Notes and comments

Runoff and water erosion on road side-slopes: Effects of rainfall characteristics and slope length

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ABSTRACT

To investigate the effects of rainfall and slope length on water erosion on road side-slopes, runoff and soil loss are measured from natural runoff plots along the Qinghai-Tibet highway near Tuotuo River. Rainfall erosivity used in the revised universal soil loss equation is a good predictor for runoff and soil loss from road side-slopes. Runoff depth, sediment concentration and soil loss decreases as slope length increases.

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1. Introduction

Water erosion on road side-slopes often leads to damage to road embankments on the Tibetan Plateau where road building and maintenance is costly and difficult (Xu et al., 2006). Accurate predictions of erosion rates and the development of effective remediation measures are thus important. Water erosion is, however, a complex process influenced by numerous factors such as rainfall intensity (Forsyth et al., 2006) and terrain (MacDonald et al., 2001) that complicate the accurate prediction of erosion rates. This study focuses on the relationships between rainfall characteristics and runoff and soil loss, and between slope length and, runoff and soil loss on road side-slopes.

2. Methodology

The Qinghai-Tibet highway focused on runs from Gelmu in Qinghai province to Lhasa in Tibet Autonomous Region with a length of 1137 km and a surface width of about 7 m. The experiment site is located 25 km south from the Tuotuo River meteorological station (34°01'N, 92°18'E), Qinghai with an elevation of about 4553 m. The average annual precipitation is 272 mm at the Tuotuo River meteorological station, about 85% of which occurs from June to September. Between 1971 and 1998, the maximum daily precipitation was 50.2 mm, and the average annual temperature was below −5 °C. The predominant grasses are cyperaceous and gramineous, i.e. Alpine Sagebrush (*Kobresia pygmaea*), Drooping Wildrye (*Elymus nantans*), Speargrass (*Splendia achnatherum*), and Alpine Rockjasmine (*Androsace alpine*). Soil texture is coarse and loose on road side-slopes, mostly sand and gravel (93.3% sand, 0.23% silt, and 6.47% clay).

A Siphonal automated record rain gauge was used to record cumulative rainfall at intervals of 10 min. Natural runoff plots were built up on road side-slopes to collect runoff and sediment. Four bare plots at 1 m, 2 m, 3 m, and 4 m in surface length

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Table 1

Characteristics of rainfall, and runoff and soil loss.

		Mean	Minimum	Maximum	Std. Deviation	Coefficients of variance
P (mm)		11.5	2.8	31.0	6.2	0.5
I_{10} (mm/h)		11.7	3.6	28.8	6.6	0.6
I_{30} (mm/h)		7.3	3.0	15.0	2.9	0.4
I_{ave} (mm/h)		3.0	1.2	8.4	1.6	0.5
El_{30} (MJ mm/ (ha h))		12.2	1.4	64.0	12.4	1.0
Runoff depth (mm)	Plot 4	1.9	0.2	13.3	2.5	1.3
	Plot 3	2.5	0.5	12.6	2.6	1.0
	Plot 2	2.8	0.4	17.8	3.3	1.2
	Plot 1	5.6	1	30.4	5.7	1.0
Soil loss (t/ha)	Plot 4	0.11	0.001	0.89	0.21	1.9
	Plot 3	0.24	0.001	2.12	0.44	1.8
	Plot 2	0.15	0.001	0.86	0.24	1.6
	Plot 1	0.45	0.02	4.11	0.84	1.9
Sediment concentration (mg/L)	Plot 4	4732	357	26,071	6359	1.3
	Plot 3	8428	355	46,106	10,791	1.3
	Plot 2	5049	357	26,126	6312	1.3
	Plot 1	7329	532	48,482	10,832	1.5

Notes: P , rainfall amount; I_{10} , I_{30} , and I_{ave} are maximum 10 min, 30 min, time-averaged rainfall intensity, respectively; El_{30} , rainfall erosivity – the product of rainfall energy (E) and I_{30} .

Fig. 1. Frequency distribution of rainfall characteristics (P , rainfall amount; I_{10} , I_{30} , and I_{ave} are maximum 10 min, 30 min, time-averaged rainfall intensity, respectively).

(denoted as Plots 1–4) are established. These are 2 m in width and 30° in gradient with measures preventing runoff from road surface. The observation periods were August 4th–31st, 2003 and June 21st–September 6th, 2004.

To allow comparison with previous studies, the data is normalized to a runoff and soil loss for a 22.13 m-long slope (similar to Liu et al., 2000). Because no runoff and soil loss data is measured at a slope of exactly 22.13 m long, regression estimates of the measured data were made using:

$$L' = a\lambda^m$$

where L' is runoff and soil loss, λ is slope length, and a and m are coefficients.

Normalizing to a unit plot of length 22.13 m, the RUSLE equation (Renard et al., 1997) is deployed:

Table 2Relationships between rainfall characteristics and, runoff and soil loss ($Y = b1x$).

Indicators	Plots	P (mm)			I_{10} (mm/h)			I_{30} (mm/h)			I_{ave} (mm/h)			El_{30} (MJ mm/(ha h))		
		$b1$	R^2	p	$b1$	R^2	p	$b1$	R^2	p	$b1$	R^2	p	$b1$	R^2	p
Runoff (mm)	Plot 4	0.19	0.66	*	0.17	0.51	*	0.30	0.58	*	0.57	0.39	*	0.17	0.89	*
	Plot 3	0.25	0.79	*	0.20	0.56	*	0.37	0.65	*	0.74	0.47	*	0.20	0.87	*
	Plot 2	0.28	0.71	*	0.23	0.51	*	0.43	0.61	*	0.80	0.40	*	0.23	0.89	*
	Plot 1	0.53	0.77	*	0.45	0.58	*	0.83	0.67	*	1.60	0.47	*	0.44	0.91	*
Soil loss (t/ha)	Plot 4	0.01	0.36	0.001	0.01	0.50	*	0.02	0.41	*	0.05	0.47	*	0.01	0.56	*
	Plot 3	0.02	0.31	0.002	0.03	0.50	*	0.04	0.41	*	0.11	0.53	*	0.02	0.44	*
	Plot 2	0.01	0.45	*	0.02	0.62	*	0.03	0.54	*	0.06	0.53	*	0.01	0.72	*
	Plot 1	0.04	0.27	0.004	0.05	0.44	*	0.07	0.36	0.001	0.20	0.50	*	0.03	0.36	0.001
Sediment concentration (mg/L)	Plot 4	324	0.29	0.003	459	0.61	*	698	0.49	*	1759	0.58	*	258	0.32	0.001
	Plot 3	580	0.31	0.002	817	0.65	*	1253	0.52	*	3130	0.61	*	464	0.35	0.001
	Plot 2	330	0.29	0.003	499	0.69	*	742	0.53	*	1870	0.62	*	275	0.35	0.001
	Plot 1	469	0.22	0.010	675	0.49	*	1040	0.40	*	2822	0.54	*	356	0.23	0.009

Notes: P , rainfall amount; I_{10} , I_{30} , and I_{ave} are maximum 10 min, 30 min, time-averaged rainfall intensity, respectively; El_{30} , rainfall erosivity—the product of rainfall energy (E) and I_{30} ; *, $p < 0.001$.

$$L = \left(\frac{\lambda}{22.13} \right)^m$$

where L is runoff and soil loss normalized to the 22.13 m long slope.

3. Results

Twenty-eight rainfall–runoff events were recorded with rainfall ranging from 2.8 to 31 mm with an averaged of 11.5 mm (Table 1). Most rainfall events were in the range from 5 to 15 mm (Fig. 1) with only four in the range of 20–30 mm. The mean maximum 10 min, 30 min, and time-averaged rainfall intensity (I_{10} , I_{30} and I_{ave}) decreased from 11.7, 7.3 to 3.0 mm/h. Of the 28 observed events, 27 I_{30} values were lower than 15 mm/h.

In terms of coefficients of determination, El_{30} provides the best explanation of the variance of runoff depth, followed in order by P , I_{30} , I_{10} , and I_{ave} (Table 2). In explaining the variance of soil loss, I_{10} is the best rainfall indicators and in terms of the variance of sediment concentration, I_{10} and I_{ave} , were the best rainfall indicators. Overall, rainfall erosivity (El_{30}) used in RUSLE is a good predictor for runoff and soil loss on road side-slopes, while rainfall intensity indicators are related to sediment concentration.¹

Runoff and soil loss decreased with slope length increasing, and the slope length exponent, m , was -0.74 for runoff, and -0.83 for soil loss (Fig. 2a and b). This differs from many other studies that found soil loss on road to be positively associated with slope length (Qiu and Fang, 1997; Megahan et al., 2001). In the cropland erosion prediction model-RUSLE, m is also positive; a finding that only Liu et al. (2000) have produced in which a low intensity (I_{30}) storms of <15 mm/h produced a negative value of m and exhibited a large decrease in runoff depth as a function of slope length increase (Fig. 2a and b). Looking at rainfall intensity, the maximum value of peak 30 min intensity is 15 mm/h (Table 1), and all I_{30} values for other events are lower in line with Liu et al. (2000). Kinnell (2000) found sediment concentration to be positively associated with slope length for short lengths (150–600 mm) using the dataset developed by Meyer and Harmon (1984, 1989). Using the dataset from Liu et al. (2000), we also found a positive relationship, but not statistically significant, link between sediment concentration and slope length (Fig. 2c). Kinnell (2000) found that by dividing the sediment concentration by rainfall intensity (I_{10}), a decreasing trend with relation to increasing slope length emerged (Fig. 2d). This may be because our study was conducted on a fill-slope with loose and coarse materials that caused relatively low runoff coefficients (runoff depth/rainfall depth) with the mean values of 0.16 for Plot 4, 0.21 for Plot 3, 0.23 for Plot 2 and 0.48 for Plot 1 (Fig. 2e). The study by Arnaez et al. (2004) also found that the runoff coefficient on fill-slopes was lower (0.34), relative to roadbed (0.46) and cut-slope (0.58); the road fill-slope thus had a high infiltration capacity, and thereby the shallow surface flow kept infiltrating into the subsurface over the distance. The flow energy also kept declining and thereby sediment concentration kept falling over distance because of the low rainfall intensity. Kinnell (2000) described how four detachment and transport systems might operate on a side-slope:

1. Raindrop detachment and splash transport. In this system, material detached by raindrop impact is splashed aerially over the surface.
2. Raindrop detachment and raindrop induced flow transport. Material detached by raindrop impact is moved across the surface by rain impacted surface flow that, if not impacted by the raindrops, would not be able to move this material.

¹ Kinnell (2000) also documented good linear relationships between rainfall intensity and sediment concentration on short sides-lopes in ridge-tillage system.

Fig. 2. Slope length in relation to (a) runoff, (b) soil loss, (c) sediment concentration, (d) runoff coefficients, (e) normalized sediment concentration by I_{10} .

Raindrop-induced flow transport operates through the combined action of raindrops and the flow and operates only in shallow flow.

3. Raindrop detachment and flow transport. Here, material detached by raindrop impact is moved across the surface without the aid of raindrop impact. For this to occur, the hydraulic shear of flowing water must be sufficient to entrain the detached particles but not sufficient to detach soil particles from soil matrix.
4. Flow detachment and flow transport. In this system, material is detached and transported by the flow without any raindrop involvement. For this to occur, the hydraulic shear of flowing water must be sufficient to detach soil particles from the soil matrix.

These systems may operate singly or in combination. Here, splash transport made no significant direct contribution to soil loss because only material transported by the flow was collected and measured. Raindrop detachment and raindrop induced flow transport dominated the erosion process because of low rainfall intensity, in which process particles travel distances varied with flow velocity. The flow velocity was low because of the low rainfall intensity and high soil infiltration capacity that runoff depth, sediment concentration, and soil loss decreased with increasing slope length.

4. Conclusions

In the 2-year study under natural conditions, the effects of rainfall and slope length on runoff and soil loss were investigated using natural runoff plots on the Qinghai-Tibet highway side-slopes. Rainfall erosivity was a good predictor for runoff and soil loss from road side-slopes, and a maximum of 10 min rainfall intensity (I_{10}) was positively correlated with sediment concentration. Contrasting with many other studies, runoff depth, sediment concentration and soil loss decreased as slope length increased. Detachment and rainfall-induced flow transport might dominate the erosion process under the combination of low rainfall intensity and high soil infiltration capacity.

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