci. Rev. 132, 1–12.
Jin, C.X., 1995. A theoretical study on critical erosion slope gradient. Acta Geograph. Sin. 50, 234–239.
Joel, A., Messing, I., Seguel, O., Casanova, M., 2002. Measurement of surface water runoff from plots of two different sizes. Hydrol. Process. 16, 1467–1478.
Kara, O., Sensoy, H., Bolat, I., 2010. Slope length effects on microbial biomass and activity of eroded sediments. J. Soils Sediments 10, 434–439.
Kimaro, D.N., Poesen, J., Msanya, B., Deckers, J.A., 2008. Magnitude of soil erosion on the northern slope of the Uluguru Mountains, Tanzania: interrill and rill erosion. Catena 75, 38–44.
Kinnell, P.I.A., 2001. Slope length factor for applying the USLE-M to erosion in grid cells. Soil Tillage Res. 58, 11–17.
Kong, X.B., 2014. China must protect high-quality arable land. Nature 506, 7.
Lai, L., Huang, X.J., Yang, H., Chuai, X.W., Zhang, M., Zhong, T.Y., Chen, Z.G., Chen, Y., Wang, X., Thompson, J.R., 2016. Carbon emissions from land-use change and management in China between 1990 and 2010. Sci. Adv. 2, e1601063.
Lavee, H., Poesen, J.W.A., 1991. Overland flow generation and continuity on stone-covered soil surfaces. Hydrol. Process. 5, 345–360.
Laws, J.O., Parsons, D.A., 1943. The relationship of raindrop site to intensity. Trans. Am. Geophys. Union 24, 452–460.
Leys, A., Govers, G., Gillijns, K., Berckmoes, E., Takken, I., 2010. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: the role of residue cover. J. Hydrol. 390, 143–154.
Liu, Q., Singh, V.P., 2004. Effect of microtopography, slope length and gradient, and vegetative cover on overland flow through simulation. J. Hydrol. Eng. 9, 375–382.
Liu, B.Y., Nearing, M.A., Risse, L.M., 1994. Slope gradient effects on soil loss for steep slopes. Trans. ASAE 37, 1835–1840.
Liu, B.Y., Nearing, M.A., Shi, P.J., Jia, Z.W., 2000. Slope length effects on soil loss for steep slopes. Soil Sci. Soc. Am. J. 64, 1759–1763.
Liu, M.X., Xu, X.L., Sun, A.Y., Wang, K.L., Liu, W., Zhang, X.Y., 2014. Is southwestern China experiencing more frequent precipitation extremes? Environ. Res. Lett. 9, 1–14.
Liu, Y., Huang, X.J., Yang, H., Zhong, T.Y., 2014. Environmental effects of land-use/cover change caused by urbanization and policies in Southwest China Karst area–a case study of Guiyang. Habitat Int. 44, 339–348.
Morgan, R.P.C., 2009. Soil Erosion and Conservation. John Wiley & Sons, Oxford, UK.
Nord, G., Esteves, M., 2010. The effect of soil type, meteorological forcing and slope gradient on the simulation of internal erosion processes at the local scale. Hydrol. Process. 24, 1766–1780.
Peng, T., Wang, S.J., 2012. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. Catena 90, 53–62.
Peñuela, A., Javaux, M., Bielders, C.L., 2015. How do slope and surface roughness affect plot-scale overland flow connectivity? J. Hydrol. 528, 192–205.
Pimental, D., 2006. Soil erosion: a food and environmental threat. Environ. Dev. Sustain. 8, 119–137.
Poesen, J., Lavee, H., 1994. Rock fragments in top soils: significance and processes. Catena 23, 1–28.
Poesen, J., Torri, D., Bunte, K., 1994. Effects of rock fragments on soil erosion by water at different spatial scales: a review. Catena 23, 141–166.
Rejman, J., Brodowski, R., 2005. Rill characteristics and sediment transports a function of slope length during a storm event on loess soil. Earth Surf. Process. Landf. 30, 231–239.
Sadeghi, S.H.R., Seghaleh, M.B., Rangavar, A.S., 2013. Plot sizes dependency of runoff and sediment yield estimates from small watershed. Catena 102, 55–61.
Stomph, T.J., Ridder, N.D., Steenhuis, T.S., Giesen, N.C., 2002. Scale effects of Hortonian overland flow and rainfall-runoff dynamics: laboratory validation of a process-based model. Earth Surf. Process. Landf. 27, 847–855.
Wang, S.J., Liu, Q.M., Zhang, D.F., 2004. Karst rocky desertification in Southwestern China: geomorphology, landuse, impact and rehabilitation. Land Degrad. Dev. 15, 115–121.
Wischmeier, W.H., Smith, D.D., Uhland, R.E., 1958. Evaluation of factors in the soil loss equation. Agric. Eng. 39 (458–462), 474.
Xu, Y.Q., Shao, X.M., Kong, X.B., Peng, J., Cai, Y.L., 2008. Adapting the RUSLE and GIS to model soil erosion risk in a mountains karst watershed, Guizhou Province, China. Environ. Monit. Assess. 141, 275–286.
Xu, X.L., Liu, W., Kong, Y.P., Zhang, K.L., Yu, B.F., Chen, J.D., 2009. Runoff and water erosion on road side-slopes: effects of rainfall characteristics and slope length. Transp. Res. Part D: Transp. Environ. 14, 497–501.
Xu, Y.Q., Luo, D., Peng, J., 2011. Land use change and soil erosion in the Maotiao River watershed of Guizhou Province. J. Geogr. Sci. 21, 1138–1152.
Yair, A., Raz-Yassif, N., 2004. Hydrological processes in a small arid catchment: scale effects of rainfall and slope length. Geomorphology 61, 155–169.
Yan, X., Cai, Y.L., 2015. Multi-scale anthropogenic driving forces of karst rocky desertification in Southwest China. Land Degrad. Dev. 26, 193–200.
Yang, H., 2014. China must continue the momentum of green law. Nature 509, 535.
Yang, H., 2016. China's soil plan needs strong support. Nature 536, 375.
Yang, H., Huang, X., Thompson, J.R., Flower, R.J., 2014. Soil pollution: urban brownfield. Science 344, 691–692.
Yuan, D.X., 1993. Environmental change and human impact on karst in southern China. Catena Suppl. 25, 99–107.
Zhang, M., Huang, X.J., Chuai, X.W., Yang, H., Lai, L., Tan, J.Z., 2015. Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: a spatial-temporal perspective. Sci Rep 5, 10233.
Zingg, A.W., 1940. Degree and length of land slope as it affects soil loss in runoff. Agric. Eng. 21, 59–64.