

Original Research

Effects of Embedded Gravel or Gravel Mulching in Southern Red Soil on Slope Sediment Yield and Runoff

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Received: 3 April 2020

Accepted: 24 May 2020

Abstract

The red soil hilly region of southern China is affected by rainy seasons (Meiyu periods). There can be large variations of total rainfall per event and rainfall vs. time. This region is therefore sensitive to rainstorms during the Meiyu periods. Rainfall can cause soil coarsening in some areas and the resulting soil contains large amounts of gravel. This form of soil erosion is serious in southern China where there is heavy rainfall and the soil layer is thin. Gravel mulching has been shown to affect soil moisture content, hydraulic conductivity, infiltration, and evaporation. We used simulated rainfall experiments to study the effects of soil surfaces with embedded gravel or gravel mulching on slope runoff and sediment yield for Southern red soils under different rainfall intensities and slope gradients. Both gravel treatments reduced sediment and runoff vs. soil with no gravel, but the amount of reduction varied. Runoff did not consistently increase with slope gradient and rainfall rate. At low rainfall intensity, embedded gravel and gravel mulching inhibited runoff formation, but at high rainfall intensity and steeper slopes, the level of inhibition was reduced. The findings are important for soil conservation and management relative to gravel content, particularly in areas of China with substantial contents.

Keywords: gravel, rainfall intensity, slope gradient, red soil, runoff, erosion, sediment

Introduction

Soil erosion is a serious threat to ecosystem sustainability and it is affected by rainfall characteristics (e.g., rainfall intensity, duration, temporal variation, and velocity) [1-3], underlying surface conditions (e.g., topography, slope gradient, and vegetative cover) [1, 4-8]. Soil erosion has been identified as one of the

major processes contributing to soil and water quality degradation [9-11].

Rainfall intensity and slope gradient are the two dominant influences on hydrologic responses related to soil erosion. They have been studied via numerical simulation, experiments and analytical solutions (e.g., [1, 3, 12]). Rainfall intensity is a dominant factor in rainfall-runoff and soil erosion processes, with higher rainfall intensity generating a larger runoff peak [3]. He et al. (2012) investigated the influence of slope gradient on both runoff and sediment yield under

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various rainfall conditions [13]. They studied six rainfall events, finding that patterns of slope runoff vs. gradient were basically the same, i.e., that runoff increased with steepening gradient and found that rainfall was important to sediment yield. Detachment, transportation, and deposition of soil particles are the three major physical processes related to interactions between rainfall characteristics, overland flow, and soil properties [5, 14, 15]. As a major topographic factor, slope gradient controls soil particle transfer [5, 16-18]. The increased slope gradient is typically associated with greater sediment transport. However, the magnitude of the effect of slope gradient on rainfall-runoff and soil erosion processes is not consistent in experimental studies.

Among soil properties, the gravel content affects erosion. Gravels are mineral particles in soil with a diameter ≥ 2 mm [19]. In China, 18% of the soils contain gravel [20, 21]. These areas include the rocky mountain in southwest Karst regions, cinnamon soil in the northern rocky mountain, purplish soil in southwestern regions, and red hilly soil in southern regions, which contain large amounts of gravel [22, 23]. Gravel mulching can affect soil moisture content, hydraulic conductivity [24, 25], infiltration [26, 27], and evaporation [28], and other soil physical characteristics and hydrologic processes. Some studies indicate that the gravel on the slope may not only promote the infiltration and redistribution of water due to more large pore flow channels [29, 30], but also may limit the water infiltration by increasing the curvature of the water flow [31].

The southern red soil hilly region of China is affected by rainy seasons (Meiyu periods) with significant fluctuations in total rainfall and rainfall per unit time. For example, one 60 minutes rainfall in Zhejiang Province during the 2009 Meiyu period was 93 mm [32]. This makes the region sensitive to rainstorms during the Meiyu periods. Soil coarsening problems exist in some regions and these soils have high proportions of gravel. This form of soil erosion is very serious in areas with heavy rainfall and thin soil layers. The whole hydrological cycle is affected by gravel. Studies of the effects of gravel on water infiltration and evaporation in soil have provided a better understanding of the mechanisms of slope runoff. However, the effects of gravel on slope erosion appear to vary in different areas.

Most studies in China have focused on loess plateaus, with some studies on purplish soil regions [33-36]. Zhang et al. (2015) studied the erosion impacts of land use and slope gradient on soil erosion in a red soil hilly watershed and found that soil erosion increased with slope gradient for all land uses [7]. Li et al. (2013) studied erosion effects, using simulated rainfall rates and tillage, on productivity in a subtropical red soil hilly region [36]. Simulated rainfall intensities did not produce significant effects on soil productivity in no-tillage systems but different farming operations

produced a significant difference in soil productivity at the same erosion intensity. The effects of rainfall intensity and slope gradient on erosion in a red soil were investigated [37]. Runoff generation of red soil slopes was impacted by both slope angle and rainfall intensity. Runoff rate became steady after an initial unsteady period and increased with increasing rainfall duration. Wang et al. [38] studied the waste slag yard of the development construction project, the results show that the topsoil gravel can trap most of the fine soil particles splashed and reduce the source of sediments washed away by the runoff. The presence of crushed rock has an important impact on the erosion process of slopes such as splash erosion, interrill erosion, gully erosion and other slope erosion processes.

There is no report on the effects or mechanisms of gravel on slope runoff in southern red soil hilly regions. Therefore, research simulating the effects of embedded or mulching gravel in red soil slopes on erosion, runoff, and sediment yield during rainfall is useful. We used simulated rainfall experiments to examine the effects of a soil surface with embedded gravel or gravel mulching on slope runoff and sediment yield for southern red soil. We tested different rainfall intensities and slope gradients. These data enable quantification of soil and water processes on slopes with heterogeneous soil and provides information useful for detailed research and incorporation into soil erosion and slope hydrologic models.

Study Area and Experimental Materials and Methods

Study Area

Soil samples were taken from Xinchang County and Linhai County in the eastern coastal province of Zhejiang, China (Fig. 1). Soil at the region is dominated by typical red soils such as pink soil and yellow mud soil with a high content of gravel. Zhejiang is mostly composed of hills, which make up ~70% of the area. Zhejiang has a humid subtropical climate with four distinct seasons. Spring is rainy with changeable weather. Summer is hot, rainy, and humid. Fall is typically dry, warm and sunny. There is abundant rainfall in early summer. By late summer Zhejiang is threatened by typhoons that form in the Pacific. Average annual temperature is approximately 18°C. Annual precipitation ranges from 1,000 to 1,900 mm.

Experimental Equipment and Materials

This experiment was conducted using artificial rainfall simulation equipment. Collection and analysis of runoff sediment samples was carried out simultaneously. Rainfall simulation was performed using a spray-type artificial rainfall system with a rainfall height of 6 m. This ensured that most raindrops could achieve

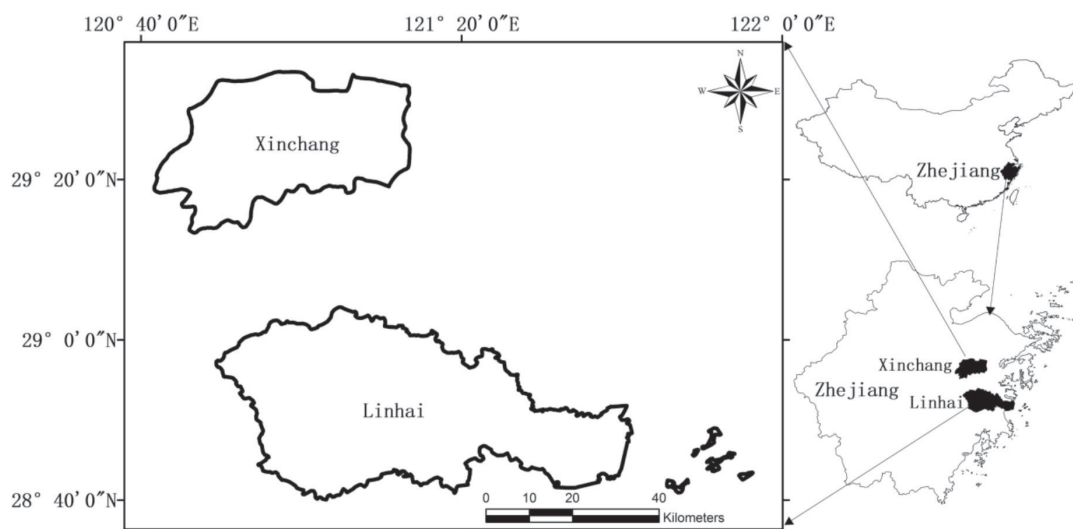


Fig. 1. Map of Xinchang County and Linhai County within Zhejiang Province and of Zhejiang within China.

the terminal velocity. We used a movable hydraulic steel flume with variable slope. The dimensions of the flume were 1.5 m long, 0.5 m wide, and 0.35 m deep. The gradient range was 0-30°. The side of the steel flume was provided with three water outlets: surface runoff (upper), subsurface flow (medium), and underlying infiltration (lower). The test soil was collected from the 0-20 cm soil layer of natural red soil slopes. The soil was air-dried before passing it through a 6 mm sieve to remove gravels, roots, and other debris.

The bottom of the flume was covered with 10 cm of quartz sand when the soil was loaded, to ensure that water infiltrating the flume was drained and the rainfall infiltration and runoff process during the simulation closely matched the actual situation. Filling of the bottom 10-cm soil layer was done by filling and compaction, with bulk density maintained at 1.5 g cm⁻³. The surface 10-cm soil layer or soil and gravel mixture was not compacted. Roughening was done by running a knife crosswise and lengthways on the slope between layers to prevent landslides during rainfall. To eliminate wall effects, soil or soil-gravel mixtures at the boundaries were compacted. Cutting rings with volume 100 cm³ were used to collect soil samples at the top, middle, and bottom of the slope before every rainfall event. The mass of these samples was measured before and after drying, and the bulk density and moisture in an early stage were quantified. This ensured that treatment of the underlying soil-gravel mixture was uniform prior to rainfall.

Experimental Design and Steps

During the experiment, test gravel with a particle size range of 6-25 mm was used (gravels of 6-10 mm, 10-20 mm, and 20-25 mm at a 3:5:2 ratio). The slope

gravel content was set to 0% (blank) and 5% (for both the mulching and embedded treatments). In the mulching treatment the gravel was placed atop the soil, whereas in the embedded treatment the gravel was mixed with surface soil. Two rainfall intensities (60 and 120 mm h⁻¹) and four slope gradients (10°, 15°, 20°, and 25°) were studied. Twenty-four rounds of rainfall experiments were carried out in two parallel flumes. Pre-rainfall on the soil was conducted before the actual rainfall event at a rainfall intensity of 30 mm h⁻¹, until there was slope runoff. The experimental sites were undisturbed for 24 h before the experiment to ensure that the soil moisture content and water distribution were consistent in every experiment. To measure rainfall intensity, four rain gauges were uniformly distributed around the steel flume before actual rainfall treatments. Rainfall uniformity was calculated using the uniformity formula based on rainfall at the various test points. The actual experiment was started once rainfall uniformity reached >85%. Historical rainfall durations and the slope erosion state of the gravel red soil slopes under various rainfall intensities during preliminary experiments were referenced for rainfall duration, and runoff duration was set to 60 min. After surface runoff started, runoff sediment samples were collected once every minute during the first 10 min. Subsequently, runoff sediment samples were collected every 5 minutes. A stopwatch was used to record the sampling time. After rainfall ended, the volume of runoff samples was measured. The sediment samples were dried in a 105°C drying oven to achieve constant weight, and the weight of the dried sediment was weighed. Sediment yield intensity was the weight of dried sediment in runoff sediment samples per unit time (g min⁻¹). The sediment yield per rainfall event at the exit section was taken to be the final volume of soil loss from the flume (g). The surface runoff volume, subsurface flow and underlying infiltration volume from

Table 1. Runoff-initiating time (min).

Soil type	60 mm h ⁻¹ rainfall intensity			
	10°	15°	20°	25°
No gravel	6.18±0.71	5.02±0.30	1.98±0.59 ^b	0.32±0.08 ^b
5% gravel embedded	10.38±1.78 ^a	7.97±1.26 ^a	4.21±1.51 ^b	1.35±0.33 ^b
5% gravel mulching	11.50±1.87 ^a	8.32±0.93 ^a	4.35±0.33 ^{a,b}	1.50±0.40 ^b
Soil type	120 mm h ⁻¹ rainfall intensity			
	10°	15°	20°	25°
No gravel	3.17±0.23	2.13±0.24	1.02±0.20 ^b	0.2±0.03 ^b
5% gravel embedded	8.05±1.17 ^a	6.93±0.33 ^a	3.53±0.66 ^{a,b}	0.92±0.11 ^b
5% gravel mulching	8.15±0.99 ^a	6.72±0.82 ^a	3.7±0.31 ^{a,b}	0.9±0.21 ^b

Two-way ANOVA showed that soil type [F (2, 12) = 24.28, $P < 0.01$] and slope [F (3, 12) = 91.75, $P < 0.01$], but not soil type \times slope interaction [F (6, 12) = 1.884, $P = 0.17$] contributed significantly to variations in the runoff-initiating time under 60 mm h⁻¹ rainfall intensity; and that soil type [F (2, 12) = 86.14, $P < 0.01$], slope [F (3, 12) = 124.1, $P < 0.01$], and soil type \times slope interaction [F (6, 12) = 8.142, $P < 0.01$] all contributed significantly to variations in the runoff-initiating time under 120 mm h⁻¹ rainfall intensity. No gravel and 10° were used as the control groups to compare with other soil types and slopes, respectively, and the P values were adjusted by Duncan's multiple comparison correction.

^a $P < 0.05$, compared with no gravel of the same slope.

^b $P < 0.05$, compared with 10° of the same soil type.

the exit section of the flume in every rainfall event was taken to be the final volume (mL).

We analyzed the effects of rainfall intensities of 60 and 120 mm h⁻¹ and four slope gradients (10°, 15°, 20°, and 25°) on runoff and sediment yield for red soil slopes under simulated rainfall conditions and compared differences between embedded gravel or gravel mulching and non-gravel containing slopes.

Results and Discussion

Before sediment yield and runoff data were collected, we recorded runoff-initiating time (Table 1). Runoff started earlier with higher slope gradient and higher rain intensity. Soil containing gravel, either embedded or mulched, started runoff later than soil without gravel.

We calculated sediment yield intensity (g min⁻¹) over time, at 60 and 120 mm h⁻¹ rainfall intensity on no gravel, gravel embedded, and gravel mulching. Fig. 2 shows that there was an increase in sediment yield intensity from 10° to 25° slope, under all rainfall and gravel situations, but the curves for the intermediate slopes (10° and 15°) fluctuated. Embedded gravel reduced the intensity, with the reduction most pronounced at 60 mm h⁻¹. Intensity was greater for the higher rain intensity (120 mm h⁻¹), for both gravel embedded and gravel mulched.

This study shows the sediment yields (g) for one hour of rainfall (at 60 and 120 mm h⁻¹), for each of the three gravel situations are shown in Fig 3. The no-gravel configuration had much greater sediment yields than either gravel configuration, at both rainfall rates.

At the 60 mm h⁻¹ rate, embedded gravel yielded less sediment than mulched gravel, except at the 25° slope. The opposite was true at 120 mm h⁻¹, for all slopes. However, the differences at both rates were much less than those for either gravel situation vs. no gravel.

The greater the rainfall intensity is, the larger the median particle size of the raindrops will be, and the stronger the splashing ability will be, thereby increasing the turbulence of the runoff on the slope [39]. If the kinetic energy of the raindrops is eliminated, the amount of soil erosion will be reduced by 20~60 times, or even 90 times [40]. The gravel cover can protect the soil from raindrop splashing, reduce the topsoil crust, and enhance the stability of the surface soil structure [38]. Poesen found that the position of gravel in fine sand has a significant effect on the surface crust strength. The soil crust strength when gravel mulching the ground is weaker than when gravel is embedded in the soil [41]. The relationship between gravel mulching and interrill erosion is complex, which is affected by factors such as topsoil structure, gravel location and size, slope gradient. Gravel mulching can more inhibit the formation of topsoil rill under higher rainfall intensity [39]. The intensity of erosion and sediment yield increases with the increase of slope under the same rainfall intensity, and the influence of this slope varies significantly with the different rainfall intensity [42]. This study shows that the gravel treatment slopes can increase surface infiltration and prevent slope erosion under the lower rainfall intensity. The amount of bare soil is higher than that of mulching gravel slopes due to embedded gravel slopes, which results in higher erosion on the slopes under the higher rainfall intensity. The impact effect of raindrops can form

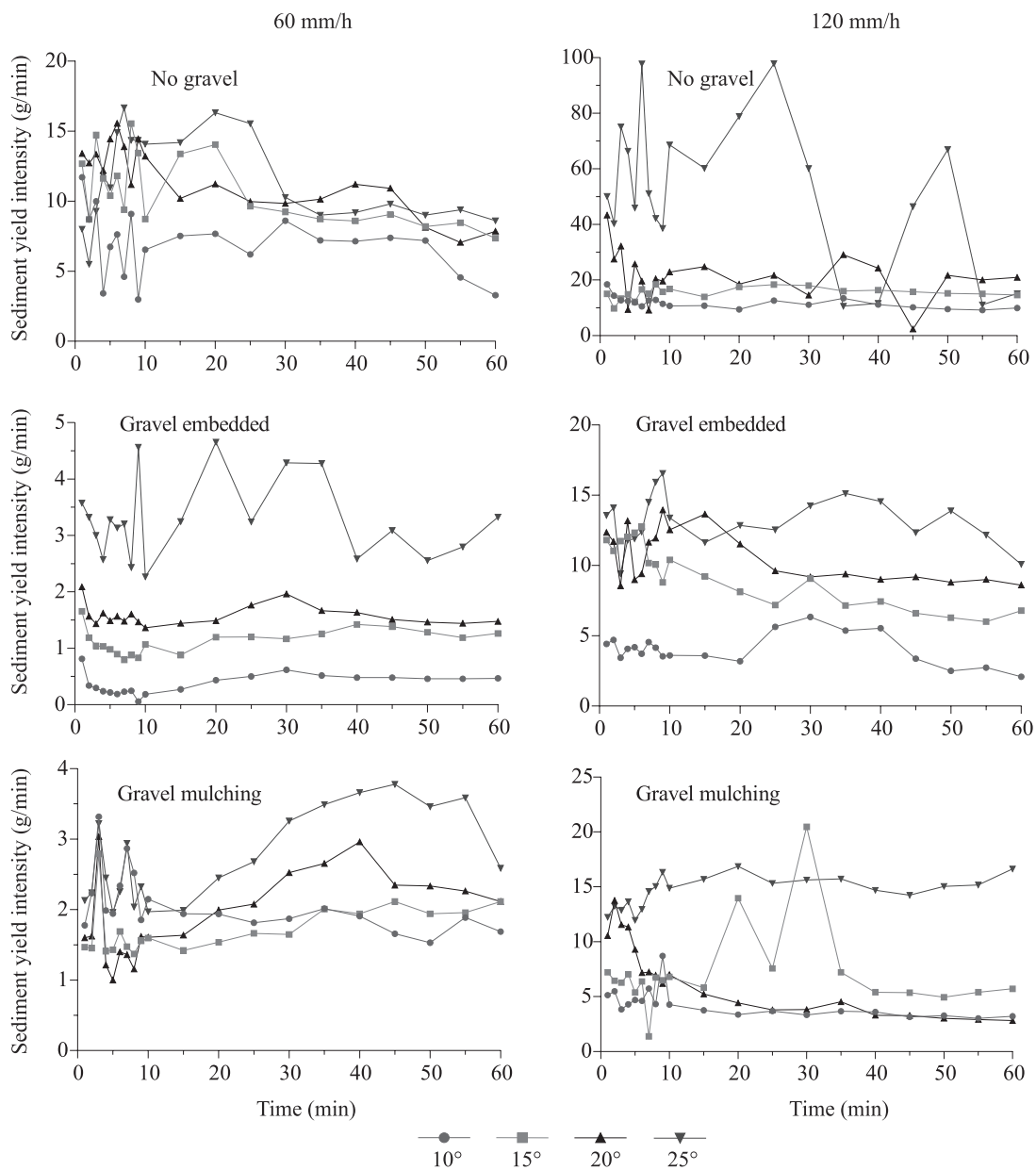


Fig. 2. Sediment yield intensity (g min^{-1}) vs. time at two rainfall intensities (60 and 120 mm h^{-1} , left and right panels, respectively) for three gravel situations (no gravel (top panels), gravel embedded (middle panels), and gravel mulching (bottom panels)). Four curves representing different slope gradients are shown by different colors (key at bottom). Each data point is the mean value from two experiments.

a dense temporary crust on the topsoil with the continuous rainfall. So that the soil erosion resistance is enhanced correspondingly and the existence of thin layer water flow, the splashing of rainfall is reduced, and the sediment yield is gradually decreased and stabilized.

The addition of gravel to the soil in this study was a variable along with slope and rainfall intensity. Both mulched and embedded gravel substantially reduced sediment over soil with no gravel. Thus, gravel might produce effects similar to vegetative cover. The contribution rate of slope to runoff and sediment yield is different. The contribution rate of slope to sediment yield is about 30%, and the contribution rate of slope

to runoff is about 60% [43]. In previous research that Komatsu et al. (2018) noted “the effect of slope on runoff generation remains unclear in many different soils including Chinese purple soil” [35]. This might explain some of the variability in runoff and sediment vs. slope. There have also been variable results from other experimental studies evaluating the effects of slope gradient on rainfall-runoff and soil erosion processes.

Runoff distribution is an important parameter, which can reflect the hydrological process of the soil. Due to the existence of gravel, soil properties are different, and its response to rainfall processes and rainfall intensity is different. The effect of rainfall intensity and gravel

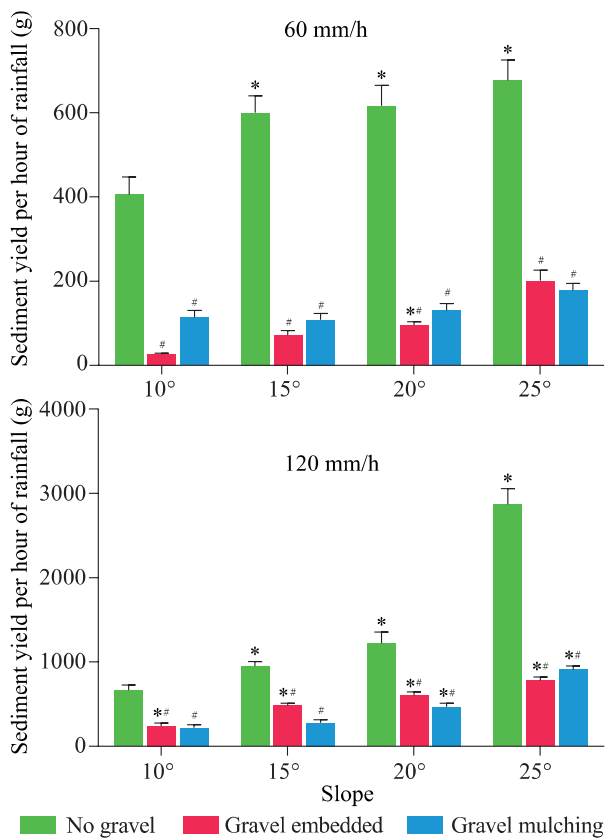


Fig. 3. Bar graph of sediment yield (g) vs. slope (x-axis) for one hour of rainfall (at rainfall intensities 60 and 120 mm h⁻¹, top and bottom panels respectively), for each of the three gravel situations (key at upper right).

Data are presented as mean±standard deviation (n = 2). Two-way ANOVA showed that soil type [F (2, 12) = 685.8, $P < 0.01$], slope [F (3, 12) = 35.73, $P < 0.01$], and soil type × slope interaction [F (6, 12) = 6.888, $P = 0.17$] all contributed significantly to variations in the runoff-initiating time under 60 mm h⁻¹ rainfall intensity, and that soil type [F (2, 12) = 389.7, $P < 0.01$], slope [F (3, 12) = 254.7, $P < 0.01$], and soil type × slope interaction [F (6, 12) = 63.08, $P < 0.01$] all contributed significantly to variations in the runoff-initiating time under 120 mm h⁻¹ rainfall intensity. No gravel and 10° were used as the control groups to compare with other soil types and slopes, respectively, and the P values were adjusted by Duncan's multiple comparison correction.

$P < 0.05$, compared with no gravel of the same slope.

* $P < 0.05$, compared with 10° of the same soil type.

situation on runoff distribution on the slope is very obvious and the results are shown in Fig. 4. In terms of 10°, 15°, 20° and 25° slopes, the ratio of surface runoff is from 47.6% to 74.2% under the 60 mm h⁻¹ rainfall intensity, which is similar to that of no gravel and gravel embedded slope. The ratio of surface runoff is 56.8% -87.9% on all slopes at 120 mm h⁻¹. The ratio of soil subsurface flow with 60 mm h⁻¹ rainfall intensity is 4.3%~15.5% on all slopes, and under 120mm h⁻¹, the proportion of the soil subsurface flow is 0.7%~5.7%. The proportion of the soil subsurface flow decreases with the increase of the rainfall intensity by 44.2%~94.0%. This result shows that the lower rainfall intensity is beneficial to the water infiltration on the soil slope and

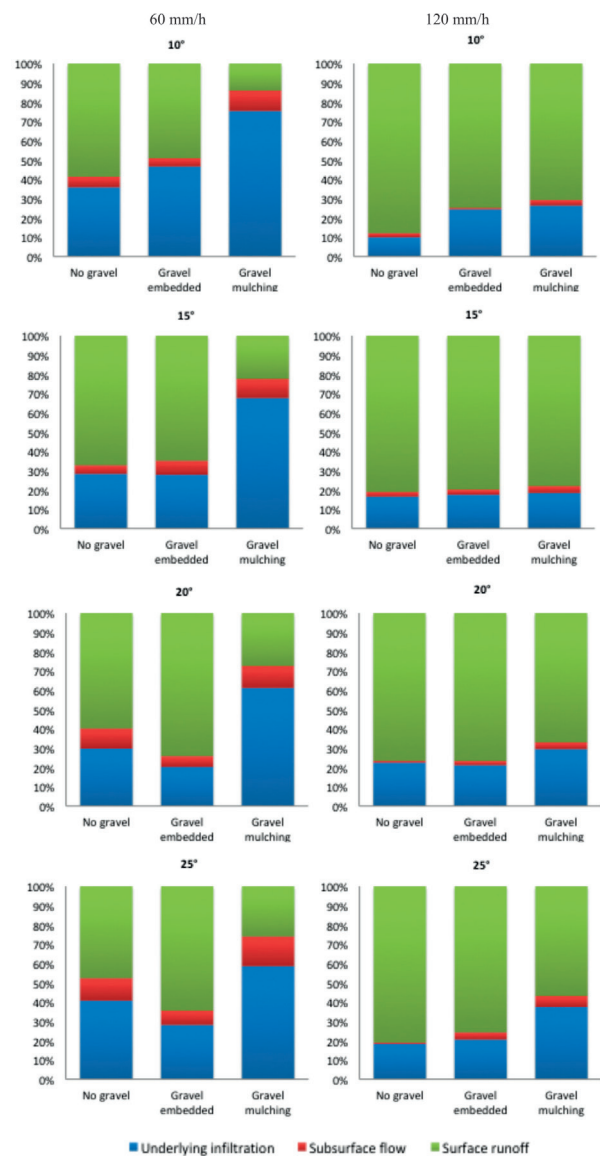


Fig. 4. Bar graph of runoff distribution (%) vs. the three gravel situations (x-axis) at rainfall intensities 60 and 120 mm h⁻¹ (left and right panels, respectively), and four slopes (10°, 15°, 20°, and 25°) (key at bottom).

promotes the subsurface flow in the soil. In addition, gravel mulching is beneficial to the development of soil subsurface flow, so the proportion of gravel mulching soil subsurface flow by rainfall at 60 mm h⁻¹ is the highest among the test slopes, which are 10.6% (10°), 10.0% (15°) 11.4% (20°) and 15.5% (25°) respectively. Under the rainfall intensity of 60 mm h⁻¹, the slope change has a greater impact on runoff distribution. The increase of rainfall intensity covers the effect of slope change on runoff distribution of each test slope.

Conclusions

Gravel, both embedded and mulching in soil, generally reduced sediment and runoff relative to soil

with no gravel. These two variables had variable levels of reduction. They did not consistently increase with the slope gradient and rainfall rate. At low rainfall intensity, embedded gravel and gravel mulching inhibited runoff formation, but at high rainfall intensity and steeper slopes, the level of inhibition was reduced. The increase of rainfall intensity covers the effect of slope change on runoff distribution of each test slope. Nonetheless, given the comparisons to soil without gravel, gravel might be considered in lieu of (or in addition to) vegetative cover for reducing runoff and sediment. These findings could be useful to researchers and practitioners involved in soil erosion, conservation, and development construction projects management, particularly in areas of southern China with red soil and substantial gravel contents.

Acknowledgments

This research was supported by National Natural Science Foundation of China (grant Nos. 41701312 and 41702247), Zhejiang Provincial Natural Science Foundation of China (LQ16D010004), project NO. ZJWEU-RWM-20200201A sponsored by the Open Research Fund of the Key Laboratory for Technology in Rural Water Management of Zhejiang province. We would like to thank all partners for their assistance with running the experiments.

Conflict of Interest

The authors declare no conflict of interest.

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