Slope Length Effects on Soil Loss for Steep Slopes

B. Y. Liu, M. A. Nearing,* P. J. Shi, and Z. W. Jia

ABSTRACT

Empirical soil erosion models continue to play an important role in soil conservation planning and environmental evaluations around the world. The effect of hillslope length on soil loss, often termed the *slope length factor*, is one of the main and most variable components of any empirical model. In the most widely used model, the Universal Soil Loss Equation (USLE), normalized soil loss, L, is expressed as a power function of slope length, λ, as $L = (\lambda/22.1)^m$, 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 gradient is 60% and the ratio of rill to interrill erosion is classified as moderate, the exponent m has the value of 0.71 in RUSLE, as compared with 0.5 for the USLE. The purpose of this study was to evaluate the relationship between soil loss and slope length for slopes up to 60% in steepness. Soil loss data from natural runoff plots at three locations on the Loess Plateau in China and data from a previous study were used. The results indicated that the exponent, m, for the relationship between soil loss and the slope length for the combined data from the three stations in the Loess Plateau was 0.44 ($r^2 = 0.95$). For the data as a whole, the exponent did not increase as slope steepness increased from 20 to 60%. We also found that the value of m was greater for intense storms than for less intense storms. These experimental data indicate that the USLE exponent, $m = 0.5$, is more appropriate for steep slopes than is the RUSLE exponent, and that the slope length exponent varies as a function of rainfall intensity.

BECAUSE PHYSICALLY BASED MODELS are either not well tested or require many input parameters, empirical soil loss models still play an important role in soil conservation planning. This is especially true for those areas where extensive soil and biological data that are required by process-based models are not readily available. The USLE (Wischmeier and Smith, 1978) is the most widely used empirical erosion model worldwide. The USLE was revised recently as the RUSLE (Renard et al., 1997). The slope length factor is one of the main factors for soil loss predictions in both the USLE and RUSLE. It is also one of the most variable factors, as we discuss below.

The slope length factor has often 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. 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 the 22.13-m-long slope. The differences of slope length factors from the literature can be compared directly by comparing the m values. Zingg (1940) proposed 0.6 as the slope length exponent. Musgrave (1947) suggested 0.3. A study conducted at Purdue University in 1956 recommended 0.5 ± 0.1 (Wischmeier et al., 1958). In the USLE (Wischmeier and Smith, 1978), the m values recommended were 0.2, 0.3, 0.4, and 0.5 for slope gradients <1, 1 to 3, 3.5 to 4.5, and 5% or greater, respectively. Thus, when the slope gradient is $>5\%$, the slope length factor for the USLE does not change with slope steepness. However, in RUSLE, m increases continuously with the slope steepness according to (Renard et al., 1997)

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

and

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

where β is the ratio of rill erosion to interrill erosion, and θ is the angle of the slope. When slope steepness is equal to 9%, the slope length exponent for both USLE and RUSLE is 0.5. When the slope is $<9\%$, the USLE has a greater slope length factor than RUSLE. When the slope is steeper than 9%, USLE has a lesser slope length factor than RUSLE. The greatest differences are for the steepest slopes (Fig. 1). According to Eq. [3] and [4], the slope length exponent, m, is 0.71 for a 60% a 60-m-long slope with a moderate rill/interrill erosion ratio. Under these conditions, RUSLE will have a slope length factor, L, which is 23% greater than that for the USLE.

Many classifications of slope steepness for soil and land surveys take 30% as a starting point for "steep" slopes (McDonald et al., 1984; Liu and Tang, 1987). The data used to develop the USLE and RUSLE involved slopes only up to 18% (McCool et al., 1989). However, McCool et al. (1993) studied the effect of both slope length and slope steepness on cropped slopes up to 56% gradient in the northwestern wheat (*Triticum aestivum* L.) region of the United States by performing field surveys of rill networks. Several hundred data points were used in their study. Mean slope steepness was 28.4%, with 95% of the data points collected on slopes ranging from 9 to 48%. The authors concluded by recommending a slope length exponent, m, of 0.5.

The purpose of our study was to analyze experimental data for slopes up to nearly 60% in steepness to evaluate the relationship between soil loss and slope length for

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Abbreviations: RUSLE, Revised Universal Soil Loss Equation; USLE, Universal Soil Loss Equation.

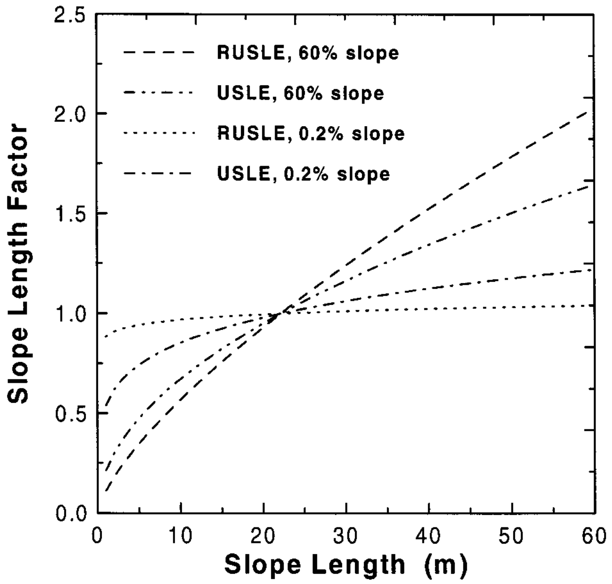

Fig. 1. Slope length factor of Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE). For the 60% slope: $m = 0.5$ for USLE and $m = 0.71$ for RUSLE. For the 0.2% slope: $m = 0.20$ for USLE and $m = 0.04$ for RUSLE.

steep slopes. The results were compared with USLE and RUSLE slope length factors. The data we chose are from three field stations with slope gradients steeper than 30%, which we consider here to be classified as steep.

MATERIALS AND METHODS

Natural rainfall soil loss data from three locations on the Loess Plateau of China were used: the Ansai (36°56′N, 109°16′E), Zizhou (37°31′N, 109°47′E), and Suide (37°29′N, 110°08′E) experimental stations. Soil texture in the Loess Plateau region changes from south to north (Liu, 1966). The plateau is divided into three zones: clayey loess in the southern part, typical loess in the middle, and sandy loess in the north. Stations used in this study were located in the typical loess and sandy loess zones. Two of the soils were fine-silty, mixed mesic Typic Udorthents, and the soil at Zizhou was a fine-loamy, mixed mesic Typic Udorthents (Table 1). The region is semiarid with annual rainfall ranging from 485 to 541mm. More than 60% of the precipitation occurs from June through September. Most of the soil losses were caused by these heavy storms. Soil loss caused by storms with >45mm h^{-1} maximum 30-min intensity (I_{30}) was 80.4% of the total soil loss for the 20-m-long plot in the Ansai station. All of the soils at these three stations were susceptible to rill erosion. After each storm, extensive rilling would be seen in the fields. Rills in this area tend to be rectangular in cross section and generally develop within, but not to the bottom of, the tillage layer. Plots at Zizhou were 15 m wide, and for the other two sites the plot widths were 5 m. The slope lengths, measured horizontally, ranged from 10 to 60 m. The slope steepness was 57.7% for Ansai station and ≈40% for other two stations (Table 2). The plots were selected from a larger database using the criteria of 30% slope or steeper with all other conditions identical. Soil loss was measured by sampling the sediment concentration of the runoff, which was collected in either metal tanks and divisors or concrete pools.

Table 2. Average annual runoff and soil loss from the three experiment sites.

Plot number	Slope length	Slope gradient	Annual runoff	Annual soil loss	Annual soil loss Normalized to 22.1 m
	m	%	mm	Mg ha^{-1}	Mg ha^{-1}
			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

The data collected from the Ansai site (Jiang et al., 1991) were from 5 yr of fallow conditions from 1985 to 1989. The slope lengths were 10, 20, 30, and 40 m. Data from the Suide site were for 4 yr from 1957 to 1960 and for the Zizhou site were 5 yr 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 3-yr rotation of millet [*Setaria italica* (L.) Beuv.], soybean [*Glycine max* (L.) Merr.], and potato (*Solanum tuberosum* L.). The slope lengths at Suide were 10, 40, and 60 m, and at Zizhou they were 20, 40, and 60 m.

Since the data used in this study were collected at 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 m for all the sites. Because no soil loss was measured at a slope exactly 22.13 m long, regression equations were fitted for each of the data sets according to Eq. [1]. Regression analysis was conducted on each data set individually to calculate the soil loss on the 22.13-m-long slope, then that value was used to normalize the measured values for each 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. The steepest slope of 57.7% was at the Ansai station, for which, according to the RUSLE equations, the slope

Table 1. Soil properties for the upper 10 cm of the three sites on the Loess Plateau of China.

Location	Sand	Silt	Clay	Cation–exchange capacity	Organic matter	1/3 Bar gravimetric	15 Bar gravimetric
	%	%	%	cmol kg^{-1}	%	%	%
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

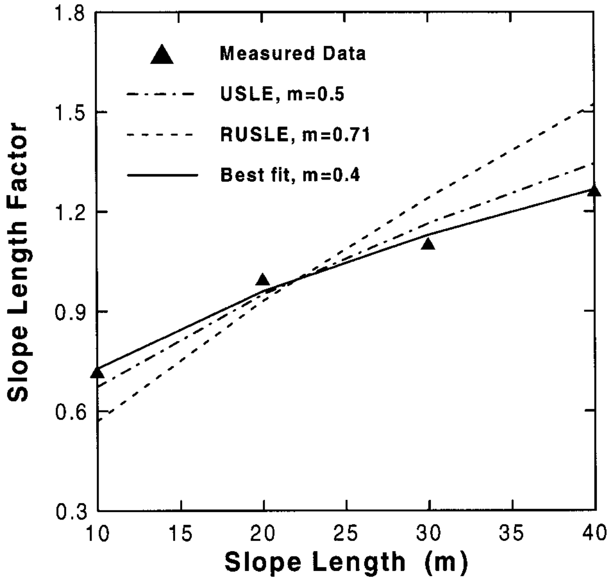

Fig. 2. Slope length factors for measured data on a 57.7% slope at the Ansai station compared with the Universal Soil Loss Equation (USLE; $m = 0.5$) and Revised Universal Soil Loss Equation (RUSLE) slope length factor ($m = 0.71$) curves.

length exponent, m, would be 0.71. As seen in Fig. 2, we found that the RUSLE L factor was greater than that from the measured data. The RUSLE overpredicted soil loss by 20% compared with the best-fit equation ($m = 0.4$) for the 40-m slope (Table 3) and underpredicted data for the 10-m slope by 21.8%. In contrast, the USLE overpredicted the measured soil loss by only 6% for the 40-m plot and underpredicted by 7.6% for the 10-m plot compared with the best-fit equation for the data. The other two data sets were collected on ≈40% slopes. The best-fit slope length exponents for the measured data at Suide and Zizhou were 0.46 and 0.44, respectively (Table 3). In summary, the data from these three stations did not indicate that the slope length exponent increased with a slope steepness increase from ≈40 to 60%.

Compiling all of the normalized soil loss data from the three stations together, Eq. [5] was derived for the combined data set ($r^2 = 0.95$):

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

From Fig. 3 we can see that the USLE relationship and Eq. [5] for slope length fit the measured data reasonably well ($r^2 = 0.91$). Interestingly, the average length exponent for the steep Loess Plateau slopes was 0.44, while the average of the 10 exponents from studies in the USA was 0.46 (McCool et al., 1989). The results from our data also compare very well with the results of McCool et al. (1993) for slopes with an average steepness of 28.4% and a maximum steepness of 56%.

Table 3. Slope length exponents, m, and parameters, a, from Eq. [1] for the three sites on the Loess Plateau of China.

Location	Parameter a	Slope length exponents, m	Determination coefficients, R^2
Ansai	**1.58**	**0.40**	**0.988**
Suide	**0.73**	**0.46**	**0.991**
Zizhou	**1.42**	**0.44**	**0.771**

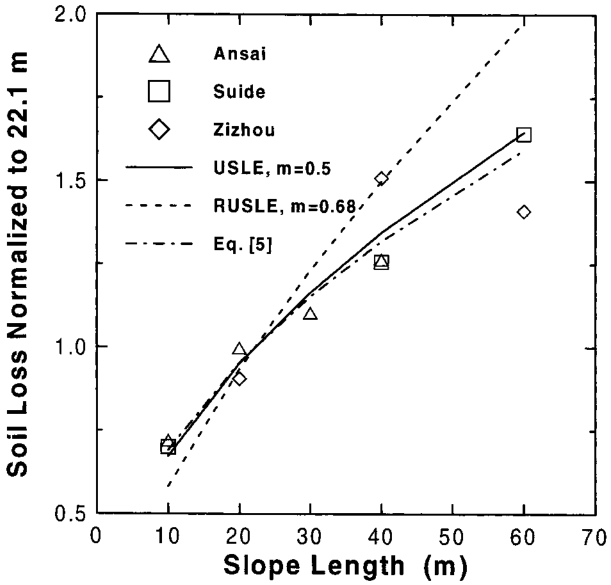

Fig. 3. Soil loss normalized to 22.13-m length from the natural rainfall plot data used in this study and the best-fit curve ($m = 0.44$) for all measured data combined.

In China, and in other parts of the world, slopes up to 60% are not unusual for cropped farmland. Thus, it is important to know and use the best relationship between slope length and soil loss for steep slopes. The RUSLE uses Eq. [3] and [4] to calculate the ratio of rill/interrill erosion (β) and the length exponent (m). Equation [3] was based on the Foster and Meyer's analyses (Foster and Meyer, 1975; Foster et al., 1977). The basic assumption was that if soil loss is primarily from rills, the exponent will approach one, but it will approach zero where erosion is dominantly from interrill processes (Meyer et al., 1975). For slopes where both rill and interrill erosion occurred, the exponent, m, can be

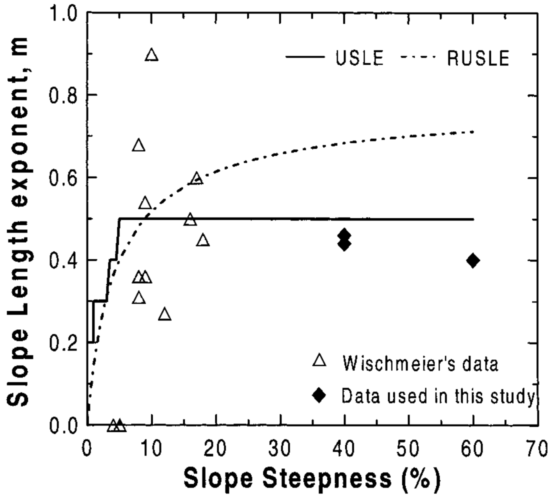

Fig. 4. Slope length exponents from the data of Wischmeier et al. (1958) and from the Loess Plateau of China compared with relationships from the Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE) as a function of slope steepness.

Table 4. Average soil loss at the Ansai station cataloged according to maximum 30-min rainfall intensity. The numbers of storms measured were 23, 9, 3, and 4 for intensities of <15, 15–30, 30–45, >45 mm h^{-1}, respectively.

Slope length	Maximum 30-min rainfall intensity (mm h^{-1})							
	<15		15–30		30–45		>45	
	Runoff	Soil	Runoff	Soil	Runoff	Soil	Runoff	Soil
m	mm	Mg ha^{-1}	mm	Mg ha^{-1}	mm	Mg ha^{-1}	mm	Mg ha^{-1}
10	1.18	0.35	2.12	4.04	14.72	15.49	35.58	93.16
20	0.85	0.37	2.08	5.83	13.30	21.60	34.14	129.17
30	0.66	0.31	1.42	4.69	10.38	20.63	33.46	149.87
40	0.56	0.28	1.50	7.40	12.30	27.30	33.35	164.76

calculated by Eq. [3]. The ratio β (Eq. [4]) was developed by McCool et al. (1989) by dividing Foster's interrill equation into his rill equation (Foster et al., 1977) and then simplifying with several assumptions to obtain Eq. [4]. According to Eq. [3] and [4], the slope length exponent is continually increasing with slope gradient. The USLE relationship, on the other hand, is constant when slopes are greater than 5%.

The fitted exponent of slope length from this study at 57.7% slope was 0.40, and at 40% slope values were 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) show that when slope steepness was 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, respectively. These results, together with our data, indicate that when slope steepness is increased from 20 to 40 and 60%, the slope length exponent does not increase (Fig. 4).

The USLE plot data (McCool et al., 1989) showed that the slope length exponent may vary from 0 to 0.9. Wischmeier et al. (1958) point out that at the majority of locations, runoff did not differ significantly with plot length for the 15 studies. However, three of them showed decreasing runoff with increased slope length. For these three studies, the length-exponent was zero. For the studies in Guthrie, OK, and in Bethany, MO, runoff showed a significant increase with increased slope length. For these two studies, the length exponent was high: 0.68 and 0.9. From these data, we might surmise that the two high values, which were collected at 8 and 10% slopes, were caused by the runoff increasing with slope rather than by increasing slope steepness per se.

The data separated by a maximum 30-min storm intensity from the Ansai station (Table 4) showed that the slope length exponent was a function of the maximum 30-min rainfall intensity (I_{30}) (Table 5). Tables 4 and 5 also provide further evidence that runoff rates may be the controlling factor for the slope length factor. The group of storms with I_{30} >45 mm h^{-1} showed the greatest effect of slope length on erosion and also showed an essentially unchanging runoff depth as a function of slope length (Table 4). Low intensity storms of <15 mm h^{-1} actually showed a negative value of slope length exponent m and exhibited a large decrease in runoff depth as a function of slope length increase.

Table 5. Results of regression analyses on slope loss as a function of slope length at different rainfall intensities according to Eq. [1] for the Ansai station.

Rainfall intensity	a	m	R^2
mm h^{-1}			
<15	0.54	−0.16	0.61
15–30	1.88	0.34	0.59
30–45	6.86	0.36	0.86
>45	36.43	0.41	0.99

CONCLUSIONS

Soil loss data from natural runoff plots at three sites on the Loess Plateau of China were reported in this study. The experimental data for slope lengths from 10 to 60 m on steep slopes showed that the relationship between slope length and soil loss was well approximated by the USLE equation, and not as well by the RUSLE equations. The exponent, m, for the relationship between soil loss and the slope length for the combined data from the three stations in the Loess Plateau was 0.44 ($r^2 = 0.95$). The three data sets from the slopes of 57.7, 40.4, and 40.4%, together with the USLE plot data distributed at Purdue University by Wischmeier et al. (1958), indicate that the slope length exponent does not increase with slope gradient increase from ≈20 to 60%. Rainfall intensity and runoff influenced the slope length exponent greatly. The slope length exponent showed greater sensitivity to differences in rainfall and runoff than to slope length per se.

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Characteristics and Modeling of Runoff Hydrographs for Different Tillage Treatments

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ABSTRACT

Surface runoff rate is a critical variable in determining the rate of soil erosion and sediment transport. Rainfall and runoff data at 1-min intervals from an experiment site at Khon Kaen, Thailand, were used to test a three-parameter runoff model originally developed for bare plots in relation to soil erosion studies. The site has a sandy soil with a slope of 3.6%. Plot length and width were 30 and 5 m, respectively. Four tillage treatments with three replicates each were considered: up- and down-slope cultivation, two contour cultivation treatments with tillage depth of 25 and 50 cm, respectively, and no tillage. Runoff data for 200 individual runoff hydrographs showed that runoff amount and peak runoff rate for the no tillage treatment were significantly less than those for other treatments at the site. On average, runoff amount and peak runoff rate for the no tillage treatment were 37 and 44%, respectively, of those for the up- and down-slope cultivation. Results for contour cultivation practices are between the two extremes, although the water retention was not greater with greater tillage depth as we originally thought would be the case at the site. For these 200 runoff events for the four treatments, the model for runoff hydrographs worked well, with an average coefficient of efficiency of 0.90 and an average standard error of 0.88 mm h^{-1}. The model performance is particularly good for large storm events with high volumetric runoff coefficient. The three model parameters vary considerably from event to event and from treatment to treatment. The initial infiltration amount was found to be inversely related to prior 10-d rainfall at the site; the spatially averaged maximum rate of infiltration can be related to the maximum retention or the Soil Conservation Service (SCS) Curve Number, and the hydrologic lag time is least variable among different storm events and tillage treatments, but tends to decrease with peak runoff rate.

SURFACE RUNOFF RATE plays a critical role in determining the rate of soil loss from agricultural lands. This is especially the case during large events with high stream power (Proffitt and Rose, 1991). In the Universal Soil Loss Equation (Wischmeier and Smith, 1978), the effect of rainfall and runoff is encapsulated in a rainfall and runoff factor, known as the *R*-factor, to represent the long-term climatic influence on soil erosion. As such, the *R*-factor should not be used to determine the soil loss on an event basis. In process-based water erosion models, runoff rate is explicitly required in order to determine the rate of soil loss. For example, in the Water Erosion Prediction Project (WEPP; Laflen et al., 1991; Flanagan and Nearing, 1995), which represents a new generation of process-based erosion models, the peak runoff rate is used to determine the rate of both interrill and rill erosion (Foster et al., 1995). In GUEST (Rose, 1993; Misra and Rose, 1996), a theoretical expression is derived for sediment concentration at the transport limit based on the stream power, which is in turn a function of the runoff rate. It is important therefore to predict runoff rates for given rainfall intensity, soil, and topographical characteristics.

As part of projects funded by the Australian Centre for International Agricultural Research (ACIAR), rainfall intensity and runoff rate were measured at 1-min intervals at a number of sites in Australia and Southeast Asia. One of the research objectives was to develop hydrologic models to predict runoff rates from rainfall rates for a range of soil types, slopes, slope lengths, and management practices in the tropical and subtropical regions of Australia and Southeast Asia. A three-parameter infiltration and runoff routing model was developed and validated using data from bare plots from six sites in Southeast Asia and Australia (Yu et al., 1997b). Apart from satisfactory performance of the model in terms of modeled hydrographs for these sites, two subsequent studies gave further support of the model as a tool for predicting runoff rate. Yu (1998) showed that one of the infiltration parameters is implicitly related to the widely used SCS Curve Number method for runoff estimation (Soil Conservation Ser-

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Abbreviations: ACIAR, Australian Centre for International Agricultural Research; DSM, downhill simplex method; SCS, Soil Conservation Service.