SOIL DETACHMENT BY SHALLOW FLOW

G.–H. Zhang, B.–Y. Liu, M. A. Nearing, C.–H. Huang, K.–L. Zhang

ABSTRACT. *A precise understanding of soil detachment rates is necessary to establish a basic understanding of soil erosion and to develop a fundamentally based erosion model. This study was conducted to investigate the relationships between soil detachment rates and flow discharge, slope gradient, flow depth, mean flow velocity, shear stress, unit stream power, and stream power. A 5–m long × 0.4–m wide hydraulic flume with constant artificial roughness upstream of and surrounding the sample area was used. Flow discharge ranged from 0.25 to 2.0 L s^{-1} and slope gradient varied from 3.5% to 46.6%. The experimental results indicated that detachment rates increased with both greater flow discharge and slope gradient. Detachment rate was affected more by discharge than by slope gradient. The influence of slope gradient on detachment rate was greater at high slopes. The effect of flow depth on soil detachment rate was also dependent on slope gradient. Stepwise variable selection analyses indicated that detachment rate could be predicted by a power function of discharge and slope gradient (R^2 = 0.97). Substituting flow depth for discharge gave a poorer prediction (R^2 = 0.92). Mean flow velocity was more closely correlated to detachment than was any other hydraulic parameter (r^2 = 0.90). Flow detachment rates were better correlated to a power function of stream power (r^2 = 0.89) than to functions of either shear stress or unit stream power. The results of this study suggest that soil detachment by shallow flow is more closely related to flow energy than to shear stress.*

Keywords. *Soil erosion, Hydraulics, Soil conservation, Erosion mechanics.*

Soil detachment is defined as the dislodgment of soil particles from the soil mass at a particular location on the soil surface. The dislodgment is caused by the forces applied on the soil particles by erosive agents, which occurs primarily by the processes of splash from raindrop impact and scour by overland flow (Owoputi and Stolte, 1995). Detachment by splash under controlled laboratory conditions has been studied in detail, but detachment of cohesive soils by shallow clear–water flow under controlled laboratory conditions has received less attention (Nearing et al., 1991).

Lyle and Smerdon (1965) first used a flume to simulate the relationship between soil erosion and shear stress. The test results indicated a unique relationship for a given soil, but the conclusion was obtained from flumes of constant slope. Nearing et al. (1991) studied the detachment process on small samples (12.7 cm diameter) in a hydraulic flume with varying bed slopes. The experimental results indicated a logarithmic relationship between detachment rate and flow depth, bed slope, and mean weight diameter of the aggregates. Detachment rate for a given soil material was not a unique function of either shear stress or stream power of the flow. The experimental results also showed a greater sensitivity to slope than to depth of flow. Nearing's experiments were conducted under well–controlled conditions, but the range of test slopes was small, ranging only from 0.5% to 2.0%.

Sediment in flow has an important and dramatic effect on the detachment rate of soil by flow. Merten et al. (2001) studied explicitly the impact of sediment load on detachment rates in rills, and showed that both bedload and suspended load significantly reduce detachment rates in rills. Two mechanisms are proposed to explain this phenomenon. One is that sediment in the flow that moves along the bed acts in part as a protection to turbulent forces that cause detachment. The second mechanism is related to the reduction in turbulence that results when sediment is added to the flow. Turbulence is a necessary and critical component of detachment of soil by flowing water (Nearing and Parker, 1994). This phenomenon is commonly referred to as a sediment feedback relationship (Nearing et al., 1990).

Cochrane and Flanagan (1997) studied the impact of water flow rate and incoming sediment concentration on detachment rate of sand in a simulated rill using a hydraulic flume with 5% slope. The results showed that all the experiments were qualitatively compatible with the sediment feedback term (i.e., the term representing the effect of sediment load on detachment rate) in the detachment equation in WEPP (Nearing et al., 1989; Flanagan and Nearing, 1995) and other process–based erosion models. The effect of slope gradient and flow discharge or flow depth on soil detachment rate was not studied.

Nearing et al. (1997; 1999) conducted a series of field experiments to evaluate rill erosion rates of several soils as a function of hydraulic shear stress, stream power, and hydraulic friction. The results illustrated that rill erosion rates were better correlated to a power function of either shear stress or stream power. It is important to understand the difference that scale makes in erosion experiments. Experiments on the small 12.7 cm diameter samples (Nearing et al., 1991; Nearing and Parker, 1994) give much higher erosion

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rates than did rill experiments such as those conducted by Nearing et al. (1999) and Laflen et al. (1991) because of the sediment feedback phenomenon discussed by Cochrane and Flanagan (1997) and Merten et al. (2001). The rill erosion experiments conducted by Nearing et al. (1997) show erosion rates varying from 0.7 to 7 g s^{-1} m^{-2} for a shear stress of 2 Pa, whereas the detachment experiments using small samples showed rates of 14 to 300 g s^{-1} m^{-2} for one experiment (Nearing et al., 1991) and 90 to 350 g s^{-1} m^{-2} (Nearing and Parker, 1994) for a second study. The experiments on small samples are pure detachment experiments; the effect of sediment load on detachment rate that can occur in the short distance over the soil sample is insignificant. Transport plays a significant role in the rill experiments. In fact, in experiments conducted by Nearing et al. (1997), the authors determined that the rills were quite near transport capacity at the end of the rill bed, and thus very little detachment occurred over a large portion of the lower part of the bed.

Most process–based erosion models assume linear relationships for soil detachment in rills as a function of some hydraulic variable, often either shear stress (Nearing et al., 1989), unit stream power (Morgan et al., 1998; De Roo et al., 1996), or stream power (Rose et al., 1983; Hairsine and Rose, 1992). The parameter best suited to describe soil detachment for erosion prediction is still unclear. The problem is complicated by difficulties in separating detachment and transport processes, and the interaction of the two processes in many rill experiments. Therefore, more controlled laboratory research is needed to better understand the relationship between soil detachment rate and hydraulic variables.

The hydraulic characteristics of flow and the properties of soil erosion on steep slopes are different than on low slopes (Govers, 1992; Nearing et al., 1997; Nearing et al., 1999). Understanding soil erosion from steep slopes is important for erosion model calibration and evaluation, and for soil conservation. In most cases, little or no applicable data exist. In particular, little is known about erosion processes on slopes steeper than 20%, since this has often been the upper limit for research in developed countries (Liu et al., 1994; Liu et al., 2000; Nearing, 1997; Grosh and Jarrett, 1994).

Soil detachment is an important component of the soil erosion process. Accurate prediction of soil detachment rate is critical to the development of a fundamentally based erosion model. The objectives of this study were to evaluate the influence of flow discharge, slope gradients, and flow depth on soil detachment rate by shallow flow and to investigate the relationship between soil detachment rate and mean flow velocity, shear stress, unit stream power, and stream power.

Materials And Methods

Soil

The soil used in this study was a Haplustalf taken from the upper reaches of the Miyun basin of Beijing. The soil contained 236.4 g kg^{-1} clay, 569.3 g kg^{-1} silt, and 167.7 g kg^{-1} sand. The organic matter content was 0.4%. The soil was sieved, and particles less than 5 mm were used as test material.

Hydraulic Parameters Determination

Detachment rates were measured in a 5–m long × 0.4–m wide flume. The bed slope of the flume could be maintained to within 0.05%, and flow depth could be controlled by valves to within 0.3 mm over the entire flume surface. The elevation of the top end of flume was adjusted by a stepping motor. The bed gradient of the flume could be adjusted up to 60%. The test soil was glued on the surface of flume bed upstream and around the sample to a depth of 5 mm. Thus, the natural soil surface condition was simulated, and at the same time the roughness of the flume bed was kept constant during the experiment.

Flow discharge was controlled by a series of valves and monitored by a calibrated flow meter. Before the experiments, flume bed slope and flow discharge were adjusted to specific values, and when the flow become stable, measurements of flow depth were made. Flow depths were measured by a level probe to an accuracy of 0.3 mm. For each flow discharge, 12 depths were measured. One maximum and one minimum flow depth were eliminated from the dataset. The average of the remaining 10 depths was considered as the mean flow depth. Flow surface velocity was determined by using the leading–edge fluorescent dye technique (Luk and Merz, 1992; Nearing et al., 1997). The water temperature was measured to determine flow viscosity. The Reynolds number (*Nr*) was calculated, and mean flow velocity was obtained by multiplying the surface velocity by 0.70 where the flow was transitional and by 0.80 where the flow was turbulent (Luk and Merz, 1992). Velocity measurements were replicated 12 times. As with the flow depth measurements, one maximum and one minimum velocity were eliminated from the dataset. The average of the remaining 10 velocities were used as the mean flow velocity.

Detachment Measurements

Soil was wetted by light spraying to a water content of 180 g kg^{-1} and allowed to equilibrate for 48 hours in a plastic bucket. Wetting the soil allowed for the forming of samples by static compression into 10–cm diameter plastic cylinders to a bulk density of 1200 kg m^{-3}. The depth of the soil samples was 5 cm. The soil samples were then placed in a container to be saturated. The water level was increased gradually (5 steps) to 0.5 cm below the top of the samples. This level was maintained for 24 hours. Just prior to the start of the experiment, the soil sample was removed from the container and placed in a hole in the bed of flume, located at a distance of 0.6 m from the lower end of flume, keeping the elevation of the sample top even with the flume bed.

Soil detachment rate was calculated as the total soil loss (original oven–dry mass minus final oven–dry mass) divided by the time of period of the test and soil sample cross–section area. Because the soil loss rate was not the same for every treatment, the test period was adjusted in order to keep a similar scouring depth of the soil samples. Each treatment was replicated five times, but some samples were lost during the test. A series of thirty combinations of flume bed slopes and flow discharge were used, as shown in table 1.

Results and Discussion

Measured detachment rates are reported in table 1. Detachment rates increased as a function of both flow

Table 1. Flow properties used in the experiments and measured detachment rates.

Slope of Bed (%)	Flow Rate (10^{-3} m^3 s^{-1})	Flow Depth (cm)	Flow Velocity (m s^{-1})	Shear Stress (Pa)	Stream Power (kg s^{-3})	Unit Stream Power (m s^{-1})	Mean Detachment Rate (g s^{-1} m^{-2})	n
3.5	0.25	0.28	0.17	0.97	0.17	0.005	2	5
	0.50	0.42	0.25	1.45	0.37	0.008	15	5
	1.00	0.61	0.37	2.09	0.77	0.012	68	5
	1.50	0.75	0.44	2.57	1.13	0.014	195	5
	2.00	0.96	0.57	3.30	1.88	0.018	289	5
8.8	0.25	0.35	0.22	2.98	0.67	0.020	10	5
	0.50	0.46	0.34	3.94	1.32	0.029	42	5
	1.00	0.57	0.46	4.87	2.24	0.040	216	5
	1.50	0.65	0.52	5.57	2.91	0.046	497	5
	2.00	0.74	0.65	6.34	4.10	0.056	975	5
17.6	0.25	0.27	0.27	4.58	1.25	0.048	15	5
	0.50	0.31	0.34	5.36	1.83	0.060	96	5
	1.00	0.46	0.56	7.89	4.44	0.099	430	5
	1.50	0.58	0.63	10.10	6.31	0.110	1048	5
	2.00	0.59	0.74	10.12	7.52	0.131	2209	5
26.8	0.25	0.25	0.29	6.44	1.89	0.079	47	4
	0.50	0.32	0.45	8.31	3.77	0.122	176	5
	1.00	0.37	0.60	9.62	5.77	0.161	786	5
	1.50	0.46	0.73	12.02	8.74	0.195	1120	5
	2.00	0.53	0.84	13.88	11.69	0.226	2431	5
36.4	0.25	0.23	0.32	8.21	2.64	0.117	66	5
	0.50	0.27	0.41	9.61	3.98	0.151	495	5
	1.00	0.32	0.65	11.46	7.47	0.237	842	5
	1.50	0.45	0.77	15.93	12.30	0.281	1368	5
	2.00	0.48	1.00	17.25	17.32	0.365	3410	5
46.6	0.25	0.20	0.29	9.20	2.65	0.134	128	5
	0.50	0.27	0.4	12.35	4.92	0.186	941	5
	1.00	0.29	0.63	13.17	8.30	0.294	2226	5
	1.50	0.44	0.78	19.90	15.50	0.363	3806	4
	2.00	0.42	0.96	19.30	18.61	0.450	4784	5

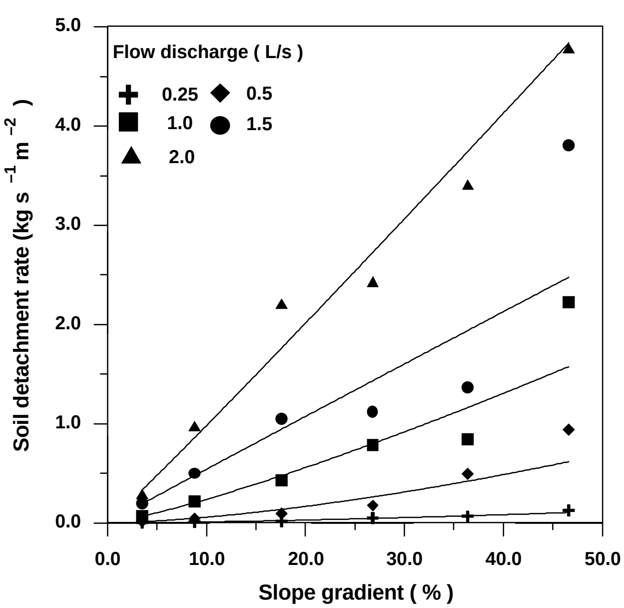

Figure 1. Measured soil detachment rate as a function of slope gradient.

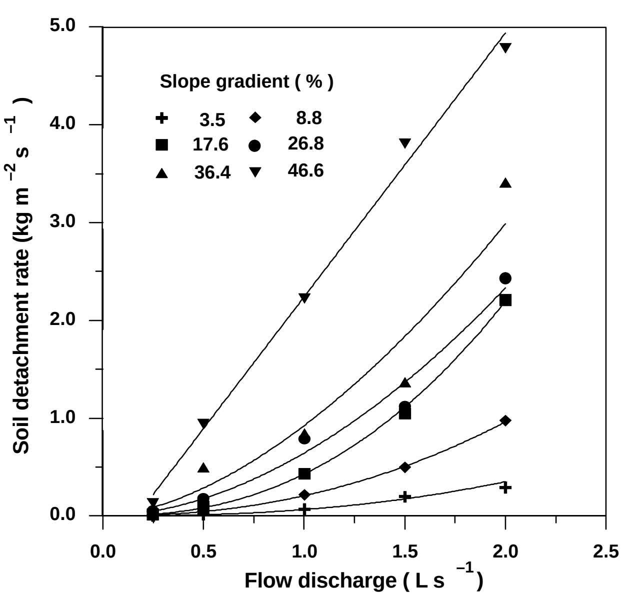

Figure 2. Measured soil detachment rate as a function of flow discharge.

discharge and slope gradient (figs. 1 and 2). The relationship was linear with slope gradient (fig. 1) for all flow rates. Detachment rate increased as a power function of discharge for most slopes, but when slope gradient was equal to 46.6%, the relation between detachment rate and flow discharge was well represented by a simple linear function (fig. 2).

Detachment rates on low slopes (3.5%) were similar to the average detachment rates for 0–1 mm and 1–2 mm aggregate size of Russell soil reported by Nearing et al. (1991). In the current study, when discharge equaled 0.5 L s^{-1}, the flow shear stress was 1.45 Pa, and the detachment rate was 16.4 g $m^{-2}s^{-1}$. In the study by Nearing et al. (1991), the flow shear stress was 1.47 Pa for two combinations of flow depth and slope gradients, and the average detachment rate for 0–1 mm and 1–2 mm aggregate size was 17.4 g $m^{-2}s^{-1}$, representing a difference of only 6% from the current results.

Further analysis indicated that at similar levels of hydraulic shear stress, the soil detachment rate at low gradient was influenced more by flow discharge than by slope. When flow discharge equaled 2 L s^{-1} combined with a slope of 8.8%, flow shear stress was 6.3 Pa, and the detachment rate was 975 g $m^{-2}s^{-1}$. When flow discharge equaled 0.25 L s^{-1} at a slope of 26.8%, flow shear stress was similar (6.4 Pa), but the detachment rate was only 47 g $m^{-2}s^{-1}$, a factor of 20 difference. In the latter case, stream power was less than in the first case (1.89 compared to 4.10 kg s^{-3}, a factor of 2 difference), which may explain part of the difference in detachment rate. In essence, shear stress is a hydraulic term associated with forces acting on the soil surface, while stream power is an energy term.

The effect of slope on detachment rate increased as slope gradient became greater. When flow discharge equaled 2 L s^{-1} at a slope of 26.8%, flow shear stress was almost the same as with the flow of 1 L s^{-1} at a slope of 46.6% (13.9 and 13.2 Pa, respectively), and the detachment rates were 2431 g $m^{-2}s^{-1}$ and 2226 g $m^{-2}s^{-1}$, respectively.

Multi–variable, non–linear regression analyses between average detachment rates, average flow discharges, and slope gradient produced the relationship:

$$D_c = 5.43 \times 10^6 \, q^{2.04} \, S^{1.27} \quad R^2 = 0.97 \tag{1}$$

where

D_c = detachment rate (kg s^{-1} m^{-2})
q = flow discharge (m^3 s^{-1})
S = slope gradient (fig. 3) (%).

The predicted detachment rates were slightly greater than measured rates at a slope of 3.5%, and predicted rates were slightly less than measured rates at slopes of 8.8% to 36.4%. At very steep slopes, the predicted rates were again slightly greater.

The relationship between detachment rate and flow depth, h (m), at different slopes is plotted in figure 4. Detachment rate increased with both greater slope gradient and flow depth, as expected. The influence of flow depth on detachment rate increased as slope gradient increased. When slope was steep, the influence of flow depth was quite strong. This result corroborates the conclusion of Nearing et al. (1991) that detachment rate for a given soil material is not a unique function of shear stress. Average flow shear stress is, by definition, directly proportional to slope multiplied by flow depth, ($S \times h$). If shear stress were an accurate variable for defining detachment rates, then detachment would have been equally sensitive to slope as to depth of flow (Nearing et al., 1991). The best–fit relationship between detachment rate, flow depth, and slope gradient for these data was:

$$D_c = 1.17 \times 10^3 \, h^{4.62} \, S^{2.37} \quad r^2 = 0.92 \tag{2}$$

Stream power, ω (kg s^{-3}), is defined mathematically as:

$$\omega = \tau V = \rho g h S V \tag{3}$$

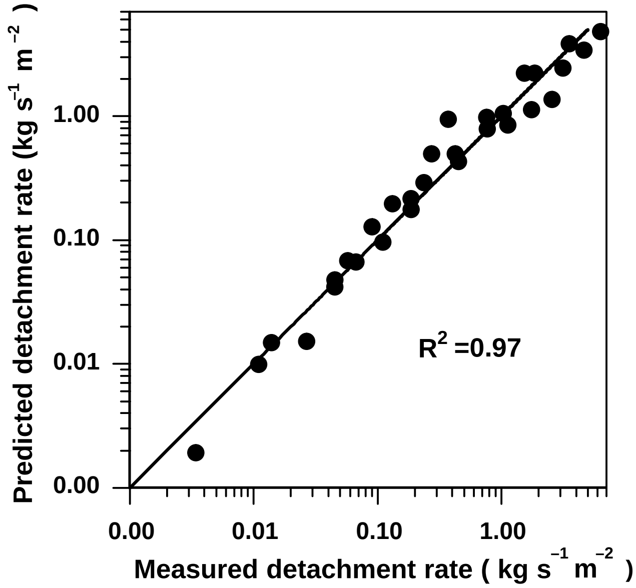

Figure 3. Predicted soil detachment rate (using eq. 1) vs. measured detachment rate.

where

τ = shear stress (Pa)
V = flow velocity (m s^{-1})
ρ = density of water (kg m^{-3})
g = constant of gravity (m s^{-2}).

The Chezy velocity–discharge relationship is an empirical relationship of the form:

$$V = C (S \times h)^{0.5} \tag{4}$$

where C is the roughness coefficient for the flow. Greater values of C indicate smoother surfaces. Given equations 3 and 4, Nearing et al. (1991) hypothesized that stream power should be proportional to $(S \times h)^{1.5}$, and hence, in order for detachment to be related to stream power, detachment must be equally sensitive to S as to h. Using that logic, the discussion in the previous paragraph regarding shear stress would suggest that stream power must also be a poor predictor of detachment, since detachment is more sensitive overall to h than it is to S (eq. 2). However, stream power is proportional to the term $(S \times h)^{1.5}$ only if C is constant. Such was not the case. In fact, the Chezy coefficient for our data was highly correlated with the flow depth (fig. 5).

Mean flow velocity is one of the more important hydraulic parameters in soil erosion modeling, because it is dependent upon flow discharge, slope gradient, topography, and surface condition. Therefore, the relationship between detachment rate and mean flow velocity was analyzed. The best fitting equation for these data was a simple power function (fig. 6):

$$D_c = 6.20 V^{4.12} \quad r^2 = 0.90 \tag{5}$$

where V is mean flow velocity (m s^{-1}). The correlation between detachment rate and mean flow velocity was greater than for either discharge or slope gradient.

In most physical process–based erosion models, detachment rate has been expressed as a function of shear stress (Nearing et al., 1989), stream power (Rose et al., 1983; Hairsine and Rose, 1992), or unit stream power (Morgan et al., 1998; De Roo et al., 1996). In order to compare those hydraulic parameters, detachment rate was plotted vs. flow

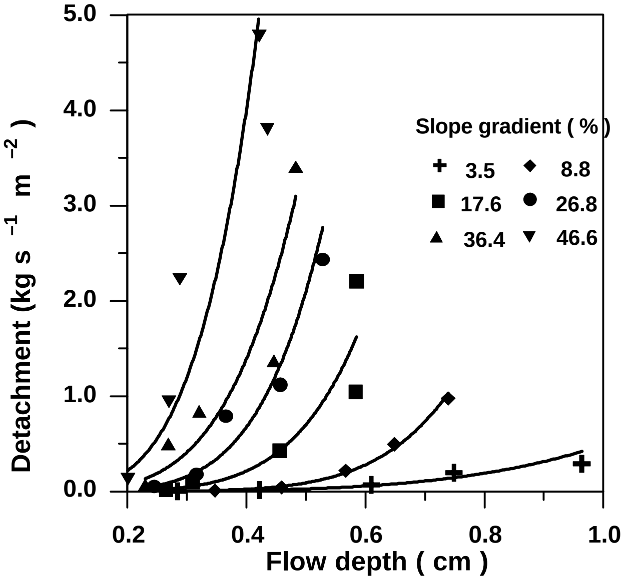

Figure 4. Measured soil detachment rate as a function of flow depth.

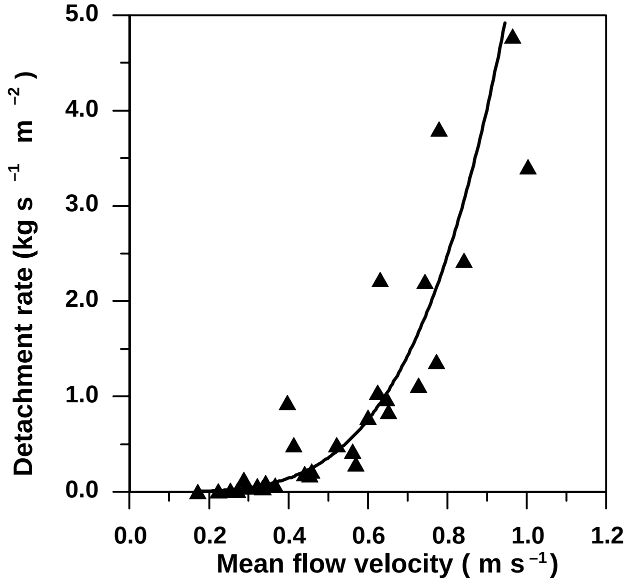

Figure 6. Measured soil detachment rate as a function of mean flow velocity.

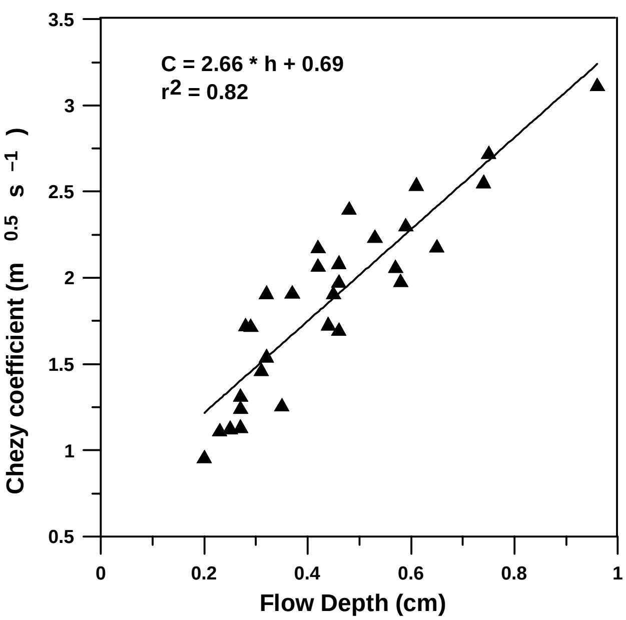

Figure 5. Chezy roughness coefficient as a function of flow depth.

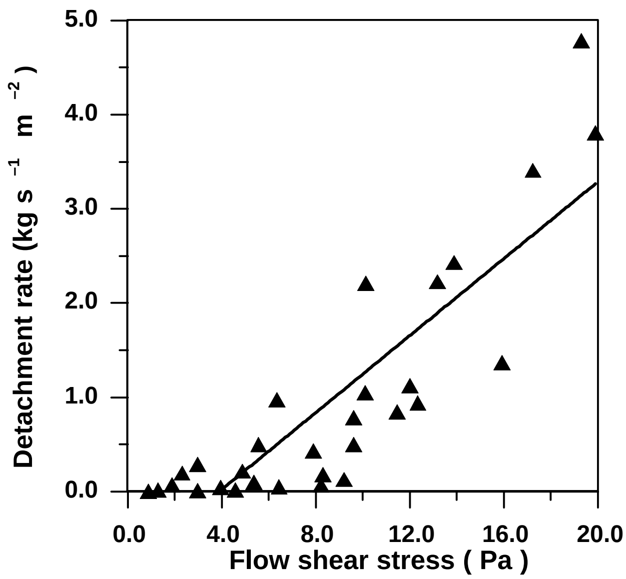

Figure 7. Measured soil detachment rate as a function of flow shear stress.

shear stress, unit stream power, and stream power (figs. 7, 8, and 9 respectively).

Detachment rate was not as well predicted by a linear shear stress model as by other models for the current data set, as shown in figure 7. Simple linear regression analysis between detachment and shear stress indicated values of 0.2065 s m^{-1} and 3.99 Pa for erodibility (K_r) and critical shear stress (τ_c), respectively.

$$D_c = 0.2065\tau - 0.8237 \quad r^2 = 0.74 \qquad (6)$$

where D_c is detachment rate (kg $s^{-1}m^{-2}$), and τ is shear stress (Pa). The erodibility parameter, 0.2065, is two orders of magnitude greater than those found in the WEPP rill erosion study (Laflen et al., 1991) and 26 times of that reported in the rill erosion study by Nearing et al. (1999). The critical shear stress, 3.99, was very similar to the value reported by Nearing et al. (1999).

Comparison of these results points out an extremely important aspect of erosion modeling. As mentioned previously, the difference between detachment rates in this study and erosion rates measured in rill studies is largely a function of feedback between sediment load and detachment; sediment in the flow reduces the rate of detachment (Merten et al., 2001). It is a scale–dependent effect. There must be sufficient upstream source area for sediment in order for the detachment rate to be decreased as a function of sediment load. The critical aspect of using data for any particular model is that the data are analyzed within the context of the model structure. The WEPP data of Laflen et al. (1991), for example, was measured at a scale appropriate to the model application (hillslope scale), and the WEPP model relationships were used to analyze the rill data. Thus, the model gives good results using the parameters from the Laflen et al. (1991) rill studies when used in hillslope–scale applications (Zhang et al., 1996).

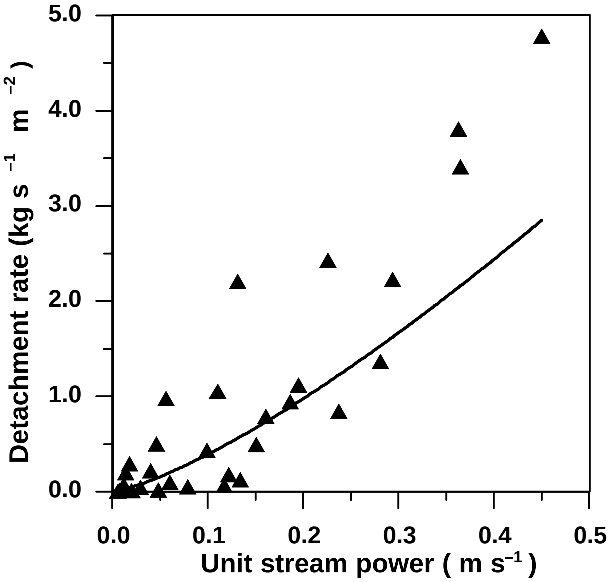

Figure 8. Measured soil detachment rate as a function of unit stream power.

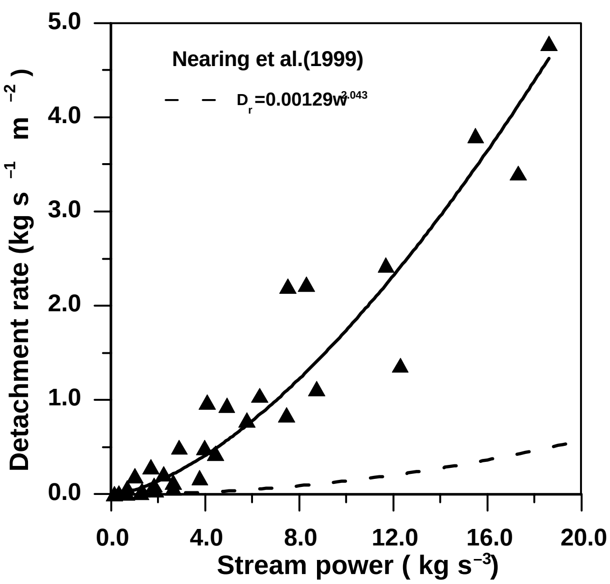

Figure 9. Measured soil detachment rate as a function of stream power.

The correlation coefficient between detachment rate and unit stream power was 0.65 (fig. 8). Detachment rate was better fitted to stream power with a power function (fig. 9). The coefficient of determination was better than for either shear stress or unit stream power. The relationship can be expressed as:

$$D_c = 0.0429\omega^{1.62} \quad r^2 = 0.89 \qquad (7)$$

where ω is the stream power (kg m^{-3}).

Conclusions

Soil detachment rate increased with flow discharge, flow depth, and slope gradient. It increased as a power function of discharge at low slope, while at the steepest slope of 46.6% the relationship changed to a linear function. Detachment rate was more sensitive to both flow discharge and depth than to slope gradient (eqs. 1 and 2). However, as slope gradient increased, the influence of slope increased. At the steepest slope (46.6%), the effects of slope gradient and discharge were nearly the same. Detachment rate by shallow flow was very well described (R^2 = 0.97) by a power function of flow discharge and slope gradient. Substituting flow depth for discharge gave a model with R^2 of 0.92. The relationship between mean flow velocity and detachment rate was more significant (r^2 = 0.90) than for detachment rate and discharge, flow depth, or slope gradient alone.

Among shear stress, unit stream power, and stream power, stream power was best related to soil detachment by shallow flow for these data. This study also corroborates recent experiments on cropland soil, which indicate that flow stream power is a better hydraulic parameter for detachment prediction than shear stress (Elliot and Laflen, 1993; Nearing et al., 1997; Nearing et al., 1999). However, the detachment rate in this study was much higher than that which has been obtained from field conditions due to the large difference in scale of this experiment relative to field experiments. Ours was a pure detachment study in the sense that clear water was used on a small sample, and the effect of sediment load on detachment did not influence results.

It is clear from these experiments that a large gap exists between fundamental erosion processes and erosion models. Rates of detachment by clear water, as evidenced in this study, are orders of magnitude greater than rates of "detachment" measured in rills. We are only beginning (Merten et al., 2001) to understand the mechanics of the sediment feedback relationship that so strongly affects detachment rates in rills. Until we are able to fully understand this scale problem, we are forced to continue using essentially empirical parameters, such as those used by the WEPP model (Laflen et al., 1991; Flanagan and Nearing, 1995), that are effective in predicting erosion rates on hillslopes but do not capture the essence of the erosion process in rills.

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