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ORIGINAL PAPER

Effects of rainfall intensity and slope gradient on erosion characteristics of the red soil slope

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Abstract Soil erosion is one of the most serious driving forces of ecosystem degradation in the world that strongly affected by rainfall intensity and slope gradient. Therefore, a laboratory simulated rainfall study, with three slope gradients (5°, 15°, and 25°) subjected to seven rainfall intensities (30, 60, 90, 120, 180, 210, and 270 mm/h), was conducted to determine the effect of rainfall intensity and slope gradient on runoff generation, rate, sediment yielding, erosion rate, and runoff hydraulics characteristics of the red soil slope. The results indicated that runoff generation of red soil slopes was influenced by both the slope angle and rainfall intensity, runoff rate showed a steady condition after an initial trend of an unsteadily increased with increasing rainfall duration, while it did not increase with the increasing slope gradients, especially under the high rainfall intensity. Under the influence of high rainfall intensities, sediment yielding of the red soil slope was controlled by detachment limitation and then by transport limitation under low rainfall intensity. Under low and moderate rainfall intensities, erosion rate increased with slope angle due to the factors related to slope angle can enhance soil detachment or limit the protective effect of surface layer. Furthermore, runoff hydraulic characteristics of the red soil slope indicating that overland flows on all slopes were considered as laminar, tranquil, and supercritical, and the Reynolds numbers were significantly correlated with rainfall intensity. Results from this study can expand the understanding of the relationship among slope gradient, rainfall intensity, and erosion characteristics in the red soil region.

Keywords Red soil · Erosion characteristics · Rainfall intensity · Slope gradient

1 Introduction

Soil erosion is one of the most serious environmental threats to the sustainability of ecosystems in the world, which depends on many parameters such as rainfall characteristics (e.g., rainfall intensity, duration, temporal resolution, moving direction, and velocity) (Donjadee and Chinnarasri 2012; Dunkerley 2012; Ran et al. 2012), underlying surface condition (e.g., topography, slope gradient, and vegetative covers) (Han et al. 2011; Donjadee and Chinnarasri 2012; Sirjani and Mahmoodabadi 2012; Zhu 2012), soil hydro-physical properties (Ali et al. 2012; Zhao et al. 2013), and so on. Meanwhile, soil erosion induced by rainfall has been demonstrated to be an important driving force of ecosystem degradation (Han et al. 2011; Zhu 2012), which is a complex phenomenon of

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detachment and transportation of soil particles by rain drop/splash and surface flow scouring that can transport particles away from original position (Sirjani and Mahmoodabadi 2012). Therein, detachment, transportation, and deposition are the three main physical processes involving interactions among rainfall characteristics, overland flow and, soil properties (Defersha et al. 2011; Shi et al. 2012; Sirjani and Mahmoodabadi 2012), in which detachment rate agented by detaching soil particles from the soil surface is always controlled by the acting force of raindrop (Shih and Yang 2009), transportation rate agented by transferring the sediment away from the soil matrix is depended on the transfer force of a thin layer of overland flow produced by rainfall (Ali et al. 2012), and then the deposition rate is governed primarily by the resistance of the underlying surface condition (Han et al. 2011).

Regarding with those parameters that the soil erosion depended, rainfall intensity and slope gradient are the two dominant factors that control the hydrologic response and have been extensively studied via numerical simulation, experiments, and analytical solutions, and are still the hot topics of the soil erosion research (Assouline and Ben-Hur 2006; Han et al. 2011; Donjadee and Chinnarasri 2012; Ran et al. 2012). Therein, rainfall intensity is one dominant factor of the rainfall-runoff and soil erosion processes via controlling the hydrologic response with higher rainfall intensity generates higher runoff peak (Ran et al. 2012), and then the slope gradient, as an important topographic factor, is often considered to be a term of control over nutrient, contaminant or particle transfer that has been demonstrated by numerous risk assessments and models based on a large amount of data collected over different slope gradients (Zhang et al. 2003; Valmis et al. 2005; Masoudi et al. 2006; Cheng et al. 2008; Sirjani and Mahmoodabadi 2012; Wang et al. 2014), generally, with increased slope gradient associated with increased sediment transport. For example, in the early version of the USLE and its revised version (RUSLE), soil erosion was predicted as a power and linear (or less than linear) function of slope gradient respectively (Fox et al. 1997; Fox and Bryan 2000; Cheng et al. 2008). However, regarding the effect of slope gradient on rainfall-runoff and soil erosion processes, contradictory results have been observed by numerous experimental studies, such as, Chaplot and Le Bissonnais (2003) conducted an experimental study on small plots with slope gradients of 4 and 8 % in tilled fields to investigate the relationship between them, the result indicated that there had no correlation between sediment concentrations in runoff and slope gradient, while Fox and Bryan (2000) reported that rainfall flow induced erosion could be predicted by the square root function of slope gradient roughly for a constant runoff rate. Besides, some studies looked into their relationship observed a critical threshold of slope gradient (Hu and Jin 1999; Cheng et al. 2008), namely, erosion increased with increasing steepness up to a critical threshold and then reduced or remained unchanged beyond this threshold. Consequently, the influences of rainfall intensity and slope gradient on hydrologic response and soil erosion have been widely investigated. However, in many sub-tropical and tropical regions of the world that have high amount and intensity of rainfall and hilliness have received less attention. Especially, there is a lack of study on the red soil area of southern China, since numerous studies were conducted in the loess plateau located at northwest China (Hu and Jin 1999; Cheng et al. 2008; Han et al. 2011). Moreover, previous study indicated that the effect of slope gradient and rainfall intensity on runoff hydraulic characteristics depends on soil type (Sirjani and Mahmoodabadi 2012).

The red soil in southern China has the most erosion condition next to the loess plateau, which is a weathering crust from quaternary loose sediments and different parent rocks in the tropical and subtropical zones that distributed to the west till the east of Tibet and to the north till the south of the Qinling Mountain-Huihe River line, accounting for 22 % of the total land area of China (Yuan et al. 2008; Zhang et al. 2009b). The red soil region in southern China is characterized by thinner soil depth, steeper slope, disproportion of soil texture with high share of heavy clay soil and coarse grained soil, higher air temperature and precipitation, and multiple cropping index (ploughing 2–4 times per year) with intensive land development and utilization, resulting in serious soil erosion condition and making the ecosystem in this region is suffering significant degradation (Yu and Lin 2009; Zhang et al. 2009b; Liu et al. 2012). According to previous study, the slight, intermediate, and severe degradation areas accounted for 21.5, 49.5, and 29.0 % of the total red soil area, respectively (Liu et al. 2012). Contrastively, although absolute erosion amount of the red soil region is less than that of the loess plateau, the fact that the lost soil thickness occupies high proportion of the total soil layer thickness is seriously resulting in occurrence of the pebbles phenomenon and significantly affecting regional agricultural activities (Zhang et al. 2009b). Because of this critical issue, studies on degradation and erosion of red soil have been receiving increasing attention. Previous studies related to this subject mainly focused on the reforestation, nutrient loss, soil microbial biomass carbon, sloping field and rainfall experiment (Ma et al. 2002; Zhang et al. 2009b; Zhu et al. 2009). However, there is still a lack of information associating with the erosion of red soil via simulation experiments using high intensity rainfall and multiple slopes. Therefore, it is clear that there is a need to comprehensively study the mechanism of soil erosion in the red soil region of southern China.

Moreover, once overland flow has taken place under certain rainfall intensity or amount, transportation of sediments detached by raindrop impact can be explained by hydraulic characteristics of overland flow (Pan and Shangguan 2006; Shih and Yang 2009; Xiao et al. 2011; Ali et al. 2012), such as unit discharge, Reynolds numbers, flow depth, Froude numbers, flow velocity, Manning roughness coefficient, and Darcy–Weisbach friction coefficients, as well as their relationships. Under overland flow conditions, these hydraulic characteristics can be easily measured in the simulation or field experiments, and in general, the transportation of sediments increases with increase of hydraulic characteristics as the energy released from certain raindrop or scouring on the bed increases with increase of hydraulic characteristics (Zhang et al. 2009a, 2010b). In addition, the relationship between hydraulic characteristics and sediments transportation is always dependent on slope angle. For example, under non-erodible bed conditions, Gut et al. (1990) and Zhang et al. (2009a) found that transport capacity increased with increasing mean flow velocity which consistently increased with slope. However, other studies proved that there was no significant relationship between slope and flow velocity (Takken et al. 1998; Giménez and Govers 2001), resulting in non-significant influence of flow velocity on sediments transportation (Ali et al. 2012). Moreover, previous research has made it clear that, the Manning roughness coefficient which is widely used to quantify the comprehensive effect of land surface roughness on overland flow (Zhang et al. 2010a), varied greatly with slope gradient, flow discharge, flow velocity, Froude number, and Reynolds number (Hessel et al. 2003; Pan and Shangguan 2006; Zhang et al. 2010a). Accordingly, the influence of hydraulic characteristics on sediments transportation needs to be further studied to better understand the erosion processes of a specific soil type. Quantitative studies on the mechanism of overland flow scouring surface soil using hydraulic characteristics of overland flow have been conducted on many soil types, especially on the loess soils (Pan and Shangguan 2006; Xiao et al. 2011). However, few studies have examined this on red soil, which is representative of land in much of southern China.

Therefore, the objective of this study was to investigate the impact of rain intensity and slope gradient on runoff generation, sediment yield, and runoff hydraulic characteristics of red soil under controlled laboratory conditions, using soil flume and rainfall simulator. Seven rainfall intensities [low (30 and 60 mm/h,), moderate (90 and 120 mm/h), and high (180, 210, and 270 mm/h)] and three slope gradients [slight (5°), moderate (15°), and steep (25°)], which are representative of rainfall intensity and slope gradient in much of southern China, were considered and classified into three categories, respectively.

2 Materials and methods

2.1 Study area

Rainfall simulation experiments were conducted in 2012 in the Rainfall Simulation Hall of the Laboratory of Red Soil Erosion and Flow Hydraulic on the South China in Guangzhou City, Guangdong Province (Fig. 1). Guangzhou is the capital of Guangdong Province located in the central region of the Pearl River Delta of southern China. As the geographical center of the fast developing metropolitan region, it is the largest city in South China covering an area of 7,434 km^2 with a population over 10×10^6 (Huang et al. 2009; Xie et al. 2011). The climate of Guangzhou City is considered to be a typical subtropical climate that controlled by the East Asian Monsoon. It is characterized by mild springs (April–June), hot and humid summers (July–September), and cool and dry autumns and winters (October–March) (Huang et al. 2009; Xie et al. 2011). The mean annual air temperature in Guangzhou is 21.9 °C, which had increased remarkably at the changing rate of 0.38°C per decade in recent 30 years (Feng and Pan 2011). Meanwhile, the maximum and minimum monthly temperature also increased, which occurred in July and January respectively (Feng and Pan 2011). The mean annual precipitation in Guangzhou is 1,623.6–1,899.8 mm, which shown a significant seasonality that with over 80 % of the annual precipitation occurs during the rainy season and less occurs during the dry season (Huang et al. 2009; Xie et al. 2011). Moreover, Guangzhou is the rainstorm city in China characterized by frequent in high intensity and centralized in distribution, which is determined by the climate, weather system, geographical position, and topography (Wang and Pan 2006). According to the historical meteorological data of recent 60 years, the rainstorm amount and days in the rainy season of the Guangzhou City increased 6.23 mm/10a and 0.27 d/10a, respectively (Zhou et al. 2011). High intensity, frequency, and centralized distribution of rainstorm in Guangzhou City can easily induce occurrence of soil and water erosion and will seriously influence and restrict the economy development and ecology sustainability of this region. Furthermore, because of the unique climatic characteristics of rainy and warm with adequate heat and light, Guangzhou area is beneficial to growth of plant and therefore has an inherent tropical biodiversity treasure with 1,400 vascular plant species (Jim 2005). However, long-term intensive developments (centuries of agricultural and recently rapid urbanization activities) of this area have caused degradation of the growth conditions in quality and quantity, and have resulted in damage of some vegetation types, including the pristine natural vegetation that the remnant of tropical rainforests (Jim 2005). The topography in Guangzhou area is primarily alluvial plains laid down by the Pearl River, followed by decentralized wetlands in coastal area, low terraces, and hills (Jim 2005; Wang and Pan 2006). The hills region, which is covered by the tropical red soil, is suffering significant degradation due to its inherent fragility and the great pressure of intensive land development and utilization.

2.2 Experimental equipment

The experimental setup used in the experiment mainly consists of a rainfall simulator and soil flumes (Fig. 1). The simulator was designed and made by Chinese Academy of Sciences (CAS), it is a lateral sprinkling automatic rainfall simulation system that consists of an array of nozzles and pressure regulators. It can produce raindrops with intensities can be precisely adjusted in the range from 0 to 350 mm/h through changing the nozzle sizes and water pressure, as the flow to each nozzle is controlled by a pressure regulator and a compression stop valve. The height of rainfall simulator is up to 13.4 m and the raindrop distribution and size of the simulated rainfall are close to those of natural rainfall with uniformity above 90 %. In addition, calibrations of the simulated rainfall intensities were conducted using four rain gauges, prior to the experiments. The experimental soil flumes mainly consist of steel flumes and plastic containers. The size of the steel flumes is 2 m × 0.5 m × 0.5 m (length × width × height) that can be able to adjust the slope gradients using a hydraulic jack. The plastic container of 20 L in volume was used to catch the runoff and sediments. It was set at the outlet of the flume at the beginning of each treatment and was changed several times in each interval, and then the total runoff volume of each interval was recorded.

2.3 Experimental treatments and measurements

The rainfall simulation experiments were conducted on slight (5°), moderate (15°), and steep (25°) slope gradients under low (30 and 60 mm/h,), moderate (90 and 120 mm/h), and high (180, 210, and 270 mm/h) rainfall intensities, respectively, which are representative of slope gradients and rainstorm intensities in the study area. A total of 21 treatment combinations were conducted. Each simulated rainfall of a treatment lasted 60 min.

The red soil used in the study was taken from the no-farming land located at Guangzhou suburb. The soil texture was characterized as a sandy loam type based on the United States Department of Agriculture (USDA) classification system. The particle size of the texted red soil consisted of 55.7 % sand (2–0.05 mm), 35.4 % silt (0.05–0.002 mm), and 8.9 % clay (<0.002 mm). The content of organic matter, total nitrogen, total phosphorus, and total potassium

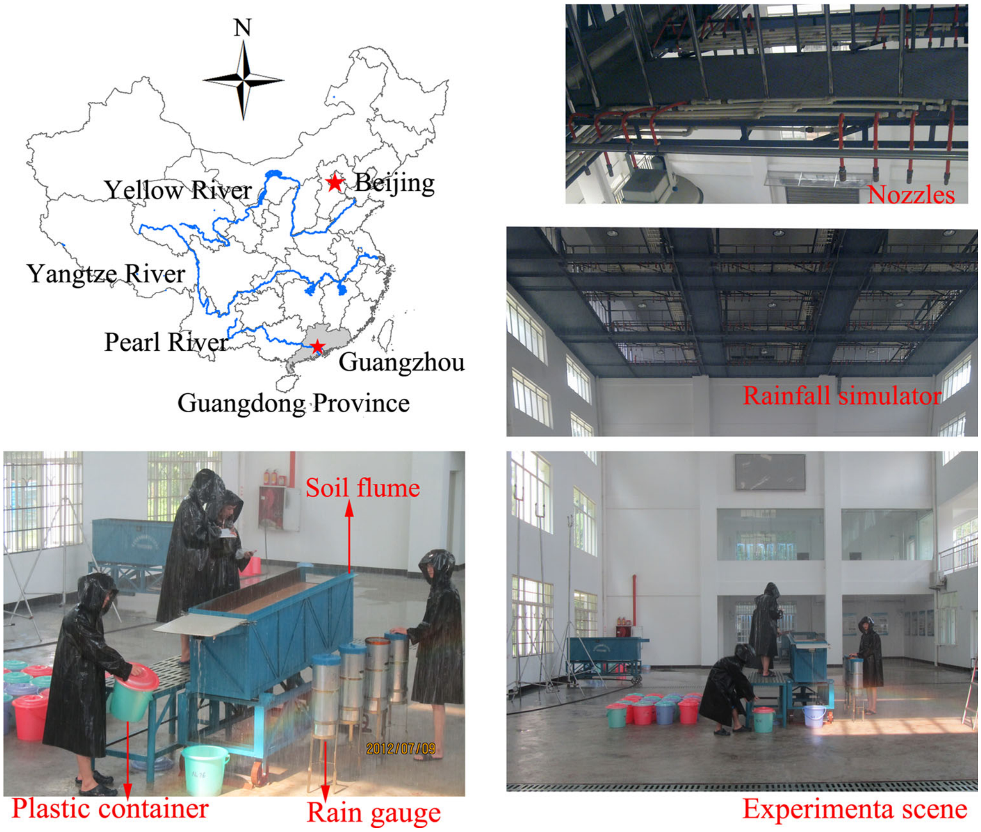

Fig. 1 Location of the study site and schematic representation of the experimental setup

was 1.89, 0.079, 0.249, and 24.6 g/kg, respectively. Before filling the flume with soil, the red soil was passed through a 2 cm sieve after it had been gently crushed. In order to minimize the difference among treatments, the sieved soil was thoroughly mixed. The 50 cm thick soil was packed in each flume in 10 cm increments with the sieved soil at a bulk density of 1.25 g cm^{-3}. To reduce the heterogeneity of the soil surface and minimize the differences among treatments, soil moisture content of the top 10 cm layer was adjusted to 8.3 % using a commonly used household sprayer. After finishing a rainfall event, the used soil was replaced from the flumes and the flumes were repacked with unused soil as described above for the next treatment.

Starting at the beginning of the each rainfall event, runoff-initiating time was measured by a stopwatch. In the process of each rainfall event, all runoff and sediment samples were collected in a marked plastic container respectively at five (0–20 min) and ten (20–60 min) minute intervals, and surface flow velocity was measured by the $\mathrm{KMnO_4}$ coloration method. According to the color-front propagation, the time elapsed for the dye tracer to travel across the flume was determined using a stopwatch. And then, surface flow velocity (U_s) measurements were converted into the profile mean velocities (U) via the relation of $U = k\ U_s$, which assumed the vertical velocity distribution with respect to the water depth in laminar flow followed by a quadratic equation with the value of the coefficient k equal to 0.67 (Li et al. 1996; Pan and Shangguan 2006). Once the rainfall event was finished, the runoff and sediment samples were settled for 24 h in plastic container till the sediment was completely deposited on the bottom of the plastic container, and then the supernatant water was poured out from the sample, thus the sediment was collected. The sediments were dried in an oven to constant weight at 105 °C for 6–8 h and then weighed to determine the dry sediment weight. Runoff rate and erosion rate were determined as dividing runoff volume and sediment load per unit area by the period of time, respectively.

2.4 Calculation of runoff hydraulics characteristics

In order to quantitative clarify the influence of hydraulic characteristics on sediments transportation of red soil, the Froude numbers (*Fr*), Reynolds numbers (*Re*), Darcy–Weisbach friction coefficient (*f*), and Manning roughness coefficient (*n*) were studied in this study according to previous researches (Pan and Shangguan 2006; Shih and Yang 2009; Xiao et al. 2011; Ali et al. 2012).

The Froude number (*Fr*) is determined as the ratio of inertia to gravitational forces (Wu et al. 2011), $Fr < 1$ and $Fr > 1$ indicates the occurrence of subcritical flow and supercritical flow, respectively. The Reynolds number (*Re*) is determined as the ratio of inertia to viscous forces (Wu et al. 2011), which is used to determine whether the water flow is laminar or turbulent for the experimental conditions, with 500 as a critical value. The Froude (*Fr*) and Reynolds (*Re*) numbers were calculated according to Eqs. (1) and (2) respectively:

$$Fr = \frac{U}{\sqrt{gh}} \tag{1}$$

$$Re = \frac{Uh}{v} \tag{2}$$

where *Fr* is the Froude number, *Re* is the Reynolds number, U is mean flow velocity (cm s^{-1}), v is kinematical viscosity ($\mathrm{cm}^2\ \mathrm{s}^{-1}$), g is acceleration of gravity (cm s^{-2}), and h is flow depth (cm). h is an important factor of surface flow that difficult to be measured due to the erosion process on plot surface (Wu et al. 2011). Assuming slope flow is uniform, h can be calculated as follow (Pan and Shangguan 2006; Wu et al. 2011):

$$h = \frac{q}{U} = \frac{Q}{U \cdot Bt} \tag{3}$$

where h is the flow depth (cm), q is the discharge ($\mathrm{m}^2\ \mathrm{s}^{-1}$) per unit width, U is mean flow velocity (cm s^{-1}), Q is the total runoff volume (m^3) during time t (s), and B is width of water-crossing section (m).

The Darcy–Weisbach friction coefficient (*f*) reflects the friction to overland flow exerted by the soil, which is determined by rainfall, soil particle, configuration, and wave friction. The Manning roughness coefficient (*n*), which is used to quantify the degree of surface roughness, is dependent on the terrain and vegetation factors. Both f and n can be used to characterize retardation of flow and were calculated according to Eqs. (4) and (5) respectively.

$$f = \frac{8ghJ}{U^2} \tag{4}$$

$$n = \frac{h^{2/3}J^{1/2}}{U} \tag{5}$$

where f is the Darcy–Weisbach friction coefficient, n is the Manning roughness coefficient, J is the surface slope (m m^{-1}), U, h, and g are as defined above.

In addition, a one-way analysis of variance (ANOVA) followed by a least significant difference (LSD) test at probability levels (p) of 0.05 was used to determine if any significant differences occurred among treatments. The redundancy analysis (RDA), which is a multivariate direct gradient analysis method widely used in soil ecology research (Zhao et al. 2014), was conducted to analyze the relationship between runoff hydraulics characteristics and slope gradient and rainfall intensity. The significance of relationship between them was assessed with a Monte Carlo permutation test with 499 permutations (Lepš and

Šmilauer 2003).The ANOVA and RDA were conducted using SPSS 15 and CANOCO 4.5 software (Centre for Biometry, Wageningen, Netherlands) (Lepš and Šmilauer 2003), respectively.

3 Results and discussion

3.1 Runoff volume and rate

Two runoff characteristics of the red soil slopes under simulated rainfall, the accumulative runoff volume and runoff rate, were measured (Figs. 2, 3; Table 1). The runoff data were taken from the moment of runoff-initiating, which is measured at 5 min interval during the first 20 min and then at 10 min interval during the following 40 min, respectively, until the rainfall stopped. The cumulative runoffs after seven intensities of rainfall are presented in Fig. 2 as a function of rainfall intensities under different slope gradients. Based on the runoff data curves, the accumulative runoff showed less difference among three slopes under the low and moderate rainfall intensities, while the difference was obvious under high rainfall intensities, suggesting the influence of rainfall intensity on runoff generation was considerable. However, the higher rainfall intensities increased runoff volumes on the same slope gradient as expected, indicating the rainfall intensity presented an appreciable impact on the runoff volume. Under the same rainfall intensity, the runoff occurred on the moderate (15°) slope was always higher than that on the slight (5°) and steep (25°) slopes, with the exception that under the rainfall intensity of 90 and 270 mm/h, indicating the difference in runoff volumes should be attributed to the interactions among slope angle, rainfall intensity, and other factors. This also suggested that accumulative infiltration of the moderate slope was lower than slight and steep slopes. Previous study found that infiltration decreased greatly with slope gradient when the slope angle was less than 18°, and then beyond 18° infiltration was less influenced by slope angle (Chen and Cai 1990; Cheng et al. 2008). Another study conducted by Jin (1996) indicated that the turning point of slope angle was 15°. However, other study demonstrated that infiltration rate decreased with increasing slope gradient without the occurrence of turning point (Fox et al. 1997). Moreover, Luk et al. (1993) indicated that rainfall duration could influence the variations in infiltration rate with slope gradient, and thus runoff rate with rainfall duration for varying rainfall intensities at different slope gradients of red soils was discussed later as plotted in Fig. 3.

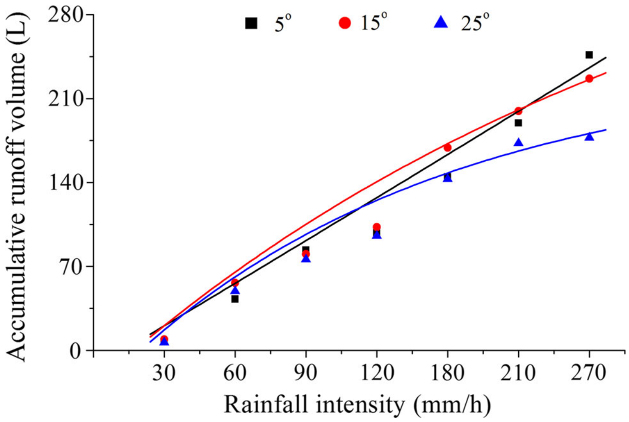

Fig. 2 Accumulative runoff volumes as a function of rainfall intensities under different slope gradients

Figure 3 shows the runoff rate curve for all rainfall intensities and slopes. The variation in the runoff rate with increasing duration of rainfall application on the three types of slope showed an initial trend of an unsteadily increased runoff rate followed by a steady condition at about 5–20 min after runoff initiation. After reaching the steady condition, the runoff rate remained nearly constant with small variations until the end of each rainfall event, which was also investigated by Donjadee and Chinnarasri (2012). However, the steady point of each experimental treatment was found at different timing, namely, higher rainfall intensity or slighter slope gradient associated with later turn up of the steady condition. This should be related with soil crust developed more rapidly on the lower slope at the initial of rainfall event, which induced increase of infiltration rate with increasing slope angle (Luk et al. 1993; Cheng et al. 2008). And then, infiltration rate decreased with increasing slope gradient after the seal had been developed (Luk et al. 1993).

There were considerable variations in the runoff rate, both within different slope gradients under the same rainfall intensity, as well as between different intensity of rainfall on the same slope (Fig. 3). On the one hand, higher runoff rate were not observed on steep slopes than that on the moderate slope gradient, with the exception of rainfall with intensities of 90 mm/h which with the highest runoff rate measured on steep slope, suggesting that the runoff rate did not increased with the increasing slope gradients. Previous studies found that when slope was less than a critical threshold, runoff rate increased greatly with slope, while when slope was steeper than the critical threshold, runoff rate was less influenced by slope (reduced or remained unchanged) (Hu and Jin 1999; Cheng et al. 2008). On the other hand, the analyses of variance performed to determine whether the three types of slope have different impacts on the runoff indicated that there was no significant difference among the different slope gradients under the influence of rainfall with intensity of 30, 90, and 120 mm/h (Table 1), indicating that the runoff rate was

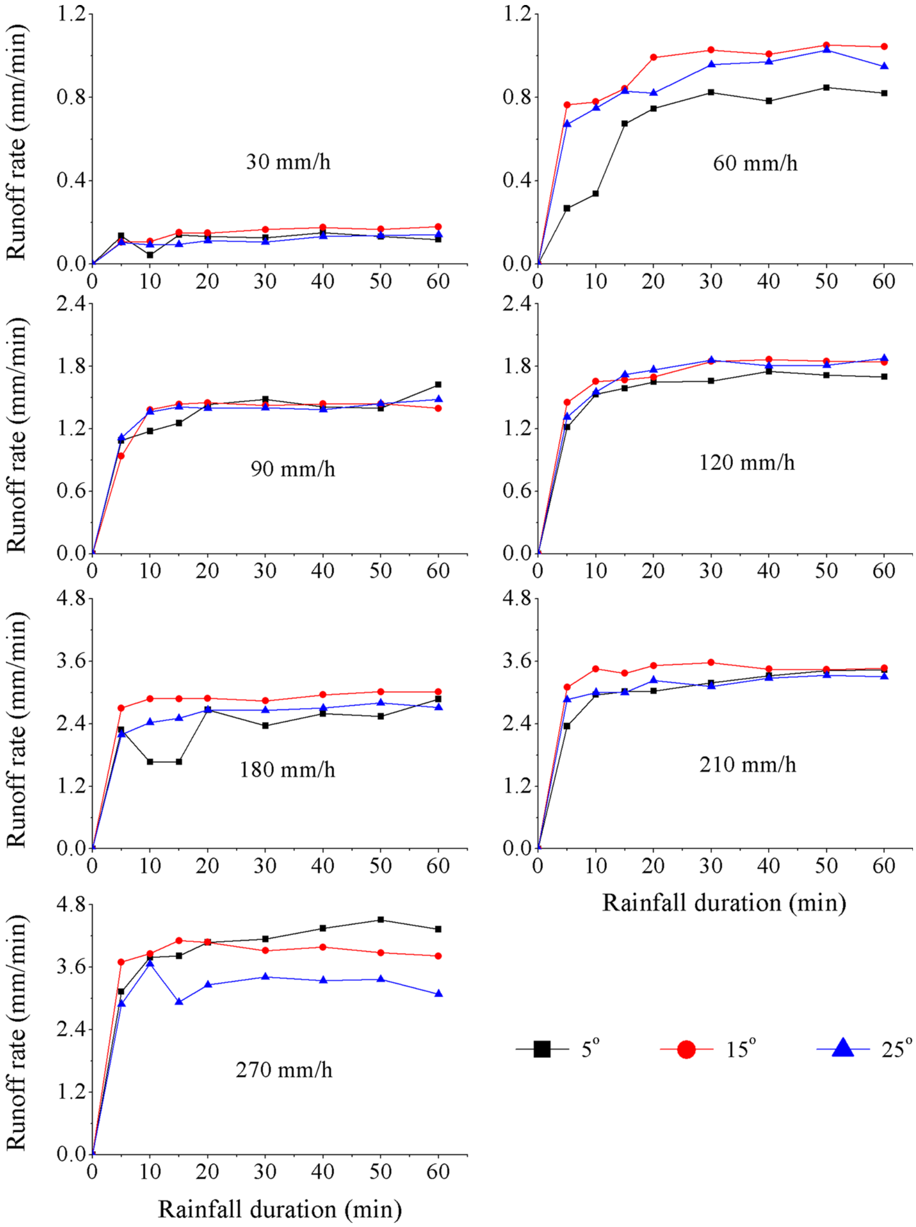

Fig. 3 Changes in runoff rates under different rainfall intensities and slope gradients

Table 1 Average runoff rate (mm/min) under different rainfall intensities and slope gradients

Slope gradient (°)	Rainfall intensity (mm/h)						
	Low		Moderate		High		
	30	60	90	120	180	210	270
5 (slight)	0.12 ± 0.03a	0.66 ± 0.23a	1.36 ± 0.17a	1.60 ± 0.17a	2.33 ± 0.45a	3.09 ± 0.35a	4.02 ± 0.44a
15 (moderate)	0.15 ± 0.03a	0.94 ± 0.12b	1.36 ± 0.17a	1.73 ± 0.14ab	2.90 ± 0.10c	3.42 ± 0.14b	3.92 ± 0.14a
25 (steep)	0.12 ± 0.02a	0.87 ± 0.12b	1.37 ± 0.11a	1.71 ± 0.19ab	2.58 ± 0.20b	3.14 ± 0.17a	3.24 ± 0.26b

Note: different letters within a column mean there are significant differences at a $p = 0.05$ level analyzed by using the least significant difference (LSD) method

only affected slightly by the low and moderate intensities of rainfall, with the exception of rainfall with intensities of 60 mm/h, and then the impacts of slope gradients on runoff rate was influenced by rainfall intensity. Thus, under higher intensity of rainfall, the influence of slope gradient on runoff rate was significant, especially the moderate slope.

3.2 Sediment load and erosion rate

Figure 4 shows the accumulative sediment load as a function of time under different rainfall intensities and slope gradients. Since the rainfall with intensity of 30 mm/h was not large enough for carrying out sediment from the soil slope, the value of accumulative sediment load under rainfall intensity of 30 mm/h equaled to zero as shown in Fig. 4. Under influence of the low and moderate rainfall intensities, the highest sediment load of the red soil slopes was always generated at the steep slope gradient, and then the lowest sediment load of the red soil slopes was always generated at the slight slope gradient. Under influence of the high rainfall intensities, the highest and lowest sediment load of the red soil slopes was observed at the moderate and steep slope gradients respectively. Moreover, under the influence of high rainfall intensities, the sediment load at the steep slopes decreased with increasing rainfall intensities, indicating that the flow transport capacity was lower than the sediment detachment rate (Assouline and Ben-Hur 2006; Donjadee and Chinnarasri 2012). According to Ran et al. (2012), the amount of sediment was controlled by transport limitation under the influence of low rainfall intensities, while it was controlled by detachment limitation under the influence of high rainfall intensities. Meanwhile, the accumulative sediment load increased with the accumulative runoff volume at the early stages after runoff generation (Figs. 2, 4), implying the process of soil surface sealing which was transport-limited may contribute to the erosion process (Assouline and Ben-Hur 2006; Ran et al. 2012).

Figure 5 shows changes in erosion rate with rainfall duration for varying rainfall intensities at different slope gradients of red soils. The erosion rate was highly variable between and within the rainfall intensity and slope gradient treatments. There was a clear and similar pattern in the erosion rate over time for most of the slope gradients and rainfall intensities, namely, the erosion rate for most treatments initially exhibited a sharp increase and then experienced a rapid decrease, suggesting the erosion process was dominated by the sediment transport-limiting regime at the early stages (Donjadee and Chinnarasri 2012; Shi et al. 2012), which may also include the flow transport system induced by raindrop impacts that was also dominated by the sediment transport-limiting regime (Assouline and Ben-Hur 2006; Shi et al. 2012). Increasing with rainfall duration, erosion process shifted from the transport-limiting regime to the detachment-limiting regime. These results were similar to that obtained by Assouline and Ben-Hur (2006) and Ran et al. (2012), and Shi et al. (2012). However, the shifting time from transport-limiting regime to the detachment-limiting regime was different with these studies (Assouline and Ben-Hur 2006; Ran et al. 2012; Shi et al. 2012), due to the differences between experiment treatments, e.g., soil type, rainfall intensities, slope gradients, soil flumes (length of flow route), and so on. In addition, previous study indicated that, in process of each rainfall event, the accumulative runoff and sediment were significantly related to rainfall duration (Zhang et al. 2009b). In the present study, similar result was observed, and the increasing rate of sediment was larger than that of runoff.

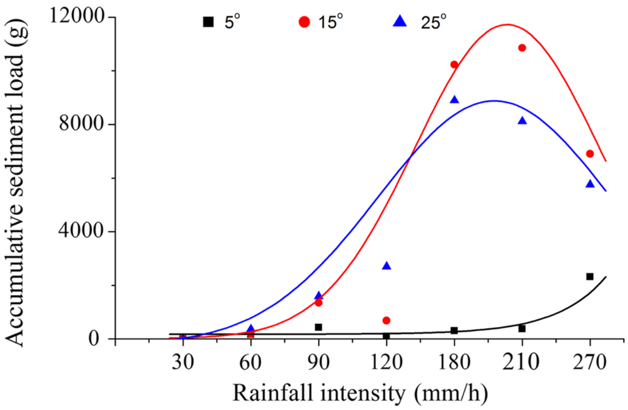

Fig. 4 Accumulative sediment load as a function of time under different rainfall intensities and slope gradients

Regarding with the whole rainfall duration, erosion rate on red soil slopes showed a down-up trend and then tended to be stable under low and moderate rainfall intensity (Fig. 5). In detail, under low rainfall intensity of 60 mm/h, erosion rate increased with increasing slope gradients during the rainfall event. However, no significant difference was observed among different slope gradients (Table 2). Under moderate rainfall intensities, erosion rate of the red soil slopes decreased at first, then increased, and thereafter became almost constant. Therein, the erosion rate at the steep slope exhibited obvious fluctuation and significantly higher than that at the slight and moderate slopes. Under high rainfall intensities, erosion rate at the slight red soil slope (5°) showed a stable condition with rainfall duration, at the moderate red soil slope (15°) exhibited certain fluctuation, and then presented a gradually increase and finally became stable at the steep red soil slope. These results indicated that, under low and moderate rainfall intensity, with the increase of slope gradient, factors associated with slope angle can increase erosion via enhancing soil detachment or limiting the protective effect of surface layer (Fox et al. 1997; Fox and Bryan 2000; Shi et al. 2012).

The average erosion rates measured at the moderate and steep slopes ranging from 3.56 to 162.83 (g/(m^2 min) with a high standard deviation, depending on both rainfall intensity and slope gradient (Table 2). When comparing

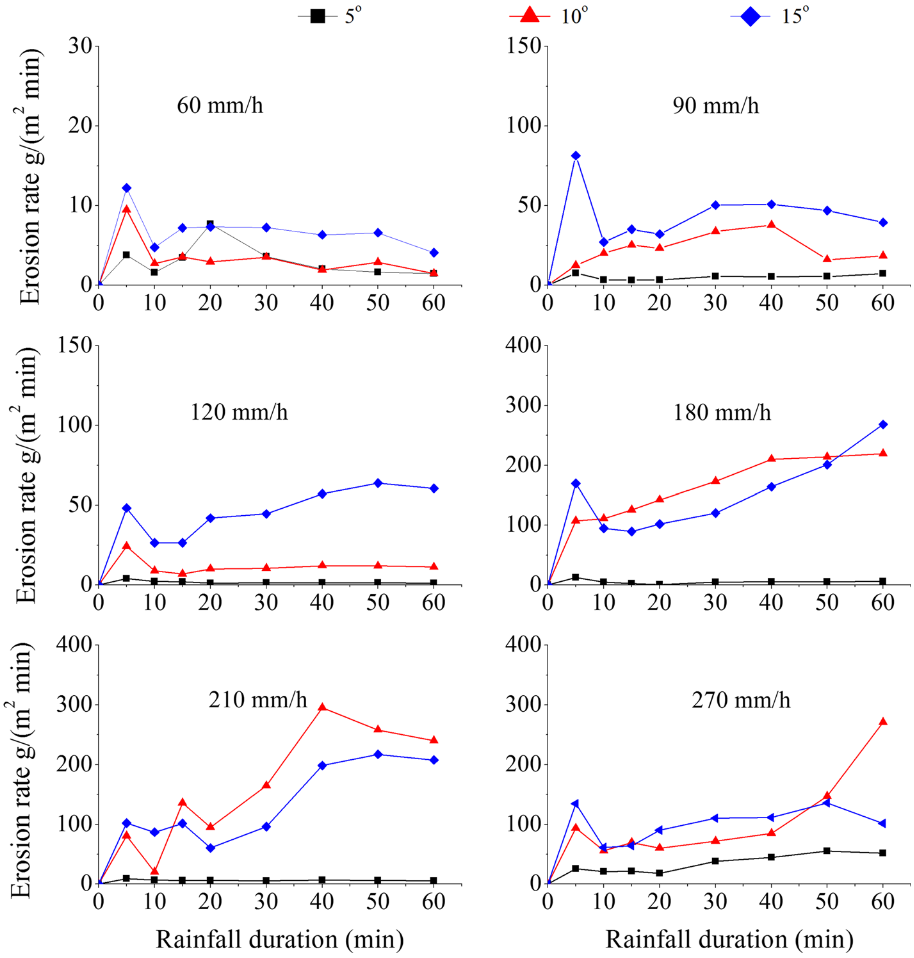

Fig. 5 Changes in erosion rates under different rainfall intensities and slope gradients

Table 2 Average erosion rate [g/(m^2 min)] under different rainfall intensities and slope gradients

Slope gradient (°)	Rainfall intensity (mm/h)					
	Low		Moderate		High	
	60	90	120	180	210	270
5 (slight)	3.16 ± 2.07a	5.16 ± 1.72a	1.79 ± 0.96a	5.07 ± 3.46a	6.49 ± 1.00a	34.45 ± 14.89a
15 (moderate)	3.56 ± 2.50a	23.41 ± 8.68b	11.99 ± 5.25a	162.83 ± 47.29b	161.19 ± 96.29b	106.82 ± 72.33b
25 (steep)	6.97 ± 2.43a	45.41 ± 16.95c	46.15 ± 14.32b	151.16 ± 62.06b	133.84 ± 62.89b	101.29 ± 28.20b

Note: different letters within a column mean there are significant differences at a $p = 0.05$ level analyzed by using the least significant difference (LSD) method

the average erosion rate measured at different slopes, it significantly increased at the moderate slope than that at the slight slope under the high rainfall intensities, while decreased insignificantly than that at the steep slope. This pattern was in disagreement with the conclusion of Fox and Bryan (2000) and Shi et al. (2012), who reported that the influence of the slope gradient on the increase in erosion rate was associated with increasing slope gradient (Fox and Bryan 2000), especially when the slope gradient exceeds 10 % (Shi et al. 2012). On the contrary, this pattern could be interpreted by some studies which found that the erosion rate increased with the slope gradient until a critical threshold slope, and beyond this critical threshold the erosion rate decreased with the increasing slope gradient (Hu and Jin 1999; Cheng et al. 2008). Therefore, moderate angle (15°) of the red soil slope should be closer to the critical threshold than the slight (5°) and steep slopes (25°), according to the critical threshold hypothesis.

On the moderate and steep slopes, the average erosion rate reached a peak value before implementation of the

Table 3 Runoff hydraulics characteristics under different rainfall intensities and slope gradients

Runoff hydraulics characteristics	Slope gradient (°)	Rainfall intensity (mm/h)						
		Low		Moderate		High		
		30	60	90	120	180	210	270
Reynolds numbers (R_e)	5 (slight)	4.17	17.45	41.71	48.41	76.16	93.48	122.34
	15 (moderate)	4.32	28.07	38.96	52.30	90.24	105.66	122.57
	25 (steep)	3.33	24.09	38.52	47.27	73.40	90.46	93.50
Froude numbers (F_r)	5 (slight)	6.60	8.26	4.22	7.80	5.24	3.78	4.05
	15 (moderate)	4.28	4.26	4.64	5.20	4.13	5.02	6.33
	25 (steep)	3.51	4.10	3.48	6.61	5.68	4.10	4.71
Manning roughness coefficient (n, 10^2 $m^{-1/3}$ s)	5 (slight)	3.33	3.04	7.08	3.63	5.94	8.73	8.33
	15 (moderate)	5.42	6.70	6.32	5.75	7.88	6.46	5.08
	25 (steep)	6.55	6.87	8.70	4.36	5.42	7.96	6.85
Darcy–Weisbach friction coefficient (f)	5 (slight)	1.60	1.02	3.92	1.15	2.54	4.87	4.24
	15 (moderate)	3.81	3.85	3.24	2.58	4.08	2.76	1.74
	25 (steep)	5.65	4.15	5.77	1.60	2.16	4.14	3.15

highest intensity of rainfall (Table 2), suggesting that erosion rate was converted from the sediment transport-limiting regime to the detachment-limiting regime (Assouline and Ben-Hur 2006; Donjadee and Chinnarasri 2012). On the other hand, previous study demonstrated that higher sediment transport capacity was not always accompanying with higher runoff (Donjadee and Chinnarasri 2012). Nonetheless, on the slight slope in the present study, higher erosion rate was accompanied by higher sediment transport capacity. These results indicated that the relationship between rainfall intensity and erosion rate was determined by the slope gradient.

3.3 Runoff hydraulics characteristics

Insight into the dynamics of runoff hydraulics characteristics was provided through the variations in Froude numbers, Reynolds numbers, Darcy–Weisbach friction coefficient, and Manning roughness coefficient for the three slopes and seven rainfall intensities (Table 3).

The results indicated that there was little difference in Reynolds numbers among different slope gradients, ranging from 3.33 to 122.57. However, Reynolds numbers increased with increasing rainfall intensities. Based on the criterion of open channel flow, overland flows on all slopes were laminar and tranquil (Pan and Shangguan 2006). Froude numbers in the present study were higher than 1, indicating that overland flows on all slopes were supercritical according to the criteria for open channel flow (Wu et al. 2011). Under low rainfall intensities, Froude numbers decreased with increasing slope gradients, this can be explained by the decreased flow depth and the increased velocity with increasing slope angles, which can result in increasing of Froude numbers. However, under moderate and high rainfall intensities, relationship between Froude numbers and slope gradients was relatively complicated, due to the combined effects of rainfall intensity and slope gradient to the flow depth and the velocity. Results from the Darcy–Weisbach friction coefficient and Manning roughness coefficient showed that the mean value of resistance coefficients increased with increasing rainfall intensities at the slight slopes, indicating that the energy along the flow path had gradually dissipated at the slight slope, which induced reduction in erodibility and transportability (Wu et al. 2011). This result further explained the lowest erosion rate at the slight slope as shown in Fig. 5. On the other hand, the mean value of resistance coefficient at the moderate and steep slopes was differing from the slight slope, in which the difference was not obvious among the three types of rainfall intensity.

In order to further analyze the responses of runoff hydraulics characteristics to rainfall intensity and slope gradient, the redundancy analysis (RDA) was performed. Before the performance of RDA, a detrended correspondence analysis was performed to determine whether the linear model of RDA was appropriate for analyzing the data of this study. The result indicated that the maximum length of the gradients for the four axes of the hydraulics characteristics was 1.075, suggesting that the linear RDA model was appropriate to analyze the relationship between runoff hydraulics characteristics and rainfall intensity and slope gradient, since the linear model was better than the unimodal model when the maximum gradient of the four axes was less than or equal to 3 (Lepš and Šmilauer 2003; Zhao et al. 2014). Thus, the RDA result clearly showed that the percentage of variance for the hydraulics characteristics

Table 4 The eigenvalues of the RDA axes for runoff hydraulics characteristics and rainfall intensity and slope gradient

Axes	1	2	3	4	Total variance
Eigenvalues	0.958	0.000	0.040	0.002	1
Hydraulics-slope and rainfall factors correlations	0.980	0.333	0	0	
Cumulative percentage variance					
Of hydraulics data	95.8	95.8	99.8	100	
Of hydraulics-slope and rainfall factors relationship	100	100	0	0	

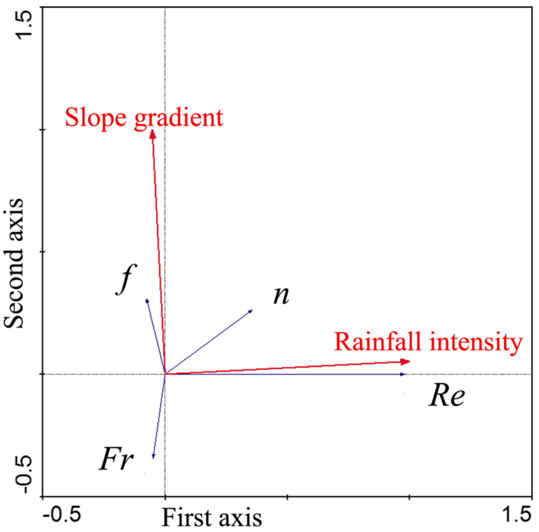

Fig. 6 Ordination axes 1 and 2 of the RDA for runoff hydraulics characteristics and slope gradient and rainfall intensity

that explained by the first axes was 95.8 % (Table 4). The Monte Carlo permutation test showed that the Reynolds numbers (R_e) were significantly correlated with rainfall intensity ($p < 0.01$) (Fig. 6), while the correlations between other hydraulics characteristics and rainfall intensity and slope gradient were not significant. The result indicated that the rainfall intensity was the most important factor influencing Reynolds numbers (R_e).

4 Conclusions

The effects of rainfall intensity and slope gradient on erosion characteristics of the red soil slope were investigated in this study. The results indicted that runoff generation of red soil slopes was influenced by both the slope angle and rainfall intensity, namely, the moderate slope that the runoff occurred on was always higher than the slight and steep slopes under the same rainfall intensity. Runoff rate with increasing rainfall duration presented a steady condition after an initial trend of an unsteadily increased. Nonetheless, for each experimental treatment, the steady point occurred later under the condition of higher rainfall intensity or slighter slope gradient. In addition, runoff rate did not increase with the increasing slope gradients, which could be explained by the critical threshold as previous studies demonstrated, while the less slope gradients set in this study cannot further prove the existence of the critical threshold of the red soil slope. Results from the sediment load and erosion rate indicated that the amount of sediment of red soil was controlled by detachment limitation under the influence of high rainfall intensities, while it was controlled by transport limitation when the rainfall intensity was low. Erosion rate for most treatments initially exhibited a sharp increase and then experienced a rapid decrease, further indicated the flow transport system induced by raindrop impacts was dominated by the sediment transport-limiting regime at the early stages. By the analyses of runoff hydraulic characteristics this study clarified that overland flows on all slopes were laminar, tranquil, and supercritical. On the slight slope, the erodibility and transportability reduced due to the energy along the flow path had gradually dissipated. However, no significant correlation between runoff hydraulic characteristics and rainfall intensity and slope gradient was observed, with the exception of Reynolds numbers, which were significantly correlated with rainfall intensity. Consequently, red soil erosion is a complex physical process, and then observation from this study can provide a good understanding for mechanism research related with soil and water conservation of the red soil region.

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