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Response of soil detachment rate by raindrop-affected sediment-laden sheet flow to sediment load and hydraulic parameters within a detachment-limited sheet erosion system on steep slopes on Loess Plateau, China

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ABSTRACT

The response of soil detachment rate by raindrop-affected sediment-laden sheet flow to sediment load and hydraulic parameters was investigated within a detachment-limited sheet erosion system on steep slopes to understand sheet erosion processes fully and derive an accurate experimental model. An experiment was conducted at slopes of 12.23%, 17.63%, 26.8%, 36.4%, 40.4% and 46.63% under rainfall intensities of 48, 60, 90, 120, 138 and 150 mm h^{-1}, respectively, by using simulated rainfall. Results showed that the soil detachment rate by raindrop-affected sediment-laden sheet flow decreased as the sediment load by sheet flow increased, and the decrease was a power function of sediment load by sheet flow with $NSE = 0.58$, $MSE = 0.0099$ and $R^2 = 0.58$. In addition, the soil detachment rate by raindrop-affected sediment-laden sheet flow increased as a linear function of shear stress, stream power and unit stream power. Shear stress and stream power could be used to predict the soil detachment rate by raindrop-affected sediment-laden sheet flow accurately through a linear equation. Stream power ($R^2 = 0.87$, $MSE = 0.003$ and $NSE = 0.87$) was a better predictor of soil detachment rate by raindrop-affected sediment-laden sheet flow than shear stress ($NSE = 0.83$, $MSE = 0.004$ and $R^2 = 0.83$). However, prediction based on unit stream power ($NSE = 0.43$, $MSE = 0.01$ and $R^2 = 0.43$) was poor. These findings can improve our understanding and modelling of sheet erosion processes on steep slopes in the loess region of China.

1. Introduction

Soil erosion is a serious global environmental problem that can lead to land degradation and landslides (Nowak and Schneider, 2017; Xu et al., 2018; Xu and Coop, 2017; Mekonnen et al., 2015; Heathcote et al., 2013; Ali et al., 2011; Karlen et al., 2003; Lal, 1998). The Loess Plateau in northwest China is one of the areas worldwide that suffered from serious soil erosion in recent decades (Zhao et al., 2013; Liu et al., 2012a; Shi and Shao, 2000). Soil erosion is commonly divided into rill erosion and interrill or sheet erosion (Meyer and Wischmeier, 1969; Laflen et al., 1991). Sheet erosion is one of the major erosion processes in the Loess Plateau of China (Liu et al., 2012b). Ellison (1944, 1947a,b,c) defined sheet erosion as "a process of detachment and transportation of soil particles" and reported that soil detachment by rainfall, transport by rainfall, detachment by runoff and transport by runoff are separate but interrelated phases of the process of soil erosion by water. Kinnell (2000, 2001, 2006) also identified four detachment and transport systems operating in sheet erosion; these four are raindrop detachment and splash transport, raindrop detachment and raindrop-induced flow transport, raindrop detachment and sheet flow transport and sheet flow detachment and sheet flow transport. However, most researchers have suggested that raindrop detachment (i.e. soil detachment is caused by raindrop impact), splash transport and sheet flow transport are the major processes for sheet erosion (Wan et al., 1996; Sutherland et al., 1996; Van Dijk and Bruijnzeel, 2003; Kinnell, 2006; Fu et al., 2011; Defersha et al., 2011; Zhang and Wang,

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2017). The third process (i.e. detachment by runoff) reported by Ellison (1944, 1947a,b,c) and the fourth process (i.e. sheet flow detachment and sheet flow transport) reported by Kinnell (2000, 2001, 2006) cannot appear in a sheet erosion system. According to Wu et al. (2018), sheet flow detachment is concealed in the sheet erosion system on steep slopes of Loess Plateau in China. Accordingly, detachment by raindrops and raindrop-affected sediment-laden sheet flow and sediment transport by raindrop-affected sheet flow are the dominant processes (i.e. detachment-limited processes). Gao et al. (2005) suggested that raindrop impact contributes considerably to soil erosion by enhancing soil detachment and water flow disturbance. Thus, assessment of soil detachment rate by raindrop-affected sediment-laden sheet flow in a detachment-limited erosion system is essential in deeply explaining sheet erosion processes on steep slopes in the Loess Plateau of China.

Soil detachment and sediment transport by water flow are crucial erosion processes, and a change in the sediment load transported by water flow during erosion leads to soil detachment from the soil body via sediment-laden flow (Nearing et al., 1999; Zartl et al., 2001; Govers et al., 2007; Wells et al., 2010). Understanding how soil detachment rate responds to the actual sediment load by water flow is essential in revealing the mechanism of soil erosion. Many researchers have suggested that detachment-limited processes occur in rill erosion. Thus, the effects of sediment load on soil detachment rate by rill flow have been extensively studied in literature (Van Liew and Saxton, 1983; Nearing et al., 1990; Govers, 1990; Nearing et al., 1991; Nearing and Parker, 1994; Foster et al., 1995; DeRoo et al., 1996; Nearing et al., 1999; Zhang et al., 2003; Govers et al., 2007; Zhang et al., 2008; Wang et al., 2016; Hai et al., 2017). However, studies that examined the effect of sediment load on the soil detachment rate by raindrop-affected sediment-laden sheet flow are scarce. Soil detachment by water flow is controlled primarily by flow hydraulics and soil properties (Liu et al., 2016; Chen et al., 2016; Su et al., 2014). Flow hydraulics control the process of soil detachment (Li et al., 2015; Zhang et al., 2003; Govers, 1992). Most studies have revealed the effect of hydraulic parameters on soil detachment rate by rill flow. However, studies on the effect of hydraulic parameters on soil detachment rate by raindrop-affected sheet flow are limited. Given this situation, the response of soil detachment rate by raindrop-affected sediment-laden sheet flow to sediment load and hydraulic parameters needs to be determined and evaluated. The objectives of the present study are to evaluate the effect of sediment load on soil detachment rate by raindrop-affected sediment-laden sheet flow and identify the best hydraulic parameter in relation to soil detachment rate. The results can provide a scientific basis for soil erosion control in the Loess Plateau.

2. Materials and methods

2.1. Experimental soil

Experimental soil was collected from a depth of 0–25 cm at the farming cropland layer in Ansai County (109°19′ E, 36°51′ N) of Shaanxi Province, China, located in the northern part of the Loess Plateau. The experimental soil was classified as typical loessial soil, which is the most common soil type on the Loess Plateau, and it is highly erodible and susceptible to erosive forces. The soil consisted of 36.21% sand (diameter: 0.05–2.0 mm), 55.3% silt (diameter: 0.002–0.05 mm) and 8.49% clay (diameter: < 0.002 mm).

2.2. Experimental setup

Experiments were conducted in the Simulation Rainfall Hall operated by the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at the Institute of Soil and Water Conservation, Chinese Academy of Sciences, and by the Ministry of Water Resources in Yangling, Shaanxi Province, China. A rainfall simulator system with nozzles on two sides was used to reproduce simulated rainfall (Fig. 1).

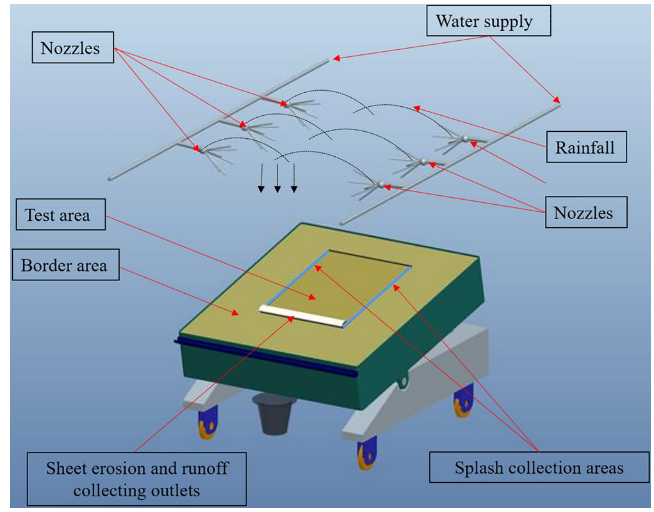

Fig. 1. The experimental setup and rainfall Simulator.

Nozzles with 7, 9, 11 and 13 mm of aperture diameter were fixed on both sides of the rainfall area and served as side-spraying simulated rainfall nozzles. The design institution of nozzles was Yellow River Institution of Hydraulic Research in Zhengzhou, Henan Province, China (Zhou et al., 2000). A specific rainfall intensity corresponded to the specific water pressure and aperture diameter of the nozzles, which were calibrated after the facilities were fixed and before they were used in the Simulated Rainfall Hall. The fall height of raindrops sprayed from the nozzles was approximately 16 m above the soil surface in all the experiments. The raindrop diameters of the simulated rainfall ranged from 0.125 to 6.0 mm, and the raindrop median volume diameters were 1.52–2.7 mm. The dispersed raindrops with different diameters were precisely created by adjusting the aperture of the nozzle orifice and the water pressure. The simulated rainfall, with uniformity higher than 85%, exhibited a similar raindrop size and distribution as natural rainfall.

An experiment soil pan with metal frames was utilised. The soil pan was 140 cm long, 120 cm wide and 25 cm deep and included test, border and splash collection areas. The test area, which was the collection area for runoff and sheet erosion, was 80 cm long, 60 cm wide and 25 cm deep. A 35 cm wide border area around the test plot was filled with soil in the same manner. Two splash collection areas (80 cm long and 2.5 cm wide) were attached to the left and right sides of the test area and served as the collection area for splash erosion. The slope gradient for this soil pan could be adjusted between 0% and 84%. Primary sheet erosion occurs when the slope exceeds 17.63%, and the slope of 46.63% is the largest observed for returning farmland to forest (Tang et al., 1998). Thus, we designed five slope gradients within this range in the Loess Plateau of China. We considered the scenario that sheet erosion still exists when the slopes are less than 17.63%. Hence, we added a slope gradient of 12.23%. These six slope gradients, namely, 12.23%, 17.63%, 26.8%, 36.4%, 40.40% and 46.63%, can help us perform an effective statistical analysis. Soil erosion in the Loess Plateau where the research area is located is produced by rainstorm. The rainfall intensity for an hour of rainfall ranges from 11.9 mm h^{-1} to more than 250 mm h^{-1} (Wang and Jiao, 1996). Thus, six rainfall intensities (48, 60, 90, 120, 138 and 150 mm h^{-1}), which are within the range of the actual rainfall intensity in the Loess Plateau of China, were selected in this study.

Before packing the soil, its water content was adjusted to 14%, which is the typical level during the flood season on the Loess Plateau when most erosion occurs (Liu et al., 2012a). A bulk density of 1.2 g cm^{-3} was designed for the study. A 5 cm thick natural sand layer was packed at the bottom of the soil pan to enable free drainage of excess water. It consisted of 2.58% clay (diameter: < 0.002 mm), 3.94% silt (diameter: 0.002–0.02 mm), fine sand 17.31% (diameter: 0.02–0.2 mm) and coarse sand 76.17% (diameter: 0.2–2 mm). The D_{50} of natural sand was 0.39 mm. The total porosity of natural sand was 49%, and the saturated hydraulic conductivity of natural sand was 5.91 mm min^{-1}. The test soil was then packed in the soil pan over the sand layer. The test soil was packed to a depth of 20 cm and in four 5 cm layers to compact the test soil to the same degree.

Two replications were undertaken for a rainfall event in each combination of rainfall intensity and slope gradient, and a total of 72 rainfall events were simulated.

2.3. Experimental procedures

In the simulated rainfall experiment for each combination of slope gradient and rainfall intensity, samples of splashed sediments, runoff and washed sediments produced by the simulated rainfall were collected for 1 and 2 min after the onset of the runoff and then for every 3 min until the end of the simulated rainfall experiment. For an individual rainfall experiment under each combination of slope gradient and rainfall intensity, 15 splash sediment, 15 runoff and 15 washed sediment samples were collected. After collection, the splash sediment samples were oven-dried at 105 °C for 24 h to determine the splash sediment weight. Splash erosion rate was defined as splash sediment weight per unit area per unit time. The wet and dry weights of the runoff and washed sediment samples were measured to calculate sediment load and soil detachment rate by raindrop-affected sediment-laden sheet flow. Sediment load was defined as sediment weight (i.e. splashed sediment weight) per unit volume of runoff, and soil detachment rate by raindrop-affected sediment-laden sheet flow was defined as washed sediment weight (i.e. washed sediment samples–splash sediment weight) per unit area per unit time.

The surface flow velocities of sheet flow were measured with 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 10 cm from each sidewall of the test area. This tracer has a purple–red colour and is easy to identify in runoff. The time required by the tracer to traverse the marked distance (50 cm) was determined based on colour-front propagation using a stop watch (Qin et al., 2018; Shen et al., 2016a,b; Wang et al., 2016; An et al., 2012).

2.4. Experimental theoretical basis

Ellison (1944, 1947a,b,c) divided the erosion process into rainfall erosion, runoff erosion and rainfall transport and runoff transport. Kinnell (2000, 2001, 2006) identified four detachment and transport systems operating in rainfall erosion, and these four are raindrop detachment–splash transport, raindrop detachment–raindrop-affected sheet flow transport, raindrop detachment–raindrop-affected sheet flow transport and raindrop-affected sheet flow detachment– raindrop-affected sheet flow transport. Given that splash erosion, which is equal to soil detachment by raindrop, and sheet erosion simultaneously exist in the same area, sheet erosion can be partitioned into splash and wash processes. Hence, erosion-limiting conditions can be identified according to the equilibrium relationships between splashed and washed sediments. When sheet erosion rates (being equal to washed sediment rates) are lower than splashed erosion rates (i.e. splashed sediment rates), which signifies that soil detachment by raindrop and transport by raindrop-affected sheet flow are the dominant processes, a transport-limited condition is defined, and sheet erosion processes are considered transport-limited. For a transport-limited condition, all sediments transported by raindrop-affected sheet flows are derived from soil detachment by rainfall impact. Raindrop-affected sheet flows cannot deliver all the sediments detached by the raindrops, and the sediments transported by raindrop-impacted sheet flows are attributed to the sediment transport capacities. Therefore, the sediment transport capacities of raindrop-impacted sheet flows are considered to be equivalent to measured sheet erosion rates for transport-limited sheet erosion processes. When the sheet erosion rates are higher than the splash erosion rates, detachment by both raindrops and raindrop-affected sheet flow and sediment transport by raindrop-affected sheet flow are the dominant processes. Such a condition is defined as a detachment-limited process, in which raindrop-affected sheet flow has sufficient power to detach soil from the soil body in addition to transporting all of the loose materials detached by raindrops. In this study, detachment-limited datasets were obtained from individual simulated events to determine raindrop-impacted sheet flow detachment under typical detachment-limiting conditions.

2.5. Experimental data calculation

2.5.1. Soil detachment rate by raindrop-affected sediment-laden sheet flow

The experimental data were selected from the detachment-limited phases of each sheet erosion event produced by the simulated rainfall. Thus, the values of soil detachment rate under raindrop-affected sediment-laden sheet flow were equal to the difference between sheet erosion and splash erosion per unit area per unit time in the detachment-limited sheet erosion system. Soil detachment rate under raindrop-affected sediment-laden sheet flow was calculated with the following equation:

$$D_s = \frac{W_w - W_s}{t \times A}, \tag{1}$$

where D_s is soil detachment rate under raindrop-affected sediment-laden sheet flow (kg m^{-2} s^{-1}); W_w is the weight of sheet erosion, which is equal to the weight of wash sediment (kg); W_s is the weight of splash erosion, which is equal to the weight of splash sediment (kg); t is the duration of detachment (s) and A is the projected area of the soil sample (m^2).

2.5.2. Sediment load of raindrop-affected sheet flow

The values of the sediment load of raindrop-affected sheet flow were equal to those of splash erosion (i.e., splash sediments) per unit plot width in the detachment-limited sheet erosion system.

2.5.3. Hydraulic parameters

Shear stress (τ, Pa; Nearing et al., 1991), stream power (Ω, W m^{-2}; Bagnold, 1966; Prosser and Rustomji, 2000) and unit stream power (P, m s^{-1}; Yang, 1972) were calculated as

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

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

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

where Ω is the stream power (W m^{-2}); τ is shear stress (Pa) and V is flow velocity, which is derived by multiplying surface flow velocity by a correction factor of 0.67 (m s^{-1}).

$$P = VS_i, \tag{4}$$

where P is the unit stream power (m s^{-1}), V is flow velocity (m s^{-1}) and S_i is the sine of the bed slope (m m^{-1}).

2.6. Analysis of experimental data

The coefficient of determination (R^2), the residual mean (MSE) and the Nash-Sutcliffe efficiency Index (NSE) (Nash and Sutcliffe, 1970) were used to evaluate the response and relationship of detachment rate to sediment load and hydraulic parameters. R^2, MSE and NSE were calculated as follows:

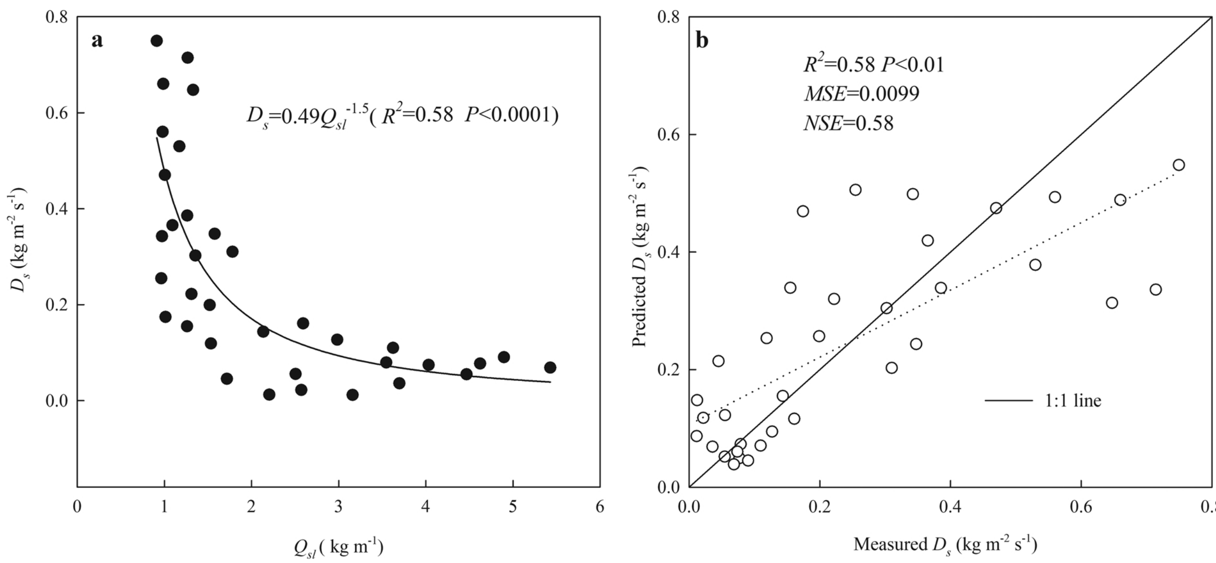

Fig. 2. D_s as a power function of sediment load by sheet flow.

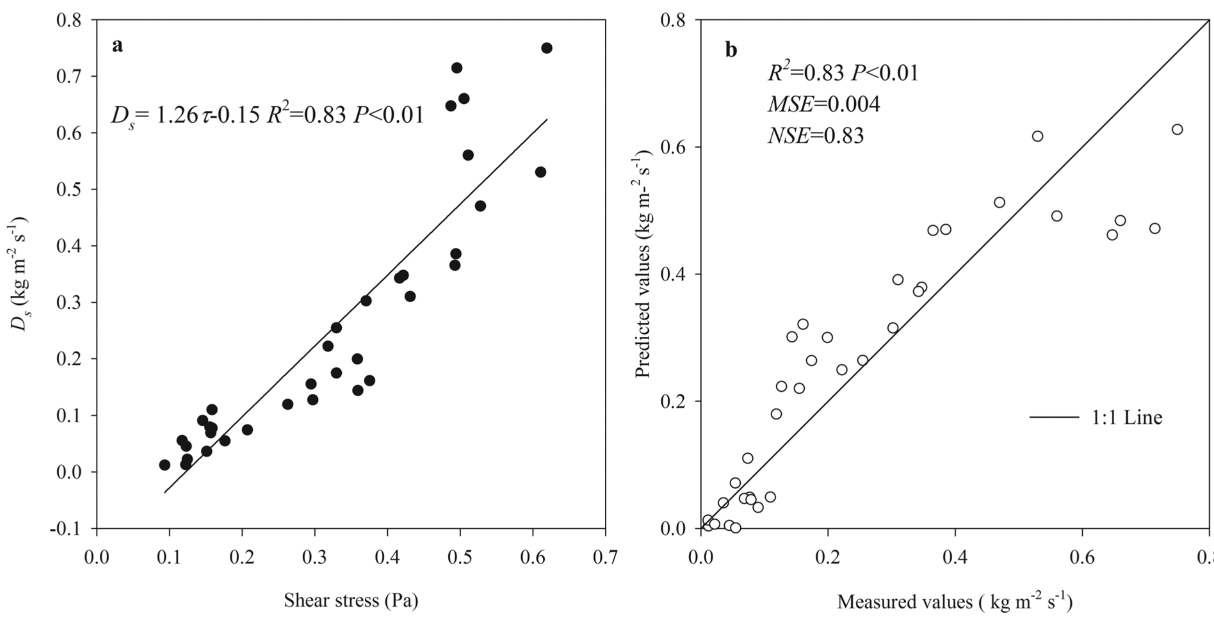

Fig. 3. D_s as a linear function of shear stress.

$$R^2 = \frac{[\sum_{i=1}^{n}(O_i-\overline{O})(P_i-\overline{P})]^2}{\sum_{i=1}^{n}(O_i-\overline{O})^2\sum_{i=1}^{n}(P_i-\overline{P})^2}, \tag{5}$$

$$MSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{n}}, \tag{6}$$

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

where O_i are the observed values, P_i are the predicted values, $\overline{O}$ is the mean of the observed value and $\overline{P}$ is the mean of the predicted value.

3. Results

3.1. Response of soil detachment rate under raindrop-affected sediment-laden sheet flow to the sediment load of sheet flow

The response of soil detachment rate under raindrop-affected sediment-laden sheet flow to the sediment load of sheet flow is illustrated in Fig. 2(a). Soil detachment rate under raindrop-affected sediment-laden sheet flow was strongly influenced by sediment load and decreased as the sediment load of sheet flow increased.

To evaluate the relationship between sediment load and soil detachment rate under raindrop-affected sediment-laden sheet flow, the experimental dataset was subjected to regression analyses. The following relationship was obtained:

$$D_s = 0.49Q_{sl}^{-1.5}(R^2 = 0.58,\ NSE = 0.58,\ P < 0.0001,\ n = 35) \tag{8}$$

where D_s is soil detachment rate under raindrop-affected sediment-laden sheet flow (kg m^{-2} s^{-1}), and Q_{sl} is the sediment load of sheet flow (kg m^{-1}). Log transform was conducted prior to testing to accurately derive the coefficients (0.49) and power (−1.5) of the power equations tested in the regression analysis. D_s is strongly ($R^2 = 0.58$) and significantly ($P < 0.0001$) correlated with Q_{sl}. Q_{sl} is a good predictor of D_s ($NSE = 0.58$). Fig. 2(b) shows the comparison between the predicted values of D_s derived with Eq. (8) and the measured values of D_s. The 1:1 line of measured vs. predicted D_s values illustrates that Eq. (8) could be used to effectively predict D_s ($NSE = 0.58$ and MSE =

0.0099 and $R^2 = 0.58$).

3.2. Response of soil detachment rate under raindrop-affected sediment-laden sheet flow to hydraulic parameters

3.2.1. Shear stress

As shown in Fig. 3(a), soil detachment rate under raindrop-affected sediment-laden sheet flow increased with shear stress. The relationship between soil detachment rate under raindrop-affected sediment-laden sheet flow and shear stress can be described with the following linear function:

$$D_s = 1.26(\tau - 0.12)\ (R^2 = 0.83\ NSE = 0.83\ P < 0.01\ n = 35) \tag{9}$$

where D_s is soil detachment rate under raindrop-affected sediment-laden sheet flow (kg m^{-2} s^{-1}), and τ is shear stress (Pa). In Eq. (9), the critical shear stress is 0.12 Pa. D_s is highly ($R^2 = 0.83$) and significantly ($P < 0.01$) correlated with τ. τ is a good predictor of D_s ($NSE = 0.83$). Fig. 3(b) presents the comparison between the predicted values of D_s derived with Eq. (9) and the measured values of D_s. The 1:1 line of measured vs. predicted D_s shows the high level of agreement between the predicted and observed values of D_s ($NSE = 0.83$ and $MSE = 0.004$ and $R^2 = 0.83$).

3.2.2. Stream power

Fig. 4(a) shows that soil detachment rate under raindrop-affected sediment-laden sheet flow increased as stream power increased. The relationship between soil detachment rate under raindrop-affected sediment-laden sheet flow and stream power can be described with the following linear function:

$$D_s = 7.77(\Omega - 0.008)\ (R^2 = 0.87\ NSE = 0.87\ P < 0.01\ n = 35) \tag{10}$$

where D_s is soil detachment rate under raindrop-affected sediment-laden sheet flow (kg m^{-2} s^{-1}), and Ω is stream power (W m^{-2}). In Eq. (10), the critical stream power is 0.008 W m^{-2}. D_s and Ω are highly ($R^2 = 0.87$) and significantly ($P < 0.01$) related. Ω is a good predictor of D_s ($NSE = 0.83$). The comparison between the predicted values of D_s derived by Eq. (10) and the measured values of D_s is shown in Fig. 4(b). The 1:1 line indicates the high level of agreement between the predicted and observed values of D_s ($NSE = 0.87$, $MSE = 0.003$ and $R^2 = 0.87$).

3.2.3. Unit stream power

Fig. 5(a) shows that soil detachment rate under raindrop-affected sediment-laden sheet flow increased as unit stream power increased. The relationship between soil detachment rate under raindrop-affected sediment-laden sheet flow and unit stream power can be described with a linear function, as follows:

$$D_s = 8.06(P - 0.0025)\ (R^2 = 0.43\ NSE = 0.43\ P < 0.01\ n = 35) \tag{11}$$

where D_s is soil detachment rate under raindrop-affected sediment-laden sheet flow (kg m^{-2} s^{-1}), and P is the unit stream power (m s^{-1}). In Eq. (11), the critical unit stream power is 0.0025 m s^{-1}. Although D_s is significantly ($P < 0.01$) correlated ($R^2 = 0.43$) with Ω, P is a poor predictor of D_s ($NSE = 0.43$). Fig. 5(b) shows the comparison between the predicted values of D_s derived with Eq. (11) and the measured values of D_s. The 1:1 line of measured vs. predicted D_s values shows that a low level of agreement exists between the predicted and observed values of D_s ($NSE = 0.43$, $MSE = 0.01$ and $R^2 = 0.43$). Therefore, the linear function provided by unit stream power models cannot predict D_s well.

3.3. Comparisons of the response of hydraulic parameters to raindrop-affected sheet flow detachment rate

The response equations of various hydraulic parameters to D_s, as well as assessment indexes, including MSE, NSE and R^2. The MSE, NSE and R^2 of observed D_s and D_s predicted by using the equations that represent the responses of various hydraulic parameters to D_s consistently show that shear stress and stream power are good predictors of D_s, whereas the unit stream power is a relatively poor predictor of D_s. Stream power is the best hydraulic parameter for the estimation of D_s given its simplicity and readily available measurements.

4. Discussion

Soil detachment rate under raindrop-affected sediment-laden sheet flow is negatively correlated with the sediment load of sheet flow. This relationship can be attributed to the following mechanisms: Firstly, the energy expenditure required for transport increases as sediment load increases; thus, the energy that is available for detachment decreases, consequently decreasing detachment rate under increased sediment load (Zhang et al., 2009; Shen et al., 2016a,b). Secondly, the sediment

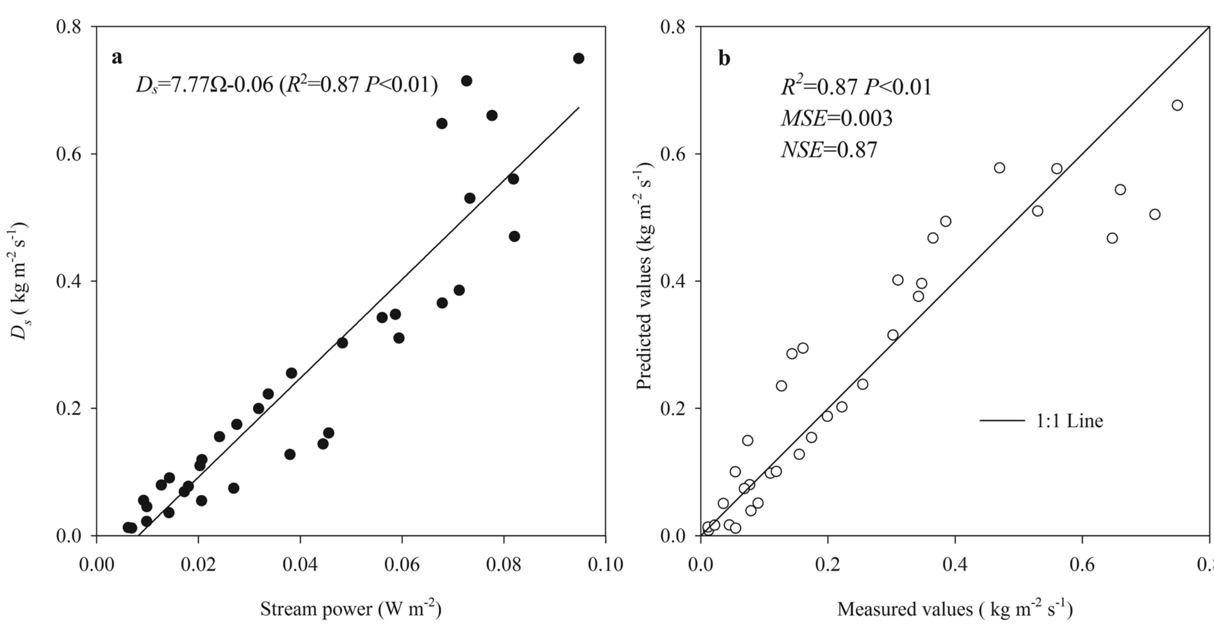

Fig. 4. D_s as a linear function of stream power.

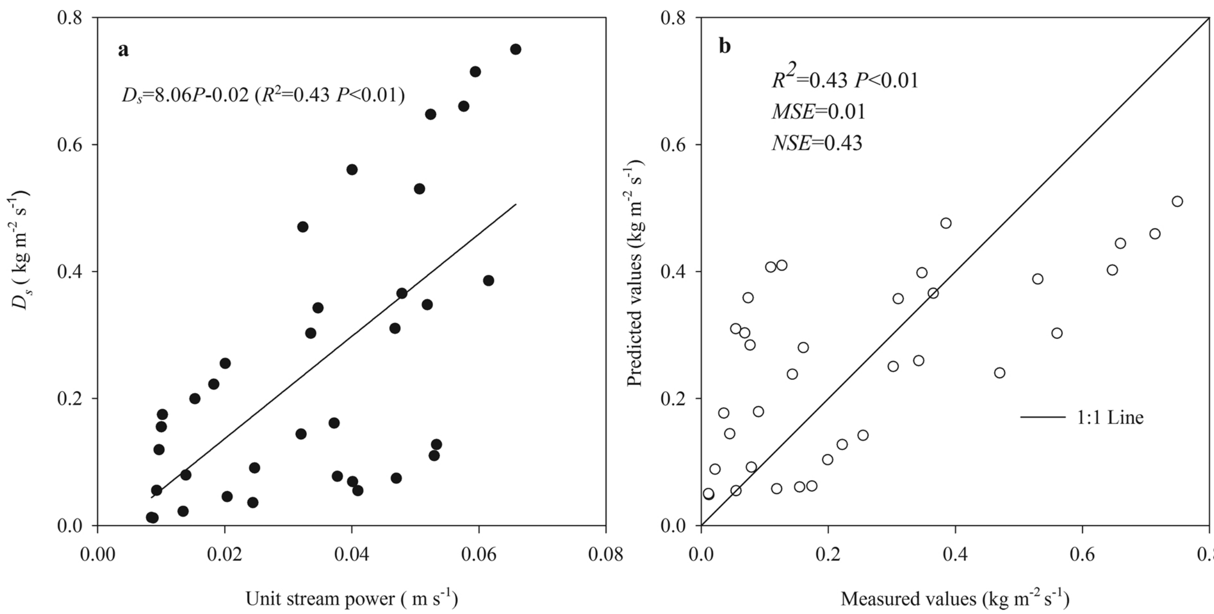

Fig. 5. D_s as a linear function of unit stream power.

that covers the soil bed during erosion shields the soil from flow forces (Merten et al., 2001; Polyakov and Nearing, 2003). Thirdly, sediments in flow decrease the contact area between flow and the soil bed. We found that soil detachment rate under raindrop-affected sediment-laden sheet flow and sediment load are related. We effectively modelled this relationship with a power function (NSE = 0.58, MSE = 0.0099 and R^2 = 0.58). The soil pan used in this study is based on the soil pan designed by Meyer and Harmon (1989) and Bradford and Foster (1996) with some modifications. Our modified soil pan can be used to measure sheet erosion and splash detachment rates on hillslopes individually. Temporal variations in sheet erosion and splash detachment rates (kg m^{-2} s^{-1}) during rainfall events could be accurately and easily obtained by using our modified soil pan. Sheet erosion, which occurs in the presence of rainfall and sheet flow produced by rainfall, is a complex phenomenon that results from soil detachment due to raindrop impact and raindrop-affected sheet flow (interrill flow or thin overland flow) and transport by raindrop-affected sheet flow. In a detachment-limited sheet erosion system, sheet erosion rates are greater than splash detachment rates, and soil detachment by raindrops, raindrop-affected sheet flow and particle transport by raindrop-affected sheet flow dominate. Raindrop-affected sheet flow has sufficient power to detach particles from the soil body in addition to transporting raindrop-detached particles. We found that soil detachment rate under raindrop-affected sediment-laden sheet flow is related to the sediment load of sheet flow and that this relationship can be described with a power function. A previous study showed that interrill soil detachment is mainly caused by raindrop impact and that interrill erosion is limited by transport under the study conditions (Kinnell, 2006; Zhang et al., 2017). However, studies on the effects of the sediment load of sheet flow or interrill flow on soil detachment under raindrop-affected sediment-laden sheet flow remain lacking. Previous experimental results for sheet erosion or interrill erosion were obtained under the conditions of gentle slope and through the measurement of soil pans without border areas (Kinnell, 2006; Zhang et al., 2017). Under the condition of absent border areas, the soil pan is subjected only to splash off and not to splash on. These conditions reduce the accuracy of sheet erosion or interrill erosion measurements. Therefore, our present results are different from previous results for sheet erosion or interrill erosion obtained under the conditions of gentle slope and through the measurement of soil pans without border areas. In addition, previous studies were performed with different soil and rainfall properties, which likely affected study results (Zhang et al., 2017). We found that soil detachment rate under raindrop-affected sediment-laden sheet flow is negatively correlated with the sediment load of sheet flow. This relationship can be described by a power function equation, which can be applied to improve our current understanding of sheet erosion processes and to promote the reasonable development of a sheet erosion prediction model that accounts for the sediment load factor in the sheet erosion equation. In addition, our results are different from the previous results that had been obtained for rill flow detachment (Merten et al., 2001; Zhang et al., 2009, 2014; Shen et al., 2016a,b). Other researchers have consistently suggested that soil detachment rate is negatively and linearly related to the sediment load of rill flow mainly because rill flow is the concentrated flow of overland flow, which is negligibly affected by raindrop impact, and not the thin, sheet or interrill flows of overland flow. These types of flow are drastically affected by raindrop impact.

We identified stream power as the best hydraulic parameter for the prediction of soil detachment rate under raindrop-affected sediment-laden sheet flow. We provided a linear function that describes the stream power of raindrop-affected sheet flow in a detachment-limited system. Our results differed from previous results, which were obtained under the conditions of gentle slope and through the experimental measurement of soil pans without border areas, and indicated that interrill erosion processes are mainly limited by transport (Wan et al., 1996; Sutherland et al., 1996; Van Dijk and Bruijnzeel, 2003; Kinnell, 2006; Fu et al., 2011; Zhang and Wang, 2017). Previous studies have mainly focused on the response of soil detachment rate under rill flow to hydraulic parameters. The hydraulic parameter-based models applied to predict soil detachment rate under rill flow are shown in Table 1. Table 1 shows that most researchers found that shear stress or stream power was the best hydraulic parameter to predict soil detachment rate by rill flow based on a linear function or power function. However, these models were used to predict soil detachment under rill flow and not under raindrop-affected sediment-laden sheet flow. We have provided a new equation that predicts soil detachment rate under raindrop-affected sediment-laden sheet flow. Our results can also be used as a reference for the development of control methods for sheet erosion in the loess slopes of China.

5. Conclusion

We quantified the relationship of soil detachment rate under

Table 1
Models applied to predict soil detachment rate using hydraulic parameters.

Model	Hydrodynamic parameters	Function types	Flow types
$D_r = 1.88\tau^{0.949}$ (Van Liew and Saxton, 1983)	Shear stress	Power function	Clear rill flow
$D_r = 0.011(\tau\text{-}9.5)$ (Knapen et al., 2007)	Shear stress	Linear function	Clear rill flow
$D_r = 0.0044\tau^{1.424}$ (Zhang et al., 2008)	Shear stress	Power function	Clear rill flow
$D_r = 0.28(\Omega\text{-}0.91)$ (Wang et al., 2016)	Stream power	Linear function	Clear rill flow
$D_r = 0.055\Omega^{0.747}$ (Hai et al., 2017)	Stream power	Power function	Sediment-laden rill flow
$D_r = 5.046(\Omega\text{-}0.207)$ (Shen et al., 2016a)	Stream power	Liner function	Sediment-laden rill flow
$D_r = 0.0088\Omega^{1.07}$ (Zhang et al., 2003)	Stream power	Power function	Clear rill flow

Where D_r is the soil detachment rate (kg m^{-2} s^{-1}), τ is the shear stress (Pa), Ω is the stream power (W m^{-2}).

raindrop-affected sediment-laden sheet flow with sediment load and hydraulic parameters (i.e., shear stress, unit stream power and stream power) under simulated rainfall. We found that soil detachment rate under raindrop-affected sediment-laden sheet flow decreases as a power function of the sediment load of sheet flow. Sediment load is a good predictor of soil detachment rate under raindrop-affected sediment-laden sheet flow (*NSE* = 0.58, *MSE* = 0.0099 and R^2 = 0.58). We studied the effects of different hydraulic parameters on soil detachment rate under raindrop-affected sediment-laden sheet flow on the basis of R^2, *MSE* and *NSE*. We ranked the linear functions that exist between soil detachment rate and hydraulic parameters in accordance with assessment indices, as follows: stream power (Ω) (NSE = 0.87, MSE = 0.003 and R^2 = 0.97) > shear stress (τ) (NSE = 0.83, MSE = 0.003 and R^2 = 0.90) > unit stream power (ω) (NSE = 0.43, MSE = 0.01, R^2 = 0.73). We identified stream power as the optimal hydraulic parameter for the prediction of soil detachment rate under raindrop-affected sediment-laden sheet flow in a detachment-limited sheet erosion system on steep slopes.

Our models well predict soil detachment rate under raindrop-affected sediment-laden sheet flow in a detachment-limited sheet erosion system. They can be used to further our understanding of sheet erosion and to develop process-based models for sheet erosion on steep slopes in Loess Plateau. However, our models should be used judiciously, and additional research is needed to develop equations/models that can be universally used to predict soil detachment rate under raindrop-affected sediment-laden sheet flow.

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