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Identifying sediment transport capacity of raindrop-impacted overland flow within transport-limited system of interrill erosion processes on steep loess hillslopes of China

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ABSTRACT

Interrill erosion processes typically involve such scientific issues as detachment-limited and transport-limited erosion behaviour. An accurate estimation of the sediment transport capacity (T_c) by raindrop-impacted overland flow is critical for interrill erosion modelling and for evaluating sediment budgets under erosion-limiting conditions. Simulated rainfall experiments with rainfall intensities from 0.8 to 2.5 mm min^{-1} over a three-area soil pan with slope gradients from 12.7% to 46.6% were conducted to identify the transport-limited cases and determine T_c by raindrop-impacted overland flow within the transport-limited systems of interrill erosion processes. Results indicated that T_c increased as a power function of rainfall intensity and slope gradient (R^2 = 0.84, NSE = 0.75), and T_c was more sensitive to rainfall intensity than to slope gradient. In terms of R^2 and NSE, stream power was the key hydraulic parameter that influenced T_c among flow velocity (R^2 = 0.64, NSE = 0.39), shear stress (R^2 = 0.53, NSE = 0.23), stream power (R^2 = 0.76, NSE = 0.52) and unit stream power (R^2 = 0.49, NSE = 0.16). The addition of rainfall physical parameters in response equations of T_c in addition to hydraulic parameter, could improve an accuracy of T_c modelling. Stream power combined with rainfall kinetic energy can best describe the T_c of raindrop-impacted overland flow within the transport-limited system of interrill erosion processes by a power-exponent function (R^2 = 0.90, NSE = 0.72). Rainfall kinetic energy can reduce the Darcy-Weisbach resistance coefficient of raindrop-impacted overland flow and thus benefit sediment transporting. This study provides another method for directly identifying the T_c of raindrop-impacted overland flow in interrill erosion processes on steep loess slopes, and points out that rainfall impacts should be particularly considered when studying T_c by raindrop-impacted overland flow.

1. Introduction

Interrill erosion occupies a pivotal position in the erosional system, which connects rainfall erosivity with those erosion triggered by concentrated flow (e.g., micro rills, rills and gullies) (Favis-Mortlock, 2002; Issa et al., 2006). In a typical hillslope erosional system, many important scientific issues, such as erosion-limiting and particle size selectivity, are implicitly involved in interrill erosion, and one of these issues is the sediment transport capacity (T_c) of raindrop-impacted overland flow.

T_c is a critical concept in understanding and modelling soil erosion processes (Yu et al., 2016). It can be used to (1) represent the potential site-specific sediment flux in water flows, (2) provide a basic indicator for identifying detachment and deposition locations, and (3) upscale for actual regional erosion rates (Prosser and Rustomji, 2000; Yu et al., 2015, 2016). In the context of interrill erosion, T_c can be defined as the maximum equilibrium sediment load that an interrill flow can carry in a given width per unit time for a given soil under given hydraulic and rainfall conditions (Zhang and Wang, 2017). The improved accuracy of interrill erosion and sediment production estimation largely depends on

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the enhanced reliability of T_c determination, especially for highly erodible areas on steep loess hillslope of China.

Simple hydraulic predictor variables (e.g., shear stress, stream power, unit stream power) are often used to estimate the T_c of overland flow. For example, flow shear stress has been successfully used in the Yalin equation (Yalin, 1963). Gilley et al. (1985) used a combination of the soil transport factor, bottom shear stress and flow velocity to estimate the T_c of overland flow. Bagnold (1966) related the T_c of overland flow to stream power. Ferro (1998) and Everaert (1991) proposed that the ability of effective stream power can be used as a predictor of T_c by rainfall-disturbed overland flows. Li and Abrahams (1999) suggested that the capability of laminar interrill flow to transport sediments was positively related to excess flow power. Li et al. (2011) and Yu et al. (2015) concluded that stream power was the best predictor for the T_c of rainfall-impacted overland flow. In addition, because hydrodynamic parameters cannot be measured directly, a simple equation ($T_c = k_1 q^{\beta} S^{\gamma}$) was developed and widely used for T_c estimation (where T_c is the sediment transport capacity per unit width of slope; q is discharge per unit width; S is the slope gradient; and k_1, β, and γ are empirical or theoretically derived constants) (Prosser and Rustomji, 2000). Prosser and Rustomji (2000) reviewed the relevant models and suggested that the recommended values for β and γ were $1.0 \le \beta \le 1.8$ and $0.9 \le \gamma \le 1.8$, respectively.

Raindrop impact plays an important role in affecting T_c. Foster (1982) and Singer and Walker (1983) found that T_c is strongly enhanced by raindrop impact and the enhancement depends on rainfall intensity and bed slope. Guy et al. (1987) found a similar enhancement of T_c from rainfall and concluded that T_c could be modelled reasonably well using squared rainfall intensity values. Julien and Simons (1985) proposed a T_c model for raindrop-impacted overland flow. The model is presented as: $q_s = b_0 q^{b1} S^{b2} I^{b3} (1\text{-}\tau_{0cr}/\tau_0)^{b4}$ (where q_s is the unit width sediment discharge ($m^2\,s^{-1}$), S is the slope gradient, q is the unit width flow discharge ($m^2\,s^{-1}$), I is the rainfall intensity ($m\,s^{-1}$), τ is the shear stress (Pa), and τ_{0cr} is the critical shear stress (Pa)). Guy (1987) found that the T_c equation for raindrop-impacted overland flow could be a two-component additive model ($q_s = (q_{sf} + q_{sr})$, where q_s is the transport capacity, q_{sf} is the contribution to transport capacity from flow, and q_{sr} is the contribution of rainfall impact to the transport capacity). Rudra et al. (2007) calibrated Guy's model as $q_{sr} = 10^{6.80}\, q^{0.82}\, I^{0.99}\, \sin\theta^{1.13} \rho^{b4}$, which indicated that the T_c was substantially affected by rainfall intensity, discharge, slope gradient, and relative density. Hui-Ming and Yang (2009) recommended the following equation to estimate the sediment capacity of rainfall-impacted overland flow: $C_{mgl} = 1.922 \times 10^6 (1 - e^{-(MP^N)I})$ (where C_{mgl} is the sediment concentration ($mg\,L^{-1}$), P is the unit stream power ($m\,s^{-1}$), I is the rainfall impact (which is a function of rainfall intensity), and M and N are coefficients determined by slope, flow velocity, and Froude number). Li et al. (2011) proposed a new equation for estimating the T_c of raindrop-impacted overland flow, which is a function of dimensionless stream power, rainfall-impacted critical dimensionless stream power and slope.

In addition, due to the technical difficulties in continuously observing the variations in raindrop-impacted overland flow-driven sediment dynamics and the limited availability of effective data sets, several available equations for estimating the T_c of raindrop-impacted overland flow are derived from those established for riverbeds or flume experiments. For example, Foster and Meyer (1972) suggested that Yalin's bed load equation (Yalin, 1963) performed favourably for rainfall-impacted overland flow. Abrahams et al. (2001) developed a model for predicting the T_c of turbulent interrill flow with datasets from 1295 flume experiments, and it showed good applicability for interrill flows both with and without rainfall.

Overall, studies that were oriented exclusively towards T_c by raindrop-impacted overland flows have not yet been extensively and systematically conducted, especially on the loess hillslopes in China. Moreover, it was few that T_c is directly obtained from the practical interrill erosion processes caused by raindrop-impacted overland flow during the rainfall processes. This heavily affected an exact modelling of T_c and the interrill erosion process driven by raindrop-impacted overland flow.

The objectives of this study were, based on separating T_c ($kg\,m^{-2}\,s^{-1}$) from the interrill erosion rate ($kg\,m^{-2}\,s^{-1}$) by raindrop-impacted overland flow within transport-limited interrill erosion processes on steep loess hillslopes of China, (1) to explore the response of the T_c to rainfall intensity and slope gradient and to determine the responding equation for clarifying variation features of the T_c with different rainfall intensities and slopes; and (2) to determine the optimal related hydraulic parameter and rainfall physical parameter to the T_c and the corresponding relationship equation for revealing the dynamic mechanism that drives T_c.

2. Materials and methods

2.1. Experimental soil samples

The soil used in this study was collected from Ansai County (109°19′ E, 36°51′ N) in Shaanxi Province of China, which is located in the middle part of the Loess Plateau. The soil was sampled from a depth of 0–25 cm on cultivated land. The soil is composed of 34.0% sand (> 0.05 mm), 56.1% silt (0.05–0.002 mm), and 9.9% clay (< 0.002 mm). The soil is poorly aggregated and readily detachable with a median diameter of 0.039 mm and composed of 0.5% organic matter.

2.2. Experimental setup

Laboratory experiments were performed in the simulated rainfall hall operated by the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling, Shaanxi Province, China. A side-spraying simulated rainfall system with a rainfall height of 16 m above the soil surface was used in this study. The system can produce desired rainfall intensities ranging from 30 to 200 $mm\,h^{-1}$ with a uniformity of more than 85% (Chen and Wang, 1991). Tap water (electrical conductivity = 0.7 $dS\,m^{-1}$) was used during all of the trials.

A three-area soil pan made of stainless steel sheets and with dimensions of 140 cm (L) × 120 cm (W) × 25 cm (D) was used in this study, which integrated a test area, a complementary border area and splash slots. A test area with dimensions of 80 cm (L) × 60 cm (W) × 25 cm (D) was placed at the centre of the soil pan. Splash slots of 80 cm (L) by 2.5 cm (W) were attached to the left and right sides of the test area. A 27.5 cm wide complementary border area surrounded the test area and splash slots. The border area was filled with soil in the same manner as the test area to equalize the opportunity for splash both onto and off the test area. A slot was created along the lower end of the test area for collecting runoff and washed sediments. Several 0.5-cm diameter apertures were created at the bottom of the soil pan to allow excess water to freely infiltrate. The three-area soil pan used in this study was the same as that utilized in Wu et al. (2017, 2018). The soil pan picture and more details about it are provided in Wu et al. (2018).

2.3. Experimental design

Six slope gradients (12.3, 17.6, 26.8, 36.4, 40.4, and 46.6%) and six rainfall intensities (0.8, 1.0, 1.5, 2.0, 2.3, and 2.5 mm/min) were designed for the study. The slope gradients were designed based on the distribution of slope gradients within the erosional environment of the Loess Plateau and the "Grain for Green" Project, which proposed that the upper limit of the cultivation slope was 46.6% (Tang et al., 1998). According to the long-term rainfall records in this region, rainfall intensities were chosen at the range of 0.8 to 2.5 $mm\,min^{-1}$ because accelerated soil erosion was frequently derived from erosive rainfall events having these intensities. Two replications were performed for each rainfall intensity-slope gradient combination in our study and a total of 72 simulated rainfall events were performed.

2.4. Experimental procedures

Soil used in the test was collected from the study area, and dried and sieved through a 5-mm mesh sieve. The soil was then evenly mixed and compacted in the soil pan to a depth of 20 cm with four successive 5 cm-thick layers over a 5 cm-thick layer of coarse sand for water drainage. To diminish the discontinuity between layers, every layer was gently scraped before the upper layer was packed. Prior to the launch of each run, the packed soil was maintained at a constant bulk density of 1.2 g m^{-3} and the antecedent soil moisture was gravimetrically maintained at approximately 14% for each run.

The time duration for each simulated rainfall event was approximately 45 min and no rills were initiated during each event. For each run, samples of splashed sediments, runoff and washed sediments were collected within 6 min after runoff occurred at 1-, 2-, and 3-min intervals for the first 3 samples and then at 3-min intervals for the remaining samples. Hence, a total of 15 sets of samples were collected. Once collected, the splash samples were oven-dried, and the dry weights were used to determine the splash erosion rates. Both the wet and dry weights of runoff and washed samples were measured to calculate the water discharges, sediment concentrations, and interrill erosion rates. In addition, surface flow velocities were measured using a $KMnO_4$ solution as a tracer along a 50-cm segment at two locations that were located 15 cm from the upper boundary of the test area and 15 cm from each side wall of the test area.

2.5. Data calculation and analysis

2.5.1. Theoretical basis of the data source

Interrill erosion sub-processes include detachment by raindrop with sediment transport by raindrop-impacted overland flow; or, detachment by both raindrop and raindrop-impacted overland flow, with sediment transport by raindrop-impacted overland flow.

In this study, the variations of the splash erosion rates (kg m^{-2} s^{-1}) and interrill erosion rates (kg m^{-2} s^{-1}) with time during rainfall events can be obtained easily. Based on the obtained splash erosion rates and the interrill erosion rates by synchronous observations of splash erosion and interrill erosion within a three-area soil pan, soil erosion-limiting processes (transport-limiting and detachment-limiting) are defined in this study according to the relatively equilibrium relationships between splashed sediments and washed sediments, which is the same as that reported by Wu et al (2018). Based on the determination of interrill erosion-limiting processes, the transport-limited data sets were easier to single out from individual simulated events to determine the T_c of raindrop-impacted overland flow under typical transport-limiting regimes. A total of 155 data sets were singled out from the rainfall process-based instantaneous data of 34 rainfall intensity-slope gradient combinations, except for the combinations of a slope gradient of 46.6% and rainfall intensities of 2.3 and 2.5 mm/min, under which the whole erosion processes of the rainfall event were subject to detachment-limited conditions.

2.5.2. Sediment transport capacity (T_c) of raindrop-impacted overland flow

All the data were selected from the transport-limited phases of each interrill erosion process event produced by simulated rainfall. Thus, the values of the raindrop-impacted overland flow transport capacities (T_c) were equal to those of the interrill erosion rates obtained under transport-limited conditions.

2.5.3. Flow velocity (V)

The dye method measures the preferential surface flow velocity (V_s) and the mean flow velocity (V) is derived by multiplying the surface flow velocity (V_s) by a correction factor (α).The formula is as follows:

$$V = \alpha V_s, \tag{1}$$

where the correction factor (α) is less than 1. A correction factor of 0.67 for laminar flow regimes (Horton et al., 1934) was used in the current study because raindrop-impacted overland flows within a transport-limited interrill erosion system were all laminar flows in this study.

2.5.4. Hydrodynamic parameters

Flow shear stress (τ) (Nearing et al., 1991), stream power (Ω) (Bagnold, 1966), and unit stream power (ω) (Yang, 1972) were used in this study, and the formulas are as follows:

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

where τ is the flow shear stress (Pa), ρ is the density of water (kg m^{-3}), g is the gravitational constant (m s^{-2}), h is the flow depth (m), and S is the sine of the bed slope (m m^{-1}).

$$\Omega = \tau V, \tag{3}$$

where Ω is the stream power (W m^{-2}) and V is the flow velocity (m s^{-1}).

$$\omega = VS, \tag{4}$$

where ω is the unit stream power (m s^{-1}).

2.5.5. Rainfall parameters

In this study, a disdrometer (Thies Clima, Germany) was used to measure the rainfall characteristics, including the following rainfall parameters: rainfall kinetic energy (KE, J m^{-2} h^{-1}), raindrop terminal velocity (v, m s^{-1}), and raindrop median volume diameter (D_{50}, mm) (Table 1).

2.6. Data analysis

The average relative error of the statistics parameters (ARE, %), the coefficient of determination (R^2), and the Nash-Sutcliffe Efficiency Index (NSE) (Nash and Sutcliffe, 1970)were used to evaluate the performance of empirical equations based on experimental data. Formulas for ARE, R^2 and NSE are as follows:

$$ARE=\frac{1}{N}\sum_{i=1}^{n}\frac{(O_i - P_i)}{O_i} \times 100, \tag{5}$$

$$R^2 = \frac{[\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})]^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(P_i - \bar{P})^2}, \tag{6}$$

$$NSE=1-\frac{\sum (O_i - P_i)^2}{\sum (O_i - \bar{O}_i)^2}, \tag{7}$$

where O_i are measured values, P_i are calculated values, $\bar{O}$ is the mean of the measured values, and $\bar{P}$ is the mean of the calculated values.

Regression analysis and test of significance were used to analyse the results obtained.

Table 1
The rainfall kinetic energy (KE), raindrop median volume diameter (D50) and raindrop terminal velocity (v) produced by simulated rainfall.

I (mm min^{-1})	D50 (mm)	V (m s^{-1})	KE (J m^{-2} h^{-1})
0.7	1.52	1.5	201.76
1.0	1.60	2.7	354.85
1.5	1.64	3.8	495.92
2.0	2.00	6.5	848.82
2.5	2.70	8.1	1059.95

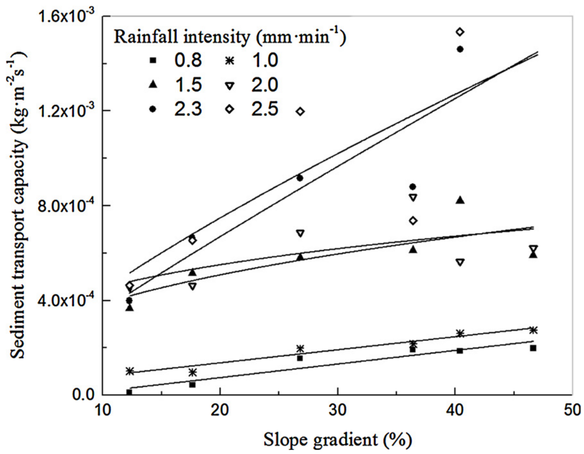

Fig. 1. Sediment transport capacity (T_c) varying with slope gradients under different rainfall intensities.

3. Results

3.1. Effect of rain intensity and slope gradient on T_c

Figs. 1 and 2 display the variations of the T_c in response to different rainfall intensities and slope gradients. There was an indication of a general tendency towards T_c increasing with increasing rainfall intensity and slope gradient.

A slight increase in T_c was observed as slope gradient increased when the rainfall intensity was 0.8, 1.0, 1.5 and 2.0 mm min^{-1} (Fig. 1). The T_c under relatively high rainfall intensities (1.5, 2.0 mm min^{-1}) ranged between 0.0004 and 0.0009 kg m^{-2} s^{-1}, which was twice as much as that under low intensities (0.8, 1.0 mm min^{-1}) (Fig. 1). However, there was a marked increase in T_c as the slope gradient increased when the rainfall intensity was 2.3 and 2.5 mm min^{-1}, respectively. The values of T_c varied from 0.0004 to 0.0016 kg m^{-2} s^{-1}, with a maximum value that was approximately twice as much as that under rainfall intensities of 1.0 and 1.5 mm min^{-1} (Fig. 1). A regression analysis was performed to obtain the correlation between T_c and slope gradient under different rainfall intensities, which can be described by a linear or power equation, as shown in Table 2.

As illustrated in Fig. 2, there was a general increasing trend of the T_c as the rainfall intensity increased under different slope gradients. The increase rate gradually decreased with the increasing rainfall intensity when the slope gradient was relatively gentle (12.3%, 17.6%), and the correlation between T_c and rainfall intensity was a logarithmic relationship (Table 3). However, as the slope gradient became steeper (from 26.8 to 46.6%), the increase rate increased with the increasing rainfall intensity, which can be described by power equation under each slope gradient (Table 3).

To evaluate the responding relationship of T_c to variations of rainfall intensity and slope gradient, a multivariate regression analysis was conducted to establish a regression equation to fit the measured T_c. The equation is as follows:

$$T_c = 8.6 \times 10^{-6} \quad I^{1.98} \quad S^{0.90} \quad (R^2 = 0.84, \quad \text{NSE} = 0.75, \quad P < 0.01, \quad n = 34), \tag{8}$$

where T_c is the sediment transport capacity (kg m^{-2} s^{-1}), I is the rainfall intensity (mm min^{-1}), and S is the slope gradient (%).

The estimated T_c using Eq. (8) appears to satisfactorily match the measured T_c with $R^2 = 0.84$, and NSE = 0.75. Fig. 3 shows good agreement between the calculated and measured sediment transport capacities. Furthermore, the exponents of the rainfall intensity and the slope gradient were 1.98 and 0.90, respectively. The exponent indicated

Table 2
Relationship between sediment transport capacity and slope gradient under different rainfall intensities.

Rainfall intensities (mm min^{-1})	Regression equations	R^2	n	P
0.8	$T_c = 6 \times 10^{-6}S\text{-}4 \times 10^{-5}$	0.89	34	< 0.01
1.0	$T_c = 6 \times 10^{-6}S + 3 \times 10^{-5}$	0.94	34	< 0.01
1.5	$T_c = 1 \times 10^{-4}S^{0.428}$	0.72	34	< 0.01
2.0	$T_c = 2 \times 10^{-4}S^{0.311}$	0.47	34	< 0.01
2.3	$T_c = 5 \times 10^{-5}S^{0.892}$	0.88	34	< 0.01
2.5	$T_c = 7 \times 10^{-5}S^{0.772}$	0.65	34	< 0.01

Where T_c the sediment transport capacity (kg m^{-2} s^{-1}), S is the slope gradient (%), R^2 is the coefficient of determination, n is the sample numbers and P is the significance level.

Table 3
Relationship between sediment transport capacity and rainfall intensities under different slope gradients.

Slope gradient (%)	Regression equations	R^2	n	P
12.28	$T_c = 4 \times 10^{-4}\ln(I) + 1 \times 10^{-4}$	0.92	34	< 0.01
14.63	$T_c = 6 \times 10^{-4}\ln(I) + 2 \times 10^{-4}$	0.92	34	< 0.01
26.79	$T_c = 2 \times 10^{-4}I^{1.7731}$	0.97	34	< 0.01
36.40	$T_c = 3 \times 10^{-4}I^{1.4225}$	0.91	34	< 0.01
40.40	$T_c = 3 \times 10^{-4}I^{1.7731}$	0.88	34	< 0.01

Where T_c the sediment transport capacity (kg m^{-2} s^{-1}), I is the rainfall intensity (mm min^{-1}), R^2 is the coefficient of determination, n is the sample numbers and P is the significance level.

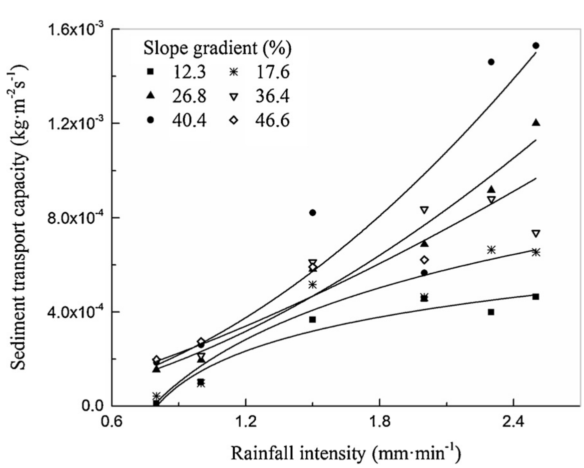

Fig. 2. Sediment transport capacity (T_c) varying with rainfall intensities under different slope gradients.

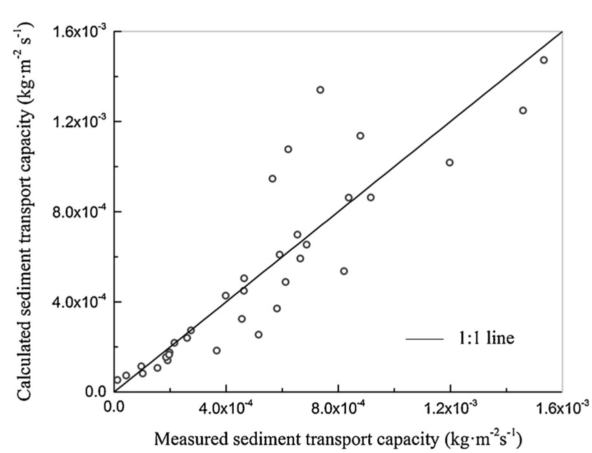

Fig. 3. Measured vs. calculated sediment transport capacity (T_c) (using Eq. (8)).

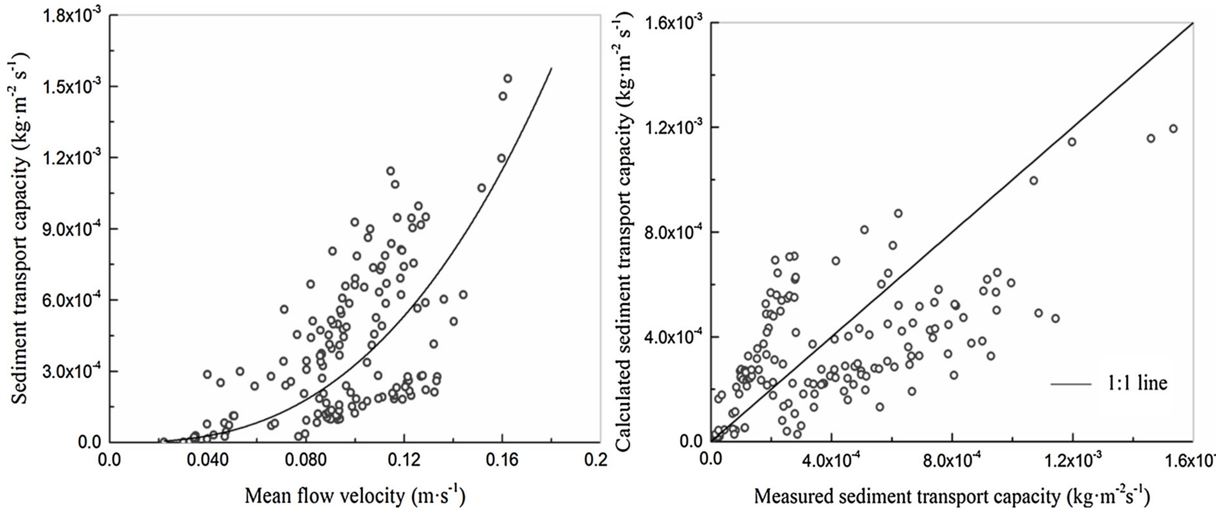

Fig. 4. Sediment transport capacity (T_c) as a function of mean flow velocity (V).

that the T_c of raindrop-impacted overland flow for transport-limited interrill erosion processes was more sensitive to rainfall intensity than to slope gradient.

3.2. Response of T_c to hydraulic parameters

3.2.1. Response of T_c to mean flow velocity

The mean flow velocity is a key factor affecting the hydraulic properties of raindrop-impacted overland flow and T_c. Fig. 4 indicates that the T_c increased with increases in the mean flow velocity. The best-fitting equation for evaluating the measured T_c with the mean flow velocity was a power function equation (Fig. 4, Eq. (9)):

$$T_c = 0.154V^{2.67}\ (R^2 = 0.64,\ NSE = 0.39,\ \text{P} < 0.01,\ \text{n} = 155), \quad (9)$$

where V is the mean flow velocity (m s^{-1}).The estimated T_c using Eq. (9) did not satisfactorily match the T_c with $R^2 = 0.64$, and $NSE = 0.39$. The disparity suggested that the mean flow velocity was not a good predictor for the T_c of raindrop-impacted overland flow in transport-limited interrill erosion systems.

3.2.2. Response of T_c to hydrodynamic parameters

Fig. 5 shows the responding relationship of T_c to flow shear stress. The best-fitting equation for evaluating the T_c with shear stress was represented in the form of a power function (Fig. 5, Eq. (10)):

$$T_c = 0.015\tau^{1.86}\ (R^2 = 0.53,\ NSE = 0.23,\ \text{P} < 0.01,\ \text{n} = 155), \quad (10)$$

where τ is the flow shear stress (Pa). The estimated T_c using Eq. (10) did not match the measured T_c with $R^2 = 0.53$ and $NSE = 0.23$. The disparity suggested that the flow shear stress was not a good predictor for T_c in the current study.

Fig. 6 shows that the measured T_c also increased with unit stream power as a power function relationship of unit stream power. The best-fitting equation is as follows (Fig. 6, Eq. (11)):

$$T_c = 0.032\omega^{1.24}\ (R^2 = 0.49,\ NSE = 0.16,\ \text{P} < 0.01,\ \text{n} = 155) \quad (11)$$

whereω is the unit stream power (m s^{-1}). The estimated T_c using Eq. (11) did not match the measured T_c with $R^2 = 0.49$, and $NSE = 0.16$. The disparity suggested that unit stream power was not a good predictor for T_c in this study.

The responding relationship of T_c to stream power is shown in Fig. 7. It indicates that a power function relationship existed between T_c and stream power (Fig. 7, Eq. (12)):

$$T_c = 0.202\Omega^{1.45}\ (R^2 = 0.76,\ NSE = 0.52,\ \text{P} < 0.01,\ \text{n} = 155), \quad (12)$$

whereΩ is the stream power (W m^{-2}).The estimated T_c using Eq. (12) matched the measured T_c satisfactorily with $R^2 = 0.76$, and $NSE = 0.52$ and suggested that stream power was a good predictor for T_c in this

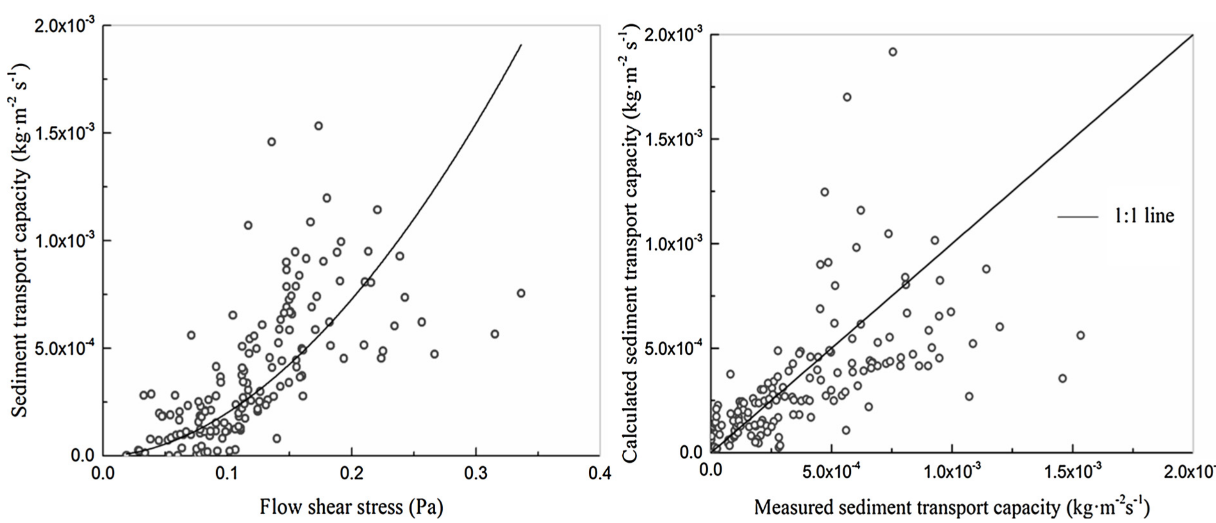

Fig. 5. Sediment transport capacity (T_c) as a function of flow shear stress (τ).

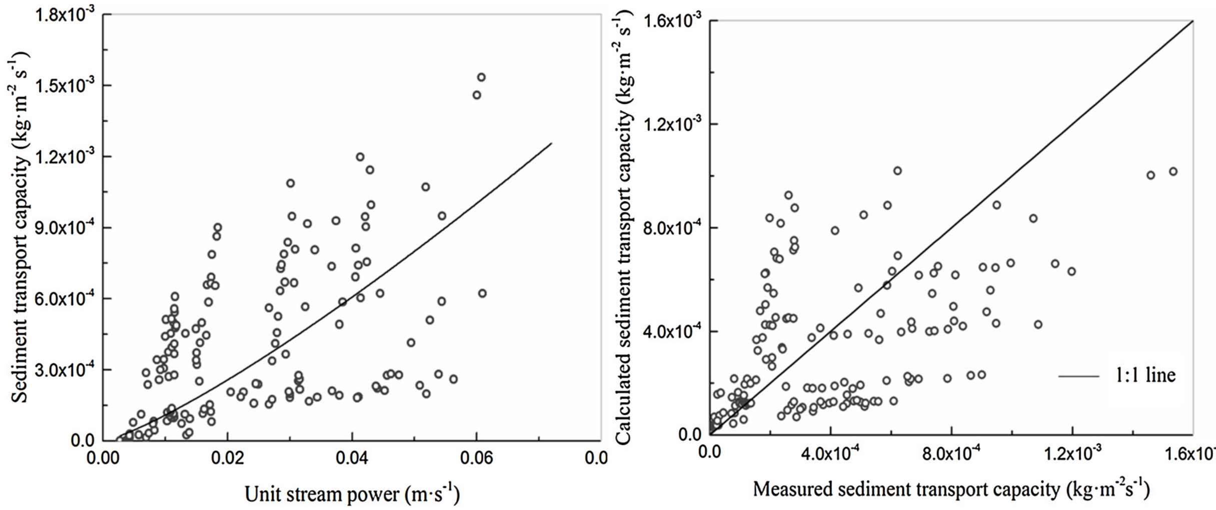

Fig. 6. Sediment transport capacity (T_c) as a function of unit stream power (ω).

study.

Given the above, it is indicated that stream power is the best hydrodynamic parameter for calculating the T_c by raindrop-impacted overland flow under the transport-limited regimes of interrill erosion processes in this study.

3.3. Comprehensive response of T_c to steam power and rainfall parameters

In addition to the influence of overland flow hydrodynamic parameter on T_c, raindrop impacts also played a non-negligible role in affecting T_c. In this study, rainfall kinetic energy (*KE*), raindrop terminal velocity (v) and raindrop median volume diameter (D_{50}) were used as rainfall parameters to analyse their influence on T_c.

Considering the comprehensive actions of both overland flow hydrodynamic parameter and raindrop impacts to T_c, multiple regression analyses were performed to analyse the comprehensive response relationships of T_c to stream power (Ω) and rainfall kinetic energy (*KE*), raindrop terminal velocity (v), raindrop median volume diameter (D_{50}), respectively. The obtained equations were respectively as follows:

$$T_c = 1.57 \times 10^{-41}\Omega^{2.88}KE^{16.11}e^{(-0.015KE-99.45\Omega+3555.16/KE+0.011/\Omega-1.99/(KE\times\Omega))}$$
$$(R^2 = 0.90,\ NSE = 0.72,\ P < 0.01,\ n = 155), \quad (13)$$

$$T_c = 4.77 \times 10^{-7}\Omega^{2.89}v^{15.58}e^{(-1.95v-100.18\Omega+25.96/v+0.01/\Omega-0.01/(v\times\Omega))}$$
$$(R^2 = 0.88,\ NSE = 0.67,\ P < 0.01,\ n = 155), \quad (14)$$

$$T_c = 1.59 \times 10^{72}\Omega^{1.8}D_{50}^{-240.56}e^{(59.03D_{50}-18.89\Omega-236.37/D_{50}+0.05/\Omega-0.08/(\Omega\times D_{50}))}$$
$$(R^2 = 0.85,\ NSE = 0.70,\ P < 0.01,\ n = 155), \quad (15)$$

where *KE* is the rainfall kinetic energy ($J\,m^{-2}\ h^{-1}$),v is the raindrop terminal velocity ($m\,s^{-1}$), and D_{50} is the raindrop median volume diameter (mm).

Comparing Eqs. (13)–(15) with Eq. (12) respectively showed that the comprehensive response relationships of T_c to steam power and rainfall parameters were obviously superior to that of T_c to stream power, improving significantly the R^2 and *NSE* of the equations or the accuracy of T_c predicting. Besides, the comparison of R^2 and *NSE* in Eqs. (13)–(15), as well as Fig. 8, revealed that stream power combined with rainfall kinetic energy were the best for describing T_c within transport-limited system of interrill erosion processes in this study.

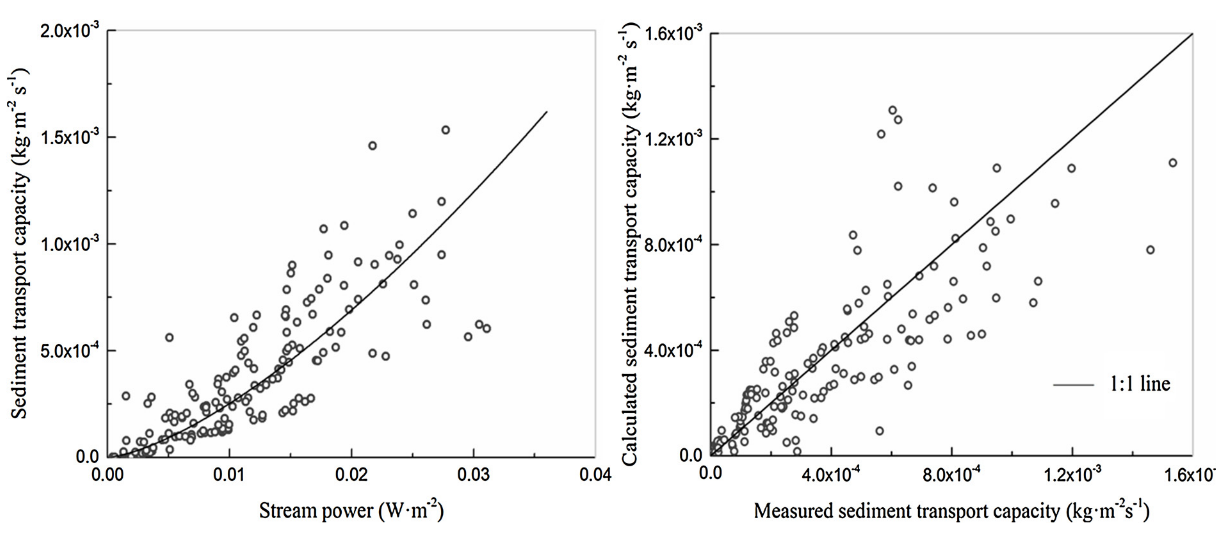

Fig. 7. Sediment transport capacity (T_c) as a function of stream power (Ω).

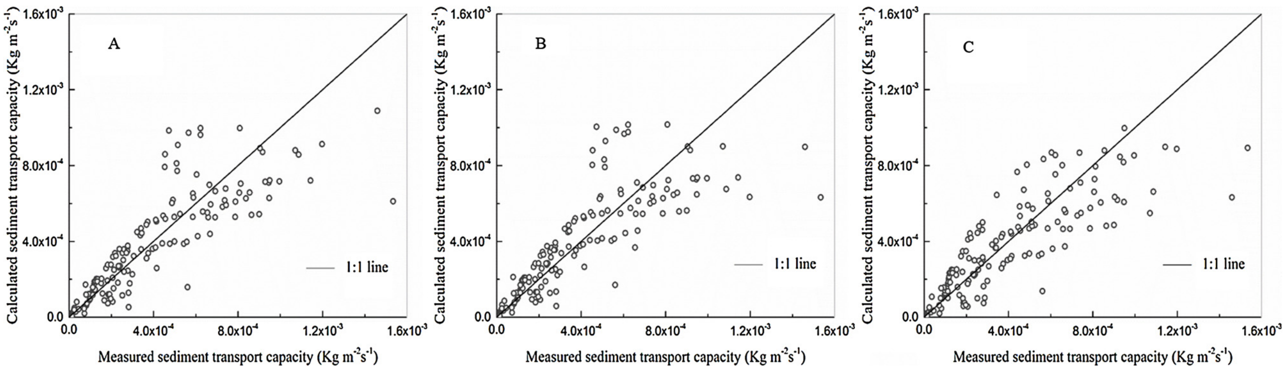

Fig. 8. Measured vs. calculated sediment transport capacity (using Eqs. (13)–(15), respectively).

4. Discussion

4.1. Effects of rainfall intensity and slope gradient on T_c of raindrop-impacted overland flow

Rainfall intensity and slope gradient are the important controlling factors that influence the T_c of raindrop-impacted overland flow within a transport-limited interrill erosion system. The study results showed that T_c increased with rainfall intensity and slope gradient increased, respectively. Rainfall intensity mainly influences how much overland flow was produced and influences the hydraulic patterns of overland flow by generating local turbulence (Yoon and Wenzel, 1971; Guy et al., 1987). The higher the rainfall intensity is, the more overland flow is produced, and the stronger the local turbulence of the overland flow is. Therefore, T_c increased with the increase of rainfall intensity, which is similar with that reported by Guy et al (1987). Slope gradient influences not only the movement status of overland flow, but also the stability of the sediments on slopes. The steeper the slope gradient is, the greater the component of the overland flow power along the slope is, and the less the stability of the sediments on slopes is. Therefore, T_c also increased with the increase of slope gradient, which is similar with that reported by Prosser and Rustomji (2000) and Ali et al. (2012). In addition, the study showed that when the slope gradient is gentle (12.3%, 17.6%), an upper limit of T_c may exist with increasing rainfall intensities, and the relationship between T_c and rainfall intensity can be described by logarithmic equation. Nevertheless, the T_c continually increased with increasing rainfall intensities under steep slope gradient conditions (26.8%–46.6%) and there were power function relationships between T_c and rainfall intensity (Fig. 2). These explained that more attention should be paid to steeper slope gradients of 26.8%–46.6% in implementing erosion control measures to prevent interrill erosion on hillslopes.

In this study, a power function of rainfall intensity and slope gradient was developed to estimate the T_c of raindrop-impacted overland flow in transport-limited interrill processes. The exponent of rainfall intensity is 1.98, which is similar to that from Guy et al. (1987) who concluded that T_c could be modelled reasonably well by using squared rainfall intensity values. However, the exponent of rainfall intensity in the model developed by Rudra et al. (2007) was 0.99, which was almost half of that in our model. The difference could be attributed to the different design of the experiment. The T_c equation by Rudra et al. (2007) was established using a two-component additive model, and rainfall intensity was only used as an index to calculate the contribution to T_c from raindrop impact. Moreover, based on the review of T_c estimation by Prosser and Rustomji (2000), the range of the exponents of discharge (β) and slope gradient (γ) were $1.0 \le \beta \le 1.8$ and $0.9 \le \gamma \le 1.8$ when T_c was calculated using a simple equation ($T_c = k_1 q^{\beta} S^{\gamma}$) and there was no strong support for one exponent to outweigh greatly the other. However, in our study, the exponent of the slope gradient was 0.90, which was 54.5% lower than that of the rainfall intensity, which indicated that it was the rainfall intensity rather than the slope gradient that had more marked effects on the T_c for raindrop-impacted overland flow. Hence, it might indicate that T_c models established from river beds or flume experiments, which typically ignored rainfall impacts were inapplicable for calculating the T_c of raindrop-impacted overland flow within a transport-limited interrill erosion system.

In addition, 1.4×10^{-6} to $1.53 \times 10^{-3}\,\mathrm{kg\,m^{-2}\,s^{-1}}$ of T_c under all conditions in our study, can be converted into 1.12×10^{-6} to $1.22 \times 10^{-3}\,\mathrm{kg\,m^{-1}\,s^{-1}}$, which is smaller than that from other researches, such as Guy et al. (1987) and Ali et al. (2012). Reasons were mainly as follows: 1) The experimental beds were different. The roughness of erodible beds is always higher than that of non-erodible beds (Hu and Abrahams, 2006), which led to higher consumption of flow energy and thereby resulted in the reduction of T_c in the condition of erodible beds in this study. 2) The source of runoff was different. In this study, the overland flow was generated by simulated rainfall, but it was generated by the inflow in some other researches such as Ali et al. (2012), which increasing T_c by increasing the flow quantity to some extent, for example, the flow depth of inflow is generally greater or much greater than that by rainfall.

4.2. Hydraulic mechanism for sediment transport within a transport-limiting interrill erosion system

The mechanical process and energy conversion involved in interrill erosion systems are complex and difficult to be accurately described by single rainfall- or runoff-related parameters. There was a need to describe T_c by the hydraulic parameters of raindrop-impacted overland flow.

Different hydraulic parameters have various hydrodynamic actions. Until now, there was no consistent conclusion about which hydraulic parameter is the original power driving runoff to transport sediment. In our study, the effects of different hydraulic parameters in determining sediment transport capacities were ranked in following order (in terms of R^2 and NSE): stream power (Ω; $R^2 = 0.76$, $NSE = 0.52$) > mean flow velocity (V; $R^2 = 0.64$, $NSE = 0.39$) > flow shear stress (τ; $R^2 = 0.53$, $NSE = 0.23$) > unit stream power (ω; $R^2 = 049$, $NSE = 0.16$). From the perspective of energy conversion, sediment transport and its variations are basically controlled by accumulation, expenditure, transfer, or redistribution of flow energy in sediment transport systems. As an energy-based hydraulic parameter, stream power indicates the rate of doing work by energy loss of flows acting on soil beds per unit area (Bagnold, 1966), and it was the best predictor to calculate the T_c in this study, which is consistent with that reported by Bagnold (1966), Li and Abrahams (1999), Abrahams et al (2001) and Li et al (2011). Although T_c also has a good relationship with flow velocity, it is only a simple and basic hydraulic parameter, and cannot comprehensively represent the hydrodynamic force of overland flow. Flow shear stress, as a mechanical index signifying the average level of hydrodynamic processes acting on the soil beds, cannot effectively describe the Tc in this study. It may because part of shear stress was dissipated by bed irregularities and bed evolution, which is consistent with Ali et al. (2012). Govers and Rauws (1986) also suggested that shear stress was not a good predictor for estimating T_c under erodible bed conditions, as an important component of the shear stress (i.e. form shear stress) may not be actively used for sediment transporting, but preferentially consumed on sediment detachment and bed form evolution. In this study, unit stream power also cannot describe the T_c well. However, Ali et al. (2012) showed that unit stream power was the optimal composite force predictor for estimating T_c as compared to stream power. The reason for the discrepancy with this study may be as follows: 1) The test conditions were inconsistent. The flow in our experiment was heavily affected by raindrop impact, while their experiment were only conducted based on the flow without rainfall; 2) The composition of experimental materials was much different. Ali et al. (2012) used well-sorted sands to research, while our test materials were loess soils picked up from farmland in our study area.

4.3. Comprehensive response of T_c to steam power and rainfall parameters

In addition to the main influence of raindrop-impacted overland flow hydrodynamic action (stream power) to T_c, raindrop impacts also play a non-negligible role to T_c. Therefore, multiple regression analysis was performed to analyse the comprehensive response relationships of T_c to stream power (Ω) and rainfall kinetic energy (KE), raindrop terminal velocity (v), raindrop median volume diameter (D_{50}), respectively. It was finally found that the addition of rainfall parameters in the response equation of T_c in addition to stream power could significantly improve the R^2 and NSE, in other word, could improve the accuracy of T_c modelling in this study (Table 4). The reasons may be as follows. 1) The depth of overland flow is very thin (the maximum depth was 0.332 mm in our study), so raindrops could hit the soil surface through the thin water layer, this behaviour changed the soil surface conditions which may be beneficial to sediment transporting as flow resistance may be reduced. To prove it, we calculated the values of Darcy-Weisbach resistance coefficient (f). The variations of f in response to different kinetic energy were shown in Fig. 9. It is obvious that f showed a decreasing tendency with the increase of rainfall kinetic energy, which confirmed that rainfall kinetic energy reduce the soil surface roughness and, as a result, benefit sediment transporting in this study. 2) Raindrops have a significant influence on the movement of sediments in the sediment-laden overland flow. This influence may make the sediment to be easier for starting motion, as well as making sediment particles to be easier for moving downslope. All these showed the importance of the influence of raindrop impact on sediment transporting. These indicated that when studying the T_c by raindrop-impacted overland flow, effects of rainfall impacts should be particularly considered.

Table 4
The comparison of sediment transport capacity equations based on different hydrodynamic and rainfall parameters.

Equations	*ARE* (%)	R^2	*NSE*	*n*	P
$T_c = 0.154V^{5.67}$	−34.68	0.64	0.39	155	< 0.01
$T_c = 0.015\tau^{1.86}$	−76.89	0.53	0.23	155	< 0.01
$T_c = 0.032\omega^{1.24}$	−62.61	0.49	0.16	155	< 0.01
$T_c = 0.202\Omega^{1.45}$	−22.35	0.76	0.52	155	< 0.01
$T_c = 1.57 \times 10^{-41}\Omega^{2.88}KE^{16.11}e^{(-0.015KE-99.45\Omega+3555.16/KE+0.011/\Omega-1.99/(KE\times\Omega))}$	−9.78	0.90	0.75	155	< 0.01
$T_c = 4.77 \times 10^{-7}\Omega^{2.89}v^{15.58}e^{(-1.95v-100.18\Omega+25.96/v+0.01/\Omega-0.01/(v\times\Omega))}$	−18.41	0.88	0.67	155	< 0.01
$T_c = 1.59 \times 10^{72}\Omega^{1.8} D_{50}^{-240.56} e^{(59.03D_{50}-18.89\Omega-236.37/D_{50}+0.05/\Omega-0.08/(\Omega\times D_{50}))}$	−12.22	0.85	0.70	155	< 0.01

Where T_c the sediment transport capacity (kg m^{-2} s^{-1}), V is the flow velocity (m s^{-1}), τ is the flow shear stress (Pa), Ω is the stream power (W m^{-2}), ω is the unit stream power (m s^{-1}), KE is the rainfall kinetic energy (J m^{-2} h^{-1}), v is the raindrop terminal velocity (m s^{-1}), D_{50} is the raindrop median volume diameter (mm), ARE is the coefficient of average relative error, R^2 is the coefficient of determination, NSE is the index of Nash–Suticliffe model efficiency, n is the sample numbers, and P is the significance level.

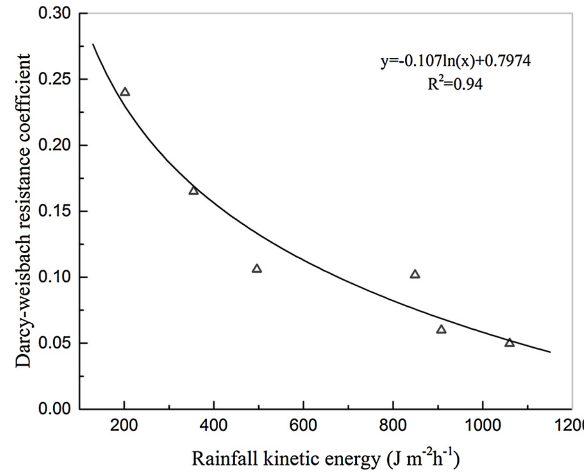

Fig. 9. Darcy-weisbach resistance coefficient (f) varying with rainfall kinetic energy.

5. Conclusions

In this study, responses of the sediment transport capacity (T_c) of raindrop-impacted overland flow to rainfall intensity, slope gradient, hydraulic parameters (flow velocity, flow shear stress, unit stream power, and stream power) and rainfall physical parameters (rainfall kinetic energy, raindrop terminal velocity, raindrop median volume diameter) were investigated in transport-limited cases of interrill erosion processes on steep loess hillslopes of China using a three-area soil pan under simulated rainfall experiments.

T_c increased with the increase of rainfall intensity and slope gradient. The response relationship of T_c to rainfall intensity and slope gradient can be described well by a power equation (R^2 = 0.84, NSE = 0.75). Rainfall intensity, rather than the slope gradient, produced more noticeable effects on the T_c. In terms of R^2 and NSE, stream power was the best hydraulic parameter that described T_c among flow velocity (R^2 = 0.64, NSE = 0.39), shear stress (R^2 = 0.53, NSE = 0.23), stream power (R^2 = 0.76, NSE = 0.52) and unit stream power (R^2 = 0.49, NSE = 0.16). The addition of rainfall physical parameters in the response equations of T_c to stream power could improve an accuracy of T_c modelling. Stream power combined with rainfall kinetic energy can best describe T_c within transport-limited system of interrill erosion processes (R^2 = 0.90, NSE = 0.72), as rainfall kinetic energy reduces Darcy-Weisbach resistance coefficient of raindrop-impacted overland flow and, therefore, benefits sediment transporting.

This study provides another method for identifying the T_c of raindrop-impacted overland flow within a transport-limited interrill erosion system. The results point out that rainfall impacts should be particularly considered when studying T_c by raindrop-impacted overland flow.

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