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Slope Length Effects on Soil Loss for Steep Slopes

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ABSTRACT

Empirical soil erosion models continue to play an important role in soil conservation planning and environment evaluations around the world. The effect of slope length on soil loss, known as the slope length factor, is one of the main and most variable of the factors in an empirical model. In the widely used model, the Universal Soil Loss Equation (USLE), the slope length factor is expressed as L=(λ/22.1) ^{m}, in which the slope exponent, m, is 0.2, 0.3, 0.4, and 0.5 for different, increasing slope gradients. In the Revised Universal Soil Loss Equation (RUSLE), the exponent, m, is defined as a continuous function of slope gradient and the expected ratio of rill to interrill erosion. When the slope is 50% and the ratio of rill to interrill erosion is classified as moderate, the exponent m has the value of 0.7 in RUSLE. RUSLE will predict 22% more soil loss than using slope exponent 0.5 suggested by USLE on 60-m long slope. Many farmlands are on very steep slopes in the loess plateau of China. The purpose of this study was to evaluate the relationship between soil loss and slope length for very steep slopes (up to 60%). Soil loss data from natural runoff plots at three locations on the loess plateau in China were used. The slope lengths ranged from 10 to 60 meters long, plot widths were 5m to 15m, and the slope steepnesses were approximately 40% at two sites and 60% at the third site. The results indicated that the exponent, m, for the exponent for the slope length equation was 0.44. These experiment data would indicate that the USLE exponent, m=0.5 is adapted better for steep slopes than the RUSLE exponent, which is greater in magnitude.

INTRODUCTION

Because physical based models are either not well tested or require many input parameters, empirical soil loss models (USLE, RUSLE, for instance) still play a important role in soil conservation planning. This is especially true for those areas where extensive soil and biological data such as process-based models require are not available. The Universal Soil Loss Equation (USLE) (Wischmeier, and Smith, 1978) is the most widely used erosion model in the world. The USLE was modified recently to become the Revised Universal Soil Loss Equation (RUSLE) (Renard et. al., 1997). The slope length factor is one of the main factors for soil loss predictions in both RUSLE and the USLE. It is also one of the most variable factors as discussed in erosion scientific literature. The slope length factor has been expressed as (Zingg, 1940):

$$L' = a\lambda^{m} \quad [1]$$

where L' is soil loss (mass per unit area per unit time), λ (m) is slope length, and *a* and *m* are empirical coefficients. If soil loss is normalized to a specified slope length, the coefficient, *a*, becomes equal to one by definition. Normalizing to a unit plot of length 22.13 m, both the USLE and RUSLE use the equation

$$L = (\lambda / 22.13)^{m} \quad [2]$$

where L is soil loss normalized to soil loss on the 22.13 m long slope. The differences of slope length factors, m, from literature can be compared directly. Zingg (1940) proposed 0.6 as the slope length exponent. Musgrave et al. (1947) suggested 0.3. A study conducted at Purdue University in July 1956 recommended 0.5±0.1 (Wischmeier et.al., 1958). In the USLE (1978), the m value was recommended as 0.2, 0.3, 0.4, and 0.5 for slope gradients less than 1%, 1-3%, 3.5-4.5%, and 5% or greater, respectively. This means that when slope gradient is greater than 5%, the slope length factor does not change with slope steepness. However in RUSLE, m continues to increase with the slope steepness according to:

$$m = \beta / (1 + \beta) \quad [3]$$

$$\beta = (\sin\theta / 0.0896) / 3.0 \sin^{0.8} + 0.56 \quad [4]$$

where β is the ratio of rill erosion to interrill erosion, and θ is the angle of the slope. When slope increase from 9% to the 60%, the exponent, m, increase from 0.5 to 0.71. According to Eqs. [3] and [4] the slope length exponent, m, is 0.7 for 50% slope with 60 meters slope length and moderate rill / interrill erosion ratio. These will predict 22% more soil loss than USLE (m = 0.5). When slope steepness is equal to 9%, slope length exponent for both USLE and RUSLE is 0.5, and they predict the same soil loss. When slope is less than 9% USLE will predict more soil loss than RUSLE. When slope is steeper than 9%, RUSLE will predict more soil loss than USLE. The greatest difference is on the very steepest slopes (Fig. 1).

Liu et al. (1994) used data from the China loess plateau

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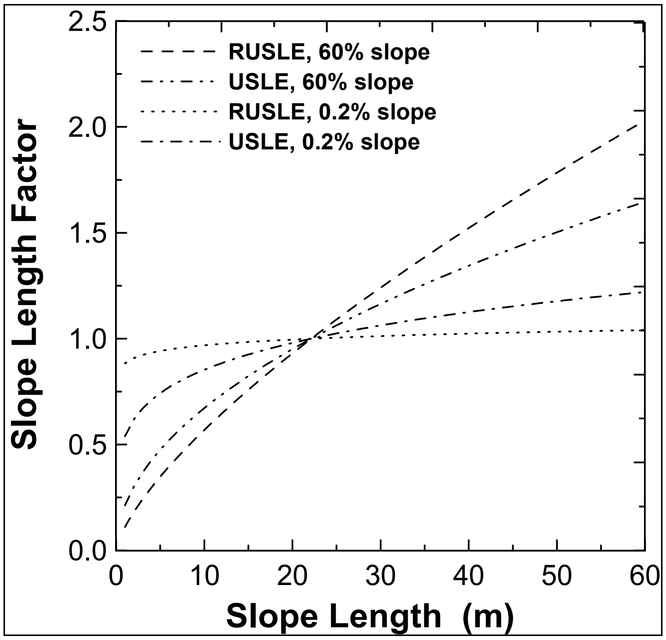

Figure 1. Slope length factors of USLE and RUSLE, for steep slopes (60%), m=0.5 for USLE, m=0.71 for RUSLE; for flat slopes (0.2%), m=0.2 for USLE, m=0.04 for RUSLE.

to assess the effect of slope gradient on erosion at very steep slopes. That work indicated that the USLE greatly over-predicted, and that RUSLE somewhat under-predicted the slope length factor on steep slopes. The purpose of this paper was to make a similar type of evaluation of the slope length factor on steep slopes. Thus, we used measured data on slopes up to nearly 60% in steepness to evaluate the relationship between soil loss and slope length. The results were compared to USLE and RUSLE slope length factors for very steep slopes. Many classifications of slope steepness for soil and land surveys take about 30% as a starting point for "steep" slopes (McDonald et. al., 1984; Liu and Tang, 1987), hence the data we chose are definitely considered to be classified as steep.

MATERIALS AND METHODS

Natural rainfall soil loss data from three locations on the loess plateau of China were used: Ansai, Zizhou, and Suide experiment stations. Soil texture in the loess plateau region changes from south to north (Liu, 1966). The plateau is divided into three zones: clayey loess, typical loess, and sandy loess. Stations used in this study were located in typical loess and sandy loess zones. Two of the soils were

Table 1 Soil properties of the three sites.

Location	Sand	Silt	Clay	Cation Exchange Capacity	Organic Matter	Field Capacity	Wilting Point
	(%)	(%)	(%)	(meq/100g)	(%)	(%)	(%)
Ansai	19.0	70.3	10.7	8.6	0.63	17.2	4.5
Suide	32.1	60.5	7.5	6.7	0.47	15.8	4.0
Zizhou	46.1	48.7	5.2	5.3	0.47	14.8	3.5

Table 2 Average annual runoff and soil loss.

Plot Number	Slope Length (m)	Slope Gradient(%)	Annual Runoff (mm)	Annual Soil Loss (t/ha)	Annual Soil Loss normalized to 22.1m
Ansai					
1	10	57.7	46.8	92.66	0.72
2	20	57.7	43.1	128.56	1.00
3	30	57.7	38.7	142.20	1.10
4	40	57.7	39.5	162.85	1.26
Suide					
12	10	40.0	20.6	15.59	0.70
29	40	42.8	17.9	28.00	1.26
34	60	40.4	14.0	36.59	1.64
Zizhou					
4	20	40.4	23.9	91.84	0.90
2	40	40.4	27.5	153.14	1.51
3	60	40.4	24.1	143.11	1.41

Table 3 Slope length exponents, m for different sites.

Location	Slope length exponents, m	Determination coefficients, r^2
Ansai	0.397	0.988
Suide	0.462	0.991
Zizhou	0.440	0.771
All sites	0.467	0.957

silt loams, and the soil at Zizhou was a sandy loam soil (Table 1). The region is semiarid with annual rainfall ranging from 485 to 541mm. Greater than 60% of the precipitation occurs from June through September. Most of the soil losses were caused by heavy storms. The soil loss caused by storms with greater than 45mm/hr maximum-30-minutes (I_{30}) was 80.4% of the total soil loss for 20m long plot in the Ansai station. All of the soils in these three stations were very susceptible to the rill erosion. After each storm extensive rilling can be see in the fields. Rills in this area tend to be rectangular in cross section, and generally developed within the tillage layer. Plots at Zizhou were 15 meters wide, and for other two sites plot widths were 5 meters. The slope length, measured horizontally, ranged from 10 meters to 60 meters. The slope steepness was 57.7% for the Ansai station and about 40% for the other two stations (Table 2). The plots were selected from a larger database using the 30% of slope or steeper as the criteria and all other conditions should be identical. Soil loss was measured by sampling the sediment concentration of the runoff which was collected in either metal tank and divisor or cement pool.

The data collected from Ansai site (Jiang et al., 1991) were from five years of fallow conditions from 1985 to 1989. The slope lengths were 10, 20, 30, and 40 meters long. Data from Suide site were for four years from 1957 to 1960, and for Zizhou site were five years from 1963 to 1967. The latter two sites were conventionally tilled farmland. Generally, the crop cover was very sparse due to insufficient soil moisture and the steep slope. The plots were cropped in a three-year rotation of millet, beans, and potato. The slope lengths at Suide were 10, 40, and 60 meters, and at Zizhou they were 20, 40, and 60 meters.

Since the data used in this study were collected in three field stations, the soil loss was different from site to site. In order to compile and compare the data together, the soil loss was normalized to 22.13 meters for all the sites. Because no measured soil loss at exactly 22.13 meters long slope, regression equations were fitted for each of the data set according to Eq. [1]. The fitted result is showed in the Table 3. We used the regression equation for each of the three data sets to calculate the soil loss on the 22.13 m long slope, and used the value for the individual site to normalize the measured soil loss data for the site.

RESULTS AND DISCUSSION

We used the average annual soil loss data to analyze the slope length relationships. Average annual soil loss and normalized values are presented in Table 2. According to the RUSLE equations the slope length exponent, m, would be 0.71 at the Ansai station, which had the steepest slope of 57.7%. As seen in Fig. 2, we found that the RUSLE L-factor was greater than the measured data for the Ansai station. RUSLE over-predicted soil loss by 20% compared to the best fit equation (m=0.4). However, USLE over-predicted the measured soil loss by only 6% compared to the best fit equation for the data (see Eq. 5, below). The other two data sets were collected on approximately 40% slopes. The slope length exponents for the measured data at those sites were 0.46 and 0.44, respectively. In summary, the data from these three stations did not indicate that the slope length exponent should increase with a slope steepness increase from approximately 40% to 60%.

Compiling all of the normalized soil loss data from the three stations together, Equation [5] was derived:

$$L = (\lambda / 22.13)^{0.44} \quad [5]$$

From Fig. 3 we can see that the USLE relationship for slope length fit the measured data well.

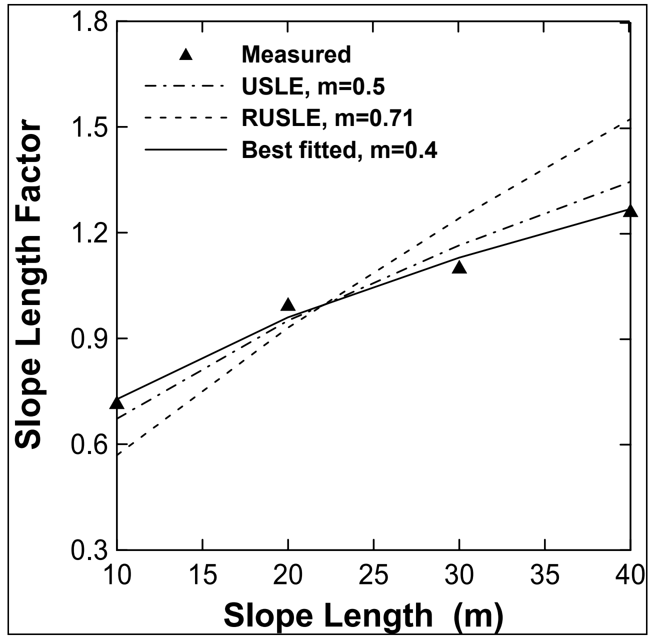

Figure 2. Normalized soil loss, from a steep slope (57.7%, Ansai station), compared with USLE m=0.5) slope length factor and RUSLE slope length factor (m=0.71). The best fit m value was 0.4.

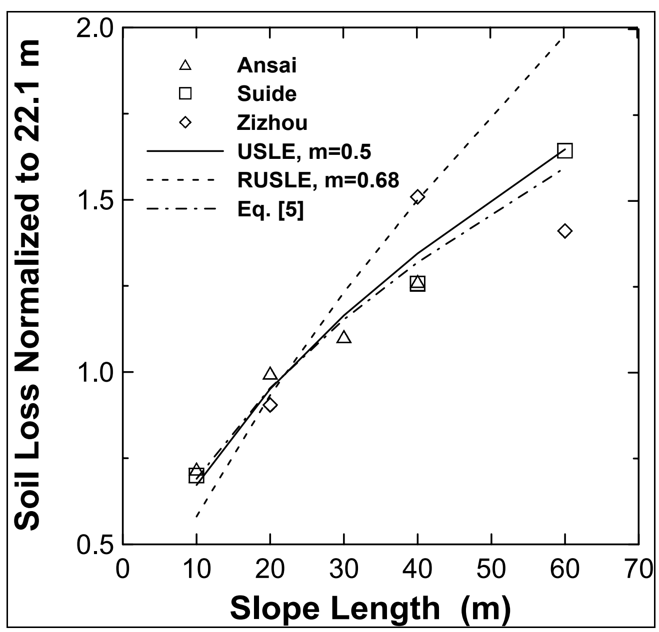

Figure 3. Soil loss normalized to 22.13m from the natural rainfall plot data used in this study, the best fit m value was 0.44 for all measured data.

The slope of the plots used in this study were up to about 60%, which in China and many other parts of the world is not unrealistic for cropped farmland. Thus under these conditions it is important to know and use the best relationship between slope length and soil loss for steep slopes. The RUSLE equations for slope length indicate a very rapid increase in L with slope steepness when slope is less than 30% (for slope lengths greater than 22.13 m). When the slope is steeper than 30%, the slope length factor does not vary so greatly with steepness (Fig 4). In other words, there is a large difference in the RUSLE L between the 10% line and the 30% line of Fig. 4, but not so much difference between the 30% and 60% lines. This is because the RUSLE use the Eqs. [3] and [4] to estimate the ratio and the slope length exponent, m. The m increases greatly with slope steepness at low slopes (Fig. 5), but not as much at high slopes. From Fig. 4 we can see that when the slope increase from 10% to the 30% the slope length factor increase 15%, when slope steepness increase from 30% to 60% the slope factor is only increased 5%.

The fitted exponent of slope length from this study at 57.7% slope was 0.4, and at 40% slope was 0.46 and 0.44. Several measured data distributed at a joint ARS-SCS workshop held in 1956 at Purdue University by W.H. Wischmeier (McCool et al., 1989) showed that when slope steepness were 16% at Lacrosse, WI; 17% at Marcellas, NY; and 18% at Arnot, NY; the slope length exponent was 0.5, 0.6, and 0.45. Those together with our data show that when slope steepness increased from about 20, to 40, and to 60%, the slope length exponent does not increase.

CONCLUSIONS

Data of soil loss from the natural runoff plots at three sites on the loess plateau of China were reported in this study. The experimental data with slope lengths from 10 meters to 60 meters on very steep slope show that the relationship of slope length and soil loss is very well approximated by the USLE equation, and not as well by the RUSLE equations. The overall slope length exponent for the data was 0.44. The three data from the slope of 57.7%, 40.4%, and 40.4% show that the slope length exponent does not increase with the slope gradient. For slope gradient greater than 30% and up to 60%, we recommend using the slope length exponent of 0.5.

One may question why our results here differ from RUSLE relationships, particularly since RUSLE in newer and ostensibly improved technology over the USLE. The fact is that the new RUSLE slope length factors for slopes greater than about 20% are based entirely on results from theoretical models. This is obviously a case wherein the theoretical model does not match reality. There is no reason why the data used in this study would not be representative of other conditions where slopes and soils are similar.

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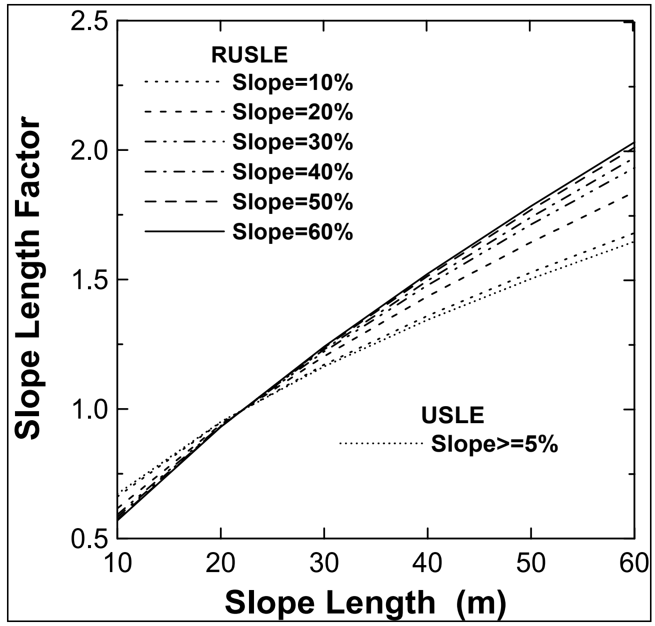

Figure 4. USLE and RUSLE slope length factor for steep slopes.

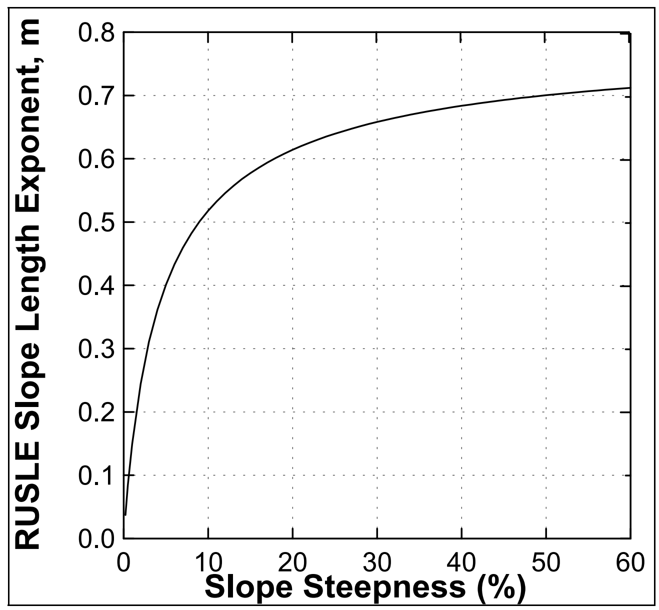

Figure 5. RUSLE slope length exponent, m, for different slopes.

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