Quantifying the Contribution of Sediment Load to Soil Detachment Rate by Sediment-Laden Rill Flow

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Sediment load changes with downslope distance during rill erosion process, and thus quantifying the potential contribution of sediment load on soil detachment rate is essential to accurately model the rill erosion process. A standardization-based method was adopted to quantify the contribution for the first time, and the rill flume with a soil-feeding hopper was specifically designed to insulate the effect of sediment load on detachment rate. Loessial soil was quantitatively fed into rill flow to produce different sediment loads. Seven flow discharges were combined with six slopes. Soil detachment rate was measured for each combination under five sediment loads (10, 25, 50, 75, and 90% of the sediment transport capacity, respectively). The results showed that soil detachment rate by sediment-laden rill flow decreased linearly with the increase in sediment load. Stream power is the best hydrodynamic parameter in relation to the detachment rate under different sediment loads compared with shear stress and unit stream power. The comprehensive response relationship of soil detachment rate to sediment load and stream power is a binary linear equation (R^2 = 0.9482). The contribution rate of sediment load to soil detachment rate is 30.43% and that of stream power is 64.39%. The negative effect of sediment load on soil detachment rate accounts for almost one-third of the total contribution. It is important to draw sediment load as a negative factor into process-based rill erosion model. This study can provide a feasible way for researchers to quantify the contribution rate of factors and can help to understand rill erosion process sufficiently.

Soil detachment is the process of soil particles being separated from the soil body by flowing water (Owoputi and Stolte, 1995; Lei et al., 2002), and it is active in hillslope farmlands where rill flow is frequently concentrated (Sun et al., 2013). The evaluation of soil detachment rate by rill flow has long been a focus in the research field of soil erosion. Soil detachment in rills proceeds under the action of rill flow, and thus the hydrodynamic behavior of rill flow acts as a driving factor dominating the soil detachment rate directly. However, a problem that may arise in evaluating soil detachment rate is the potential effect the sediment load in rill flow may have on soil detachment rate (Gimenez and Govers, 2002). Rill erosion is the process of rill flow to detach soil particles and concomitantly transport the produced sediments downstream (Zhang et al., 2014; Foster, 1986). Therefore, sediment load in rill flow changes with the downslope distance during the erosion process (Nord and Esteves, 2007; Lei

Core Ideas

- **A standardization-based method was adopted to quantify the contribution rate.**
- **The experiment was specifically designed to isolate the effect of sediment load on detachment rate.**
- **The negative contribution of sediment load on detachment rate was almost one-third of the total.**
- **This study aimed at rill erosion of loessial soil.**

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et al., 2006), which leads to soil detachment by a sediment-laden rill flow in different sediment loads. The potential effect that sediment load in rill flow may have on soil detachment process needs to be given more importance compared with the acknowledged driving effect of hydrodynamic behavior. Quantifying the contribution of sediment load to soil detachment rate by a sediment-laden rill flow can help to sufficiently understand rill erosion process and accurately evaluate rill erosion intensity.

The detachment–transport coupling function proposed by Foster and Meyer (1972) states that soil detachment rate in rills decreased with sediment load increased. This function is used as the govern equation in Water Erosion Predict Project (WEPP) and is expressed as follows:

$$D_r = D_c\left(1-\frac{G}{T_c}\right) \qquad [1]$$

where D_r is the net soil detachment rate in rills (kg m^{-2} s^{-1}); D_c is the detachment capacity by rill flow (kg m^{-2} s^{-1}); G is the actual sediment load in rill flow (kg m^{-1} s^{-1}); and T_c is the sediment transport capacity (kg m^{-1} s^{-1}). This detachment–transport coupling function assumes a linear equation between two extreme cases of clear water ($G/T_c = 0$) and transport capacity ($G/T_c = 1$) (Nearing et al., 1990).

Cochrane and Flanagan (1997) estimated soil detachment rate in a simulated rill and concluded that the experiment data was consistent with the sediment–feedback term ($1-G/T_c$). Whether sediment load affected soil detachment rate was investigated by Merten et al. (2001) through a variable flume experiment and results show that the detachment rate dose appeared to reduce as the increasing sediment load. Lei et al. (2002) studied the soil detachment rates for sediment loaded flow in rills at different rill lengths, and found that soil detachment rate was negative correlated with sediment concentration and rill length. Spatially distributed rill erosion data derived by rare earth element tracers was conducted by Zhang et al. (2005) and the results confirmed that the soil detachment rates decrease linearly with the growing sediment load. Spatial distribution data measured with sediment-laden water samples taken along an eroding gully shows the same results (Zhang et al., 2014). Riverbed sediments were used as sediment source to study the relationship of soil detachment and sediment transport, and the results demonstrated that there was a feedback effect of sediment transport on soil detachment rate (Zhang et al., 2009a).

Conversely, Meyer and Wischmeier (1969) proposed a model that characterizes soil erosion by treating soil detachment and sediment transport separately. A field experiment conducted by Huang et al. (1996) also proposed that the rill detachment rate is irrelevant to sediment load, as proposed by Meyer and Wischmeier's (1969) model. Gimenez and Govers (2002) found that the process of soil detachment and the process of sediment transport were governed by different hydraulic variables, thus the two processes can't be linked simply and different equations are needed to predict the detachment process and the transport process, respectively. Lei et al. (2006) traced the sediment distribution of eroding rills using rare earth element tracers, and found that slope gradients greatly affected the sediment concentration in rills; this finding indicates that the rill erosion process may be different between gentle and steep slopes and that a large slope range from gentle to steep is necessary to be introduced in experimental research. A large range of flow discharge due to the direct influence of flow discharge to sediment load was also necessary (Sirjani and Mahmoodabadi, 2014).

The effect of sediment load on soil detachment rate was studied in the literature. However, the results in these studies remain controversial, and the potential contribution of sediment load in rill flow to soil detachment rate has not been quantified with percentage value. A standardization method was adopted in this study to quantify the contribution rate of sediment load to soil detachment rate to solve the controversial problem and to understand rill erosion process further. Moreover, the rill flume experiment in this study was intentionally designed to insulate the effect of sediment load on soil detachment rate to eliminate the error caused by deposition and re-detachment. The objectives of this present study are as follows: (1) to test the effect of sediment load on soil detachment rate by sediment-laden rill flow using data from flume experiment, (2) to identify the best hydrodynamic parameter in relation to soil detachment rate under different sediment loads, (3) to establish a binary response correlation of soil detachment rate to sediment load and hydrodynamic parameter, and (4) so as to quantify the partial contribution of sediment load to soil detachment rate by sediment-laden rill flow.

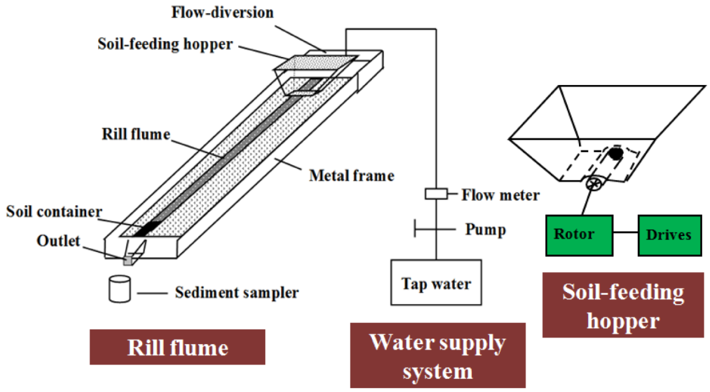

Fig. 1. Experimental devices: a rectangular rill flume, a water supply system, and a soil-feeding system.

MATERIAL AND METHODS

Experimental Devices and Design

The experimental devices in this study was similar with that in a previously published study of our research group (Shen et al., 2016), but the objective of this study was completely different from that of the previous one. To facilitate reading and understanding, the experiment details are described here again.

As shown in Fig. 1, the experimental devices mainly consisted of a rill flume, a water supply system, and a soil-feeding system. The shape of rill flume is rectangular. The length, width, and depth of the rill flume were 4, 0.1, and 0.1 m, respectively. The flume length of 4 m was designed mainly based on the summary of many previous researches that conducted flume experiment and the concern of avoiding unnecessary waster of flume material etc. The slope range of the flume was 5° to 35°. The flume bed is non-erodible. A thin sheet of test soil was evenly glued to the surface of the flume bed to simulate natural roughness and kept constant for all experiments. A chamber was cut 0.3 m above the lower end of the flume for the insertion of a soil container 0.1 m in length, 0.1 m in width, and 0.05 m in depth. The soil container was filled with test soil through different preparations for different purposes in the measurement of transport capacity and detachment rate. The surface of the soil in the soil container was at the same level as the flume bed after the container was inserted. A sliding plate was placed on the soil container to protect the soil from detaching before the flow discharge, and the soil-feeding rate was well adjusted. Tap water was pumped quantitatively to the upstream end of the flume by a water supply system, which mainly included a flowmeter and a pump. A soil-feeding hopper containing a rotor was installed above the upstream end of the flume to feed soil to rill flow. The soil-feeding rate was adjusted by a variable frequency drive that could control the rotation speed of the rotor. Air-dried soil, which was sieved through a 2-mm sieve, was added to the soil-feeding hopper for feeding.

The soil used in this study was loess collected from a typical hilly region of the Loess Plateau called Ansai in Shaanxi Province, China. The soil consisted of 36.58% sand (0.05–0.25 mm), 54.72% silt (0.002–0.05 mm), and 8.7% clay (<0.002 mm). The collected soil was air-dried and sieved through a 2-mm sieve to remove small stones and weeds.

Seven unit flow discharges (1.11, 1.56, 2.00, 2.44, 2.89, 3.33, and 3.78 × 10^{-3} m^2 s^{-1}) were combined with six slopes (10.51, 15.84, 21.26, 26.79, 32.49, and 38.39%). The sediment transport capacity (T_c) was measured for each combination. The soil detachment rate by sediment-laden rill flow was measured for each combination under five sediment loads, which were 10, 25, 50, 75, and 90% of the measured T_c.

Measurements

Flow Hydraulics

Flow velocity and depth were measured for each combination of unit flow discharge and slope. The water depth was measured by an electric probe with an accuracy of 0.02 mm from the surface of water to the non-erodible flume bed after the slopes and flow discharges were well adjusted. Flow depth was measured across two sections at 0.02 m and 1.22 m upstream from the chamber. Each section included three measurement points located 0.01 m from the left rill wall, 0.01m from the right rill wall, and in the middle of the two side walls. Flow velocity was measured using the dye method across a 2-m distance, which is 0.02 to 2.02 m upstream from the chamber. Three starting points located 0.01 m from the left rill wall, 0.01 m from the right rill wall, and the middle of the two side walls were applied for velocity measurement. The correction factor of 0.8 was multiplied with the flow velocity to convert the velocity of the leading edge of the dye into the mean flow velocity (Emmett, 1970; Li et al., 1996). The velocity and depth measurements were repeated three times, and thus 18 flow depths and 9 flow velocities were obtained for each combination of slope and flow discharge. The average of these measured depths and velocities represented the flow depth and flow velocities, respectively.

Sediment Transport Capacity (T_c)

Sediment transport capacity was measured for calibrating soil-feeding rates to quantitatively produce sediment-laden rill flow with different sediment loads. Two soil sources were adopted in this measurement. One main soil source was supplied by the soil-feeding hopper. The switch of the soil-feeding hopper was turned on to feed test soil to the rill flow after the flow discharge and slope were well adjusted. The soil feeding rate was slowly adjusted from small to large for the achievement of the potential T_c. Another additional soil source was the soil in the soil container. Air-dried test soil was loaded into the soil container loosely, and then the soil container was put in a in a plastic bucket to absorb water until saturation. This additional soil source would provide loose soil for flow transport if soil feeding from the hopper was slightly inadequate. The soil feeding rate did not increase anymore when the rill flow is unable to transport the soil supplied by the hopper completely. Then, the sliding plate was removed from the soil container, the sediment sample flowed from flume outlet was picked up and the sampling duration was timed. Five samples were picked up for each combination of flow discharges and slopes.

The obtained sediment samples were dried by oven and weighted. Transport capacity, T_c (kg m^{-1} s^{-1}) was equal to the weight of the dry soil divided by the sampling duration (s) and the width of the rill (m); T_c was measured under 42 combinations of 7 flow discharges and 6 slope gradients, and each combination was repeated once.

Soil Detachment Rate under Various Sediment Loads

This measurement was the same with the measurement in a previously published study of our research group (Shen et al., 2016). The objective of the previous study was completely different from that of this one. To facilitate reading and understanding, the measurement details are shown here again.

The previously measured sediment transport capacity for each combination of flow discharge and slope was used to regulate the soil-feeding rate to produce sediment-laden rill flow with different sediment loads of 10, 25, 50, 75, and 90% of T_c. In this measurement of soil detachment rate, the soil container was filled with test soil with 14% moisture content to a density of 1.2 g cm^{-3} and was then saturated for 24 h, which was designed to produce soil samples in a natural soil condition of erosion. The prepared soil samples were applied to be detached by the sediment-laden rill flow, and the soil detachment rates under different sediment loads were observed eventually.

The sliding plate covering the soil container was removed, and the detachment process began after the sediment-laden rill flow was well adjusted. The soil container was again covered by the sliding plate to stop detaching once the detachment depth of 1.5 cm was reached. The durations of detachment were recorded. The residual wet soil in the soil container was dried by oven and weighed. A series of 210 combinations (7 flow discharges × 6 slope gradients × 5 sediment loads) was conducted, and each combination was repeated once. The soil detachment rate by clear rill flow under 42 combinations of 7 flow discharges × 6 slope gradients was also measured to compare with the soil detachment rate by sediment-laden rill flow.

Calculations

Soil Detachment Rate

The soil detachment rate was calculated by the following Eq. [2]:

$$D_r = \frac{W_b - W_a}{t \times A} \qquad [2]$$

where D_r is the soil detachment rate (kg m^{-2} s^{-1}), W_b is the weight of the dry soil before testing (kg), W_a is the weight of the dry soil after testing (kg), t is the duration of detachment (s), and A is the projected area of the soil sample (m^2).

Hydrodynamic Parameter

Shear stress (τ, Pa) (Foster et al., 1984; Nearing et al., 1991; Cochrane and Flanagan, 1997), stream power (ω, W m^{-2}) (Bagnold, 1966; Zhang et al., 2009b; Misra and Rose, 1996), and unit stream power (U, m s^{-1}) (Yang, 1972, 1976; Morgan et al., 1998; Govers et al., 2007) were calculated by the Eq. [3], [4], and [5], respectively:

$$\tau = \rho g h S \qquad [3]$$

$$\omega = \tau V \qquad [4]$$

$$U = V \times S \qquad [5]$$

where ρ is the water density (kg m^{-3}), g is the gravitational acceleration (m s^{-2}), h is the flow depth (m), S is the sine value of the slope gradients, and V is the mean flow velocity (m s^{-1}).

Contribution Rate

First, multiple regression was conducted to relate the dependent variable of soil detachment rate to the factors of sediment load and stream power, which is the fundamental step to calculate the contribution rate of each factor to the dependent variable of sediment load. The determination coefficient (R^2) of the regression equation means that R^2×100% of the dependent variable could be explained by the factors, and thus the sum of the contribution rates of each factor to the dependent variable is equal to R^2×100%. (1 – R^2)×100% of the dependent variable could not be explained by the factors due to the effect produced by errors exceeding the analysis extent. Second, the regression coefficients of each factor obtained from multiple regression were standardized by Eq. [6] to eliminate the differences of units among the factors, so that the effect produced by different factors could be evaluated in the same standard (Allen, 1986; Wang et al., 2006). The values of standardized regression coefficients can show which of the factors has a greater effect on the dependent variable in the multiple regression analysis. Finally, the contribution rate of factor i to the dependent variable, P_i, was calculated by Eq. [7] as proposed by Huoluo (1983):

$$\beta_i = b_i \frac{\sigma_{xi}}{\sigma_y} \qquad [6]$$

$$P_i = R^2 \frac{\beta_i^2}{\sum_{i=1}^{n} \beta_i^2} \times 100\% \qquad [7]$$

where P_i is the contribution rate of factor i, R^2 is the determination coefficient of the regression equation, β_i is the standardized regression coefficient of factor i, b_i is the regression coefficient of factor i, σ_{xi} is the standard deviation of factor i, and σ_y is the standard deviation of the dependent variable.

RESULTS AND DISCUSSION

Effect of Sediment Load on Soil Detachment Rate

The variation of soil detachment rate with sediment load under different slopes and those under different flow discharges are shown in Fig. 2 and Fig. 3, respectively. The soil detachment rate by sediment-laden rill flow decreased with the sediment load increased for each trail, and the decreasing rates among different slopes and flow discharges were similar. The condition change of gentle slope to steep slope (10.51–38.39%) and the condition change of low flow discharge to high flow discharge (0.00111–0.00378 m^2 s^{-1}) did not cause an obvious difference in the variation characteristic. Regression analysis was performed to identify the relationship between soil detachment rate and sediment load for different slopes and for different flow discharges; Table 1 and Table 2 show these results, respectively. The correlation of soil detachment rate and sediment load was a negative linear relationship.

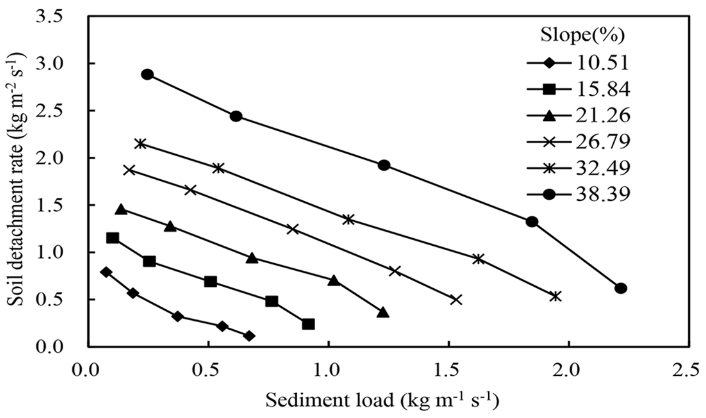

Fig. 2. Variation of soil detachment rate with sediment load under different slopes (unit flow discharge: 2.44 × 10^{-3} m^2 s^{-1}).

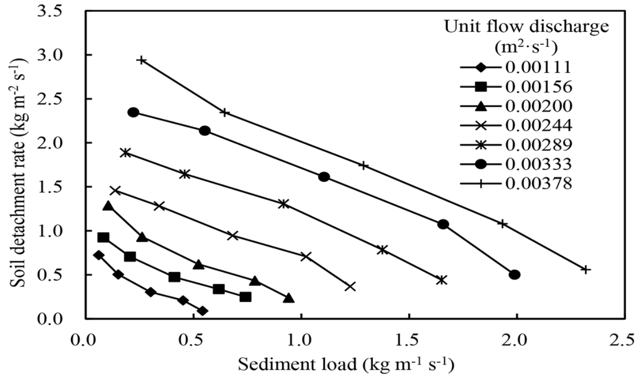

Fig. 3. Variation of soil detachment rate with sediment load under different unit flow discharges (slope: 21.26%).

The R^2 of each equation were greater than 0.95 ($P < 0.01$; $n = 5$ for each equation). The highly statistically significant equations illustrate that the more sediment rill flow transported, the less soil could be detached from soil body by the sediment-laden rill flow per unit time.

Soil detachment rate by clear rill flow was adopted to compare with that by sediment-laden rill flow (Fig. 4). The mean soil detachment rate by clear rill flow is higher than that by sediment-laden rill flow. The higher sediment load produced the greater reduction of soil detachment rate compared with clear rill flow. Clear water has the maximum capacity, which is also known as the detachment capacity, to detach soil particles from soil body (Knapen et al., 2007; Wang et al., 2016). The existence of sediment in rill flow acts as if it were a resistance to the process of soil detachment. How much influence this resistance could produce on the soil detachment rate is derived by the succeeding subsections.

There could be three reasons why sediment load has a negative effect on soil detachment rate. First, change of energy distribution during soil erosion process. An increased sediment load can cause rill flow to expend more energy for transport sediment and act less on soil detachment, which result in a decreased detachment rate with growing sediment load (Zhang et al., 2009a). Second, soil detachment by flow does not occur without turbulence (Escauriaza and Sotiropoulos, 2011; Nearing and Parker, 1994). Increasing sediment load suppresses localized turbulence, which leads to the decrease in the soil detachment rate (Bennett et al., 2014; Zhang et al., 2010; Lei et al., 2002; Wang and Larsen, 1994; Wilson, 1993). Third, the bed load sediment shields the soil bed and protects the soil from detaching (Polyakov and Nearing, 2003; Merten et al., 2001).

Table 1. Relationship between soil detachment rate and sediment load under different slopes.

Unit flow discharge	Slope	Regression equation†	R^2	P
$m^2\ s^{-1}$	%			
0.00244	10.51	$D_r = 0.8054 - 1.0820G$	0.9547	<0.01
	15.84	$D_r = 1.2217 - 1.0377G$	0.9845	<0.01
	21.26	$D_r = 1.6007 - 0.9547G$	0.9864	<0.01
	26.79	$D_r = 2.0737 - 1.0088G$	0.9975	<0.01
	32.49	$D_r = 2.3677 - 0.9214G$	0.9964	<0.01
	38.39	$D_r = 3.1682 - 1.0809G$	0.9819	<0.01

† In the equations, D_r is the soil detachment rate by sediment-laden rill flow (kg $m^{-2}\ s^{-1}$), and G is the sediment load in rill flow (kg $m^{-1}\ s^{-1}$).

Table 2. Relationship between soil detachment rate and sediment load under different unit flow discharges.

Slope	Unit flow discharge	Regression equation†	R^2	P
%	$m^2\ s^{-1}$			
21.26	0.00111	$D_r = 0.7346 - 1.2227G$	0.9558	<0.01
	0.00156	$D_r = 0.9452 - 0.9895G$	0.9660	<0.01
	0.00200	$D_r = 1.3143 - 1.1697G$	0.9649	<0.01
	0.00244	$D_r = 1.6034 - 0.9556G$	0.9859	<0.01
	0.00289	$D_r = 2.1054 - 0.9724G$	0.9902	<0.01
	0.00333	$D_r = 2.6620 - 1.0205G$	0.9811	<0.01
	0.00378	$D_r = 3.1590 - 1.1067G$	0.9946	<0.01

† In the equations, D_r is the soil detachment rate by sediment-laden rill flow (kg $m^{-2}\ s^{-1}$), and G is the sediment load in rill flow (kg $m^{-1}\ s^{-1}$).

Hydrodynamic Index of Soil Detachment Rate under Various Sediment Loads

The power needed for soil detachment process is provided by the rill flow. If the hydrodynamic force of rill flow surpasses a critical value, soil cohesion and force of friction are overcome and then soil is eventually detached from the soil body. Flow shear stress, stream power, and unit stream power are the widely used hydrodynamic parameters in soil erosion models (Flanagan and Nearing, 1995; Misra and Rose, 1996; Morgan et al., 1998; DeRoo et al., 1996). Which hydrodynamic parameter is the best in relation to soil detachment rate under conditions of different sediment loads needs to be identified to reveal the dynamic source of soil detachment and to lay foundation for the further study of the comprehensive response.

The relationship between soil detachment rate and flow shear stress, stream power, and unit stream power under different sediment loads of 10, 25, 50, 75, and 90% of T_c are shown in Fig. 5–7. The soil detachment rate under different levels of sediment loads increased with the increasing flow shear stress, stream power, and unit stream power, respectively. The data points of stream power distributed the most closely around the trend line, followed by shear stress and then by unit stream power, the data point of which was scattered around the trend line. Regression

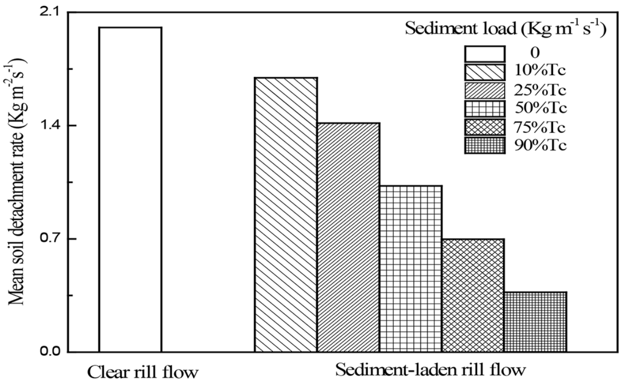

Fig. 4. Soil detachment rate by clear rill flow and by sediment-laden rill flow.

analysis was performed for the correlation between soil detachment rate under different sediment loads and hydrodynamic parameter. As shown in Table 3, the soil detachment rate is linearly correlated with flow shear stress under each sediment load (R^2 ranged 0.8986–0.9356, $P < 0.01$, $n = 42$ for every equation). The stream power is also linear in relation to the soil detachment rate. The determination coefficient of the equations ranged 0.9512 to 0.9775; that is, $R^2 > 0.95$ ($P < 0.01$; $n = 42$ for every equation). The correlation of soil detachment rate and unit stream power could be described by power functions for different sediment loads. The determination coefficient ranged 0.7431 to 0.7657 ($P < 0.01$; $n = 42$). The coefficient of hydrodynamic parameters in the regression equations decreased with the growth of sediment load, thus illustrating that the closer sediment-laden rill flow is to the saturated state, the smaller growth rate of soil detachment rate with the hydrodynamic parameter.

Clearly, the data points between the soil detachment rate and stream power are particularly close to the trend line, and the determination coefficient for the detachment rate with stream power is higher than that for shear stress and unit stream power. Therefore, stream power is the best hydrodynamic parameter in relation to soil detachment rate under conditions of different sediment loads, and it is capable of simulating the soil detachment rate by sediment-laden rill flow. This finding is in accordance with those of Elliot and Laflen (1993), Nearing et al. (1999), Mahmoodabadi et al. (2014), and Zhang et al. (2015b), where stream power is reported as the hydrodynamic index of soil detachment process and is recognized as the power source of soil detachment.

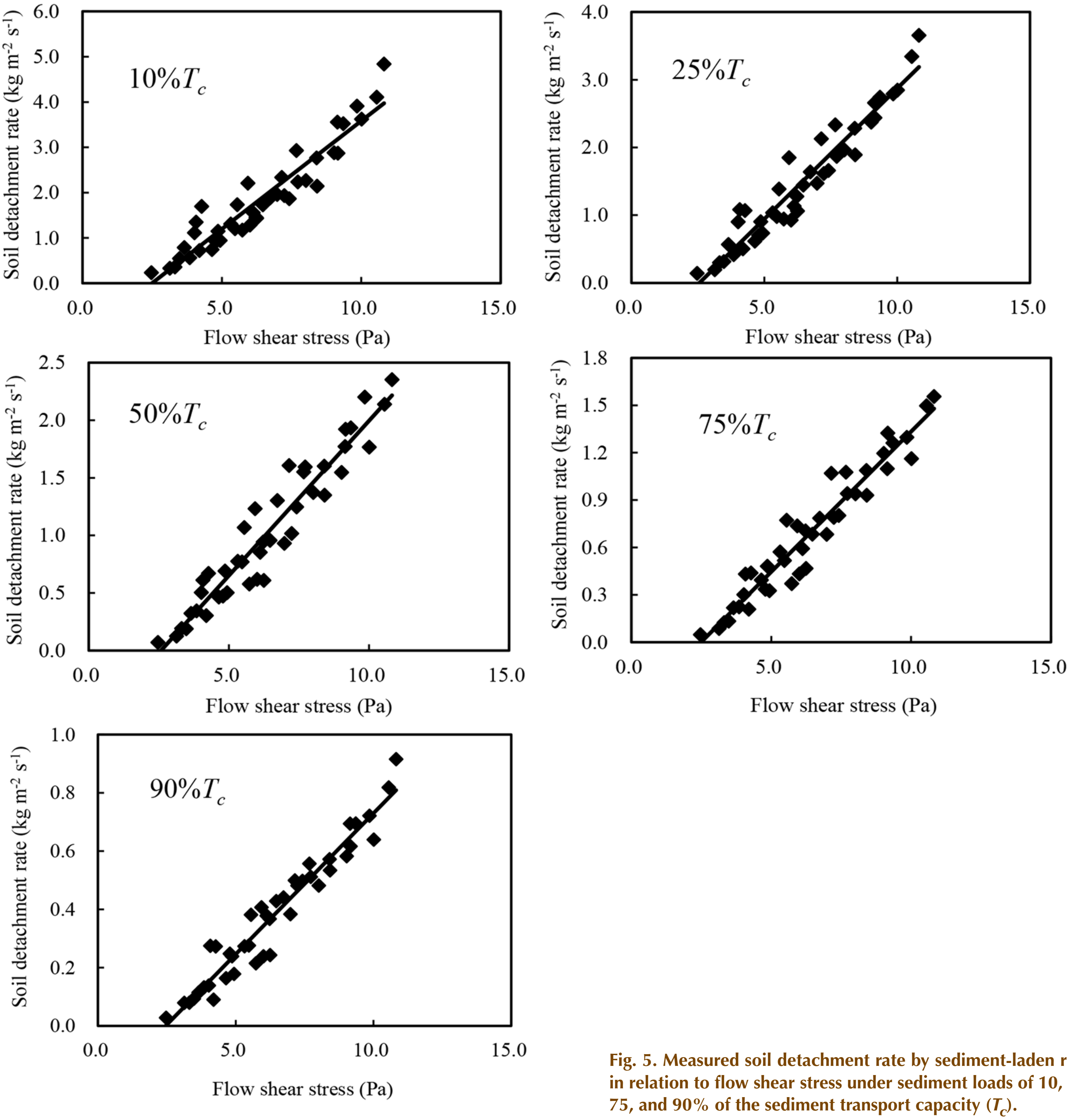

Fig. 5. Measured soil detachment rate by sediment-laden rill flow in relation to flow shear stress under sediment loads of 10, 25, 50, 75, and 90% of the sediment transport capacity (T_c).

Comprehensive Response of Soil Detachment Rate to Sediment Load and Hydrodynamic Parameter

Comprehensive Response Relationship for Different Slopes

Multiple regression analysis was performed to study the comprehensive response relationship of soil detachment rate to sediment load and stream power. The comprehensive response relationship of soil detachment rate to sediment load and stream power under different slopes was a binary linear correlation for different slopes, as is shown in Table 4. The soil detachment rate was negatively associated with sediment load and positively related to stream power. The determination coefficients for different slopes were 0.9115–0.9791 ($P < 0.01$, $n = 35$). The average relative error was relatively high, and the Nash–Sutcliffe efficiency was relatively low in the gentle slope of 10.51% compared with other slopes. This result indicates that the binary linear regression equation under the gentle slope of 10.51% has lower accuracy in describing the soil detachment rate than that under a steep slope. The measurements of detachment rate, sediment load, flow velocity, and depth were error prone under the condition of a gentle slope because measurements on a gentle slope require high precision, which is difficult to achieve. As a result, the comprehensive response equation for the gentle slope of 10.51% has a large error and low accuracy.

Comprehensive Response for Different Flow Discharges

The comprehensive response relationship of soil detachment rate to sediment load and stream power for different flow discharges was a binary linear correlation (Table 5). The soil detachment rate

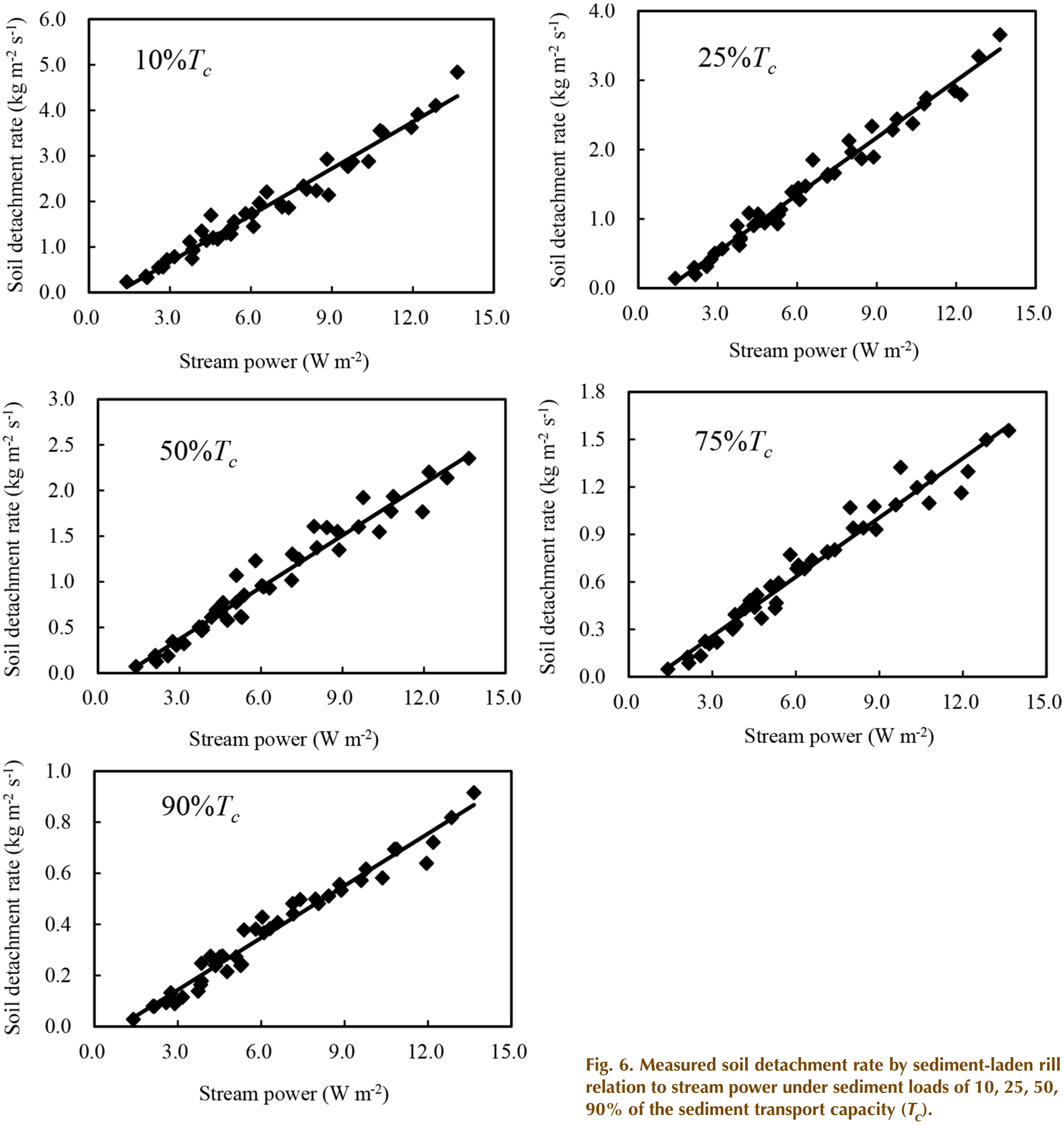

Fig. 6. Measured soil detachment rate by sediment-laden rill flow in relation to stream power under sediment loads of 10, 25, 50, 75, and 90% of the sediment transport capacity (T_c).

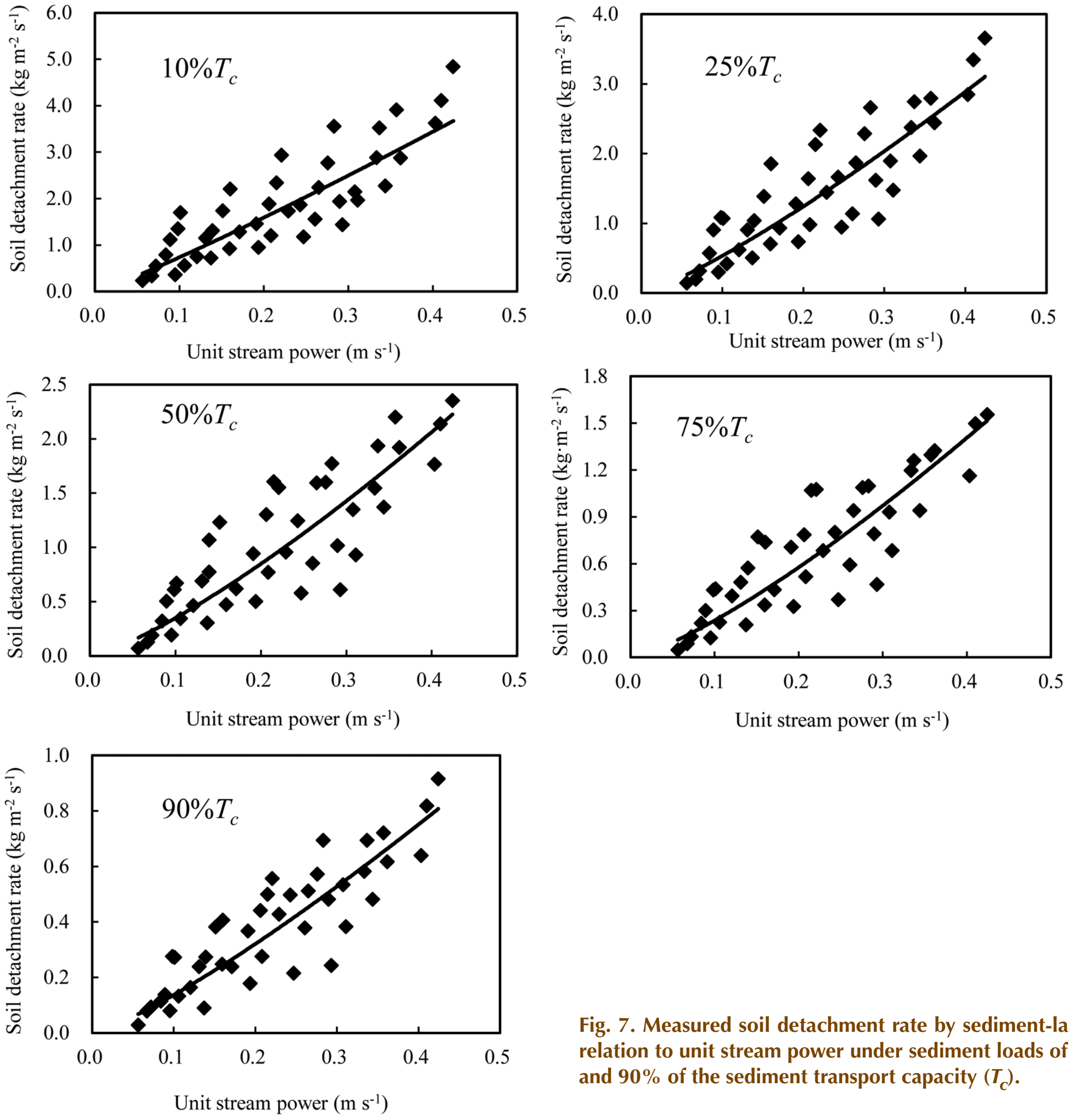

Fig. 7. Measured soil detachment rate by sediment-laden rill flow in relation to unit stream power under sediment loads of 10, 25, 50, 75, and 90% of the sediment transport capacity (T_c).

was negatively related to sediment load and positively associated with stream power for each flow discharge. The determination coefficient ranged 0.9658 to 0.9813 ($P < 0.01$, $n = 30$). The average relative error was relatively higher in the lowest flow discharge of 0.00111 m^2 s^{-1} than those in other flow discharges. The reason for this outcome is the same as that for the gentle slope of 10.51%.

Comprehensive Response for All Combinations

Multiple regression analysis showed that the comprehensive response relationship of soil detachment rate to sediment load and stream power for all combinations (7 flow discharges × 6 slope gradients ×5 sediment loads) could be well described by the following binary linear equation (Eq. [8]). The soil detachment rate by sediment-laden rill flow was negatively related to sediment load and positively associated with stream power. The determination coefficient (R^2) and Nash-Sutcliffe efficiency (NSE) was 0.9482 ($P < 0.01$, $n = 210$), and the average relative error (ARE) was 27.5698%. This highly statistically significant equation could accurately model the process of soil detachment in rills:

$$\begin{aligned} &D_r = -0.3567 - 1.0046G + 0.3537\omega \\ &(R^2 = 0.9482,\ \mathrm{NSE} = 0.9482, \\ &P < 0.01,\ \mathrm{ARE} = 27.5698\%) \end{aligned} \qquad [8]$$

where D_r is the soil detachment rate by sediment-laden rill flow (kg m^{-2} s^{-1}), G is the sediment load (kg m^{-1} s^{-1}), and ω is stream power (W m^{-2}).

Contribution Rate of Sediment Load to Soil Detachment Rate

The comprehensive response relationship of soil detachment rate to sediment load and stream power was set up previously, and thus the influence of sediment load on soil detachment rate in the comprehensive response relationship will be quantified in this subsection.

Contribution Rate of Sediment Load to Soil Detachment Rate for Different Slopes

Based on the linear regression equation and its determination coefficient in Table 4 generated previously, the contribution rate of sediment load to soil detachment rate for different slopes was calculated by Eq. [6] and [7]. As shown in Table 6, the contribution rate of sediment load to soil detachment rate is in the range of 32.51 to 43.23% and that of stream power is in the range of 53.83 to 62.92% for different slopes. The contribution rate of sediment load to soil detachment rate grew with the growth in slope gradient overall, but it is always less than the contribution of stream power for each slope. This result indicates that the resistance effect of sediment load on soil detachment process is incapable of swaying the dominant status of stream power, which is the original driving power of soil detachment (Zhang et al., 2015b).

Contribution Rate of Sediment Load to Soil Detachment Rate for Different Flow Discharges

As shown in Table 7, the contribution rate of sediment load to soil detachment rate is in the range of 34.38 to 49.47% and that of stream power is in the range of 47.74 to 62.20% for different flow discharges. The contribution of sediment load to soil detachment rate increased from 34.38 to 49.47% with the increase inflow discharges overall. A large flow discharge could transport a large sediment load, and the increased sediment load could depress flow turbulence more effectively, thus sediment load contributed a larger negative effect on detachment processes under higher flow discharge (Sirjani and Mahmoodabadi, 2014; Bennett et al., 2014; Zhang et al., 2010). Table 7 also shows that sediment load contributes less than stream power to the soil detachment rate except at the unit flow discharge of 0.00378 m^2 s^{-1}. Whether the unit flow discharge of 0.00378 m^2 s^{-1} is a critical flow discharge that could change the main contribution factor from stream power to sediment load needs to be investigated by introducing flow discharges higher than 0.00378 m^2 s^{-1} in future experiments.

Contribution Rate of Sediment Load to Soil Detachment Rate for All Combinations

Equation [8] was a statistically significant multiple regression relationship that relating soil detachment rate to sediment load and stream power under all combinations. The contribution rate of the factors to soil detachment rate in Eq. [8] was calculated by Eq. [6] and [7]. As shown in Fig. 8, the contribution rate of sediment load to soil detachment rate is 30.43%, and the contribution rate of stream power was 64.39%. The contribution rate of stream power was 33.96% more than that of sediment load. In the meantime, the contribution rate of sediment load accounted for almost one-third of the total contribution.

The above results indicate that sediment load and stream power influence the process of soil detachment together. Although the resistance effect of sediment load on detachment process is less than the driving effect of stream power, the role of sediment load in soil detachment should not be ignored (Cochrane and Flanagan, 1997; Lei et al., 2002; Zhang et al., 2005). The resistance effect

Table 3. Relationship between soil detachment rate and hydrodynamic parameters under different sediment loads.

Hydrodynamic parameter†	Sediment load‡	Regression equation§	R^2	P
	kg m^{-1} s^{-1}			
τ	10% T_c	$D_r = 0.4769\ \tau - 1.1866$	0.8986	<0.01
	25% T_c	$D_r = 0.3857\ \tau - 0.9838$	0.9248	<0.01
	50% T_c	$D_r = 0.2691\ \tau - 0.6949$	0.9166	<0.01
	75% T_c	$D_r = 0.1777\ \tau - 0.4427$	0.9322	<0.01
	90% T_c	$D_r = 0.0967\ \tau - 0.2376$	0.9356	<0.01
ω	10% T_c	$D_r = 0.3419\ \omega - 0.3567$	0.9641	<0.01
	25% T_c	$D_r = 0.2745\ \omega - 0.2993$	0.9775	<0.01
	50% T_c	$D_r = 0.1894\ \omega - 0.1966$	0.9512	<0.01
	75% T_c	$D_r = 0.1248\ \omega - 0.1169$	0.9600	<0.01
	90% T_c	$D_r = 0.0680\ \omega - 0.0608$	0.9661	<0.01
U	10% T_c	$D_r = 9.5321\ U^{1.1123}$	0.7431	<0.01
	25% T_c	$D_r = 8.8085\ U^{1.2162}$	0.7574	<0.01
	50% T_c	$D_r = 6.6832\ U^{1.2824}$	0.7438	<0.01
	75% T_c	$D_r = 4.5700\ U^{1.2863}$	0.7648	<0.01
	90% T_c	$D_r = 2.3139\ U^{1.228}$	0.7657	<0.01

† τ is flow shear stress (Pa); ω is stream power (W m^{-2}); U is unit stream power (m s^{-1}).

‡ T_c is the sediment transport capacity (kg m^{-1} s^{-1}).

§ In the equations, D_r is the soil detachment rate by sediment-laden rill flow (kg m^{-2} s^{-1}).

Table 4. Comprehensive response relationship of soil detachment rate to sediment load and stream power for different slopes.

Slope	Regression equation†	R^2	P	NSE‡	ARE§
%					
10.51	$D_r = -0.5522 - 0.9948\ G + 0.4552\omega$	0.9115	<0.01	0.9115	62.3570
15.84	$D_r = -0.6014 - 0.8856G + 0.4192\ \omega$	0.9543	<0.01	0.9543	25.6601
21.26	$D_r = -0.6430 - 1.0065G + 0.3983\ \omega$	0.9476	<0.01	0.9476	24.6537
26.79	$D_r = -0.5247 - 1.0478G + 0.3725\omega$	0.9791	<0.01	0.9791	8.1085
32.49	$D_r = -0.6783 - 0.9932G + 0.3791\omega$	0.9588	<0.01	0.9588	15.0652
38.39	$D_r = -0.7984 - 1.1144G + 0.4082\omega$	0.9706	<0.01	0.9706	11.1108

† In the equations, D_r is the soil detachment rate by sediment-laden rill flow (kg m^{-2} s^{-1}), G is the sediment load in rill flow (kg m^{-1} s^{-1}), and ω is stream power (W m^{-2}).

‡ NSE is the Nash-Sutcliffe efficiency.

§ ARE is the average relative error (%).

Table 5. Comprehensive response relationship of soil detachment rate to sediment load and stream power for different unit flow discharges.

Unit flow discharge	Regression equation†	R^2	P	NSE‡	ARE§
m^2 s^{-1}					
0.00111	$D_r = -0.1381 - 1.2564\ G + 0.2927\omega$	0.9707	<0.01	0.9707	25.3833
0.00156	$D_r = -0.3525 - 1.1212\ G + 0.3575\omega$	0.9658	<0.01	0.9658	19.9889
0.00200	$D_r = -0.3676 - 1.1058G + 0.3427\omega$	0.9674	<0.01	0.9674	21.9594
0.00244	$D_r = -0.2740 - 0.9972G + 0.3232\omega$	0.9672	<0.01	0.9672	11.0102
0.00289	$D_r = 0.0206 - 1.0001G + 0.3002\omega$	0.9802	<0.01	0.9802	9.1052
0.00333	$D_r = -0.0109 - 1.0178G + 0.3331\omega$	0.9813	<0.01	0.9813	9.6239
0.00378	$D_r = 0.1797 - 1.0823\ G + 0.3329\omega$	0.9721	<0.01	0.9721	11.5858

† In the equations, D_r is the soil detachment rate by sediment-laden rill flow (kg m^{-2} s^{-1}), G is the sediment load in rill flow (kg m^{-1} s^{-1}), and ω is stream power (W m^{-2}).

‡ NSE is the Nash-Sutcliffe efficiency.

§ ARE is the average relative error (%).

Table 6. Contribution of sediment load (*G*) and stream power (*ω*) to soil detachment rate for different slopes.

Slope	P_G†	P_ω‡	*Error*§
	%		
10.51	32.95	58.20	8.85
15.84	32.51	62.92	4.57
21.26	34.43	60.33	5.24
26.79	41.02	56.89	2.09
32.49	41.38	54.50	4.12
38.39	43.23	53.83	2.94

† P_G is the contribution rate of sediment load (%).

‡ P_ω is the contribution rate of stream power (%).

§ *Error* is the influence produced by error (%).

of sediment load on soil detachment rate holds accounts for almost one-third of the total effect of sediment load and stream power. The resistance factor of sediment load is essential to be introduced into the model equation of rill detachment to avoid the overestimation of rill erosion intensity. Moreover, stream power is the driving factor affecting the soil detachment process under the experimental conditions. Therefore, adopting soil and water conservation measures, such as contour tillage, to reduce surface flow and increase infiltration can control rill erosion effectively (Xi et al., 2012; Xu et al., 2013). Sadeghi et al. (2012) used the Taguchi method to investigate the contribution rate of different factors on soil erosion and sediment yield. This method was assessed by Zhang et al. (2015a) in inter-rill erosion and proved it to be timesaving and laborsaving. To explore the optimal method to quantify contribution, further studies should be performed to compare the contribution rate calculated by the Taguchi method and that calculated by the method adopted in this article.

CONCLUSIONS

The contribution of sediment load to soil detachment rate by sediment-laden rill flow was studied through a flume experiment under seven flow discharges, six slopes, and five sediment loads. Soil detachment rate by sediment-laden rill flow decreased linearly with the increase in sediment load. Stream power is the best hydrodynamic parameter in relation to soil detachment rate under different sediment loads. The comprehensive response correlation of soil detachment rate to sediment load and stream power is a binary linear equation. Sediment load is a resistance factor to the process of soil detachment and stream power is a driving factor. The contribution rate of sediment load to soil detachment rate by sediment-laden rill flow for all combinations is 33.96% and stream power is 64.39%. The negative effect of sediment load on soil detachment rate holds accounts for almost one-third of the total effect of sediment load and stream power. It is important to draw sediment load as a negative factor into process-based rill erosion model to predict erosion intensity. Meanwhile, adopting soil and water conservation measures to reduce surface flow so as to weaken the driving energy of stream power is effective for controlling rill erosion. This study can provide a feasible way for researchers to quantify the effect of factors on dependent variable, and can help to sufficiently understand rill erosion process and develop process-based rill erosion models. Further studies need to be conducted to apply other methods to calculate the contribution rate of sediment load to soil detachment rate and to explore the optimal one.

Table 7. Contribution rate of sediment load (*G*) and stream power (*ω*) to soil detachment rate for different unit flow discharges.

Unit flow discharge	P_G†	P_ω‡	*Error*§
$m^2\ s^{-1}$	%		
0.00111	36.91	60.16	2.93
0.00156	34.38	62.20	3.42
0.00200	35.86	60.88	3.26
0.00244	36.22	60.50	3.28
0.00289	43.63	54.39	1.98
0.00333	45.43	52.70	1.87
0.00378	49.47	47.74	2.79

†P_G is the contribute rate of sediment load (%).

‡ P_ω is the contribution rate of stream power (%).

§ *Error* is the influence produced by error (%).

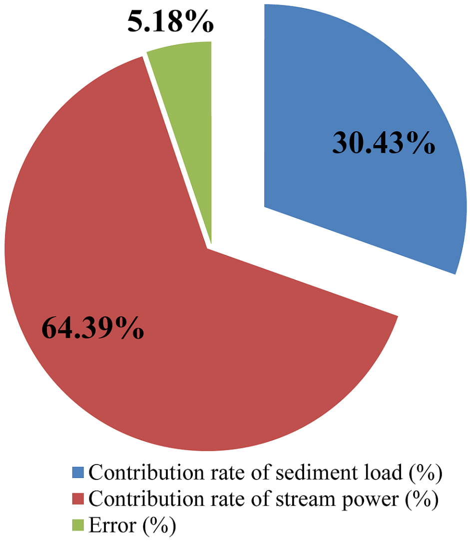

Fig. 8. The contribution rate of the factors sediment load and stream power to soil detachment rate.

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REFERENCES

Allen, M.P. 1986. Understanding regression analysis. J. Educ. Bus. 65(6):264–269.

Bagnold, R.A. 1966. An approach to the sediment transport problem from general physics. US Geol. Surv. Prof. Pap. 422(1):22–37.

Bennett, S.J., Y.T. Hou, and J.F. Atkinson. 2014. Turbulence suppression by suspended sediment within a geophysical flow. Environ. Fluid Mech. 14(4):771–794. doi:10.1007/s10652-013-9323-2

Cochrane, T.A., and D.C. Flanagan. 1997. Detachment in a simulated rill. Trans. ASAE 40(1):111–119.

DeRoo, A.P.J., C.G. Wesseling, and C.J. Ritsema. 1996. LISEM: A single-event physically based hydrological and soil erosion model for drainage basins.1. Theory, input and output. Hydrological Processes 10(8):1107–1117.

doi:10.13031/2013.21255

Elliot, W.J., and J.M. Laflen. 1993. A process-based rill erosion model. Trans. ASAE 36(1):65–72. doi:10.13031/2013.28315

Emmett, W.W. 1970. The hydraulics of overland flow on hillslopes. US Geol. Surv. Prof. Pap. A21. United States Department of the Interior, Washington, DC.

Escauriaza, C., and F. Sotiropoulos. 2011. Initial stages of erosion and bed form development in a turbulent flow around a cylindrical pier. Journal of Geophysical Research-Earth Surface 116(F3).

Flanagan, D.C., and M.A. Nearing, 1995. USDA Water Erosion Prediction Project hillslope and watershed model documentation. NSERL Rep. No. 10. USDA-ARS National Soil Erosion Research Laboratory, West Lafayette, IN.

Foster, G.R., and L.D. Meyer. 1972. A closed-form soil erosion equation for upland areas. In: Shen, H., editor, Sedimentation: Symp. to Honor Prof. H.A. Einstein. 17–19 June 1971. H.W. Shen, Fort Collins, CO. p. 12.1–12.17.

Foster, G.R., L.F. Huggins, and L.D. Meyer. 1984. A laboratory study of rill hydraulics. II. Shear stress relationships. Trans. ASAE 27(3):797–804. doi:10.13031/2013.32874

Foster, G.R. 1986. Understanding ephemeral gully erosion, Soil conservation, Vol. 2. National Academy of Science Press, Washington, DC. p. 90–125.

Gimenez, R., and G. Govers. 2002. Flow detachment by concentrated flow on smooth and irregular beds. Soil Sci. Soc. Am. J. 66(5):1475–1483. doi:10.2136/sssaj2002.1475

Govers, G., R. Gimenez, and K. Van Oost. 2007. Rill erosion: Exploring the relationship between experiments, modeling and field observations. Earth Sci. Rev. 84(3-4):87–102. doi:10.1016/j.earscirev.2007.06.001

Huoluo, H.N. 1983. The prediction of agricultural production effect. (translated into Chinese from Russian by J.W. Tan and T.F. Liu). Agriculture Press, Beijing.

Huang, C.H., J.M. Bradford, and J.M. Laflen. 1996. Evaluation of the detachment-transport coupling concept in the WEEP rill erosion equation. Soil Sci. Soc. Am. J. 60(3):734–739. doi:10.2136/sssaj1996.03615995006000030008x

Knapen, A., J. Poesen, G. Govers, G. Gyssels, and J. Nachtergaele. 2007. Resistance of soils to concentrated flow erosion: A review. Earth Sci. Rev. 80(1-2):75–109. doi:10.1016/j.earscirev.2006.08.001

Lei, T.W., Q.W. Zhang, J. Zhao, and M.A. Nearing. 2006. Tracing sediment dynamics and sources in eroding rills with rare earth elements. Eur. J. Soil Sci. 57(3):287–294. doi:10.1111/j.1365-2389.2005.00737.x

Lei, T.W., Q.W. Zhang, J. Zhao, W.S. Xia, and Y.H. Pan. 2002. Soil detachment rates for sediment loaded flow in rills. Trans. ASAE 45(6):1897–1903.

Li, G., A.D. Abrahams, and J.F. Atkinson. 1996. Correction factors in the determination of mean velocity of overland flow. Earth Surface Processes and Landforms 21(6):509–515.

Mahmoodabadi, M., H. Ghadiri, B. Yu, and C. Rose. 2014. Morpho-dynamic quantification of flow-driven rill erosion parameters based on physical principles. J. Hydrol. 514:328–336. doi:10.1016/j.jhydrol.2014.04.041

Merten, G.H., M.A. Nearing, and A.L.O. Borges. 2001. Effect of sediment load on soil detachment and deposition in rills. Soil Sci. Soc. Am. J. 65(3):861–868. doi:10.2136/sssaj2001.653861x

Meyer, L.D., and W.H. Wischmeier. 1969. Mathematical simulation of the processes of soil erosion by water. Trans. ASAE 12:0754–0758. doi:10.13031/2013.38945

Misra, R.K., and C.W. Rose. 1996. Application and sensitivity analysis of process-based erosion model GUEST. Eur. J. Soil Sci. 47(4):593–604. doi:10.1111/j.1365-2389.1996.tb01858.x

Morgan, R.P.C., J.N. Quinton, R.E. Smith, G. Govers, J.W.A. Poesen, K. Auerswald, G. Chisci, D. Torri, and M.E. Styczen. 1998. The European Soil Erosion Model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms 23(6):527–544.

Nearing, M.A., J.M. Bradford, and S.C. Parker. 1991. Soil detachment by shallow flow at low slopes. Soil Sci. Soc. Am. J. 55(2):339–357. doi:10.2136/sssaj1991.03615995005500020006x

Nearing, M.A., L.J. Lane, E.E. Alberts, and J.M. Laflen. 1990. Prediction technology for soil erosion by water. Soil Sci. Soc. Am. J. 54:1702–1711. doi:10.2136/sssaj1990.03615995005400060033x

Nearing, M.A., and S.C. Parker. 1994. Detachment of soil by flowing water under turbulent and laminar conditions. Soil Sci. Soc. Am. J. 58(6):1612–1614. doi:10.2136/sssaj1994.03615995005800060004x

Nearing, M.A., J.R. Simanton, L.D. Norton, S.J. Bulygin, and J. Stone. 1999. Soil erosion by surface water flow on a stony, semiarid hillslope. Earth Surface Processes and Landforms 24(8):677–686.

Nord, G., and M. Esteves. 2007. Evaluation of sediment transport formulae and detachment parameters in eroding rills using PSEM_2D and the Water Erosion Prediction Project (WEPP) database. Water Resour. Res. 43(8). doi:10.1029/2006WR005444

Owoputi, L.O., and W.J. Stolte. 1995. Soil detachment in the physically-based soil-erosion process–A review. Trans. ASAE 38(4):1099–1110. doi:10.13031/2013.27927

Polyakov, V.O., and M.A. Nearing. 2003. Sediment transport in rill flow under deposition and detachment conditions. Catena 51(1):33–43. doi:10.1016/S0341-8162(02)00090-5

Sadeghi, S.H., V. Moosavi, A. Karami, and N. Behnia. 2012. Soil erosion assessment and prioritization of affecting factors at plot scale using the Taguchi method. J. Hydrol. 448-449:174–180. doi:10.1016/j.jhydrol.2012.04.038

Shen, N., Z.L. Wang, and S. Wang. 2016. Flume experiment to verify WEPP rill erosion equation performances using loess material. J. Soils Sediments 16(9):2275–2285. doi:10.1007/s11368-016-1408-3

Sirjani, E., and M. Mahmoodabadi. 2014. Effects of sheet flow rate and slope gradient on sediment load. Arab. J. Geosci. 7(1):203–210. doi:10.1007/s12517-012-0728-x

Sun, L.Y., H.Y. Fang, D.L. Qi, J.L. Li, and Q.G. Cai. 2013. A review on rill erosion process and its influencing factors. Chin. Geogr. Sci. 23(4):389–402. doi:10.1007/s11769-013-0612-y

Wang, D.D., Z.L. Wang, N. Shen, and H. Chen. 2016. Modeling soil detachment capacity by rill flow using hydraulic parameters. J. Hydrol. 535:473–479. doi:10.1016/j.jhydrol.2016.02.013

Wang, H.Y., F.T. Yang, and L. Liu. 2006. The comparison of standardized coefficient and partial correlation coefficient and application (in Chinese). Journal of Quantitative Technical Economics 23(9):150–155.

Wang, Z.Y., and P. Larsen. 1994. Turbulent structure of water and clay suspensions with bed-load. J. Hydraul. Eng. 120(5):577–600. doi:10.1061/(ASCE)0733-9429(1994)120:5(577)

Wilson, B.N. 1993. Development of a fundamentally based detachment model. Trans. ASAE 36(4):1105–1114. doi:10.13031/2013.28441

Xi, T.H., S.W. Fang, M.H. Mo, J. Yang, and H.J. Zheng. 2012. Effect of soil and water conservation measures on runoff and sediment reduction in red-soil slope land, Poyang Lake Basin. Adv. Mater. Res.-Switz. 518-523:4599–4603.

Xu, Q.X., T.W. Wang, C.F. Cai, Z.X. Li, Z.H. Shi, and R.J. Fang. 2013. Responses of runoff and soil erosion to vegetation removal and tillage on steep lands. Pedosphere 23(4):532–541. doi:10.1016/S1002-0160(13)60046-6

Yang, C.T. 1972. Unit stream power and sediment transport. J. Hydraul. Div. 98:1805–1826.

Yang, C.T. 1976. Minimum unit stream power and fluvial hydraulics. J. Hydraul. Div. 102:919–934.

Zhang, F.B., Z.L. Wang, and M.Y. Yang. 2015a. Assessing the applicability of the Taguchi design method to an interrill erosion study. J. Hydrol. 521:65–73. doi:10.1016/j.jhydrol.2014.11.059

Zhang, G.H., Y.M. Liu, Y.F. Han, and X.C. Zhang. 2009a. Sediment transport and soil detachment on steep slopes: II. Sediment feedback relationship. Soil Sci. Soc. Am. J. 73(4):1298–1304. doi:10.2136/sssaj2009.0074

Zhang, G.H., Y.M. Liu, Y.F. Han, and X.C. Zhang. 2009b. Sediment transport and soil detachment on steep slopes: I. Transport capacity estimation. Soil Sci. Soc. Am. J. 73(4):1291–1297. doi:10.2136/sssaj2008.0145

Zhang, G.H., R.C. Shen, R.T. Luo, Y. Cao, and X.C. Zhang. 2010. Effects of sediment load on hydraulics of overland flow on steep slopes. Earth Surf. Process. Landf. 35(15):1811–1819. doi:10.1002/esp.2019

Zhang, L.T., Z.L. Gao, S.W. Yang, Y.H. Li, and H.W. Tian. 2015b. Dynamic processes of soil erosion by runoff on engineered landforms derived from expressway construction: A case study of typical steep spoil heap. Catena 128:108–121. doi:10.1016/j.catena.2015.01.020

Zhang, Q.W., Y.Q. Dong, F. Li, A.P. Zhang, and T.W. Lei. 2014. Quantifying detachment rate of eroding rill or ephemeral gully for WEPP with flume experiments. J. Hydrol. 519:2012–2019. doi:10.1016/j.jhydrol.2014.09.040

Zhang, X.C., Z.B. Li, and W.F. Ding. 2005. Validation of WEPP sediment feedback relationships using spatially distributed rill erosion data. Soil Sci. Soc. Am. J. 69:1440–1447. doi:10.2136/sssaj2004.0309