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Effects of rainfall and the slope gradient on the soil and water loss in a purple soil area

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Abstract: Soil and water losses in purple soil area is becoming an increasingly severe problem, bringing enormous challenges to environmental protection in rural areas. In this study, simulated rainfall experiments were conducted to analyse the effects of rainfall and the slope conditions on the soil and water loss. Purple soil from a typical slope in the Beibei District of Chongqing was selected as the experimental soil. Twenty rainfall scenarios with varying rainfall intensities and slope conditions were created in the simulation. The results indicate that the runoff initiation time shortened with an increased rainfall intensity and slope gradient. There was a logarithmic relationship between the effect of the rainfall amount on both the runoff intensity and sediment yield intensity. Generally, both the runoff and sediment yield showed a positive linear relationship with the rainfall intensity under different slope gradient conditions. In terms of the same rainfall intensity, both the runoff intensity and sediment yield intensity increased with the slope. Furthermore, a critical slope gradient for the soil and water loss was found between 20° and 25°. This study aimed to provide a reference for soil and water conservation research in a purple soil area.

Keywords: precipitation; Sichuan Basin; simulated rainfall experiment; soil erosion; topography

The Sichuan Basin is the largest outflow basin in China, where purple soil accounts for about 62% of the whole basin (Long et al. 2006; Hua et al. 2014). As the most typical soil type in the upper reaches of the Yangtze River, purple soil accounts for more than 70% of the region (Ouyang et al. 2017). It is weathered by purple rocks and characterised by thin soil layers with high risk of soil erosion (Wei et al. 2018). Moreover, the Sichuan Basin is characterised by a steep terrain, uneven rainfall distribution, and high precipitation, creating optimal conditions for soil and water loss (Zhou et al. 2014; Qian et al. 2015). This problem becomes serious on account of the large population, extensive farming, excessive reclamation, etc. (Li et al. 2016; Cai et al. 2018). As rainfall is the precondition of runoff and soil water erosion, and a hillslope could exacerbate the soil and water loss as gravity aggravates the transportation of the runoff and sediment (Taye et al. 2013; Mishra et al. 2014; Nourani et al. 2015; Larsen et al. 2016), therefore, it is essential to understand the effects of the rainfall and slope gradient on the soil and water losses in a purple soil area.

In recent decades, researchers have paid significant attention to the influences of rainfall and topographic conditions on the soil and water loss (Maltsev &Yer-

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molaev 2019; Belayneh et al. 2020; Zhang et al. 2021). Rainfall simulation experiments conducted in the arid Sistan region of Iran revealed that the sediment yield was strong at the beginning of the rainfall yet lowered over time when the soil became saturated (Shojaei et al. 2020). A field experiment was advanced to investigate the effects of the slope gradient on the surface runoff, runoff coefficient, and sediment yield under natural rainfall conditions, and it was indicated that the runoff responses to rainfall for plots with different slope gradients showed a linear behaviour that significantly increased with the gradient (Jourgholami et al. 2021). Through a simulated rainfall experiment in the Loess Plateau, the result of a study showed that while enhancing the variations among the slope gradients, an overlying sand layer hindered the runoff generation, decreased the cumulative runoff, and increased the cumulative soil loss compared with uncovered slopes (Zhang et al. 2017). By means of artificial simulated rainfall experiments on a bare loess soil, Wu et al. (2018) found a linear correlation between the runoff and the rainfall intensity for different slopes, whereas the correlations between the sediment yield and rainfall intensity were weak. By simulating precipitation and topography conditions of a purple soil area, a study found that the total phosphorus (TP) load and TP concentration increased with an increasing rainfall amount (Ding et al. 2017). It follows that the studies that investigated the effect of the slope and rainfall on the soil and water loss are concentrated mainly in Loess areas. Although some scholars have undertaken relevant studies on the production of runoff and sediment of sloping lands in the purple soil regions, their studies mainly focused on the benefits of soil and water conservation measures and the transformation of nitrogen and phosphorus (Jin et al. 2019; He et al. 2022). Few studies have reported on the effects of the slope and rainfall on the runoff and sediment yield.

China is undertaking ecological and environmental protection and restoration efforts for the Yangtze River. Constant soil erosion has resulted in an average soil loss rate of 2 741 t/km^2/year in the area, of which about 3 440 km^2 reached the rate of over 8 000 t/km^2/year (Qian et al. 2020). Research on the soil and water loss mechanism can provide theoretical support for preventing and controlling soil and water loss under various rainfall intensities and topographic conditions in the upper reaches of the Yangtze River, and even the whole basin, thus offering decision-making support for promoting the protection of the Yangtze River. It is desired to have further discussions on the influence of the rainfall amount, rainfall intensity and slope gradient on the runoff intensity, sediment yield intensity, runoff volume and sediment yield in a purple soil area.

This study aimed to reveal the effects of the rainfall and topography conditions on the soil and water losses in a purple soil area through simulated rainfall experiments, deepening the understanding of soil erosion patterns in purple soil regions and provide a theoretical basis for soil erosion management in the region.

MATERIAL AND METHOD

Experimental devices and material. Considering the characteristics of the soil, rainfall and geography, a sloping field (106°43'E, 29°53'N) in the Beibei district of Chongqing city was chosen as the experiment plot. The original soil was collected from the soil layer in the experiment plot, which was less than 20 cm below the ground, to avoid any potential experimental error caused by the physical and chemical property changes of the deep soil. The soil was then dried naturally. Next, the original soil was screened and filtered with an aperture of 7 mm when the moisture content of the soil decreased to a particular value. Finally, the screened soil's physical properties were measured. The density of the screened soil was 1.3 g per cm^3, and its soil moisture content was 12.16%.

After sampling and pre-treatment, the soil was filled into several soil tanks for simulated rainfall experiments. According to the research by Huang et al. (2013), appropriate length, width and depth ranges for a soil tank were between 1–2, 0.5–1, and 0.22–0.5 m, respectively. Therefore, three steel soil tanks were designed, each with a length, width and depth of 1.0, 0.6, and 0.25 m, respectively. In addition, the bottom of each soil tank extended outwards for 0.1 m along the long side where the water collecting groove was set, and a small hole at the bottom of the groove collected the runoff and sediment. One side of each soil tank contained many holes for the runoff and sediment collection. One axis was installed on the bottom of each soil tank to adjust its gradient from 0° to 65°. The structure of the soil tank is shown in Figure 1.

This study utilised a NORTON artificial rainfall simulator (USDA-ARS Soil Erosion Research Laboratory, USA), with an 80~100 VeeJet spray nozzle, a hydraulic

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pressure of 0.04 MPa and a nozzle height of 2.5 m. The device breaks water into tiny droplets when ejected from the nozzle. The rainfall uniformity coefficient can reach 85% or more, in line with the characteristics of natural rainfall. The structure of the NORTON artificial rainfall simulator is shown in Figure 2.

Experimental design. Before the simulated rainfall experiments, the soil tank was filled with five layers of pre-treated soil, each 5 cm in height, added layer by layer. To prevent delamination, all the soil layers except for the topmost layer were raked before filling. To make the density of the pre-treated soil in the soil tank close to its natural value, the cutting-ring method was used to measure the density around 1.3 g/cm^3 after loading to ensure the experiment's accuracy.

Based on the meteorological data from the Sichuan Basin, the maximum rainfall intensity is more than 100 mm/h, while the rainfall intensity simulation range of the rainfall simulator is between 30 and 150 mm/h. Four rainfall intensities were designed: 30, 60, 90 and 120 mm/h. Then, five slopes (5°, 10°, 15°, 20°, 25°) were designed for the simulation, and a total of twenty rainfall scenarios were created based on the combinations of the rainfall intensity and the slope. During the experiment, pots were placed under the soil tank and replaced every 5 min to continually gather the water and sediment. To facilitate the statistical analysis and comparison of the data, the runoff yielding time was defined as 40 min for each rainfall experiment. To ensure the accuracy of the experiment and reduce the influence of changes in the soil physicochemical characteristics on the experimental results, the soil was resampled and the soil tank was refilled after each rainfall experiment.

The primary characteristics of interest in the rainfall process were the rainfall amount, rainfall intensity and rainfall duration. Additionally, the slope gradient was considered a vital terrain factor that influenced the soil and water loss. Concerning the soil erosion, the runoff volume and sediment yield were the main indicators to reflect the degree of the soil and water loss. Moreover, the runoff intensity and sediment yield intensity were introduced to reflect the effects of the rainfall and slope gradient on the soil and water loss more clearly.

Data. As mentioned, due to the different combinations of the rainfall and slope, the runoff initiation time was different in each scenario. The rainfall duration was the sum of the runoff initiation time and runoff yielding time (40 min), and the rainfall intensity could be designed by the artificial rainfall simulator. Therefore, the rainfall amount could be obtained by multiplying the rainfall duration by the rainfall intensity. Moreover, the slope gradient was adjusted by the axis installed on the bottom of the soil tank. During the simulated rainfall experiments under different scenarios, the runoff volume could be obtained by measuring the volume of water in the pots during each rainfall simulation. The runoff intensity, defined as the runoff volume per minute, was also used to analyse the effects of the rainfall and slope gradient on the soil and water loss. In addition, the sediment yield was weighed by an electronic balance

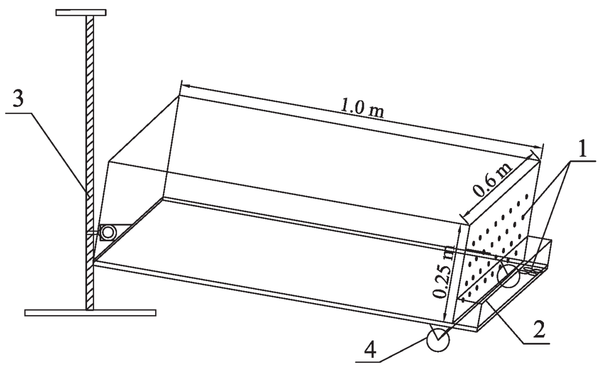

Figure 1. The structure of the soil groove (Ding et al. 2017)
1 – holes; 2 – groove; 3 – axis; 4 – wheels

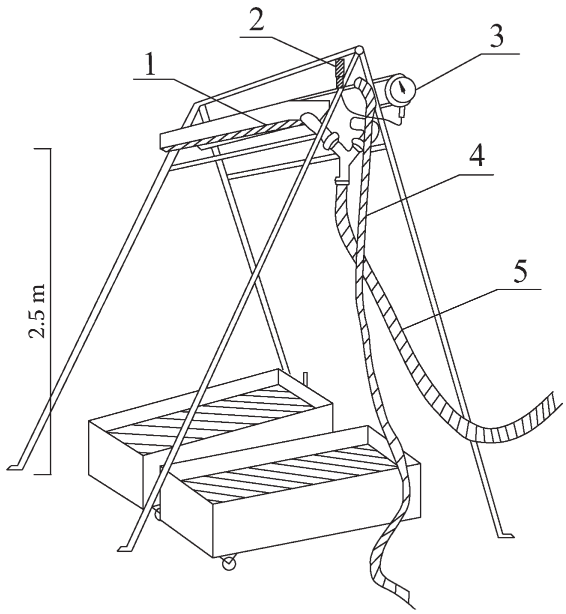

Figure 2. The structure of the NORTON artificial rainfall simulator (Ding et al. 2017)
1 – sprinkle; 2 – small motor; 3 – pressure gauge; 4 – water supply pipe; 5 – water hose

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after the moisture in the sediments was removed through the drying method. The sediment yield intensity (specifically, sediment yield per minute), was used to analyse the soil and water loss under different rainfall and terrain conditions. After the experimental data for each scenario were acquired, Excel was used to analyse the relationship between the rainfall amount, rainfall intensity, slope gradient and sediment yield.

RESULTS AND DISCUSSION

Effects of the rainfall amount on the soil and water loss. As the raindrops fell on the slope surface, they would first infiltrate the soil. Therefore, a time existed between the beginning of the rainfall and the runoff production, termed the runoff initiation time. During this time, most of the rainwater infiltrating the soil was converted into soil water, while the rest was consumed through evaporation. When the soil receives more rainwater than it can infiltrate, excessive rainwater flows along the slope surface, resulting in runoff. In the natural environment, the generation of hillslope runoff results from the joint effects of meteorological and geographical factors, which refer to atmospheric precipitation, subsurface flow, depression storage, and more. (Zhang et al. 2019).

The runoff initiation time of 20 simulated rainfall scenarios in this study is shown in Table 1. The results indicated that the runoff initiation time decreased with the increased rainfall intensity under a constant slope gradient condition, which was more evident on gentle slopes. In the case of an identical soil background, the greater the rainfall intensity, the more rainwater a slope would carry per unit time, and the faster the runoff generation. Meanwhile, the runoff initiation time also decreased with an increasing slope gradient for a certain rainfall intensity. Lei et al. (2020) found that with an increase in the slope gradient, the effect of infiltration weakens, leading to an increase in the runoff velocity, which is consistent with the results of this study.

The relationships between the rainfall amount and runoff intensity are shown in Figure 3. In the data processing, the runoff intensities under different rainfall intensities for the same slope gradient were integrated into one curve to reveal the relationship between the rainfall amount and runoff intensity under various slope gradient conditions. At the beginning of each scenario, the runoff intensity was small and increased with the rainfall amount. After some time, the runoff intensity stabilised and the runoff volume grew linearly as the rainfall amount increased. As stated above, low runoff occurs since most of the rainwater infiltrates into the soil at the beginning of the rainfall. Meanwhile, in the early stage of the runoff generation, single streams gradually converge into large streams, with a subsequent increase in the runoff intensity (Shen et al. 2016). The mean value of the rainfall amount when the runoff intensity of the five slope conditions reached stability under the same rainfall intensity indicate that the runoff intensity increased until the rainfall amount reached 14.46, 23.69, 25.64 and 32.564 mm, respectively. After a while, the soil moisture content became saturated, indicating that the infiltration rate decreased and the runoff intensity reached stability. It took 15–20 min for the runoff intensity to reach stability when the rainfall intensity was 30 and 60 mm/h, and 10–15 min when rainfall intensity was 90 and 120 mm/h.

The curve-fitting method was also used to reflect the effects of the rainfall amount on the sediment yield intensity, revealing the relationship shown in Figure 4. When the rainfall intensity was small, the sediment yield intensity was minor and increased slightly with the heightened rainfall amount, then stabilised. In the early stage of the rainfall, only a little sediment was carried as the runoff volume was relatively small. Then, as the runoff intensity continued to rise, the sediment yield intensity consequently increased. The fitting of the rainfall amount and sediment yield intensity is consistent with the research of Li et al. (2009) on Sichuan purple soil farmland, which shows a logarithmic relationship between the rainfall amount and sediment yield intensity.

During heavier rainfall, the sediment yield intensity was initially relatively high and gradually decreased. Most of the loose sand and gravel on the slope were washed away early in rainfall, and the thickening

Table 1. Runoff initiation time for the hillslope of the purple soil area under different rainfall scenarios (in min)

Slope (°)	Rainfall intensity (mm/h)			
	30	60	90	120
5	12.43	6.53	4.53	3.06
10	10.28	5.50	3.62	2.63
15	8.27	4.78	3.00	2.18
20	7.45	3.58	2.07	1.77
25	6.17	3.05	1.85	1.31

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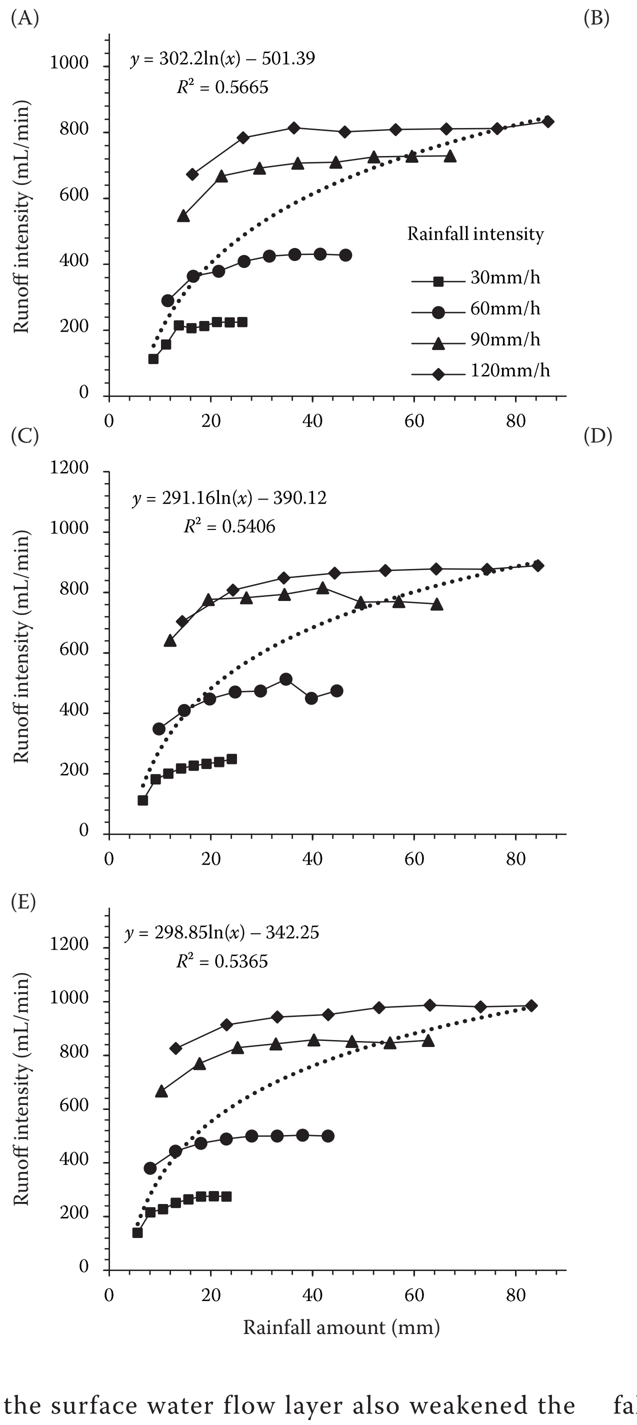

Figure 3. Relationships between the rainfall amount and the runoff intensity under the slope gradients of 5° (A), 10° (B), 15° (C), 20° (D), 25° (E)

of the surface water flow layer also weakened the erosion effect of the rainwater hitting the ground (He et al. 2017; Zambon et al. 2021). All these reasons led to a downward trend in the sediment yield intensity.

The sediment yield intensity and its fluctuations were generally more substantial under high rainfall intensities than under low rainfall intensities. The increase in the rainfall intensity enhanced the splash erosion of the raindrops, resulting in more loose sand and gravel on the slope surface. Jiang et al. (2018) studied rill erosion processes and found that rainfall with high intensity and long duration may lead to collapse. A transient phenomenon of alternating deposition and erosion occurs in the gully, leading to fluctuations in the sediment yield intensity in the later stage.

Effects of the rainfall intensity on the soil and water loss. During the analysis, a minimum rainfall value (23.085 mm) was consistently used under 20 rainfall scenarios to eliminate its influence. The effects of the rainfall intensities on the runoff volume are shown in Figure 5. The higher the rainfall intensity,

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the more pronounced the increase of the runoff volume. The greater the slope was, the greater the growth of the runoff volume (Table 2). Under the five slope conditions, when the rainfall intensity increased from 30 to 120 mm/h, the runoff volume increased by 2 573.52, 2 442.09, 3 148.75, 4 050.89 and 4 318.79 mL, respectively.

When the slope was gentler (5–10°), the influence of gravity on the slope was less significant, and more raindrops infiltrated the soil. However, excess rain would still generate runoff when the rainfall intensity exceeded the infiltration rate. If the infiltration rate was relatively low, the proportion of rainfall that converted into slope runoff would be more prominent. Similarly, relatively high rainfall intensity (90 and 120 mm/h) would increase the hillslope runoff when the slope gradients were relatively large (15–25°). For steeper slopes, gravity would increase the runoff velocity. The contact time between the runoff and the slope became shorter, weakening the infiltration effect and increasing the runoff volume. Though less apparent, this effect was also shown when the rainfall intensity was small. In line with previous studies, the rainfall intensity

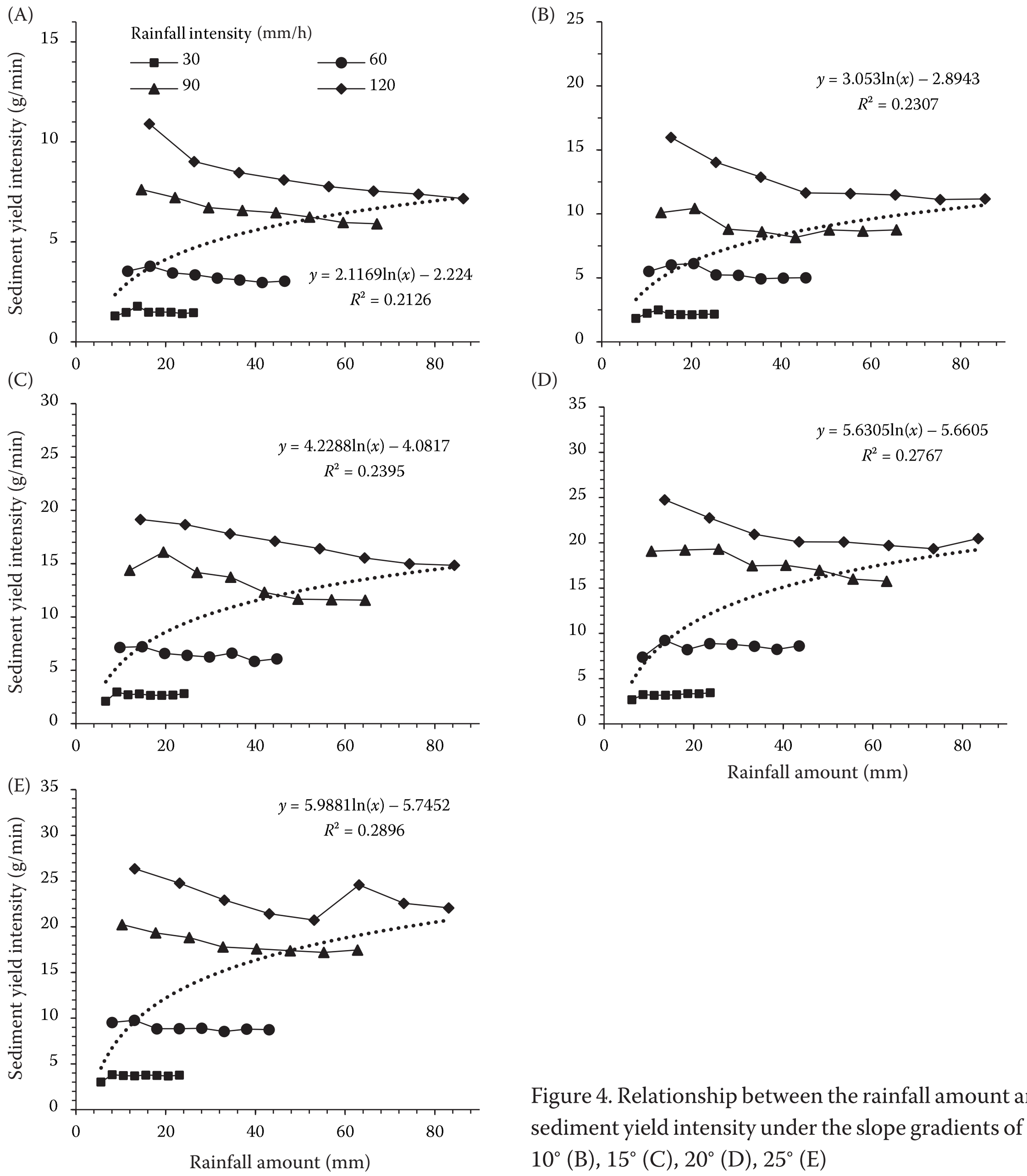

Figure 4. Relationship between the rainfall amount and the sediment yield intensity under the slope gradients of 5° (A), 10° (B), 15° (C), 20° (D), 25° (E)

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Table 2. Correlations between the slope gradient and the runoff volume

Rainfall intensity (mm/h)	Correlation	Correlation coefficient
30	$y = 664.05x + 5557.4$	0.9639
60	$y = 744.07x + 5396.1$	0.9403
90	$y = 1364.9x + 5567.0$	0.9124
120	$y = 1174.0x + 7334.4$	0.9914

Table 3. Correlations between the slope gradient and the sediment yield

Rainfall intensity (mm/h)	Correlation	Correlation coefficient
30	$y = 21.804x + 29.553$	0.9931
60	$y = 31.479x + 32.803$	0.9883
90	$y = 59.812x + 19.110$	0.9589
120	$y = 68.198x + 51.539$	0.9896

was positively correlated with the surface runoff (Zhang et al. 2018).

Generally, a higher rainfall intensity induces an increased runoff volume and causes serious soil and water losses when other external conditions remain unchanged. From the data in Figure 6, it could be found that the sediment yield increased with the rainfall intensity under various slope gradients, and this trend was more evident for steeper slopes. When the slope is 25°, the sediment yield of the four rainfall intensities reached 2.8–3.7 times of that of when the slope is 5°. Under the different rainfall intensities, the correlation between the slope gradient and sediment yield was also positive (Table 3). A previous study found that when the amount of rainfall on the slope surface per unit time increased with increasing rainfall intensity, the kinetic energy of the raindrops also increased (Zambon et al. 2020). This phenomenon made the striking of raindrops at high rainfall intensities more likely to damage the surface soil structure and loosen the surface soil when compared to low rainfall intensities, thus, increasing the likelihood of soil particles being carried away by the runoff. In addition, with the increase in the rainfall intensity, the runoff volume on steep slopes increased rapidly, which caused erosion and scouring on the soil to be more significant than that at a low rainfall intensity. Eventually, these effects lead to an increase in the sediment loss.

Effects of slope gradients on soil and water loss. Trends in the runoff intensity on different slopes under various rainfall intensities are shown in Figure 7. The runoff intensity increased rapidly with time in the early stage of the runoff duration and tended to stabilise after 15–20 min. When the runoff intensity was stable, the runoff volume steadily increased based on the rainfall duration. The elapsed time for the runoff intensity to stabilise in light rainfall conditions lagged behind the heavy rainfall conditions.

Figure 7 demonstrates that the runoff intensity increased with the slope gradient. When the slope increased from 5°–25°, the runoff intensity increased from 225–276, 428–520, 729–896 and 833–987 mL per min, respectively, under four different rainfall intensities simulated for 40 min. As previously noted, increasing the slope gradients led both the soil infil-

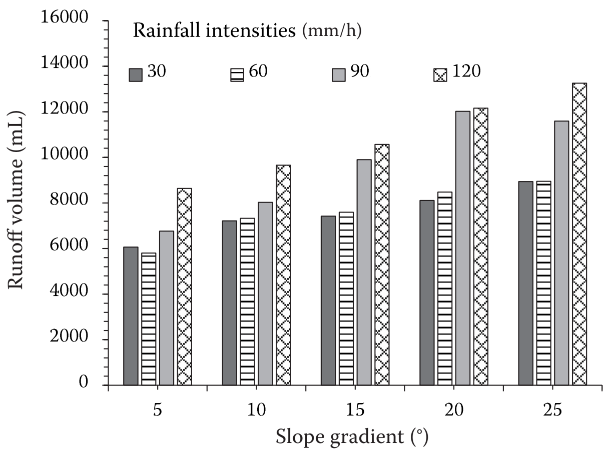

Figure. 5. Runoff volumes under the different rainfall intensities and slope gradients

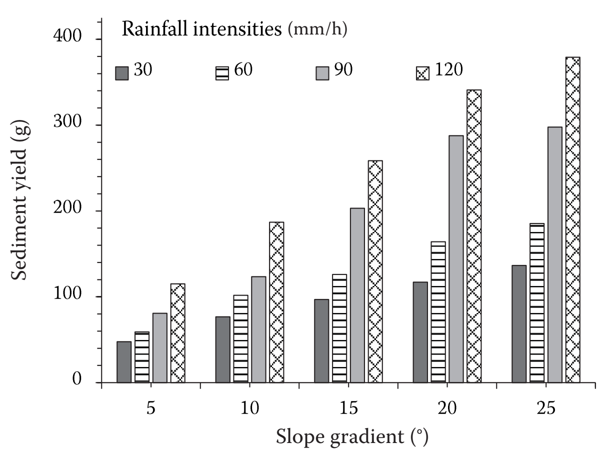

Figure 6. Sediment yield under the different rainfall intensities and slope gradients

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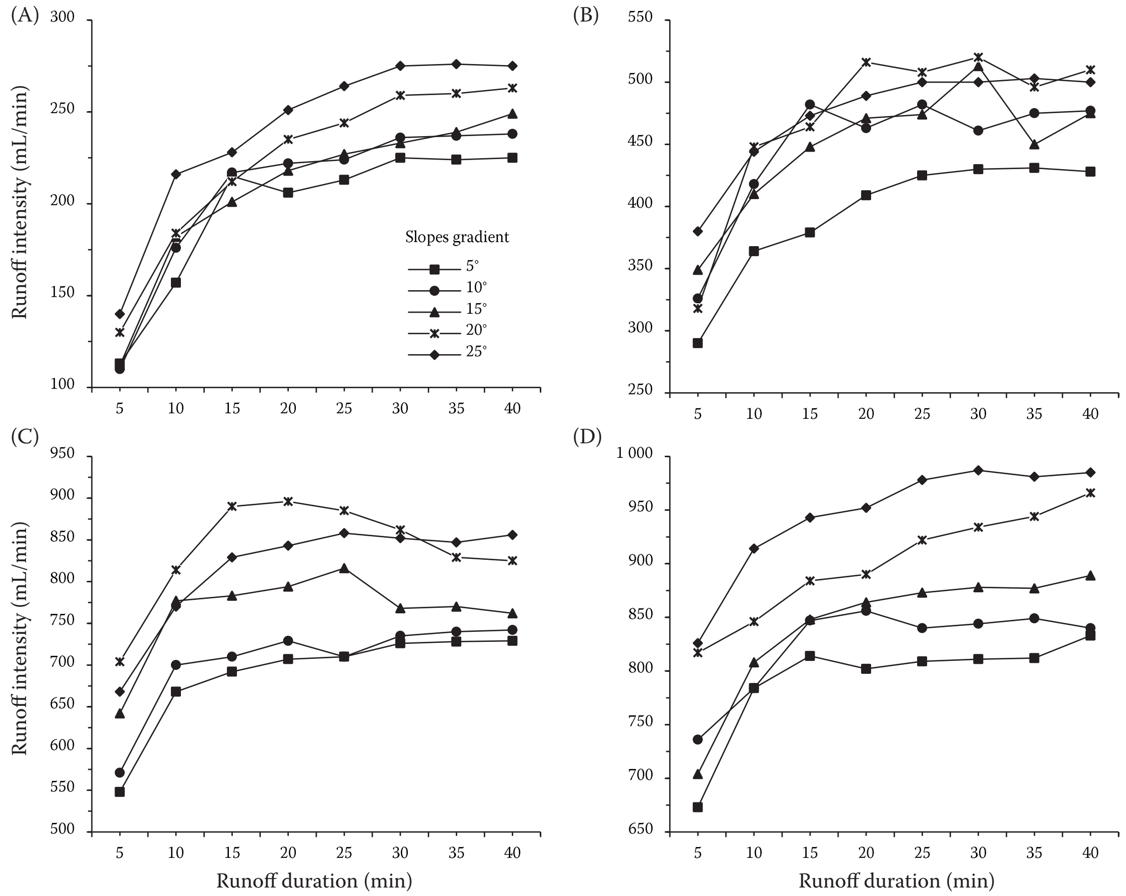

Figure 7. Trends of the runoff intensities on the different slope gradients under the rainfall intensities of 30 mm/h (A), 60 mm/h (B), 90 mm/h (C), 120 mm/h (D)

tration rate and residence time of the rainfall on the slope to decrease. The runoff flow velocity on the slope increased, thus enlarging the runoff intensity. Meanwhile, in the same period, it took less time for the soil moisture to reach saturation under heavy rain. Heavy rain can also produce a large amount of runoff in a short time. All these factors led to a shorter time for the runoff intensity to reach stability under the heavy rainfall intensity.

The relationship between the sediment yield intensity and the runoff duration on different slopes under various rainfall intensities is shown in Figure 8. The sediment yield intensity generally rose with the slope gradient across all the rainfall intensities. Under the four rainfall intensity conditions, the sediment yield intensity at a slope of 25° was 2.55, 2.81, 2.84 and 2.95 times higher than that at a slope of 5°, respectively. According to the previous analysis, the reason was that the component of the gravity in the slope direction accelerated the slope runoff, enhanced the sediment carrying capacity of the runoff, aggravated the soil erosion, and led to more severe sediment loss. When the rainfall intensity was higher, the flow velocity of the runoff formed by rainwater was faster. At this time, the erosion ability and sediment carrying capacity of the rainwater were stronger. The greater the slope, the greater the fluctuation in the sediment yield intensity data. This trend arises since the soil erosion process was affected by the combination of gravity of the soil particles and the runoff scouring on the steeper slope.

In addition, Figure 8 indicates that the sediment yield intensity increases with an increasing slope gradient in the range of 5–20°. However, such a trend was not apparent under higher slope gradients. When the rainfall intensities were 60 and 90 mm/h, the influence of a 20° slope on the sediment transport was not particularly different from that of the 25° slope. The decreased rainfall amount per unit slope area led to less erosion on the slope. Previous research has demonstrated that the velocity of the runoff and the force of the soil erosion increases with the slope gradient when it is within a certain degree (Wang

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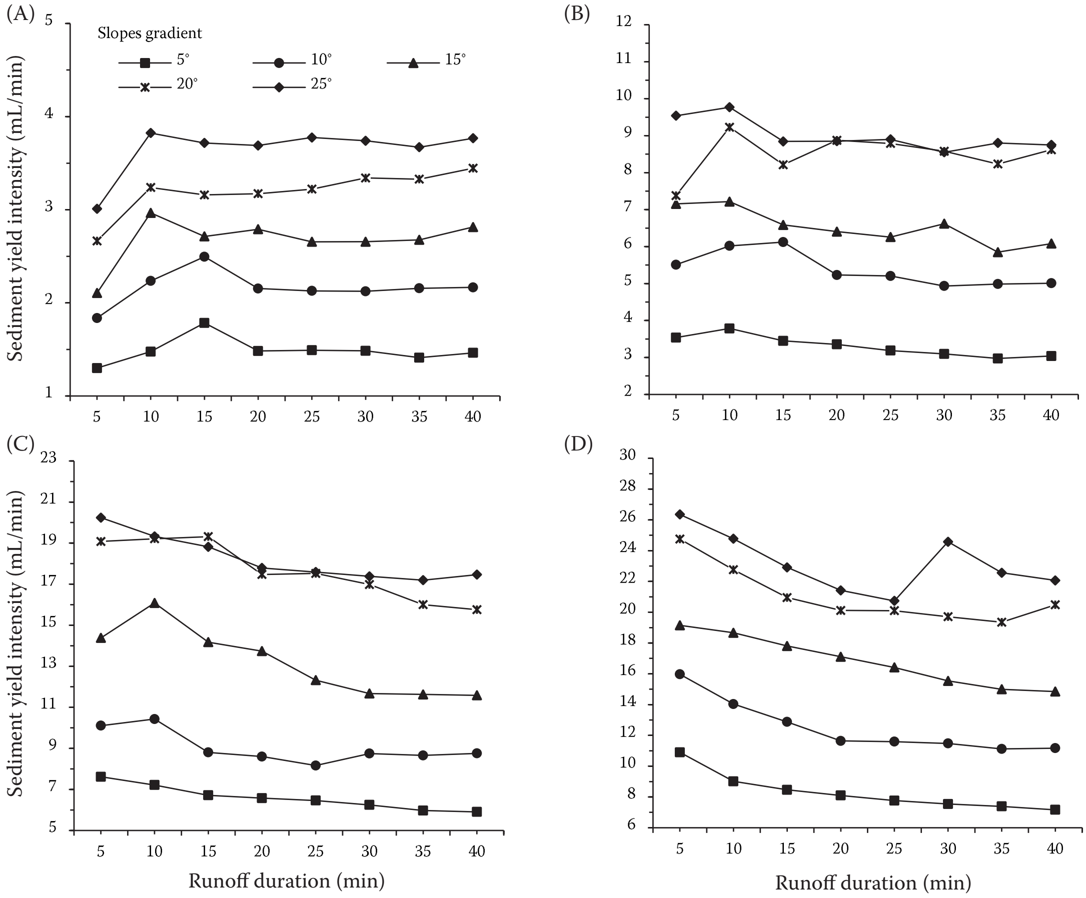

Figure 8. Variation tendencies of the sediment yield intensities on the different slope rainfall intensities of 30 mm/h (A), 60 mm/h (B), 90 mm/h (C), 120 mm/h (D)

et al. 2019). In this study, the critical slope gradient was found between 20° and 25°.

CONCLUSION

This study revealed the effects of the rainfall and slope on the hillslope soil and water loss through a series of simulated rainfall experiments. The results showed a runoff initiation time (1.31–12.43 min) that shortened with an increased rainfall intensity and slope gradient. Both the runoff volume and sediment yield increased significantly in the initial stage of the runoff yield, but tended to stabilise later, demonstrating a clear logarithmic relationship. Meanwhile, the runoff intensity was more sensitive to variation in the rainfall intensity. A positive correlation was found between the slope gradient and runoff intensity and the slope gradient and sediment yield intensity under the same rainfall intensities. The simulated rainfall experiments indicated a critical slope gradient between 20° and 25°. Generally, high-intensity rainfall and steep slopes tend to cause serious soil and water loss; thus, effective soil and water conservation measures should be implemented on higher slopes.

This study is based on a small-scale laboratory simulation of rainfall to study the erosion characteristics of a purple soil, which can be extended to larger-scale watershed erosion characteristics as a theoretical basis in future studies. Furthermore, the critical slope gradient of the soil and water loss, the runoff generation coefficient, and the effect of the interaction between the rainfall and slope gradient on the soil and water loss could be further explored.

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