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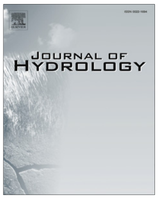

Modeling soil detachment capacity by rill flow using hydraulic parameters

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SUMMARY

The relationship between soil detachment capacity (Dc) by rill flow and hydraulic parameters (e.g., flow velocity, shear stress, unit stream power, stream power, and unit energy) at low flow rates is investigated to establish an accurate experimental model. Experiments are conducted using a 4 × 0.1 m rill hydraulic flume with a constant artificial roughness on the flume bed. The flow rates range from $0.22 \times 10^{-3}\ \mathrm{m^2\ s^{-1}}$ to $0.67 \times 10^{-3}\ \mathrm{m^2\ s^{-1}}$, and the slope gradients vary from 15.8% to 38.4%. Regression analysis indicates that the Dc by rill flow can be predicted using the linear equations of flow velocity, stream power, unit stream power, and unit energy. Dc by rill flow that is fitted to shear stress can be predicted with a power function equation. Predictions based on flow velocity, unit energy, and stream power are powerful, but those based on shear stress, especially on unit stream power, are relatively poor. The prediction based on flow velocity provides the best estimates of Dc by rill flow because of the simplicity and availability of its measurements. Owing to error in measuring flow velocity at low flow rates, the predictive abilities of Dc by rill flow using all hydraulic parameters are relatively lower in this study compared with the results of previous research. The measuring accuracy of experiments for flow velocity should be improved in future research.

1. Introduction

The Loess Plateau in China is one of the most severely eroded regions in the world (Chen and Luk, 1989; Fu and Gulinck, 1994; Jiang, 1997; Shi and Shao, 2000; Tang, 2004; Wu and Yang, 1998; Zhang and Liu, 2005). Rills are distributed widely and densely on slopes, and therefore rill erosion is the main sediment sources on hillslopes (Zhang and Zhang, 2000). Soil erosion occurs by overland flow following the detachment and displacement of soil particles (Govers, 1990). The detachment of soil particles by rill flow is crucial to sediment generation on hillslopes in the Loess Plateau.

Soil detachment is the separation of soil particles from the soil matrix at a particular location at the soil surface by erosive agents (Ellison, 1947; Wang et al., 2014; Zhang et al., 2003). Different relationships for soil detachment by rill flow are used in soil erosion models to estimate erosion rates by scouring in rills (Govers et al., 2007; Laflen et al., 1991). Understanding the basic mechanisms of soil detachment is essential in order to develop physically based erosion equations for use in developing soil erosion control measures (Laflen et al., 1991; Lal, 1994).

Erosion models are effective tools for predicting soil erosion and making decisions concerning soil erosion control, such as the Water Erosion Prediction Project (WEPP) (Nearing et al., 1989), the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965), the European Soil Erosion Model (EUROSEM) (Morgan et al., 1998), the Griffith University Erosion System Template (GUEST) (Misra and Rose, 1996), and the Limburg Soil Erosion Model (LISEM) (De Roo et al., 1996). Soil detachment capacity (Dc) is a key parameter in WEPP and other process-based erosion models. Given the widespread use of detachment prediction methods, their rigor is critical to the development of process-based erosion models.

In the past decades, numerous investigations were conducted to study the mechanisms of soil detachment by rill flow. The results indicate that soil detachment is strongly influenced, and in some cases controlled, by hydraulic parameters, such as flow regime, discharge, slope gradient, flow depth, velocity, friction, and sediment concentration (Cochrane and Flanagan, 1997; Govers et al., 1990; Govers, 1992; Nearing et al., 1991, 1999; Zhang et al., 2002, 2003, 2008, 2009). Dc increases with flow discharge and slope gradient, but it is more sensitive to flow discharge (Nearing et al.,

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1991). It increases as a power function of either flow discharge or slope gradient, both of which have been shown to be useful predictors of Dc (Nearing et al., 1999; Zhang et al., 2002, 2003). The results of these studies indicate that a logarithmic relationship exists between the detachment rate and the parameters of flow depth, slope, and mean weight diameter (Nearing et al., 1991). The detachment rate by rill flow is also known to decrease as sediment loads increase, because the energy expended to transport sediments is increased, thus reducing the energy available to detach new soil particles (Moore and Burch, 1986; Nearing et al., 1991). As sediment concentrations in the flow increase, the detachment rate in rills declines because of the feedback relationship between sediment load and detachment rate (Govers et al., 2007; Knapen et al., 2007; Merten et al., 2001). Therefore, the maximum soil detachment rate, which occurs when the sediment concentration in the flow is zero, is termed Dc.

The hydraulic parameters commonly used in simulating detachment rates are shear stress (Nearing et al., 1991), stream power (Hairsine and Rose, 1992a,b), and unit stream power (Morgan et al., 1998; Yang, 1972). Rill detachment rates are also better correlated with the power functions of shear stress and stream power (Nearing et al., 1999). Soil detachment by shallow flows is more closely correlated with flow energy than with shear stress (Zhang et al., 2002). Some studies indicate that stream power is better than shear stress for Dc prediction (Cao et al., 2009; Knapen et al., 2009; Zhang et al., 2003).

The hydraulic characteristics of flow and the properties of soil detachment at low flow rates, which are also important for soil detachment models, differ from those at high flow rates. However, little or no data exist regarding soil detachment processes at low flow rates (<0.00067 $m^2\ s^{-1}$ used in this study).

Overall, despite the various studies, the hydraulic parameter best suited to describing soil detachment during erosion remains unclear. The problem is complicated by the difficulties in separating detachment and transport processes, and the interaction of the two processes in many rill experiments. This debate indicates that the fundamental mechanisms of detachment in rills are not fully understood. Therefore, more controlled laboratory research is required to better understand the relationship between soil detachment rate and hydraulic variables (Zhang et al., 2002).

The objective of this study is to investigate the relationship between the Dc by rill flow and hydrodynamic parameters, as well as establish a new and more accurate experimental model of Dc by rill flow at low flow rates.

2. Materials and methods

2.1. Test locations and soil

Experiments were conducted at the Simulated Rainfall Hall of the Institute of Soil and Water Conservation, Chinese Academy of Sciences. Test soil was loessial soil sourced from Ansai, Shaanxi Province, and soil mechanical composition was showed in Table 1, contents of soil organic matter is 0.3–0.6%. To remove stones, grass, and other debris from the soil, the air-dried sample was sieved through a 2 mm mesh, wetted by light spraying to achieve a soil water content of 14%, and equilibrated for 48 h in a plastic bucket. The soil sample box was packed to a bulk density of 1.2 $g\ cm^{-3}$. Immediately prior to the start of the experiment, the soil sample box was installed into the sample hole in the flume bed, with the elevation of the sample top kept even with the flume bed (Zhang et al., 2002).

2.2. Experimental design

To render rill erosion, detachment capacity was measured in a 4 × 0.1 m hydraulically adjustable flume. The slope of the flume bed could be adjusted between 8.8% and 46.6% to within 0.05% of a desired slope. Test sediment was evenly and smoothly glued to the surface of the flume bed to ensure that grain roughness remained constant for all the experiments (Zhang et al., 2008). Five flow rates (0.22, 0.33, 0.44, 0.56, and 0.67 × $10^{-3}\ m^2\ s^{-1}$) and five slope gradients (15.8%, 21.3%, 26.8%, 32.5%, and 38.4%) were tested, with each combination of flow rate and slope gradient tested twice, resulting in a total of 84 experiments.

For each experiment, the loess sample was packed into the soil box (10.5 cm in length, 9.9 cm in width, and 5 cm in depth) and placed in the flume, with the soil surface flushed with the flume bed surface. A cover panel was used to prevent soil samples from scouring before the sample surface was adjusted to be even with the flume bottom. Flow rate, which was controlled by a series of valves, was determined by collecting water flowing to a graduated container within a given time frame. The flow discharge was applied to the flume from the upper edge. Once setup was complete and the flow stabilized, the panel was removed and the detachment experiment was initiated. Experiments were timed as soon as they began, and ended when the depth of the eroded soil in the soil sample box reached 1.5 cm. The wet soil was oven-dried at 105 °C for 24 h and then weighed.

2.3. Determination of hydraulic parameters and detachment capacity

2.3.1. Flow rate and water depth

Flow rate was measured directly using a calibrated flow meter. When the flow stabilized, flow depth was measured by a level probe (±0.01 mm) at points 0.02, 0.62, and 1.22 m above the lower end of the flume. At each distance, depths were measured twice, at points 1.0 cm from each side and at the center of the flume, resulting in a total of 9 positions and 18 measurements for each experiment. The mean flow depth for each combination of flow rate and slope gradient was defined as the average of the 18 measurements.

2.3.2. Velocity

Velocity of the flow surface was determined using $KMnO_4$ as a tracer. Velocity measurements were replicated nine times. The water temperature was monitored. Reynolds number (Re) was calculated, and mean flow velocity was obtained by multiplying the surface velocity by 0.6 where the flow was laminar, by 0.70 where the flow was transitional, and by 0.80 where the flow was turbulent (Abrahams et al., 1985).

2.3.3. Hydraulic parameters

Shear stress (τ, measured in Pa; Nearing et al., 1991), stream power (ω, measured in $W\ m^{-2}$; Bagnold, 1966; Prosser and

Table 1
Soil composition.

Granulometric class	Clay	Silt	Very fine sand	Fine sand	Coarse sand
Particle size (mm)	<0.002	0.002–0.05	0.05–0.1	0.1–0.25	>0.25
Percentage (%)	5.95	61.17	27.67	5.22	0

Rustomji, 2000), and unit stream power (U, measured in m s^{-1}; Yang, 1972, 1976) were calculated as:

$$\tau = \rho g h S \tag{1}$$

where ρ is the water density (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), h is the flow depth (m), and S is the sine value of slope gradients.

$$\omega = \tau V = \rho g h S V \tag{2}$$

where V is the mean flow velocity (m s^{-1}).

$$U = VS \tag{3}$$

The unit energy (E, measure in cm; Zhao and He, 2010) was calculated as:

$$E = \alpha V^2 (2g)^{-1} + h\cos\theta \tag{4}$$

where α is the kinetic energy correction factor ($\alpha = 1$), and θ is the slope gradient (°).

2.3.4. Dc

Dc by rill flow (expressed in kg m^{-2} s^{-1}) was calculated as:

$$D_c = \frac{W_W - W_d}{t \times A} \tag{5}$$

where W_W is the weight of the dry soil before testing (kg), W_d is the weight of the dry soil after testing (kg), t is the duration of the test (s), and A is the sample cross-section area (m^2).

2.4. Statistical analysis

All statistical analyses were carried out using Excel. The relationships between Dc and the hydraulic parameters were analyzed by a regression analysis method. The following statistical parameters were used to evaluate the performance of simulated results:

$$\mathrm{RE} = \frac{(O_i - P_i)}{O_i} \times 100 \tag{6}$$

$$\mathrm{EE} = \frac{1}{N}\sum_{i=1}^{n}\left(\frac{O_i - P_i}{O_i}\right) \times 100\% \tag{7}$$

$$\mathrm{RME} = \frac{1}{N}\sum_{i=1}^{n}\left|\frac{O_i - P_i}{O_i}\right| \times 100\% \tag{8}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \bar{O}\right)\left(P_i - \bar{P}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \bar{O}\right)^2 \sum_{i=1}^{n}\left(P - \bar{P}\right)^2} \tag{9}$$

$$\mathrm{NE} = 1 - \frac{\sum (O_i - P_i)^2}{\sum\left(O_i - \bar{O}\right)^2} \tag{10}$$

where RE is the relative error, EE is the average relative error, RMA is the average absolute values of relative error, R^2 is the coefficient of determination, NE is the Nash–Sutcliffe efficiency index (Nash and Sutcliffe, 1970), O_i is the measured value, P_i is the predicted value, $\bar{O}$ is the average measured value, $\bar{P}$ is the average predicted value, and N is the sample number.

3. Results

3.1. Predicting Dc by rill flow using hydraulic parameters

3.1.1. Flow velocity

Mean flow velocity is one of the most important hydraulic parameters in soil erosion modeling because it is dependent upon flow discharge, slope gradient, topography, and surface condition. The results show that Dc by rill flow increases as flow velocity increases for each of the various flow rates and slope gradients, and the relationship can be defined by linear equations (Table 2). The comparison of observed and predicted Dc (Fig. 1) indicates that Dc by rill flow can be predicted using a linear function of flow velocity (Fig. 2), which is expressed as:

$$\mathrm{Dc} = 3.0615\ (V - 0.4209)(R^2 = 0.8819,\ P = 0.01) \tag{11}$$

Eq. (11) shows that the rill erodibility parameter is 3.0615 kg m^{-3}, critical flow velocity is 0.4209 m s^{-1}, and coefficient of determination (R^2) is 0.8819. These results show that the detachment capacity of this study can be predicted using the linear flow velocity models.

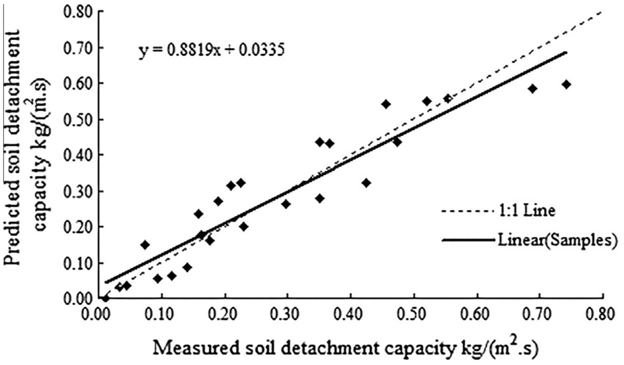

Fig. 1. Measured vs. predicted soil detachment capacity (Dc), using the model: Dc = 3.0615 (V − 0.4209).

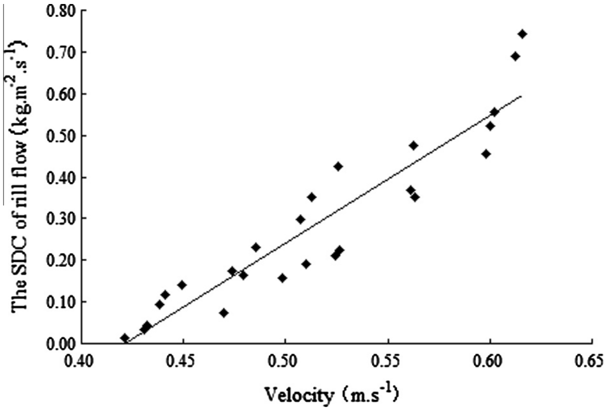

Fig. 2. Relationship between soil detachment capacity (Dc) by rill flow and velocity at all flow rates and slopes.

Table 2
Empirical equations of variation of Dc by rill flow with velocity (V) at the various flow rates or slopes.

Flow rate (m^2 s^{-1})	Empirical equation	R^2	P	Slope (%)	Empirical equation	R^2	P
0.00022	$y = 1.8614V - 0.7398$	0.7614	0.01	15.8	$y = 1.8661V - 0.7757$	0.9639	0.01
0.00033	$y = 3.4496V - 1.4434$	0.9418	0.01	21.3	$y = 3.7242V - 1.5649$	0.9701	0.01
0.00044	$y = 3.1059V - 1.3523$	0.836	0.01	26.8	$y = 2.5082V - 1.0294$	0.926	0.01
0.00056	$y = 2.9087V - 1.2432$	0.8828	0.01	32.5	$y = 2.7552V - 1.1192$	0.8498	0.01
0.00067	$y = 4.1254V - 1.8574$	0.8120	0.01	38.4	$y = 3.9738V - 1.7656$	0.8852	0.01

Table 3
Empirical equations of variation of Dc by rill flow with shear stress (τ) at the various flow rates or slopes.

Flow rate ($m^2\ s^{-1}$)	Empirical equation	R^2	P	Slope (%)	Empirical equation	R^2	P
0.00022	$y = 0.0822\tau - 0.1708$	0.9631	0.01	15.8	$y = 0.0000007\tau^{13.159}$	0.9233	0.01
0.00033	$y = 0.1366\tau - 0.29$	0.9619	0.01	21.3	$y = 0.00000001\tau^{15.058}$	0.8793	0.01
0.00044	$y = 0.1675\tau - 0.3424$	0.9686	0.01	26.8	$y = 0.000006\tau^{8.918}$	0.9833	0.01
0.00056	$y = 0.1661\tau - 0.2505$	0.9907	0.01	32.5	$y = 0.000002\tau^{8.385}$	0.9533	0.01
0.00067	$y = 0.1997\tau - 0.258$	0.9660	0.01	38.4	$y = 0.000006\tau^{0.883}$	0.8830	0.01

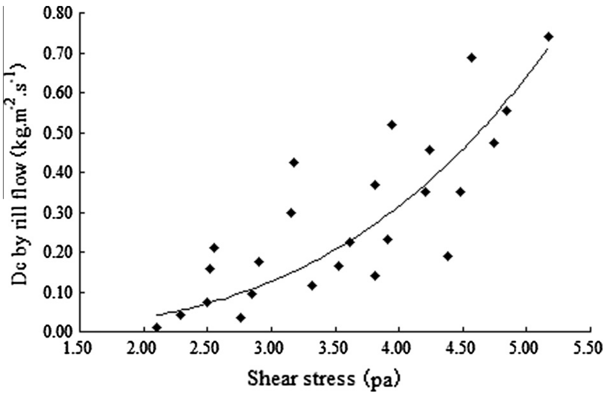

Fig. 3. Relationship between soil detachment capacity (Dc) by rill flow and shear stress at all flow rates and slopes.

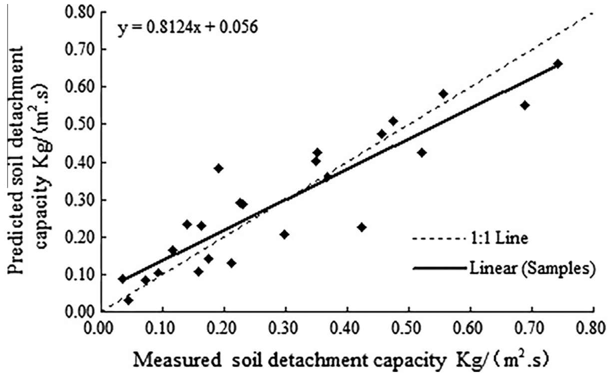

Fig. 5. Measured vs. predicted soil detachment capacity (Dc), using the model: Dc = 0.2794 (ω – 0.9159).

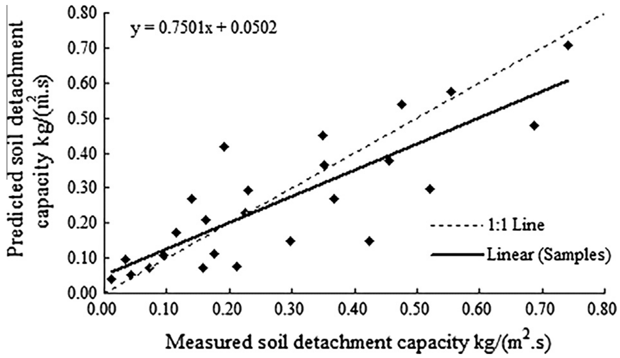

Fig. 4. Measured vs. predicted soil detachment capacity (Dc), using the model: Dc = $0.038\tau^{3.1821}$.

3.1.2. Shear stress

Dc by rill flow increases as shear stress increases, and the relationship is well described by linear equations for the various flow rates and by power function equations for the various slope gradients (Table 3). Further analysis indicates that Dc by rill flow for all combinations of flow rates and slope gradients can be fitted to shear stress with a power function (Fig. 3), which is expressed as:

$$\mathrm{Dc} = 0.0038\ \tau^{3.1821}\ (R^2 = 0.6796,\ P = 0.01) \tag{12}$$

The coefficient of Eq. (12) is 0.0038, power is 3.1821, and R^2 is 0.6796. The comparison of observed and predicted Dc indicates that a low level of agreement between predicted and observed values for all combinations of flow rates and slope gradients (Fig. 4). In this study, Dc by rill flow cannot be predicted very well using the power function shear stress models.

3.1.3. Stream power

Dc by rill flow increases as stream power increases, and the relationship is well described by linear equations for the various flow rates and by power function equations for the various slope gradients (Table 4). The relationship between Dc by rill flow and stream power for all combinations of flow rates and slopes can be fitted with a linear equation, which is expressed as in Eq. (13). The comparison of observed and predicted Dc shows a high level of agreement between predicted and observed values (Fig. 5).

$$\mathrm{Dc} = 0.2794\ (\omega - 0.9159)\ (R^2 = 0.8308,\ P = 0.01) \tag{13}$$

Eq. (13) shows that the rill erodibility parameter is $0.2794\ s^2\ m^{-2}$, critical stream power is $0.9159\ W\ m^{-2}$, and R^2 is 0.8308.

3.1.4. Unit stream power

Dc by rill flow increases as the unit stream power increases, and the relationships at various flow rates or slope gradients are well described by linear equations (Table 5). The relationship between Dc by rill flow and unit stream power at all combinations of flow rates and slope gradients fits a simple linear equation, expressed as:

$$\mathrm{Dc} = 3.3792\ (U - 0.0511)\ (R^2 = 0.6604,\ P = 0.01) \tag{14}$$

Table 4
Empirical equations of variation of Dc by rill flow with stream power (ω) at the various flow rates or slopes.

Flow rate ($m^2\ s^{-1}$)	Empirical equation	R^2	P	Slope (%)	Empirical equation	R^2	P
0.00022	$y = 0.1373\omega - 0.1125$	0.9453	0.01	15.8	$y = 0.027\omega^{6.3912}$	0.9562	0.01
0.00033	$y = 0.2239\omega - 0.1977$	0.9757	0.01	21.3	$y = 0.0142\omega^{6.3235}$	0.9064	0.01
0.00044	$y = 0.2343\omega - 0.1979$	0.9531	0.01	26.8	$y = 0.0302\omega^{3.1362}$	0.9866	0.01
0.00056	$y = 0.2167\omega - 0.1$	0.9753	0.01	32.5	$y = 0.0283\omega^{2.9415}$	0.9736	0.01
0.00067	$y = 0.2632\omega - 0.0995$	0.9478	0.01	38.4	$y = 0.0187\omega^{3.1245}$	0.8650	0.01

Table 5
Empirical equations of variation of Dc by rill flow with unit stream power (*U*) at the various flow rates or slopes.

Flow rate ($m^2\ s^{-1}$)	Empirical equation	R^2	*P*	Slope (%)	Empirical equation	R^2	*P*
0.00022	$y = 1.6065\ U – 0.0914$	0.9499	0.01	15.8	$y = 11.929\ U – 0.7757$	0.9639	0.01
0.00033	$y = 2.5861\ U – 0.1426$	0.985	0.01	21.3	$y = 17.912\ U – 1.5649$	0.9701	0.01
0.00044	$y = 2.9232\ U – 0.1399$	0.9713	0.01	26.8	$y = 9.6908\ U – 1.0294$	0.9260	0.01
0.00056	$y = 2.66\ U – 0.0214$	0.9738	0.01	32.5	$y = 8.9161\ U – 1.1192$	0.8498	0.01
0.00067	$y = 3.6773\ U – 0.0393$	0.9533	0.01	38.4	$y = 11.089\ U – 1.7656$	0.8852	0.01

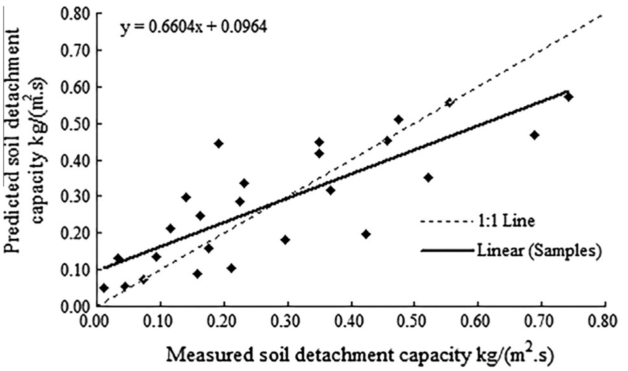

Fig. 6. Measured vs. predicted soil detachment capacity (Dc), using the model: Dc = 3.3792 (*U* – 0.0511).

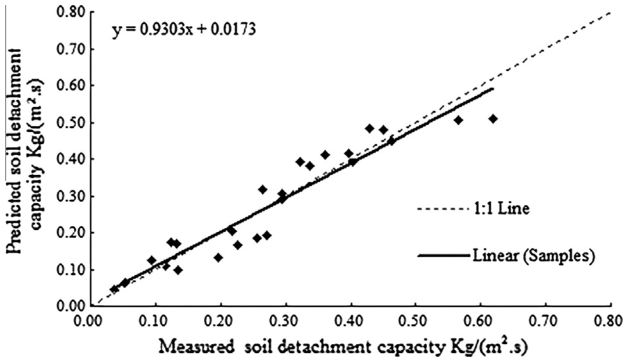

Fig. 7. Measured vs. predicted soil detachment capacity (Dc), using the model: Dc = 0.5753 (*E* – 0.9862).

Eq. (14) shows that the critical unit stream power is 0.0511 m s^{-1}, rill erodibility parameter is 3.3792 kg m^{-3}, and R^2 is 0.6604. The comparison of observed and predicted Dc indicates Dc by rill flow in this study is not well predicted by linear unit stream power models (Fig. 6).

3.1.5. Unit energy

Dc by rill flow increases as the unit energy increases, and the relationship between Dc by rill flow and unit energy at all flow rates or slopes is well described by linear equations (Table 6). The relationship between Dc by rill flow and unit energy at all combinations of flow rates and slope gradients can be fitted with a linear equation, expressed as:

$$\mathrm{Dc} = 0.5753\ (E - 0.9862)\ (R^2 = 0.8843,\ P = 0.01) \tag{15}$$

Eq. (14) shows that the critical unit energy is 0.9862 cm, rill erodibility parameter is 0.0058 kg $m^{-3}\ s^{-1}$, and R^2 is 0.8843. The comparison of observed and predicted Dc indicates Dc by rill flow of this study is well predicted by linear unit energy models (Fig. 7).

3.2. Comparisons of Dc responses by rill flow to hydraulic parameters

Table 7 shows the response equations of Dc by rill flow to various hydraulic parameters, as well as the assessment indexes, including RE, EE, RMA, NE, and R^2. The RE, EE, RMA, NE, and R^2 of observed Dc and Dc predicted with response equations of Dc by rill flow to hydraulic parameters consistently show that flow velocity, stream power, and unit energy are good predictors of Dc by rill flow, and the shear stress and unit stream power are relatively poor predictors. Owing to its simplicity and availability of measurements, flow velocity is a preferred hydraulic parameter for estimating Dc by rill flow.

4. Discussions

Flow velocity is a basic hydraulic parameter. As flow velocity increases, the kinetic energy by rill flow increases. Therefore, Dc by rill flow increases as flow velocity increases, and Dc by rill flow is closely correlated with flow velocity. In this study, the relationship between Dc by rill flow and flow velocity is linear, which is similar to those reported from previous studies (Zhang et al., 2002, 2003).

Shear stress is often used to predict Dc by rill flow (Laflen et al., 1991; Nearing et al., 1999; Zhang et al., 2002, 2003). In this study, the relationship between Dc by rill flow and shear stress can be described by a power function, which differs from the relationship reported in previous studies (Laflen et al., 1991; Nearing et al., 1999; Zhang et al., 2002, 2003). Flow shear stress is, by definition, directly proportional to the slope multiplied by flow depth ($S \times h$), indicating that Dc must be equally sensitive to both *S* and *h*. However, this study showed that Dc is more sensitive to *h* than *S* (Table 3). Thus, shear stress appears to be a poor predictor for Dc in this study.

The detachment rate for a given soil material is not a unique function of shear stress (Laflen et al., 1991). Eq. (2) shows that if stream power were an accurate variable for defining detachment

Table 6
Empirical equations of variation of Dc by rill flow with unit energy (*E*) at the various flow rates or slopes.

Flow rate ($m^2\ s^{-1}$)	Empirical equation	R^2	*P*	Slope (%)	Empirical equation	R^2	*P*
0.00022	$y = 0.3949\ E – 0.3633$	0.7191	0.01	15.8	$y = 0.3675\ E – 0.3742$	0.9652	0.01
0.00033	$y = 0.7703\ E – 0.7984$	0.9387	0.01	21.3	$y = 0.7336\ E – 0.7534$	0.9757	0.01
0.00044	$y = 0.6134\ E – 0.6766$	0.8228	0.01	26.8	$y = 0.4642\ E – 0.4394$	0.9464	0.01
0.00056	$y = 0.543\ E – 0.568$	0.8748	0.01	32.5	$y = 0.5018\ E – 0.4556$	0.8696	0.01
0.00067	$y = 0.7306\ E – 0.837$	0.7994	0.01	38.4	$y = 0.6769\ E – 0.7173$	0.8919	0.01

Table 7
Statistical evaluation of the response relationships between Dc and the hydrodynamic parameters of the rill flow.

Hydrodynamic parameters	Model	RE (%)	EE (%)	RMA (%)	NE	R^2
Velocity (V)	Dc = 3.0615 (V−0.4209)	−102 to −96	0.55	29.53	0.8819	0.8819
Shear stress (τ)	Dc = $0.0038\tau^{3.1821}$	−232 to −64	16.92	48.54	0.6614	0.6796
Stream power (ω)	Dc = 0.2794 (ω−0.9159)	−154 to −114	−6.81	36.10	0.8308	0.8308
Unit stream power (U)	Dc = 3.3792 (U−0.0511)	−309 to −54	−35.07	58.71	0.6604	0.6604
Unit energy (E)	Dc = 0.5753 (E−0.9862)	−104 to −97	0.63	29.80	0.8843	0.8843

rates, then detachment would be equally sensitive to slope, depth of flow, and flow velocity. The Manning velocity–discharge relationship is an empirical relationship of the form of Eq. (16):

$$V = (S^{1/2} \times h^{2/3})/n \tag{16}$$

where n is the roughness coefficient for the flow. Given Eqs. (2) and (16), stream power should be more sensitive to h than S. which is in line with the finding that Dc is more sensitive to h than S. As a result, a linear relationship between Dc and stream powered resulted, indicating stream power is a good predictor of Dc. And hence Dc by rill flow increases as stream power increases for all combinations of flow rates or slope gradients.

Unit stream power is usually used in process-based erosion models. In this study, detachment capacities are predicted by linear unit stream power models. However, the low determination coefficient of relationship between Dc by rill flow and unit stream power indicate that Dc by rill flow in this study is not well predicted by linear unit stream power models, which are similar to those reported in previous studies (Laflen et al., 1991; Nearing et al., 1999; Zhang et al., 2002, 2003).

As the Dc by rill flow is more closely related to flow energy than to shear stress (Zhang et al., 2002), the current study introduced the hydraulic parameter of unit energy. Compared with the results of previous research (Hairsine and Rose, 1992a,b; Laflen et al., 1991; Nearing et al., 1991, 1999; Yang, 1972; Zhang et al., 2002, 2003), the predictive abilities of Dc by rill flow using all hydraulic parameters are relatively lower in this study. This outcome may be attributed to two influencing factors. (1) In contrast with the large flow rate experiments, the difficulty of measuring flow velocity increases in low flow rate experiments, and thus measurement errors of flow velocity increase. Therefore, in this study, measurement errors of flow velocity reduced the predictive accuracy of Dc by rill flow when using the calculated hydraulic parameters from the measured flow velocity and flow rate. (2) When scouring or detaching soil by rill flow, both soil sample surface shape and flow hydraulics change at the eroding area, but the calculated hydraulic parameters do not take this into account, which inevitably produces errors.

5. Conclusions

In this study, the relationship between Dc by rill flow and hydrodynamic parameters (e.g., flow velocity, shear stress, unit stream power, stream power, and unit energy) at low flow rates is investigated. Experimental results indicate that the response relationships of detachment capacity by rill flow to all hydrodynamic parameters at the various flow rates, and to flow velocity, unit stream power, and unit energy at the various slope gradients can be described by linear functions. In contrast, the relationships of detachment capacity by rill flow to flow shear stress and stream power can be described by power functions at the various slope gradients.

Regression analyses indicate that Dc by rill flow can be predicted by linear equations of flow velocity, stream power, unit stream power, and unit energy. Further analysis indicates that Dc by rill flow can be fitted to shear stress with power function equations. Predictions of Dc by rill flow based on flow velocity, unit energy, and stream power are powerful, whereas predictions of Dc by rill flow based on shear stress, and especially on unit stream power, are relatively poor. Predictions based on flow velocity provide the best estimates of Dc by rill flow because of the simplicity and availability of its measurements.

Compared with the conclusions of previous studies, the predictive abilities of Dc by rill flow using all hydraulic parameters are relatively lowered in this study. Errors in measuring flow velocity at low flow rates are the main reason for this outcome. Therefore, the observation accuracy of experimental equipment for flow velocity measurement should be improved in future research.

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