Estimating the Effect of Rain Splash on Soil Particle Transport by Using a Modified Model: Study on Short Hillslopes in Northern China

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Abstract: Splash erosion is an important soil erosion process in sloping lands. This study aims to improve the model of rain splash transport based on the results of previous studies and field experiments involving rainfall simulation. A field study was conducted to examine the effects of rainfall properties, herbaceous cover and surface flow on splash processes on hillslopes in northern China. On the basis of the experimental results, a comprehensive model of rain splash was established through the quantitative analysis of the interactive effects of rainfall kinetic energy, vegetation coverage and overland runoff depth on splash erosion rate and the probability density of splashed particles and maximum splash distance. The results showed that the estimated and observed values of splash transport exhibit high consistency and adaptability. However, several discrepancies were observed between the estimated and observed values for events with high vegetation coverage. These differences can be ascribed to the variation in overland runoff connectivity and the differences in soil surface cohesion at various wetness degrees. The proposed model provides insights into splash erosion characteristics and suggestions for erosion control practices on hillslopes.

Keywords: splash erosion; raindrop energy; herbaceous cover; splash distance; overland flow

1. Introduction

Rain splash is an essential contributor to soil particles detachment and transport in slope erosion [1–3]. Splash erosion is directly caused by the kinetic energy of raindrops [4,5], which is an important parameter in erosion prediction models. Ground cover reduces soil erosion and surface flow on hillslope landscapes, and different vegetation conditions affect the occurrence and development of splash erosion [6–9]. The two parameters used to study and predict splash erosion are the detachment rate and probability density of splashed particles within a certain distance [10–12]. Previous studies have presented the relationships between various factors and splash erosion rate [13,14] by mostly considering the effects of raindrops on soil selectivity, size and distribution [15,16]. The distribution of splashed particles at different distances is important in analysing splash erosion. Numerous studies have considered the transport distance of splashed particles along slopes from their origins [17]. Various methods and devices can be used to measure splash erosion depending on research objectives and conditions [18–20]. New techniques are applied to improve the investigation of splash erosion. For example, Furbish et al. (2007) [21] generated a physical image depicting raindrop–grain momentum...
transfer and its relationship with the proportion of ejected grains through high-speed imaging. In addition to rainfall and soil properties, hillslope conditions and overland flow play an important role in water erosion by covering the topsoil. Therefore, the effect of the latter on soil material detachment and transport should be considered in prediction models. The instability of the soil particle structure increases with an increase in slope gradient, and cohesion amongst particles is weakened [22]. Vegetation and runoff connectivity are important factors that affect hillslope erosion [23]. Vegetation reduces the influence of raindrops on surface soil particles and prolongs runoff generation; meanwhile, surface roughness and microtopography affect flow distribution and rill development on a slope [24,25]. Torri et al. (1987) [26] considered the effects of raindrop diameter and runoff depth on the detachment rate model. Ghahramani et al. (2011a) [12] established the effects of overland flow on preventing raindrop splash and developing a soil particle transport model. However, these models disregard the time variance of the processes, which can be affected by numerous uncertainties. In addition, a clear explanation of the interaction between runoff depth and rain splash detachment rate during a rainfall event remains lacking.

The mountainous region of northern China exhibits an important type of soil erosion with the following characteristics: (a) coverage of a thin soil layer with rich gravel, (b) severe soil loss under steep slopes, (c) concentration of rainstorms during summer and (d) sustainable use of soil and water resources with the massive population explosion in the region. Previous studies have examined the effect of ground cover on splash erosion [27–29]. However, most of these studies have focused on forested landscapes and litter conditions [30]. Herbaceous vegetation is an effective means of controlling soil and water losses in this region. Although vegetation cover is important in preventing soil erosion [9], the role played by herbaceous layers in modulating surface runoff and soil erosion on hillslope areas remains unclear.

Splash detachment and transport are associated with overland flow depth [12]. The effect of herbaceous cover on the interaction between raindrops and overland runoff should be understood to improve soil erosion and sediment transport models [31,32]. In the current study, we conducted field experiments with simulated rainfall to investigate splash erosion rate, probability density function (PDF) of splashed particles and change in surface runoff depth on hillslopes under herbaceous cover in Yanqing District, Beijing. The objective of this research is to understand the transport characteristics of splashed particles under the simultaneous interactions of rainfall properties, herbaceous cover and overland runoff to illustrate the related mechanism and theoretical principles. We also aim to develop a comprehensive model of the splash erosion process.

2. Model Development

2.1. Development of the Splash Erosion Model

Water erosion refers to the interaction amongst rainfall erosion force, runoff and soil resistance under various factors. Rain splash erosion plays an important role in understanding the effects of different rainfall characteristics on soil particle detachment under varying ground covers on hillslopes. Ghahramani et al. (2011a) [12] developed a 1D splash transport model that considers the effects of soil detachment, ground cover and surface flow depth on preventing detachment.

\[ S_d = S_b (1 - G_c) K_h, \]

where \( S_b \) (g/m²) represents the splash erosion rate for bare soil in the period defined for \( S_d \) (g/m²), \( G_c \) (%) denotes the ground cover fraction and \( K_h \) indicates the overland flow reduction factor.

The distribution of splashed particles is an essential factor in soil erosion transport models [33–35]. Many scholars have obtained substantial and constructive results in soil detachment and transport by
Splashed particles are exponentially distributed along the maximum transport length $L_{\text{max}}$ (m) at different distances [13,20], and PDF can be defined as

$$f(L) = \int_{0}^{L_{\text{max}}} ae^{-bX} dx,$$  \hspace{1cm} (2)

where $X$ is the distance from the study plot to the settling point (m) of the splashed particles; and $a$ and $b$ are the empirical coefficients that are dependent on slope gradient and ejection length, respectively [26].

### 2.2. Model Modification

Different experimental plot sizes have been used in accordance with specific conditions and scientific purposes. For example, to monitor rainfall splash, Morgan et al. (1984) [36] and Leguedois et al. (2004) [37] used trays with areas of 50 cm $\times$ 50 cm; by contrast, Issa et al. (2006) [14] and Ghahramani et al. (2011a, 2001b) [12,29] used experimental plots with areas more than 10 m$^2$. In our previous studies, no significant difference was observed in splash erosion rate between circular and rectangular plots with an area of 1 m$^2$. Thus, the hypothesis based on hillslopes can be expressed as follows. In slope erosion, the entire erosion area is considered an aggregate of several smaller erosion units that are under the same conditions as the slope surface (i.e., ground cover and slope gradient). These units are arranged in accordance with a certain spatial structure. Erosion amount in the splashed area is derived on the basis of the erosion unit (Figure 1). The splash erosion equation for the same horizontal erosion area based on the width of the source area can be written as

$$S_d = \sum_{i=0}^{n} S_{bi} C_v K_h \text{ for } (0 < i \leq n),$$ \hspace{1cm} (3)

where $S_{bi}$ (g/m$^2$) denotes the splash erosion rate of a single bare erosion unit, $C_v$ indicates the ground cover reduction factor and $n$ represents the order of the coordinate axis $X_n$.

**Figure 1.** Hypothesised spatial distribution in slope erosion.

Ghahramani et al. (2011a) [12] conceptualised splashed particles dispersion by dividing the detachment source area along $L_{\text{max}}$ into erosion areas. Figure 2 illustrates the conceptual probability
distribution of splashed particles based on our hypothesis. The PDF equation along a downslope can be written as

\[ f_m(L) = \int_{L_{\text{max}}-mL}^{L_{\text{max}}} ae^{-bx} \, dx \quad (0 < f_m(L) < 1), \tag{4} \]

where \( L \) indicates the length of the erosion unit, and \( m \) presents the order of the erosion unit area starting from the plot outlet. By using Equations (3) and (4), splash transport soil particles along the maximum splash distance for an exact rainfall event can be obtained as

\[ S_t = \sum_{0}^{N} S_d f_m(L), \tag{5} \]

where \( S_t \) (g) denotes the total transported and deposited soil particles caused by raindrops from an upslope area with a given slope width and a length of \( L_{\text{max}} \), and \( N \) indicates the number of source areas (\( N \approx \frac{L_{\text{max}}}{L} \)).

Figure 2. Conceptual use of probability density function (PDF) based on hypothesised.

3. Materials and Methods

3.1. Study Site

The field site is located at the National Water and Soil Conservation Science and Technology Park in Yanqing District, Beijing (40°26'19" N, 116°3'11" E). This area has a typical continental monsoon climate and a mean annual precipitation of 474.5 mm. Rainfall commonly occurs from May to November. In accordance with the soil taxonomy of the United States Department of Agriculture, surface soil type is cinnamon soil. Experimental devices were installed on hillslopes under different herbaceous vegetation coverages. Given that the hillslopes are under long-term monitoring through artificial management, designing experiments to account for the micro-terrain elevation of a slope is beneficial.
3.2. Experiment Design

Field measurements for point-scale and plot-scale experiments were conducted using simulated rainfall. The first point-scale experiments (Experiment 1; Figure 3a) were performed on a slope of 25°, which is a common slope gradient in northern China, to obtain splash erosion rate and probability density from the erosion area. Improved and easy-to-move splash trays comprising four individual quadrants (Figure 3a) with 20 intervals were used to measure splashed particles at different distances. Each quadrant of the splash trays was marked as upper or lower left and right. Meanwhile, 20 splash rings with 8 cm-wide intervals were labelled with numbers ranging from 0 to 20 in accordance with their distance from the inner circular area. In the beginning of the experiment, four individual quadrant splash trays were assembled in accordance with the marked order to form an integrated circular splash tray. The inner circular area (splash source) with a diameter of 40 cm at the centre of the splash trays was the experimental area that received the simulated rainfall. Splashed particles from the inner circular area were collected by the surrounding quadrant splash trays. A plastic cover was placed above the splash trays to prevent secondary splash erosion during the rainfall period. The effect of vegetation coverage on splash erosion was evaluated under 12 levels of rainfall intensity (i.e., 25 ± 0.64, 35 ± 0.78, 45 ± 1.14, 55 ± 1.43, 65 ± 1.65, 75 ± 1.93, 85 ± 2.35, 95 ± 2.89, 105 ± 3.25, 115 ± 3.82, 125 ± 4.26 and 135 ± 4.67 mm/h) and 7 vegetation coverage values (i.e., 0%, 10%, 25%, 35%, 50%, 65% and 80%). A total of 84 rainfall events were involved in this study. In particular, 12 experiments were performed under zero coverage, and the remaining 72 experiments were conducted under different vegetation coverages (each vegetation coverage comprised 3 plots). Each rainfall event was continued until surface runoff occurred. The splash trays were removed and washed with deionised water after the artificial rainfall event to protect the structure of the splashed soil particles. The samples were brought to the laboratory and oven-dried at 105 °C for 24 h for weighing. Through the experiment, we obtained the PDF of the splashed particles and the retardation factor of the vegetation coverages on splash erosion rate.

The second plot-scale experiments (Experiment 2; Figure 3b) were performed on plots with a width of 2 m and a length of 4 m with the same slope to examine the number of splashed particles and amount of runoff during erosion. Erosion plots with average coverages of 0%, 20%, 50% and 80% were installed and separated by steel plates. Ghahramani et al. (2011b) [29] conducted an experiment to collect splashed and washed soil particle samples from plots on forested hillslopes under natural precipitation. In reference to this previous study, our experimental devices included two parts, namely, a splash tray and 20 L plastic containers installed at the plot outlet. A gap of 3 cm existed between the splash trays and the bottom surface to separate the splashed soil particles and water flowing from surface. Each treatment consisted of 5 tests at rainfall intensities of 35 ± 0.78, 65 ± 1.65, 100 ± 3.25 and 120 ± 4.26 mm/h. The plots on the hillslopes were short and relatively smooth, thus, we assumed that overland flow exhibits high connectivity to the experimental slope [38]. To study the effect of runoff depth on the amount of splash erosion, each treatment included 10 groups of rainfall duration (i.e., 3, 6, 9, 12, 15, 18, 21, 24, 27 and 30 min) and was replicated three times. Abrahams et al. (1990) [39] emphasised that considerable errors occur in the calculation of water depth through the hydraulic model due to the limitation of discharges and microtopography. We measured the runoff depth of the erosion unit every 3 min by using a digital needle water level gauge (precision = 0.02 mm). On the basis of the findings of Misra and Roes (2010) [40], who asserted that splash erosion is the most sensitive factor to slope conditions and sediment characteristics during the inter-rill and rill erosion stages [41–43], we adopted short simulated rainfall durations to maintain a stable plot slope topography and minimise the change in water layer depth. The objective of our experiment was to measure the number of splashed particles on the downslope sides and obtain a net mass flux per unit width of the hillslope.
density from the erosion area. Improved and easy-to-move splash trays comprising four individual quadrants (Figure 3a) with 20 intervals were used to measure splashed particles at different distances. Each quadrant of the splash trays was marked as upper or lower left and right. Meanwhile, 20 splash rings with 8 cm-wide intervals were labelled with numbers ranging from 0 to 20 in accordance with their distance from the inner circular area. In the beginning of the experiment, four individual quadrant splash trays were assembled in accordance with the marked order to form an integrated circular splash tray. The inner circular area (splash source) with a diameter of 40 cm at the centre of the splash trays was the experimental area that received the simulated rainfall. Splashed particles from the inner circular area were collected by the surrounding quadrant splash trays. A plastic cover was placed above the splash trays to prevent secondary splash erosion during the rainfall period. The effect of vegetation coverage on splash erosion was evaluated under 12 levels of rainfall intensity (i.e., 25 ± 0.64, 35 ± 0.78, 45 ± 1.14, 55 ± 1.43, 65 ± 1.65, 75 ± 1.93, 85 ± 2.35, 95 ± 2.89, 105 ± 3.25, 115 ± 3.82, 125 ± 4.26 and 135 ± 4.67 mm/h) and 7 vegetation coverage values (i.e., 0%, 10%, 25%, 35%, 50%, 65% and 80%). A total of 84 rainfall events were involved in this study. In particular, 12 experiments were performed under zero coverage, and the remaining 72 experiments were conducted under different vegetation coverages (each vegetation coverage comprised 3 plots). Each rainfall event was continued until surface runoff occurred. The splash trays were removed and washed with deionised water after the artificial rainfall event to protect the structure of the splashed soil particles. The samples were brought to the laboratory and oven-dried at 105 °C for 24 h for weighing. Through the experiment, we obtained the PDF of the splashed particles and the retardation factor of the vegetation coverages on splash erosion rate.

Figure 3. Diagram of the experimental setup: (a) schematic and dimensions of point-scale Experiment 1 for obtaining splashed particles and (b) view of plot-scale Experiment 2 for monitoring the characteristics of slope splash erosion.

3.3. Experiment Preparation

Two common local herbaceous plants, namely Pennisetum alopecuroides and Festuca arundinacea, were selected for the field experiments. During plant growth, the surface and vegetation coverage conditions of the experimental slopes were observed and changed weekly by removing understory litter and keeping the slope surfaces smooth and level to ensure compliance with the experimental requirements. Photographs of 1 m × 1 m squares were taken to quantify the herbaceous cover fraction (Figure 4). Previous studies have indicated that overland flow and sediment characteristics are affected by antecedent soil moisture content [44,45]. To maintain a constant soil moisture content (16.21% ± 1.2%), we subjected all plots to 3 min of simulated rainfall and protected them with plastic cover 1 week prior to the experiment. Before the beginning of the simulated rainfall, we collected 10 soil samples at intervals of 2 m from the experimental slope and tested the major physical and chemical properties. The results are summarised in Table 1.

Table 1. Physical and chemical properties of the field site.

| Particle Size Fraction/% | Clay 0–2 mm | Fine 0.002–0.02 mm | Coarse Silt 0.02–0.05 mm | Fine Sand 0.05–0.2 mm | Coarse Sand 0.2–2 mm | Soil Density (g cm⁻²) | Organic Matter (g kg⁻¹) |
|--------------------------|-------------|-------------------|--------------------------|------------------------|---------------------|----------------------|------------------------|
| 8.8 ± 1.5                | 17.9 ± 1.2  | 24.8 ± 0.8        | 34.3 ± 1.1               | 14.2 ± 2.3             | 1.13 ± 0.23         | 8.28 ± 0.68          |
Approximately 20% coverage  Approximately 50% coverage  Approximately 80% coverage

Figure 4. Growth of herbaceous plants on the slope.

3.4. Rainfall Simulation

An artificial simulated rainfall device (QYJY-501, Xi’an Qingyuan Measurement and Control Technology Corporation, Xi’an, China) with a spray system was used in the experiment. The sprinkler system was positioned 4 m above the soil surface. The uniformity of each simulated rainfall exceeded 90%. Rainfall was produced by four groups of nozzles located at the corner of a rectangular frame, and these nozzles were supplied with tap water through a water supply system. Simulated rainfall with intensities ranging from 20 mm/h to 150 mm/h was controlled by the water pressure adjuster, and thus, raindrops can cover the entire experimental slope. Raindrops have an initial velocity. Thus, we assumed that raindrops falling to the ground approached the terminal velocity of natural rainfall. During the experiment, the rainfall simulation system was protected by a plastic cover to isolate the effect of wind on the experiments. Rainfall kinetic energy and raindrop diameter were measured using an optical spectrum pluviometer [46]. The results are presented in Table 2.

Table 2. Raindrop diameter and rainfall kinetic energy under different rain intensities.

| Rainfall Intensity (mm·h⁻¹) | 25  | 35  | 45  | 55  | 65  | 75  | 85  | 95  | 105 | 115 | 125 | 135 |
|-----------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Mean drop size (mm)         | 1.51| 1.65| 1.83| 1.91| 2.05| 2.13| 2.28| 2.40| 2.59| 2.81| 3.12| 3.51|
| Maximum size (mm)           | 2.05| 2.34| 2.51| 2.75| 2.91| 3.02| 3.35| 3.81| 4.05| 4.34| 4.81| 5.08|
| Minimum size (mm)           | 1.08| 1.23| 1.19| 1.28| 1.32| 1.48| 1.59| 1.72| 1.79| 1.86| 2.02| 2.18|
| Rainfall kinetic energy (J·m⁻²·s⁻¹) | 0.32| 0.43| 0.53| 0.63| 0.73| 0.82| 0.91| 1.00| 1.09| 1.18| 1.26| 1.35|

4. Results

4.1. Characteristics of Splash Erosion

The total amount of splash erosion dispersion is equal to the number of splashed soil particles in all directions. The number of downslope splashed particles in steep slopes is extremely high [29]. Although our experimental apparatus collected soil particles from the upper and lower left and right sides, we selected the downslope splash fractions as the research object. The relationship of downslope splash erosion rate with rainfall kinetic energy and ground cover without overland flow is obtained from Experiment 1. As shown in Figure 5, the variations in splash erosion rate ($S_b$) with rainfall kinetic energy ($E$) on bare land can be defined as

$$S_b = 201.06E^{0.78}.$$  (6)
Ghahramani et al. (2011a) [12] suggested that the proportion of exposed ground \( (1-G_c) \) can be used to estimate soil detachment from a source area. A power function can be applied to delineate the correlation between splash erosion rate and ground coverage objectively with increasing rainfall kinetic energy in Experiment 1 (Figure 6). The downslope splash fractions under 10%, 25%, 35%, 50%, 65% and 80% herbaceous coverage are reduced by 14–27%, 29–38%, 43–51%, 52–60%, 59–67% and 69–87%, respectively, compared with that on bare land [47,48]. Therefore, the relationship between different herbaceous coverages and splash erosion rate was analysed using a nonlinear regression method to obtain the required ground cover reduction factor \( (C_v) \) on a slope of 25°, which can be determined as

\[
C_v = 0.992e^{-0.017G_c} \quad (R^2 = 0.91, 0 < C_v < 1). 
\]  
(7)

Figure 6. Relationship between splash erosion rate and rainfall kinetic energy under different herbaceous coverages.

4.2. Characteristics of Splash Sediment Transport

To minimise errors in determining splash distribution, we classified splash distance on the basis of twenty 8 cm-wide intervals to measure soil particles at different distances. The corresponding average
splash distances of the intervals are 4, 12, 20, 28, 36, 44, 52, 60, 68, 76, 84, 92, 100, 108, 116, 124, 132, 140, 148 and 156 cm. Vegetation cover plays an important role in alleviating splash erosion rate and particle detachment on hillslopes. The shelter effect from the centre to the edge of an eroded area varies due to different plant heights [49]. Therefore, we pooled all the data (n = 36) collected for the bare slope in Experiment 1 to monitor splash distance and distribution of splash transport. The PDF of splash distance exhibits variation in rainfall kinetic energy (Figure 7). Moreover, the experimental results indicate that the distribution of downslope splash transport presents an exponential function similar to that reported by Ghahramani et al. (2011a) [12]. The maximum transport downslope distance in all the experiments ranges from 0.6 m to 1.48 m. The probability density empirical coefficient in Equation (4) can be obtained from Experiment 1 because the test conditions (e.g., antecedent soil moisture and slope gradient) are maintained as consistent as possible, except for overland flow generation time. Therefore, we used the mean values of a (0.281) and b (0.946) for Equation (4).

\[ L_{\text{max}} = 0.52 \ln(E) + 1.03 \quad (R^2 = 0.98). \]  

Figure 8 shows that maximum splash distance and rainfall kinetic energy exhibit a logarithmic relationship on a slope of 25°. The former can be derived as

\[ L_{\text{max}} = 0.52 \ln(E) + 1.03 \quad (R^2 = 0.98). \]
4.3. Model Application and Validation

Woolhiser et al. (1990) [51] defined the equation for the overland flow reduction factor \( K_h \) by calculating the damping coefficient \( (ch) \) and overland flow depth \( (h) \); that is,

\[
K_h = \exp(-ch \cdot h),
\]

where \( ch \) is the damping coefficient \( (ch = 2/D_{50}, \text{and } D_{50} \text{ represents the mean drop size (ft)}) \), and \( h \) is the depth of the surface runoff \( (ft) \). Therefore, we can obtain the \( K_h \) values of different source areas under a simulated rainfall intensity of \( 65 \pm 1.65 \text{ mm/h} \) (Table 2).

We subsequently constructed the splash soil transport model for the source area along \( L_{max} \) towards adjacent subsource areas. From the hypothesised spatial distribution shown in Figure 2, \( n = 5 \) in Equation (3) because the inner circular area has a central diameter of 40 cm. By substituting Equations (6) and (7) into Equation (3), downslope splash erosion rate \( S_d \) \( (\text{g} \cdot \text{m}^{-2}) \) is obtained as

\[
S_d = \sum_{0}^{5} \left( 201.06E^{0.78} \right) \left( 0.992e^{-0.017G_s} \right) K_h.
\]

Equation (11) can be used to predict the number of splashed particles from the upslope erosion area with ground cover \( (G_s) \) and overland runoff depth \( (h) \) effect. Equation (5) is used to determine the proportion of soil detached by splashing from the Nth subsource area. Lastly, 1D downslope rain

![Figure 8. Relationship between maximum splash transport distance and rainfall kinetic energy.](image-url)
splash transport soil particles along the maximum splash distance for a given single rainfall event can be calculated as

\[ S_t = \sum_{0}^{3} S_d f_3(L). \]  

(12)

The total number of splashed particles from the upslope erosion area can be estimated using Equations (11) and (12). The factors that affect rain splash erosion were quantified in the model; dimension was eliminated and splashed particles were defined by different rainfall kinetic energies, vegetation coverages and overland flow depths of various rainfall events [51]. The analysis of the model structure shows that the effect of overland runoff on splash erosion improves the comprehensiveness of the models. Given the explicit physical definitions of each parameter, direct calculations can be performed using the relevant formula or reference experimental model. As shown in Figure 9, the estimated and observed values of splashed particles are highly consistent and evenly distributed on both sides of the 1:1 line (the numerical difference values are within 20%). In conclusion, the developed model of transport via raindrop splash erosion can be adapted to the study area.

![Figure 9. Comparison between the observed and estimated values of splashed particles.](image)

5. Discussion

Raindrop splash affects the occurrence and development of slope erosion. In the beginning of a rainfall event, the soil particle structure is destroyed and dispersed by raindrops. Under the effect of continuous rainfall, the cohesive force amongst soil particles is enhanced as soil moisture increases; such enhancement improves soil erosion resistance [52]. Splash erosion is affected by surface runoff on a slope, and experiments illustrate a decrease in splash when runoff is at a critical depth. Previous laboratory experiments have reported varying threshold behaviour of runoff depth [53]. When surface runoff is sufficiently deep, raindrops cannot directly strike surface soil particles, increasing runoff erosion. In our model, the improved agreement between the estimated and observed values of total splashed particles for rainfall events is associated with the effect of overland flow.

During slope erosion, the detachment and transport of soil particles by raindrop splash are two different processes, but we have no strict distinction between them. In the current study, we focus on splashed particles transport along a downslope towards the exit section of the experiment plot to consider inward splash erosion and upslope particle transport in erosion units. Given the occurrence
of internal splash erosion, the re-decomposition of splashed particles may influence particle size. However, the corresponding effects on splash distance and splash amount along a downslope are relatively low. For upslope transport particles, we can only monitor those that reach the measured area. Therefore, measuring the PDF of splashed particles is important. The results show that splash transport is associated with overland flow depth. Raindrop splash decreases when runoff depth exceeds 0.6–1 times of the raindrop diameter [11,26]. Cruse and Larsen (1977) [54] reported that soil shearing strength affects raindrop splash detachment and soil wetness increases soil shear force [55] and production. The shielding effects of the critical shear force and critical runoff depth on raindrop splash are not considered in the experiment. In addition, raindrops can disturb surface flow and increase runoff transport capacity. Hence, additional variable control experiments must be conducted and the spatial distribution of water flow on a slope must be considered.

Although result agreement varies amongst vegetation coverage events, the estimated splashed particles exhibit good agreement in exposed and low coverage areas. To improve the application of the proposed model, the dynamic interactions of vegetation covers, soil wetness and runoff distribution should be considered. The conclusion of this study can be used as a reference for developing control methods and models for splash erosion. Given that soil degradation has become one of the most important international issues that affect human activities [56,57], the effect of splash erosion on fields must be controlled. Furthermore, knowledge regarding the processes of soil degradation and nutrient loss should be enhanced to develop effective protection methods for promoting land restoration.

6. Conclusions

In this study, we investigated dynamic changes in soil and runoff during erosion on hillslopes under simulated rainfall. The results confirmed that the number of splashed particles from the erosion source decreases exponentially with an increase in distance. In addition, transport distance was determined as a function of flow energy. The maximum transport splash distance and PDF of splashed particles transport were affected by rainfall kinetic energy. The proposed model considered soil splash processes and demonstrated that slope conditions were critical for predicting splash erosion. The inclusion of overland flow depth can considerably improve the predictive capability of the model, particularly during periods of low vegetation coverage events. The proposed model also identified the characteristics of soil particle transport under raindrop splash for specific conditions. This model structure can be applied to different situations to predict long-term splash on hillslopes. Our models fairly accurately predict transported splashed particles via raindrops under rainfall kinetic energy and herbaceous coverages in a hillslope erosion system. Therefore, these models can be used to improve the understanding of the slope erosion process and develop models of erosion dynamics on hillslopes. However, our models should be used with caution, and additional quantitative studies should be conducted subsequently to explore the scope of the extended model.

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