

## Modeling Interrill Sediment Delivery

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### ABSTRACT

Shallow surface runoff is a primary transport agent for interrill sediment delivery. Runoff, rainfall intensity, and slope interactively affect interrill erosion. We hypothesized that the inclusion of a runoff factor in an interrill erosion model can reduce the dependence of the interrill soil erodibility ( $K_i$ ) on soil infiltration characteristics as well as improve model predictability. A complete factorial rainfall simulation experiment with two soils (Cecil sandy loam, a clayey, kaolinitic, thermic Typic Kanhapludult, and Dyke clay, a clayey, mixed, mesic Typic Rhodudult), four rainfall intensities, four slopes, and two replicates was conducted under prewetted conditions to measure runoff and sediment delivery rates. Tap water with electrical conductivity  $<0.2 \text{ dS m}^{-1}$  was used in all the runs. Rainfall intensity  $I$ , unit discharge  $q$ , slope  $S$ , soil type, and their interactions significantly affected sediment delivery per unit area ( $D_i$ ). Sediment delivery had the greatest correlation ( $r = 0.68$ ) with unit discharge; however, neither discharge nor rainfall alone adequately predicted sediment delivery. The equation  $D_i = K_i I^{1/2} S^{2/3}$  was proposed. The linear intensity term ( $I$ ) represents detachment of soil by raindrop impact and enhancement of transport capacity of sheet flow, while the product of  $q^{1/2} S^{2/3}$  describes sediment transport by sheet flow. Validation with independent data showed that the model predicted soil erodibilities well. The mean  $r^2$  for four validation soils was 0.93 when the proposed model was fitted to validation data to predict interrill erodibility ( $K_i$ ). The better estimation of  $K_i$  indicates that interrill erosion processes were adequately described by the model.

**T**O BETTER DESCRIBE EROSION MECHANICS, upland erosion has been divided into interrill and rill erosion processes (Meyer et al., 1975). For interrill erosion, detachment of soil materials by raindrop impact and transport of sediment by rainfall-disturbed sheet flow are the predominant processes (Kinnell, 1991; Moss and Green, 1983), while detachment by sheet flow and transport by raindrop splash are negligible (Young and Wiersma, 1973).

Two approaches have been taken to develop interrill erosion models. One is to develop physically based models. In this approach, detachment by raindrop impact and transport by thin overland flow are modeled separately, and sediment delivery rate is either set to the lesser of the two (Gilley et al., 1985) or calculated by solving a sediment continuity equation (Hairsine and Rose, 1992). This approach tends to decrease model errors by representing the erosion processes more precisely, but it also leads to greater parameter estimation errors because physical models require more parameters, which are difficult to determine experimentally. The other approach, which has been widely used, is to statistically develop lumped parameter models. The basic model structure in this case is the multiplication-of-factors type. Models developed using this approach are generally reliable, simple, and easy to calibrate; how-

ever, these models usually don't delineate between transport and detachment processes explicitly. This may lead to greater model errors compared with physically based models. Therefore, a compromise between the two error sources is often necessary in order to formulate the best prediction models.

Rainfall intensity, slope, runoff rate, flow depth, and soil type, along with their interactions, are major factors affecting interrill sediment delivery. Raindrop impacts not only cause soil detachment, but also enhance sediment transport by thin overland flow. Guy et al. (1987) reported that 85% of sediment delivered from interrill areas could be attributed to enhancement of transport capacity by raindrop impact, and only 15% was attributed to undisturbed runoff. Recently, the role of runoff on sediment delivery was examined (Hairsine and Rose, 1992; Kinnell, 1991; Huang, 1995; Flanagan and Nearing, 1995), and improved predictions with models that include a separate runoff parameter have been reported (Watson and Lafren, 1986; Zhang, 1993; Truman and Bradford, 1995).

The interactive effects on sediment delivery among some of these factors have been reported. Interaction between soil type and slope was discussed by Kinnell and Cummings (1993) and Bradford and Foster (1996). The interactive effects of runoff and slope on interrill sediment delivery were presented in depth by Huang (1995). But due to the nature of these intricate interactions, different models have emphasized different factors or aspects of the interrill processes.

Several slope factors,  $S_i$ , have been proposed to describe the slope effects on interrill sediment delivery:

$$S_i = S^b \quad (\text{Neal, 1938}) \quad [1]$$

$$S_i = 3.0(\sin\theta)^{0.8} + 0.56 \quad (\text{McCool et al., 1987}) \quad [2]$$

$$S_i = 1.05 - 0.85\exp(-4\sin\theta) \quad (\text{Elliot et al., 1989}) \quad [3]$$

where  $S$  is the slope steepness ( $\text{m m}^{-1}$ ),  $\theta$  is the slope angle (in degrees), and  $b$  is a constant. Both linear ( $b = 1$ ) and convex curvilinear ( $b < 1$ ) slope factors of Eq. [1] have been observed or used in interrill models (Kinnell and Cummings, 1993; Huang and Bradford, 1993; Watson and Lafren, 1986). McIsaac et al. (1987) reported that either a linear function of slope percentage or  $(\sin\theta)^{0.8}$  fit their data equally well for plots  $<4 \text{ m}$  in length. As for the intercept term, a fundamental difference exists among the proposed slope factors. A non-zero intercept implies non-zero soil loss at zero slope; however, both positive (Lattanzi et al., 1974) and negative estimates (Watson and Lafren, 1986) have been reported.

Using rainfall simulator data, Meyer (1981) found that the effects of rainfall intensity on sediment delivery for a given slope steepness could be described by

$$D_i = K_i I^2 \quad [4]$$

where  $D_i$  is the interrill sediment delivery per unit area per unit time;  $K_i$  is a relative erodibility parameter; and  $I$  is the rainfall intensity. To account for runoff as well

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as infiltration effects on sediment transport, this model was modified and used in the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) as

$$D_i = K_i I R S_f \quad [5]$$

where  $R$  is the rainfall excess rate and  $S_f$  is the slope factor of Eq. [3]. This equation is basically the same as those proposed by Kinnell and Cummings (1993) except that different slope factors were used. Using regression analyses, Huang (1995) found that sediment delivery related well to either runoff rate or slope steepness in a quadratic model. The interactive effects between slope and runoff on sediment delivery could be accommodated by regression coefficients in each model. Most lumped parameter models developed using simulated rainfall data tend to simulate the transport process, because sediment delivery is often limited by transport capacity under most experimental conditions (Guy et al., 1987; Gilley et al., 1985; Bradford and Foster, 1996). Guy et al. (1987) found that sediment transport capacity was proportional to the square of rainfall intensity, which was similar to the relationships for sediment delivery found by Meyer (1981) and Watson and Laflen (1986) from their field experiments.

Models developed solely on rainfall characteristics, such as Eq. [4], may produce a satisfactory prediction for steady-state conditions because rainfall intensity is closely related to runoff rate at this state. However, the model may not adequately predict sediment delivery for non-steady-state conditions because the sediment transport processes, i.e., transport by rainfall-disturbed sheet flow, are not explicitly simulated (Kinnell, 1993; Zhang, 1993) and the effects of infiltration rate on sediment delivery are not accounted for directly in the model. Therefore, this type of model incorporates the infiltration parameter into the soil erodibility factor (Nearing et al., 1990). On the other hand, models without a rainfall parameter, which attempt to simulate interrill sediment delivery as a primary transport process by sheet flow alone (Huang, 1995), can only be used as a first approximation because these models fail to describe the enhancement of sediment transport by rain-drop impact explicitly.

Model prediction errors result from errors in representation of physical processes (model errors) and errors in parameterization (input parameter errors). Increased model complexity tends to decrease model errors, but it also tends to increase parameter estimation errors. Therefore, a complicated physically based model will not necessarily provide the best predictions of erosion. The objectives of this study were to: (i) evaluate the effects of discharge and its interactions with rainfall and slope on interrill sediment delivery, and (ii) develop a simple lumped parameter model that provides better predictions of interrill sediment delivery and soil erodibility.

## MATERIALS AND METHODS

Two Ultisols with contrasting soil textures were used in this study. Cecil sandy loam, which was formed in granitic parent materials on old Piedmont landscapes, contains 69% sand,

20% silt, 11% clay, and 8.7 g kg<sup>-1</sup> organic matter. The aggregates of this soil are unstable under wet sieving conditions (Chiang et al., 1993). The Dyke clay, which has relatively more stable aggregates, is composed of 27% sand, 33% silt, 40% clay, and 14.5 g kg<sup>-1</sup> organic matter. The two soils are predominantly kaolinitic, with Dyke clay having a higher content of oxidic minerals. The soil samples were collected from the Ap horizon, and were air dried and sieved through a 6-mm sieve.

A rainfall simulator with oscillating nozzles (Veejet 80150, Spraying Systems Co., Wheaton, IL) as described by Meyer and Harmon (1979) was used. The nozzles deliver a median drop size of 2.3 mm and a kinetic energy of 28 J m<sup>-2</sup> mm<sup>-1</sup> of rain. Four small runoff pans (0.4 m long by 0.2 m wide) similar to those of Miller and Baharuddin (1987) were placed on a rotating table, which ensured a uniform rainfall delivery to each pan. The slope of each pan could be easily adjusted. Splash guards were not used and the splash loss of soil and water was not measured. Tap water with electrical conductivity <0.2 dS m<sup>-1</sup> was used throughout the experiment.

A 2.5-cm layer of sieved soil was packed loosely into pans over a 7.5-cm layer of medium sand to simulate the freshly tilled and freely drained conditions of a seedbed. The soil surfaces were smoothed to minimize microtopographic effects. The soils were wetted from the bottom drainage holes by capillarity overnight and were allowed to drain freely for 0.5 h prior to the 60-min rainfall simulation. Sediment and runoff were collected at 5-min intervals, and were determined gravimetrically. In general, steady-state soil loss and runoff rates were reached within 25 min into the rains for both soils. Only the steady-state values were used in the model formulation.

A complete factorial design (four levels of slope, four levels of rainfall intensity, two soil types, and two replicates) was used, resulting in a total of 64 runoff pans. The slope gradients were 8.7, 17.6, 26.8, and 36.4%, and rainfall intensities were 42, 62, 78, and 90 mm h<sup>-1</sup>. Rainfall intensity was checked before and after each run, and was found to vary only slightly. New soils were used for each run to eliminate the effects of erosion history and surface modification on sediment delivery. Replicate means were used in data analyses.

Correlation analyses (SAS Institute, 1990) between slope, unit discharge, rain intensity, and sediment delivery were conducted. A nonlinear least square procedure of the Gauss-Newton method (SAS Institute, 1990) was used to estimate model parameters. A three-way analysis of variance (SAS Institute, 1990) was conducted to test the main and interactive effects of selected factors on interrill sediment delivery under steady-state conditions.

## RESULTS AND DISCUSSION

### Factors Affecting Sediment Delivery

The factorial analysis of variance showed that rainfall intensity, slope, and soil type had significant effects on steady-state sediment delivery, and their interactions were significant at  $P = 0.01$  except for the three-way interaction of intensity, slope, and soil type (Table 1).

**Table 1. Factorial analysis of variance for selected parameters with sediment delivery rate as a dependent variable using combined data from two soils.**

Source	df	Mean square	F value	P > F
Intensity (I)	3	577.4	148.9	0.0001
Slope (S)	3	407.1	104.9	0.0001
Soil type (ST)	1	483.6	124.7	0.0001
I × S	9	37.5	9.7	0.0001
I × ST	3	84.2	21.7	0.0001
S × ST	3	19.5	5.0	0.0057
I × S × ST	9	4.2	1.1	0.397

**Table 2.** Pearson correlation coefficients among the selected parameters using combined data from two soils.

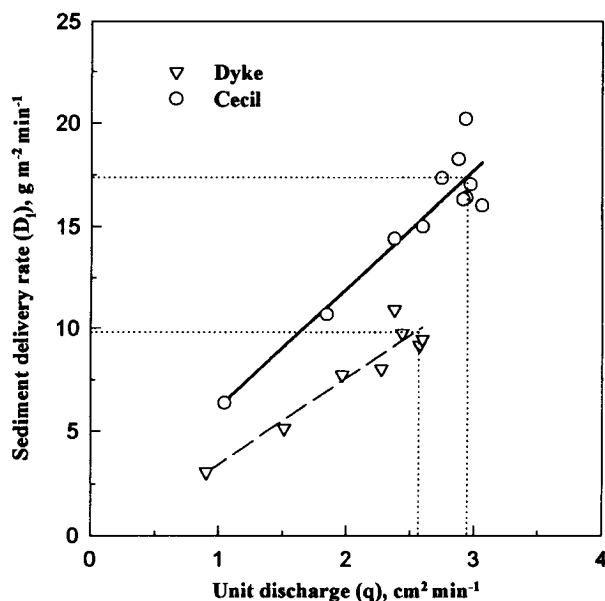
	Intensity ( <i>I</i> )	Slope ( <i>S</i> )	Unit discharge ( <i>q</i> )	Sediment delivery† ( <i>D<sub>i</sub></i> )
<i>I</i>	1.0 (0)‡	0 (1.0)	0.9376 (0.0001)	0.6229 (0.0001)
<i>S</i>		1.0 (0)	-0.0050 (0.98)	0.5252 (0.0001)
<i>q</i>			1.0 (0)	0.6787 (0.0001)

† Per unit area per unit time.

‡ Numbers in parentheses are significance levels.

Since the steady-state runoff rate was correlated with rainfall intensity, similar results were obtained when runoff instead of rainfall intensity was used (data not shown). Interactions between runoff and slope and between runoff and soil were significant at  $P = 0.01$ . Some of these interactions have been reported, as mentioned above.

The Pearson correlation coefficients were calculated using steady-state values and are presented in Table 2. Sediment delivery had the greatest correlation coefficient with discharge, indicating the importance of discharge in predicting sediment delivery. Previous studies have shown that model predictability is improved when a runoff factor is included in interrill models (Watson and Laflen, 1986; Truman and Bradford, 1995). Considering the non-steady-state conditions, the need to include runoff in interrill models is even more pronounced. This is clearly shown in Fig. 1 where sediment delivery is plotted against unit discharge (runoff volume per unit time per unit plot width) for a selected treatment. Sediment delivery was negligible prior to runoff initiation, and then increased gradually as runoff increased with time. This trend can be better simulated by the models that include a runoff parameter. In addition,



**Fig. 1.** Effects of varying discharge on sediment delivery (replicate means) during a selected rain at 62 mm h<sup>-1</sup> rainfall intensity and 27% slope. Dotted lines indicate the steady-state parameter values.

tion, the inclusion of a runoff term directly accounts for the effects of infiltration rate on sediment delivery.

Rainfall intensity correlated well with sediment delivery (Table 2). The good correlation was expected because rainfall was closely related to runoff under steady-state conditions. These results may indicate that rainfall alone was adequate for predicting sediment delivery under steady-state conditions. However, considering non-steady-state conditions and parameter interactions, neither rainfall nor runoff alone was able to provide accurate predictions. Raindrop disturbance or rainfall-runoff interactions have been reported to be responsible for 85% of the sediment transport capacity of sheet flow (Guy et al., 1987). This suggests that both rainfall and runoff parameters should be used in prediction models in order to better describe the enhancement of transport capacity. Foster and Meyer (1975) and Kinnell (1991) used a linear intensity term, which was related to the frequency of raindrop impacts, to represent raindrop detachment and the enhancement of transport capacity. An alternative to a linear intensity term is to use the kinetic energy of rainfall, as proposed by Sharma et al. (1995), because energy flux is not only a good descriptor of raindrop impacts, but also has the potential to minimize extrapolation errors due to differences in drop-size distribution, such as when a model developed under simulated rainfall is to be used under natural rainfall conditions. In addition, the effects of canopy height on raindrop impact energy and sediment transport can be better simulated with the kinetic energy term. However, linear rainfall intensity is used here because it was linearly related to kinetic energy for the constant drop-size distribution used in our experiment.

### Effect of Slope and Intensity on Sediment Delivery

Slope factors  $S_i$  in Eq. [1] to [3] are normally used to form lumped parameter models. In this study, exponent  $b$  of Eq. [1] was estimated by fitting the model  $D_i = aS_i^b$  to measured data at each intensity level. The mean values of the fitted exponents were 0.63 for the Cecil soil and 0.68 for the Dyke soil. Since the two averaged values are close to 0.67 for both soils and the fitted  $b$  values are not different from 0.67 at  $P = 0.05$  at each intensity level, the slope factor  $S_i \propto S_i^{2/3}$  was used as a first approximation for slope effects in this study. However, the exponent can be further refined to account for additional soil- or intensity-slope interactions if the need arises and more specific information becomes available.

Although Eq. [2] and [3] also represent our data well, a linear regression with zero intercept between the soil loss ratio and the slope factors (both normalized at 9% slope) revealed that the slope factor  $S_i^{2/3}$  described our data better. The coefficients of determination using the combined data set from the two soils were 62% for Eq. [2] and [3] and 67% for  $S_i^{2/3}$ , and regression slopes were 1.33, 1.30, and 1.03, respectively. The near-unity regression slope for  $S_i^{2/3}$  indicated a lesser bias for this slope factor for the soils used in this study. These results

indicated that a slope factor without an intercept could be used at steep slopes. The fitted slope factors (Fig. 2) along with Eq. [2] and [3] are convex curvilinear in shape. These slope factors show that the degree of slope effect on sediment delivery decreases as slope steepness increases. Meyer et al. (1975) attributed this tapering effect to the shift of erosion mechanisms from transport limiting at low slopes to detachment limiting at high slopes.

If interrill sediment delivery is plotted against the fitted slope factor  $S_f \propto S^{2/3}$  instead of slope  $S$  as is shown in Fig. 2, linear plots result, but the inclination of these plots would vary with rainfall intensity. The nonparallel plots indicate that there exists an interaction between rainfall intensity and slope steepness. The interaction shown in these data can be adequately described by the multiplication-of-factors type model. For the transformed linear plots of Fig. 2, interrill sediment delivery can be expressed as

$$D_i \propto \frac{dD_i}{dS_f} S_f \quad [6]$$

where  $dD_i/dS_f$  is the slope of the plots, and  $S_f$  is a slope factor equal to  $S^{2/3}$ . Equation [6] can be written as

$$D_i \propto \frac{dD_i}{dI} \frac{dI}{dS_f} S_f \quad [7]$$

Based on Eq. [4],  $dD_i/dI$  is proportional to  $I$ , and  $dI = dR$  under steady-state infiltration conditions (where  $R$  is the runoff rate), so Eq. [7] can be further written as

$$D_i \propto I S_f \frac{dR}{dS_f} \quad [8]$$

The  $dR/dS_f$  term, which represents the effects of runoff as well as the runoff-slope interaction, may be empirically characterized by a runoff factor.

### Model Formulation and Development

The effect of steady-state unit discharge on sediment delivery for all rains is shown in Fig. 3. The Dyke clay

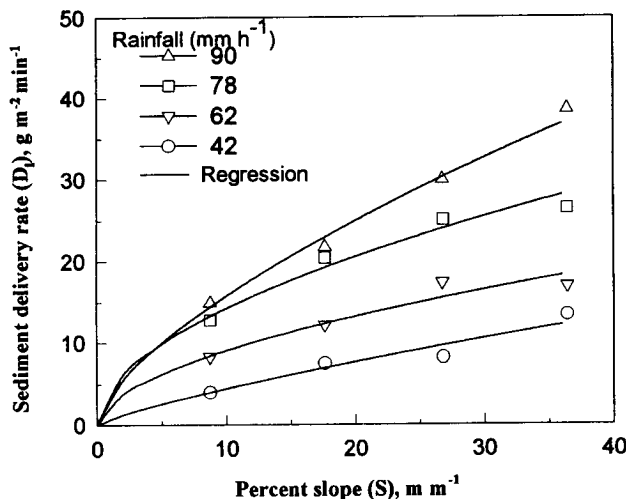


Fig. 2. Effects of slope steepness and rainfall intensity on interrill sediment delivery for the Cecil soil.

showed greater variability than did the Cecil sandy loam. However, the average steady-state discharge was positively related to equilibrium sediment delivery for both soils (also see Table 2). Since the plots for different slope gradients varied in slope, the interaction between slope and discharge was evident. A similar trend and interaction were shown when rainfall intensity instead of discharge was plotted with sediment delivery, owing to the close correlation between runoff and rainfall under steady-state conditions. Based on the interrill erosion mechanics and further considering the interactions between parameters as discussed above, the following equation was proposed to fit our experimental data:

$$D_i = K_i I q^c S^{2/3} \quad [9]$$

where  $q$  is the unit discharge, and  $c$  is a regression coefficient. The optimized  $c$  values using a nonlinear best-fit procedure were 0.29 for the Dyke soil and 0.52 for the Cecil soil, and the  $r^2$  (calculated as the ratio of the sum of the squares of the regression to the sum of the squares of the uncorrected total) values were 0.939 and 0.994, respectively. The smaller  $c$  value for the Dyke clay soil than for the Cecil sandy loam soil suggests that Dyke sediments are less transportable. This could indicate that for well-aggregated soils, large aggregates might have limited sediment delivery. Equation [9] was

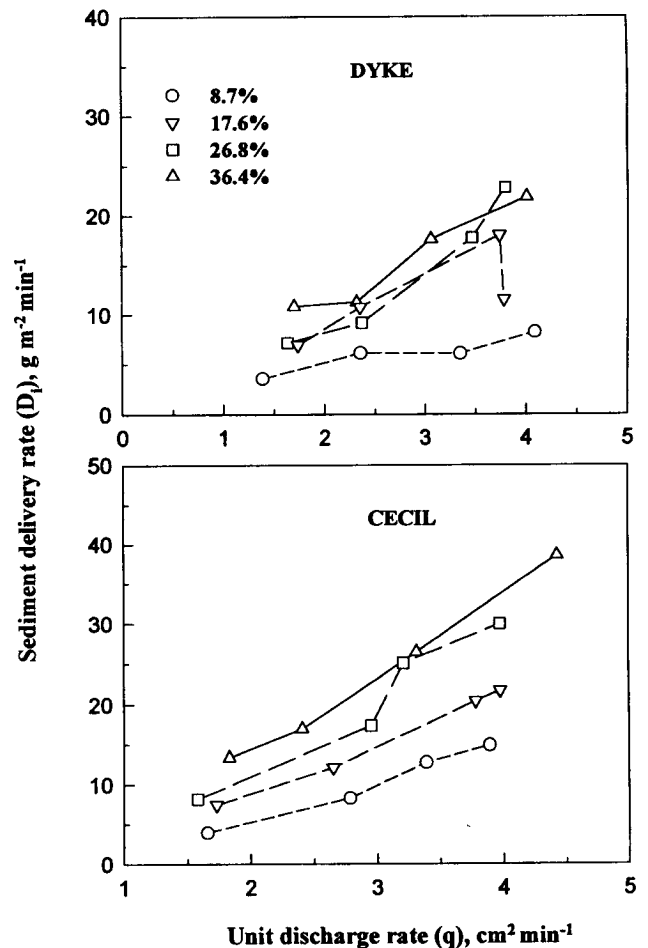


Fig. 3. Effects of unit discharge and slope steepness on interrill sediment delivery under steady-state conditions.

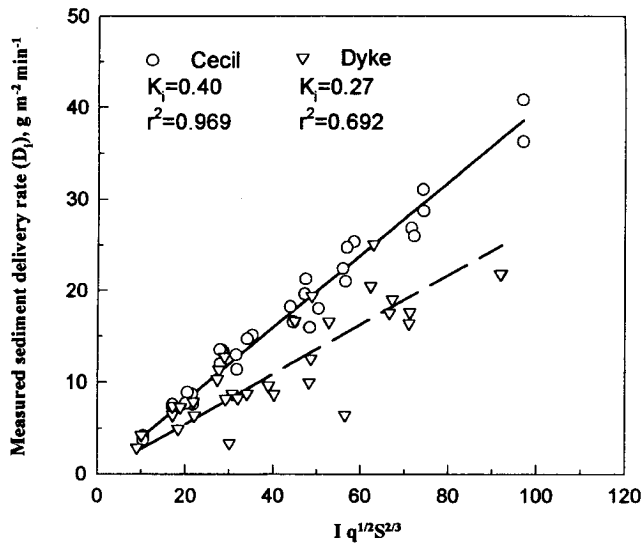


Fig. 4. Linear regression with zero intercept between sediment delivery rate and the scaling factor of Eq. [10].

also fitted to the combined data from the two soils, with optimized  $c$  close to 0.5 and  $r^2 = 0.942$ . The fitted  $c$  value for each soil was not different from 0.5 at  $P = 0.05$ . Owing to the large variability associated with the Dyke soil, a value of 0.5 fit the data set adequately. Further considering the simplicity and generality, a value of 0.5 was recommended:

$$D_i = K_i I q^{1/2} S^{2/3} \quad [10]$$

However, exponent  $c$  can be altered to account for additional or specific soil- and slope-runoff interactions.

The linear intensity term in Eq. [10], which describes the frequency of raindrop strikes, was considered to represent raindrop detachment and the enhancement of transport capacity due to raindrop impact. Since the bed shear stress of rainfall-disturbed thin overland flow is proportional to  $q^{1/3} S^{2/3}$  (Julien and Simons, 1985), the product of  $q^{1/2} S^{2/3}$  in Eq. [10] might be considered an approximation of the bed shear stress and therefore be used to describe sediment transport by thin overland flow.

To examine the model performance, Eq. [10] is graphically illustrated in Fig. 4 for both soils. The linearized relationship for such a wide range of rainfall intensities, slope steepnesses, and discharge suggests that Eq. [10] adequately simulates interrill erosion. As mentioned above, Dyke clay showed more variability than did Cecil sandy loam. The slope of the linear plot was proposed to reflect the interrill soil erodibility relative to the proposed model. As shown in Fig. 4, the fitted slope  $K_i$  was 0.40 for Cecil and 0.27 for Dyke, with the standard error being 0.006 for Cecil  $K_i$  and 0.013 for Dyke  $K_i$ . Interrill erodibility for the easily eroded Cecil soil was expected to be greater than that of the stable Dyke soil.

As stated above, steady-state discharge was used to develop Eq. [10]. The hypothesis was that the effects of discharge on sediment delivery can be characterized with steady discharge values. Therefore, Eq. [10] can be used to approximate sediment delivery for unsteady conditions. To examine this hypothesis, Eq. [10] was

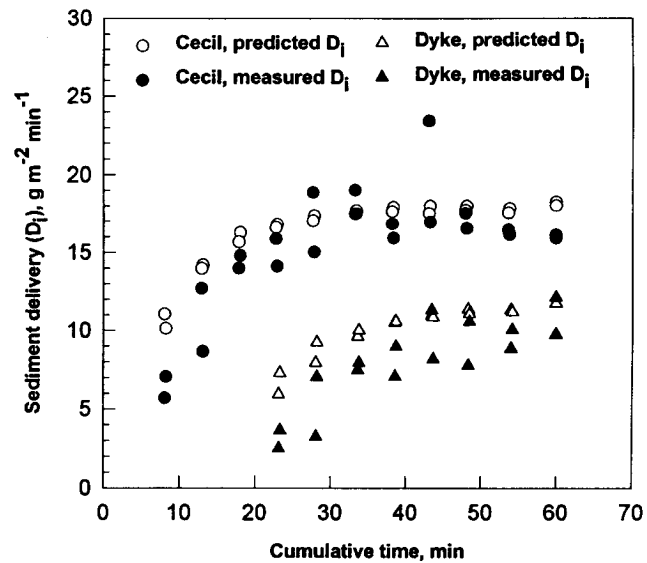


Fig. 5. Measured and predicted sediment delivery during a selected rain at  $62 \text{ mm h}^{-1}$  rainfall intensity and 27% slope for the two soils.

used to predict sediment delivery rates for the rainfall event of Fig. 1, and the results were plotted with time in Fig. 5. In general, the model predicted sediment delivery reasonably well. However, the sediment delivery rates in the early runoff stages were slightly overpredicted by the model.

### Model Validation

Experimental data of Meyer and Harmon (1989) were used for validation. That experiment was conducted using four soils at four slopes (5, 10, 20, and 30%), four slope lengths (15, 30, 45, and 60 cm), and four rainfall intensities (14, 27, 76, and  $114 \text{ mm h}^{-1}$ ), totaling 96 treatments for each soil. Detailed information about experimental materials and procedures may be found in Meyer and Harmon (1989). Steady-state runoff and soil loss rates during the last 10 min of each run were used for this validation. For convenience, Eq. [10] can be rewritten as

$$q_s = K_i I q^{1/2} S^{2/3} L \quad [11]$$

where  $q_s$  is sediment discharge per unit plot width, and  $L$  is the plot length. The regression coefficient in Eq. [11] for a linear model with zero intercept is an estimate of  $K_i$ , and the  $r^2$  value reflects how well the model predicts interrill erosion for the data (Fig. 6).

The hypothesis of this test was that if Eq. [11] adequately represented interrill erosion processes, then the "intrinsic" interrill erodibility, being independent of rainfall intensity, discharge, infiltration, and slope steepness, could be accurately estimated. The reverse was also possible, i.e., if the intrinsic interrill erodibility for a given soil under a wide range of experimental conditions such as different rainfall intensities and slope steepnesses could be accurately estimated, then Eq. [11] was proven to represent interrill erosion processes well. As is shown in Fig. 6, all the data points from each soil followed a linear pattern, with the lowest  $r^2$  (0.91) for

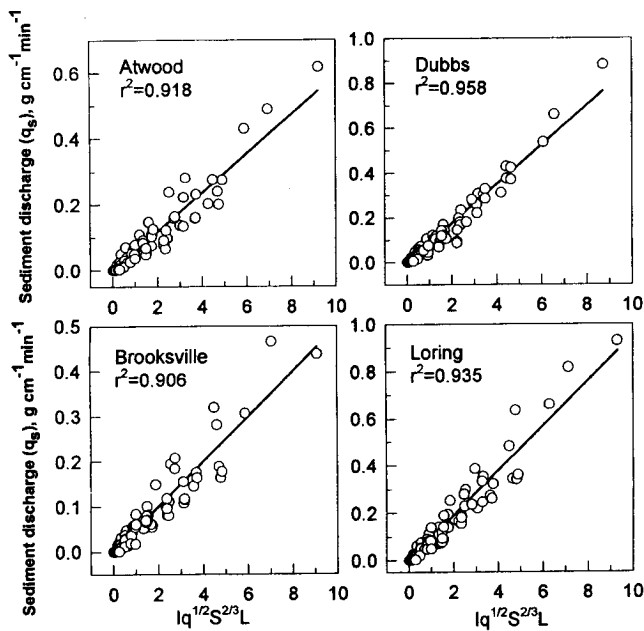


Fig. 6. Measured unit sediment discharge vs. the scaling factor of Eq. [11] for four soils of Meyer and Harmon (1989). Linear regression lines were forced through the origin.

the Brooksville soil, which contained 38% clay. We observed in our experiment that the clayey Dyke soil exhibited a greater variability in measured sediment delivery rates than did the Cecil soil. Overall, Eq. [11] represented interrill erosion processes reasonably well for the data of Meyer and Harmon (1989).

Similarly, a linear regression with zero intercept was carried out for the other three selected models, and these models and  $r^2$  values are given in Table 3. The 90% confidence limits for the squared coefficients of correlation are also given in parentheses. Model 1 as suggested by Kinnell (1993) and Model 2 as used in the WEPP model (Flanagan and Nearing, 1995) are essentially the same except that a linear slope factor was used in Model 1 while Eq. [3] was used in Model 2. Model 3 is similar to Model 1 except that rainfall excess rate rather than rainfall intensity was used. Based on the 90% confidence limits, not many coefficients of determination were significantly different among these models for any individual soil. However, the averaged  $r^2$  for the four soils showed that Eq. [11] was slightly superior to the other models, indicating its potential in predicting interrill sediment delivery. The overall improvement of Model 1 over Model 3 in terms of mean

$r^2$  shows that rainfall intensity should be included in interrill models, and runoff characteristics alone cannot adequately simulate interrill erosion processes even though runoff is the primary transport agent in interrill areas. This is because rainfall intensity has double effects, i.e., detachment of soil and enhancement of transport capacity of thin overland flow. A better performance of Model 2 over Model 1 indicates that the convex curvilinear slope factor of Eq. [3] is better than the linear slope factor in describing slope effects for this data set. In general, the predictability of all these models varied with soil properties (soil type), indicating that slope- or runoff-soil interactions were not fully accounted for in these models. These interactions could be further accommodated by altering the exponents of slope or unit discharge in Eq. [11] based on the specific soil properties.

CONCLUSIONS

Discharge, rainfall intensity, slope steepness, and their interactions affected sediment delivery rate per unit area. Among these parameters, discharge had the greatest correlation coefficient with sediment delivery. A convex curvilinear slope factor described slope effects well for high slopes. Results showed that neither runoff nor rainfall alone can adequately simulate interrill sediment delivery (Fig. 1 and Table 3).

Considering the effects of these factors as well as their interactions, a multiplication-of-factors type structure was used to formulate the model. The final model took the form of  $D_i = K_i I q^{1/2} S^{2/3}$ . The linear intensity term, which describes the frequency of raindrop impacts, represented detachment of soil by raindrop impacts and enhancement of transport capacity of thin overland flow. Rainfall kinetic energy might be used to replace the  $I$  term because the use of kinetic energy minimizes the potential errors in extrapolating experimental results to rains with different characteristics. The product of  $q^{1/2} S^{2/3}$  was considered to represent sediment transport by thin overland flow.

The model was validated with the experimental data of Meyer and Harmon (1989). Results showed that the model predicted interrill erodibility reasonably well for a given soil under a wide range of intensity, unit discharge, and slope conditions. This implies that the model adequately describes the interrill erosion processes. However, the applicability of this model to longer slope lengths and low-gradient slopes needs further testing.

Table 3. Coefficients of determination for four soils from a linear regression model with a zero intercept for selected interrill models.

Models†	Atwood	Brooksville	Dubbs	Loring	Mean $r^2$
1.	0.955	0.843	0.932	0.921	0.9128
$q_s = K_i I q S$	(0.937–0.968)‡	(0.789–0.887)	(0.905–0.951)	(0.892–0.944)	
2.	0.918	0.952	0.870	0.950	0.9225
$q_s = K_i I q S_i$	(0.907–0.952)	(0.947–0.973)	(0.834–0.913)	(0.943–0.971)	
3.	0.950	0.847	0.893	0.916	0.9015
$q_s = K_i R q S$	(0.931–0.965)	(0.795–0.890)	(0.854–0.923)	(0.885–0.940)	
4.	0.918	0.906	0.958	0.935	0.9293
Eq. [11]	(0.891–0.943)	(0.871–0.933)	(0.949–0.974)	(0.913–0.955)	

†  $q_s$  = unit sediment discharge,  $K_i$  = interrill erodibility,  $I$  = intensity,  $q$  = unit water discharge,  $S$  = slope,  $S_i$  = Eq. [3],  $R$  = rainfall excess rate.  
 ‡ Numbers in parentheses are 90% confidence limits for the squared coefficients of correlation.

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