Soil & Tillage Research 198 (2020) 104539

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Size-selective characteristics of splash-detached sediments and their responses to related parameters on steep slopes in Chinese loessial region

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ARTICLE INFO

Keywords:
Splash detachment
Particle size selectivity
Rainfall parameter
Hydraulic parameter
Clay loam

ABSTRACT

Knowledge of the size-selective characteristics of splash-detached sediments can progress the understanding of splash and subsequent interrill wash erosion processes, as well as improve their modelling. Rainfall intensity (*I*) and slope gradient (*S*), as well as rainfall kinetic energy (*KE*), runoff depth (*h*) and runoff velocity (*v*) have important effects on splash-detached sediment size. The objectives of this study were to explore the responses of the size-selective characteristics (expressed by mean weight diameter, MWD) of splash-detached sediments to *I* and *S*, and to identify the relationships of MWD of splash-detached sediments with *KE*, *h* and *v*. Simulated rainfall experiments were conducted on clay loam under different rainfall intensities (0.7, 1.0, 1.5, 2.0, and 2.5 mm min^{-1}) and slope gradients (7, 10, 15, 20, and 25°) at the simulated rainfall hall in Yangling, China in 2017. Results showed that the MWD was 72.74–164.17 μm for the splash-detached sediments, which was lower than that of the soil matrix (183.23 μm). MWD increased logarithmically with increasing *S*, and MWD first increased and then decreased with increasing *I* or *KE* parabolically. The relationship of MWD with *I* and *S* can be described by an exponential-power combination equation ($MWD = 216\, e^{-1.25I}\, I^{1.81}\, S^{0.28}$, $R^2 = 0.88$). MWD was negatively related to *h* and positively related to *v*. Comprehensive response of MWD to *KE*, *h* and *v* can be described by an exponential-power combination equation ($MWD = 0.33\, e^{-0.002KE}\, KE^{1.18}\, h^{-0.20}\, v^{0.27}$, $R^2 = 0.85$). These findings showed that splash-detached sediment size was significantly affected by *I* and *S*, as well as *KE*, *h* and *v*. The study could be helpful in soil conservation management for similar conditions of soil, rainfall and land use.

1. Introduction

Sediment size is a key determinant for understanding selectivity of soil erosion and quantifying nonpoint source pollution (Wan and Elswaify, 1998). Detachment of soil particles by raindrop splash is an important process and is considered as the first step in rain-induced soil erosion (Van Dijk et al., 2002; Legout et al., 2005a; Fernandez-Fernández-Raga et al., 2017; Hu et al., 2018b). This process mainly provides loose sediments for interrill flow transportation (Legout, et al., 2005b). An improved understanding of particle size of splash-detached sediments can shed light on the splash and subsequent interrill wash erosion, as well as their modelling. Further study can also provide a basis for understanding the transfer of nutrients and contaminants.

The splash detachment process involves two main sub-processes: top soil aggregate breakdown by raindrop impact and soil fragment movement (Legout et al., 2005b; Abu-Hamdeh et al., 2006; Warrington et al., 2009). The extent to which soil aggregates succumb to detachment depends on the strength of the cohesive forces holding the particles together, and the magnitude of the net effect of disaggregation forces (Wuddivira et al., 2009). When Sutherland et al. (1996) conducted simulated rainfall experiments on an Oxisol at different slope gradients, they found that the most easily detached aggregate size by

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https://doi.org/10.1016/j.still.2019.104539
Received 24 December 2018; Received in revised form 27 October 2019; Accepted 11 December 2019

splash was 500–1000 μm, and the geometric mean aggregate diameter of splashed sediment was similar to that of the original soil. Issa et al. (2006) conducted field- and laboratory-scale simulated rainfall experiments on poorly aggregated sandy soils and concluded that the mean weight diameter values of splashed particles at the field and laboratory scales ranged from 120 to 300 μm and 210 to 320 μm, respectively, which were all lower than the value of the original soil. Chen et al. (2015) tested the characteristics of splash distance and fragment size distribution of splashed sediments using a modified splash tray and found that the particles with a size of 50–200 μm can most easily be splashed.

Raindrop impact is considered as the driving force that causes soil particle movement. Rainfall properties, such as rainfall intensity, raindrop shape and size, drop velocity, kinetic energy and their various combinations, exert significant effects on splash erosion (Quansah, 1981; Park et al., 1983; Sharma et al., 1991; Salles et al., 2000; Brodowski, 2013; Fu et al., 2016; Hu et al., 2018a). The mass of detached particles increases with rainfall intensity (Quansah, 1981; Mermut et al., 1997; Iserloh et al., 2012; Ma et al., 2014), and the most important parameter affecting splash erosion is reported to be the kinetic energy of raindrops (Hammad et al., 2006; Fernández-Raga et al., 2010, 2017; Vaezi et al., 2017). Total splash erosion, directional components of splash erosion and net splash erosion significantly increased with rainfall kinetic energy (Hu et al., 2016a, b). A higher rainfall kinetic energy also resulted in a higher percentage of sand-sized particles in splashed sediments, thereby reflecting the selective behaviour of splash erosion (Zhao and Wu, 2001). The existence of a critical kinetic energy to initiate soil splash detachment has also been studied (Salles et al., 2000; Brodowski, 2013; Hu et al., 2016b). Salls et al. (2000) proposed that this threshold energy equals 5 μJ for fine sand and 12 μJ for silt loam. Hu et al. (2016b) found that the critical kinetic energy for splash erosion initiation was between 3 and 6 J m^{-2} mm^{-1}.

This process is also soil dependent. The size and weight of soil aggregates determine the threshold of rainfall kinetic energy that a drop needs to move a particular aggregate (Leguédois et al., 2005; Salles and Poesen, 1999, 2000; Salles et al., 2000). Al-Durrah and Bradford (1981) found that soil splash is a function of the ratio of kinetic energy to the shear strength of the soil. Legout et al. (2005a) analyzed the splash mass, average splash distance and fragment size distribution; they found the greatest mass of splash sediments was measured for the sand, followed by the silt loam and then the clay soils. Qinjuan et al. (2008) showed that maximum splash erosion occurs in soils with a high concentration of sand particles, and minimum splash erosion occurs in soils with high aggregate concentration, aggregate stability and high organic matter concentration. Saedi et al. (2016) found that a high detachability of fine silt directly increases splash erosion, while its capacity to form a surface crust reduces splash erosion.

The splash detachment process was also directly related to runoff characteristics, such as runoff depth (Mutchler and Hansen, 1970; Moss and Green, 1983; Torri et al., 1987; Kinnell, 2005; Mahmoodabadi and Rouhipour, 2011) and runoff velocity. The kinetic energy of raindrops is partly consumed by the runoff layer, which would weaken the eroding force of raindrops for soil detachment (Moss and Green, 1983; Ferreira and Singer, 1985; Proffitt et al., 1991; Wan et al., 1996; Dunne et al., 2010). This effect was included in rainfall detachment algorithms of some erosion models, such as EUROSEM (Morgan et al., 1998).

Although extensive work related to soil erosion has been done to date, the ratio between papers focused on splashed erosion and soil erosion was less than 0.05 (Fernández-Raga, et al.,2017). More studies are needed to ascertain the splash erosion, especially its particle size selective behaviour. Among previous studies on particle size selective behaviour by splash erosion, few studies have been conducted on the relationship equations of size-selective characteristics of splash-detached sediments with rainfall and hydraulic parameters, such as rainfall kinetic energy, runoff velocity and runoff depth, as well as the relationship equation with rainfall intensity and slope gradient. Thus, the hypothesis of this study is that splash-detached sediment size is significantly related to rainfall intensity and slope gradient, as well as rainfall and hydraulic parameters (rainfall kinetic energy, runoff depth and runoff velocity).

The objectives of this study were to (i) explore the responses of the size-selective characteristics (expressed by mean weight diameter, MWD) of splash-detached sediments to rainfall intensity and slope gradient, and determine the corresponding equation to clarify variation features of MWD of splash-detached sediments with different rainfall intensities and slope gradients; and (ii) identify the relationships of MWD of splash-detached sediments with rainfall kinetic energy, runoff depth and runoff velocity, and thereby determine an equation that manifests their relationship. The study can deeply improve the understanding of interrill erosion processes including splash and subsequent raindrop-impacted interrill wash erosion, and lay an important foundation for developing interrill erosion process model.

2. Materials and methods

2.1. Experimental soils and apparatus

In this study, soil samples were collected from Tianshui, Gansu Province, which is located in the south of the Loess Plateau in China. Soil was sampled from the top 0 − 25 cm layer of the cultivated land, transported from the study area to the laboratory and air dried. Plant residues and pebbles were removed by passing the soil through a 5-mm sieve, and then the soils were mixed thoroughly. The ultimate particle size distribution (i.e. dispersed particle size distribution) of the test soil was 244.6 g kg^{-1} clay (< 0.002 mm), 358.1 g kg^{-1} silt (0.002–0.02 mm) and 397.3 g kg^{-1} sand (0.02 − 2 mm). Based on the soil texture classification system of the International Union of Soil Science (IUSS) (International Society of Soil Science, 1929), the test soil was clay loam. The effective particle size distribution (i.e. undispersed particle size distribution) was 93.9 g kg^{-1} particles with < 0.002 mm diameter, 154.7 g kg^{-1} particles with 0.002–0.02 mm diameter and 751.4 g kg^{-1} particles with 0.02 − 2 mm diameter. The ultimate and effective particle size distribution of the test soil are shown in the Fig. 1.

Experimental studies were conducted at the simulated rainfall hall in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau in Yangling, Shaanxi Province of China. Five rainfall intensities (0.7, 1.0, 1.5, 2.0 and 2.5 mm min^{-1}) and five slope gradients (7, 10, 15, 20 and 25°) were designed in this study. Two replicates were completed for each combination, and the means were used in all analyses. To simulated rainfall, tap water (electrical conductivity = 0.7 dS

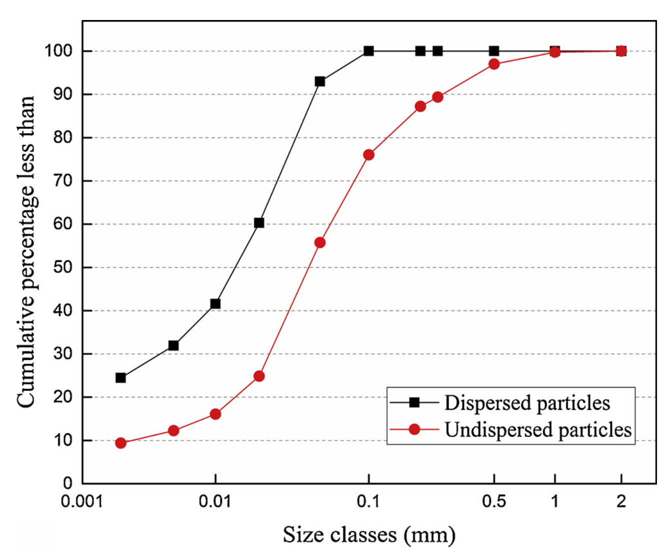

Fig. 1. The ultimate and effective particle size distribution of the test soil.

m^{-1}) was applied using a rainfall simulator with two-sided nozzles, capable of producing rainfall intensities ranging from 0.5 to 3.3 mm min^{-1}. The raindrop fall height was 16 m, which guaranteed that all raindrops would reach the terminal speed. The simulated rainfall could produce a controllable intensity with distribution uniformity of over 85 %.

The experimental soil pan used in this study consisted of three parts: test area, splash collecting area and buffer area, which were the same as those in our previous studies (Wu et al., 2018; Zhang et al., 2018, 2019). The test area was 0.8 m in length, 0.6 m in width and 0.25 m in depth. On both sides of the test area, two splash collecting areas were set, both of which were 0.8 m in length and 0.035 m in width. Surrounding the test and splash collecting areas was the buffer area, which was filled with the soil in the same manner as the test area to equalize the opportunity for splash onto and off the area. A picture of the soil pan is provided in the studies by Wu et al. (2018) and Zhang et al. (2019).

2.2. Experimental procedures and treatments

When the test soil was packed into the soil pan, a 5-cm-thick sand layer was placed at the bottom of the soil pan as a filter to simulate a drainage system. The soils were packed uniformly into the experimental pans in four 5-cm-thick layers to a total depth of 20 cm. The surface of each sub-surface soil layer was gently scored prior to packing of the subsequent layer to reduce discontinuities between layers. Soil was compacted to obtain an appropriate bulk density of 1.2 g cm^{-3}, which was almost equal to that of the soil under natural conditions. The packed soil pan was then pre-wetted under the rainfall simulator with a rainfall intensity of 25 mm min^{-1} lasting for approximately 30 min. This created uniform soil surface moisture conditions and reduce the micro-relief variability that may be produced during the soil packing process. Approximately 15 h after pre-wetting, the soil pan was adjusted to the desired slope gradient, and the simulated rainfall event began.

Each rainfall run lasted approximately 40 min. During each run, particles detached by splash, and sediment-laden flow consisting of runoff and washed sediments were collected continuously at intervals of 1 and 2 min within the first 3 min after runoff production and at 3-min intervals thereafter. Once collected, splash-detached samples, and sediment-laden flow consisting of runoff and wash sediments were measured gravimetrically. The splashed samples were then immediately transported to the laboratory to measure the effective particle size distribution using a Master sizer 2000 laser diffraction device (Malven Instrument Ltd., UK), which has a measurement range of 2 − 2000 μm in diameter. The results of the laser diffraction are expressed in volume frequencies. After measuring the effective particle size distribution, the splashed samples were oven-dried at 105 °C for 24 h to determine the splash detachment rates. Sediment-laden flow consisting of runoff and wash sediments were also oven-dried at 105 °C for 24 h to calculate the mean runoff depth on the test area. In addition, surface runoff velocities on the test area were measured using a $KMnO_4$ solution as a tracer along a 50-cm segment.

2.3. Data calculation

A disdrometer (Thies Clima, Germany) was used to measure the rainfall kinetic energy (KE, J m^{-2} h^{-1}), which was 196.35, 354.85, 495.92, 848.82 and 1059.95 J m^{-2} h^{-1} at the rainfall intensity of 0.7, 1.0, 1.5, 2.0 and 2.5 mm min^{-1}, respectively. The splash detachment rate was defined as the weight of sediments detached by raindrops per unit area per unit time. Mean weight diameter (MWD) was used to express the effective particle size distribution of splash-detached sediments. This was calculated as the sum of the mass percentage of each size fraction multiplied by the arithmetic mean size of the fraction (Le Bissonnais, 1996; Legout et al., 2005a). The formula is as follows:

$$MWD = \frac{\sum_1^i \bar{x}_i w_i}{100} \quad (1)$$

where $\bar{x}_i$ is the mean diameter of the ith size class, w_i is the percentage of particles of the ith size class, and i is the size classes (i = 4 in this study). For the measurements of effective particle size distribution of the splash-detached sediment samples, the 0–2000 μm size range was subdivided into 4 size intervals (0–2 μm, 2–50 μm, 50–250 μm and 250–2000 μm). The bulk density of the different size fractions was assumed to be constant in this study, which was consistent with the assumptions of other studies (Legout et al., 2005 a).

The runoff velocity was calculated by multiplying the surface runoff velocity with a correction factor (α), because the dye method only measures the surface runoff velocity in this study. In this study, all flows under different rainfall intensities were laminar. So the correction factor (α) was set to a value of 0.67, as suggested by Horton et al. (1934). Runoff depth was calculated by the following formula:

$$h = \frac{1000(R_i - m_i)}{\rho_i V W t_i} \quad (2)$$

where h is the runoff depth (mm), R_i is the total weight of the runoff and washed sediments during sampling time (kg), m_i is the weight of the wash sediments during sampling time (kg), ρ_i is the mass density of the runoff (kg m^{-3}) V is the runoff velocity (m s^{-1}), W is the runoff width (it is equal to the width of test area of experimental soil pan) and t_i is the sampling time (s).

3. Results

3.1. Splash detachment rate and MWD of splash-detached sediment under different rainfall intensities and slope gradients

Fig. 2 shows the splash detachment rates under different rainfall intensities and slope gradients. Both rainfall intensity and slope gradient have positive effects on the splash detachment rate. Increases in rainfall intensity or slope gradient caused an increase in splash detachment rate, with rainfall intensity displaying a greater effect.

Fig. 3 shows that the MWD of splash-detached sediment was strongly effected by rainfall intensity and slope gradient. For the same rainfall intensity, the MWD of splash-detached sediment increased with increasing slope gradient. The steeper slope gradient led to a lower increase rate of MWD of splash-detached sediment. For the same slope gradient, the MWD first increased and then decreased with increasing rainfall intensity. MWD increased when rainfall intensity increased

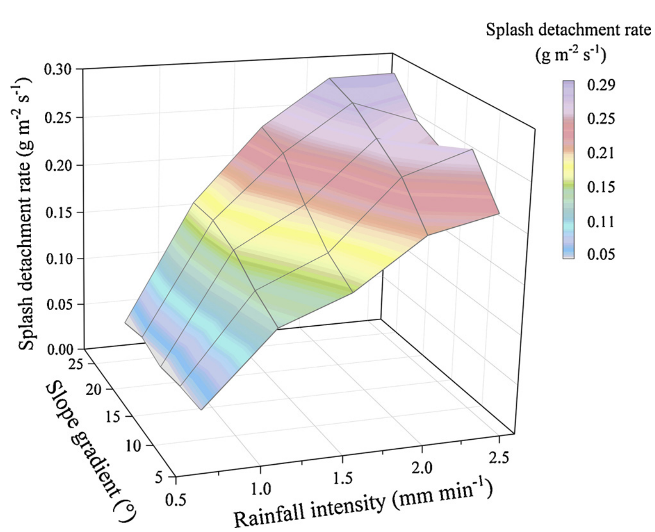

Fig. 2. Splash detachment rate varying with slope gradient and rainfall intensity.

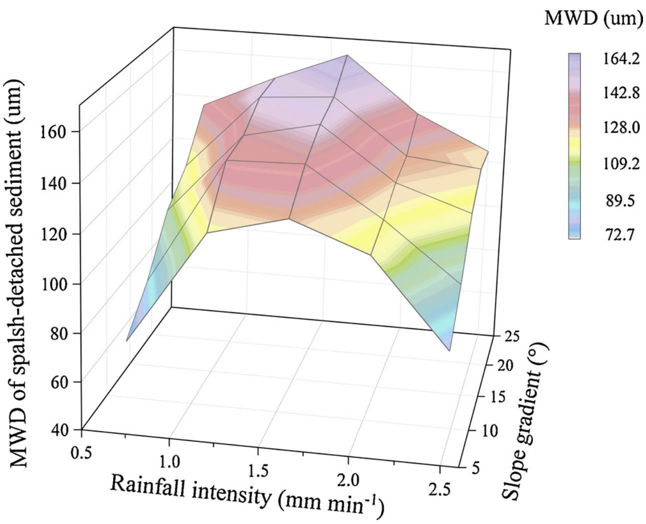

Fig. 3. MWD of splash-detached sediment varying with slope gradient and rainfall intensity.

from 0.7 to 1.5 mm min^{-1}, although a decreasing trend was observed when the rainfall intensity increased from 1.5 to 2.5 mm min^{-1}. The MWDs of the splash-detached sediment ranged from 72.74 to 164.17 μm, with the highest value of 164.17 μm being reached at rainfall intensity of 1.5 mm min^{-1} under slope gradient of 25°. All MWD values of the splash-detached sediment were lower than that of the soil matrix (182.23 μm).

To analyse the relationship between MWD of splash-detached sediment and slope gradient, we applied logarithmic functions to fit the experimental data. Table 1 shows the fitted equations under different rainfall intensities. All determination coefficients (R^2) were satisfactory (R^2 ranged from 0.86 to 0.99). Similarly, to analyse the relationship between MWD of splash-detached sediment and rainfall intensity, we applied parabolic functions to fit the experimental data. The results showed that the relationships between MWD of splash-detached sediment and rainfall intensity under different slope gradients can be satisfactorily expressed by parabolic functions (R^2 ranged from 0.70 to 0.99) (Table 2). Indeed, as shown in Table 2, the MWD of splash-detached sediment could reach the highest value under the rainfall intensity of 1.502-1.621 mm min^{-1}.

To evaluate the relationship of the MWD with both rainfall intensity and slope gradient, multivariate and nonlinear regression analyses were conducted. The equation is as follows:

$$MWD = 216e^{-1.25I}I^{1.81}S^{0.28} \ (R^2 = 0.88,\ P < 0.01,\ n = 25), \quad (3)$$

where MWD is the mean weight diameter of splash-detached sediment (μm), S is the slope gradient (°), I is the rainfall intensity (mm min^{-1}), and n is the number of samples.

As shown in Eq. (3), the relationship of MWD with both rainfall intensity and slope gradient can be described by an exponential-power combination equation, with a determination coefficient (R^2) of 0.88. Fig. 4 also shows good agreement between the calculated and measured MWD of splash-detached sediment. The response of MWD of splashed detached sediment to rainfall intensity was an exponential-power combination function, which is more complex than that for slope gradient (Eq. 3). For $f(I) = e^{-1.25I}I^{1.81}$, when I was less than 1.448 mm min^{-1}, $f(I)$ increased with increasing rainfall intensity, whereas when I was larger than 1.448 mm min^{-1}, $f(I)$ decreased with increasing rainfall intensity. The $f(I)$ had a maximum value when I was 1.448 mm min^{-1}.

Table 1
Relationship between MWD of splash-detached sediment (MWD, μm) and slope gradient (*S*, °).

Rainfall intensity (mm min^{-1})	Equations	R^2
0.7	MWD = 55.75ln(*S*) - 38.79	0.94
1.0	MWD = 44.38ln(*S*) + 24.10	0.97
1.5	MWD = 19.23ln(*S*) + 114.90	0.84
2.0	MWD = 19.81ln(*S*) + 80.30	0.67
2.5	MWD = 38.53ln(*S*) + 5.06	0.96

Table 2
Relationship between MWD of splash-detached sediment (MWD, μm) and rainfall intensity (*I*, mm min^{-1}).

Slope gradient (°)	Equations	R^2
7	MWD = $-81.84(I-1.61)^2+142.54$	0.96
10	MWD = $-83.93(I-1.60)^2+151.49$	0.88
15	MWD = $-58.87(I-1.53)^2+164.64$	0.89
20	MWD = $-34.52(I-1.46)^2+155.32$	0.64
25	MWD = $-51.58(I-1.49)^2+174.09$	0.91

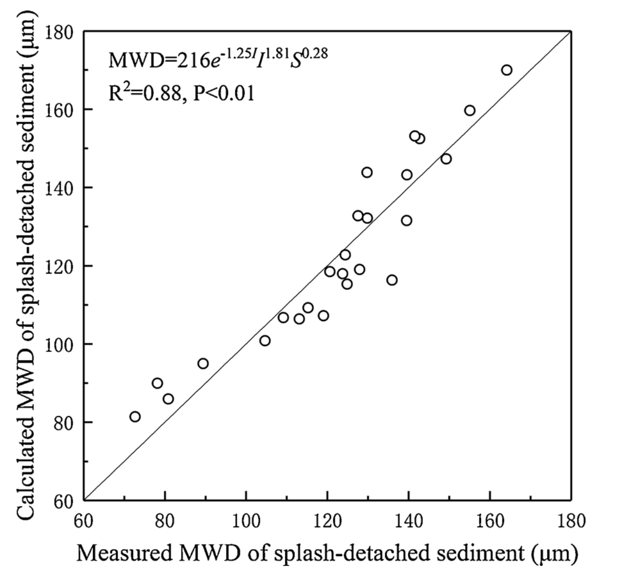

Fig. 4. Measured vs. calculated (using Eq. 3) MWD of splash-detached sediment.

3.2. Response of MWD of splash-detached sediment to rainfall and hydraulic parameters

3.2.1. Variations of MWD of splash-detached sediment with rainfall kinetic energy, runoff depth and runoff velocity

Similar to the trend of MWD of splash-detached sediment with rainfall intensity, the MWD of splash-detached sediment first increased and then decreased with rainfall kinetic energy (Fig. 5). The relationship can be expressed by a parabola equation:

$$MWD = -2.98 \times 10^{-4}(KE-642.6)^2 + 152.65 \quad (R^2 = 0.70,\ P < 0.01,\ n = 25), \quad (4)$$

where MWD is the mean weight diameter of splash-detached sediment (μm), KE is the rainfall kinetic energy (J $m^{-2}h^{-1}$) and n is the number of samples.

The variations of MWD of splash-detached sediment with runoff depth are presented in Fig. 6. Evidently, the MWD of splash-detached sediment decreased as runoff depth increased under different rainfall intensities, and their relationships can be described by linear equations (R^2 ranged from 0.68 to 0.98).

The variations in MWD of splash-detached sediment with runoff velocity are presented in Fig. 7. Unlike the negative correlation of runoff depth to MWD, the MWD of splash-detached sediment increased

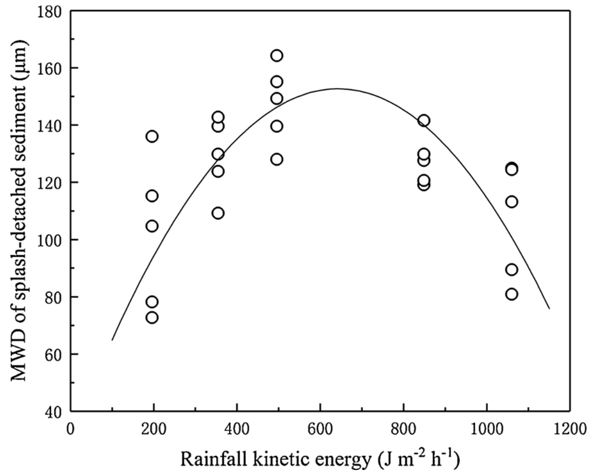

Fig. 5. MWD of splash-detached sediment varying with rainfall kinetic energy.

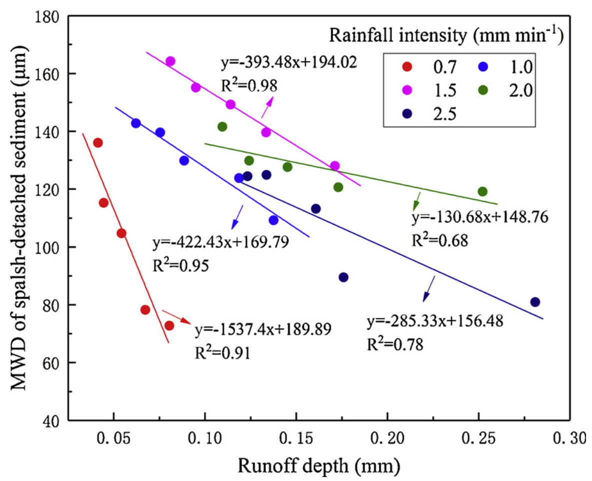

Fig. 6. Relationships between MWD of splash-detached sediment and runoff depth.

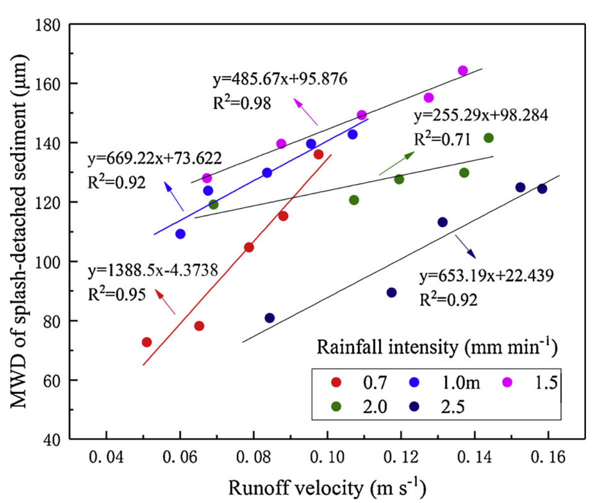

Fig. 7. Relationships between MWD of splash-detached sediment and runoff velocity.

as runoff velocity increased under different rainfall intensities. The relationship between the MWD of splash-detached sediment and runoff velocity can also be described by a linear equation (R^2 ranged from 0.71 to 0.98).

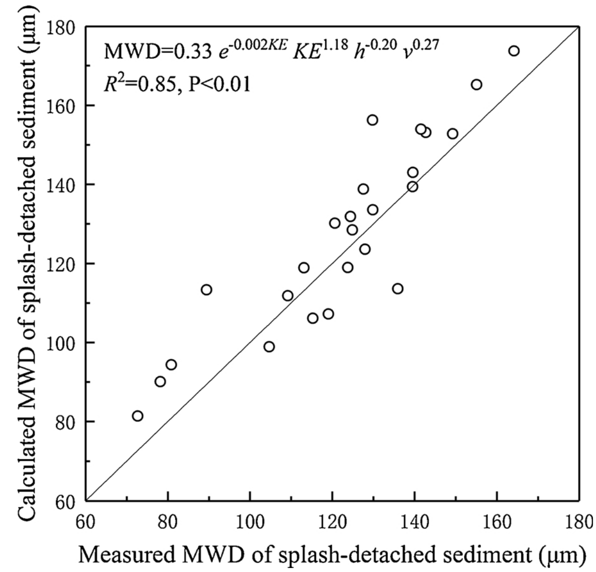

Fig. 8. Measured vs. calculated (using Eq. 5) MWD of splash-detached sediment.

3.2.2. Comprehensive response of MWD of splash-detached sediment to rainfall kinetic energy, runoff depth and runoff velocity

Considering the comprehensive effects of rainfall characteristics (represented by the parameter of rainfall kinetic energy) and overland flow hydraulic characteristics (runoff depth and runoff velocity) on the splash detachment process, we performed multiple regression analysis to examine the relationship of MWD with rainfall kinetic energy, runoff depth and runoff velocity. The obtained equation was as follows:

$$MWD = 0.33\ e^{-0.002KE}\ KE^{1.18}\ h^{-0.20}\ v^{0.27}\quad (R^2 = 0.85,\ P < 0.01,\ n = 25), \tag{5}$$

where MWD is the mean weight diameter of splash-detached sediment (μm), KE is the rainfall kinetic energy (J m^{-2} h^{-1}), h is the runoff depth (mm), v is the runoff velocity (m s^{-1}), and n is the number of the samples. As shown in Eq. (5), the relationship of the MWD with rainfall kinetic energy, runoff depth and runoff velocity can be described by an exponential-power combination equation, with a determination coefficient (R^2) of 0.85. Fig. 8 also shows good agreement between the calculated and measured MWD of splash-detached sediment. The response of MWD of splashed detached sediment to rainfall kinetic energy was an exponential-power combination function, which was more complex than that for runoff depth and velocity (Eq. 5). For $f(KE) = e^{-0.002KE} KE^{1.18}$, when KE was less than 590 J m^{-2} h^{-1}, $f(KE)$ increased with increasing rainfall kinetic energy, while when KE was larger than 590 J m^{-2} h^{-1}, $f(KE)$ decreased with increasing rainfall kinetic energy. Runoff depth decreased MWD, while runoff velocity increased MWD, and the MWD was more sensitive to runoff velocity than to runoff depth.

4. Discussion

This study hypothesized that splash-detached sediment size is significantly related with rainfall intensity and slope gradient, as well as rainfall kinetic energy, runoff depth and runoff velocity. The objectives of this study were to explore the responses of MWD of splash-detached sediments to rainfall intensity and slope gradient, and to identify the relationships of MWD of splash-detached sediments with rainfall kinetic energy, runoff depth and runoff velocity.

Results showed that rainfall intensity had a positive effect on splash detachment rate, whereas the MWD of splash-detached sediment first increased and then decreased with increasing rainfall intensity or rainfall kinetic energy. This asynchronization in the effect of increasing rainfall intensity on splash detachment rate and MWD was attributed to the complex effect of rainfall kinetic energy on the splash detachment process. As reported previously by Kinnell (2005) and Wuddivira et al. (2009), rainfall kinetic energy overcomes the bonding forces that hold particles at the soil surface, and transport the detached particles away from the site of impact. High rainfall intensity corresponds to the large erosive force (large rainfall kinetic energy) in soil splash detachment, so that the splash detachment rate increased with an increase of rainfall intensity, which was consistent with previous findings (Park et al., 1983; Mermut et al., 1997; Chen et al., 2015; Mahmoodabadi and Sajjadi, 2016). For example, Mahmoodabadi and Sajjadi (2016) showed that splash detachment rates were 0.83×10^{-2} and 1.15×10^{-2} g m^{-2} s^{-1} under rainfall intensities of 0.95 and 1.33 mm min^{-1}, respectively. However, higher rainfall kinetic energy can also lead to more severe aggregate disintegration and increase the fractions of finer-sized sediments when detaching particles from the soil surface (Ekwue and Ohu, 1990). Thus, the MWD of the splash-detached sediment firstly increased, and then decreased with increasing rainfall intensity or rainfall kinetic energy in this study. However, Chen et al. (2015) found different results. In their study, the MWD of splash-detached sediment were about 130, 170, 200 and 270 μm when rainfall intensity were 0.6, 1.3, 1.7 and 2.0 mm min^{-1}, respectively, which showed that the MWD of splash-detached sediment was positively related to rainfall intensity. The difference between the results of this study and those of Chen et al. (2015) were mainly attributed to the differences in soil texture and measurement of splash sampling, with clay loam soil in a soil pan being used in this study, while sandy loam soil and a splash tray were used in that of Chen et al. (2015).

Results further showed that MWD of splash-detached sediment decreased as runoff depth increased. This may be explained by the following: (1) the water layer has a cushion effect and shields soil particles from splash (Moss and Green, 1983; Proffitt and Rose, 1991; Wan et al., 1996; Dunne et al., 2010); (2) raindrops must penetrate through the water layer to detach soil particles, a process that consumes the rainfall kinetic energy. Thus, a lower efficiency of rainfall kinetic energy was used to detach large soil particles when the runoff depth was thicker; (3) Soil aggregates, which are not stable enough, can be easily disintegrated and collapse into small fragments when immersed in water, and the thicker the water layer is, the more serious the soil aggregates may disintegrate. Thus, the MWD of the splash-detached sediment decreased as runoff depth increased in this study.

Results also showed that MWD of splash-detached sediment increased as runoff velocity increased. Runoff velocity, to a certain extent, reflects the downward force of runoff on the soil particles along the slope. A high runoff velocity can decrease the stability of soil particles for splash, which has a positive effect on soil particles to be splash detached. Runoff velocity can also affect the raindrop splash angle, thereby increasing the component of raindrop impact force along the slope to a certain extent. These two may have the force assistance for raindrops to detach large soil particles.

In this study, a new equation of Eq. (5) was established to quantify the size-selective characteristics (expressed by MWD) of splash-detached sediment using rainfall kinetic energy, runoff depth and runoff velocity ($R^2 = 0.85$, $P < 0.01$), which was absent in previous studies. Raindrop impact is the driving factor behind the detachment of soil particles. Rainfall kinetic energy was the main kinetic parameter in determining the MWD of splash-detached sediment, while runoff velocity and runoff depth affected the MWD of splash-detached sediment to a lower degree. According to Eq. (5), the MWD of splash-detached sediment was more sensitive to changes in runoff velocity than to changes in runoff depth, which indicated that effects of runoff velocity in the splash detachment process should also be considered, especially regarding particle size selective behaviour on a sloping surface.

The study fully achieved its objectives, and the results significantly supported the hypotheses. The findings implied that reducing efficient raindrop impact on soil and increasing surface roughness to reduce runoff velocity by increasing surface covers can efficiently maintain the soil quality by reducing the particle size selectivity by splash detachment. This study not only indicated that particle size selectivity by splash detachment needs to be considered in modelling raindrop-impacted interrill wash erosion, but can also be helpful for soil conservation management for similar conditions of soil, rainfall and land use.

5. Conclusion

The hypothesis that splash-detached sediment size is significantly related to rainfall intensity and slope gradient, as well as rainfall kinetic energy, runoff depth and runoff velocity was verified in this study.

The results showed that the MWD of splash-detached sediment first increased, and then decreased with increases in rainfall intensity or rainfall kinetic energy, which can be described by parabolic functions. As slope gradient increased, the MWD increased, which can be expressed by logarithmic functions. However, all MWD values of splash-detached sediment (72.74–164.17 μm) were lower than that of the soil matrix (182.23 μm) under all combinations of rainfall intensity and slope gradient. The relationship of MWD with rainfall intensity and slope gradient can be described by an exponential-power combination equation ($R^2 = 0.88$). The MWD of splash-detached sediment decreased linearly as runoff depth increased and increased linearly as runoff velocity increased. A new equation, Eq. (5), was established to quantify the MWD of splash-detached sediment using rainfall kinetic energy, runoff depth and runoff velocity ($R^2 = 0.85$). Rainfall kinetic energy was the main kinetic parameter in determining the MWD of splash-detached sediment, while runoff velocity and runoff depth further increase and decrease the MWD of splash-detached sediment.

These findings could be helpful for understanding and modelling the splash and subsequent interrill wash erosion processes, and for soil conservation management for similar conditions of soil, rainfall and land use.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Financial support for this research was provided by the National Natural Science Foundation of China funded project (41830758; 41907054; 41907046; 41867015; 41601282; 41471230); the National Key Research and Development Program of China (2017YFD0800502; 2016YFC0402401); Special-Funds of Scientific Research Programs of State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau (A314021403-C2).

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