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Analysis of Runoff and Sediment Losses from a Sloped Roadbed under Variable Rainfall Intensities and Vegetation Conditions

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Abstract: Vegetation plays an important role in reducing soil erosion. By exploring the allocation and coverage of different types of vegetation, we can improve management practices that can significantly reduce soil erosion. In this experiment, we study runoff and sediment losses on a shrub-grass planted, grass planted, and bare slope under different rainfall intensities. Results showed that the runoff generation time for the three subgrade types decreased as rainfall intensity increased ($p < 0.05$). The slopes planted with either grass or shrub-grass were able to effectively delay runoff generation. As rainfall intensity increased, the runoff amount increased for all treatments, with runoff in the bare slope increasing the most. The runoff reduction rate from the shrub-grass slope ranged from 54.20% to 63.68%, while the reduction rate from the slope only planted with grass ranged from 38.59% to 55.37%. The sediment yield from the bare slope increased from 662.66 g/m^2 (15 mm/h) to 2002.95 g/m^2 (82 mm/h) with increasing rainfall intensity in the plot. When compared with the bare slope, both the shrub-grass and planted grass slopes were able to retain an additional 0.9 g/m^2 to 4.9 g/m^2 of sediment, respectively. An accurate relationship between rainfall intensity, sloped vegetation types, and runoff reduction rate was obtained by regression analysis and validated. These results can provide a reference for improving soil and water conservation via improved vegetation allocation on a sloped roadbed.

Keywords: precipitation; shrub-grass; soil erosion; soil and water conversation

1. Introduction

The process of modernization, construction, and land use change can have a negative impact on the environment unless the processes by which changes are made are well-understood and sustainable [1]. When public transportation systems such as roads and railways are improved, the construction of slopes via excavation and fill can change the original landform, increasing discharge and erosion from sloped surfaces, with consequences for both natural and human systems. The speed and peak flow of runoff caused by rainfall in hardened areas is much higher than that in non-hardened areas, which results in frequent ponding in roads, flooding, and other storm water management problems [2–6]. The subgrade slope of the roadbed and the stability of the slope can be increased, which can ultimately protect and improve local conditions. Adding vegetation to slopes is also beneficial by reducing sediment loads associated with runoff, and has the added effect of regulating water resources and conserving groundwater [7]. These practices can also help with ecological restoration and have gradually become an important method of protecting railway subgrade slopes [1]. Many highway or railway subgrade surfaces have concrete skeletons, or sashes, and greening to reduce runoff. Subgrade greening types vary, but better results at landscape scale have been achieved by planting grass and adding irrigation systems, as well as by using pure grass.

Festuca elata Keng ex E. Alexeev (Festuca) is a cold-season turf grass that has been proven to have good greening effects [8] and is widely used in greening construction [9]. *Photinia* × *fraseri Dress* is commonly used in the construction of green projects, while the more widely-used plant species are more suitable in east and Southwest China [10]. As a semi-deciduous shrub, *Ligustrum japonicum* is often used for greening and is well-adapted to winter conditions [11]. In recent years, most studies of greening vegetation have focused on the effects of pollutant removal and the relationships among sediment production, rainfall, and slope. Vincent et al. [12] showed that the removal rate of ammonia nitrogen by grass cover was 268% higher than that of bare land. Anton et al. and Truman et al. [13,14] report that these herbaceous plants have better heavy metal absorption, enrichment, and removal efficiency in the rain. By using runoff plots, Blanco et al. [9] found that the runoff generation and soil erosion modulus were linearly correlated with rainfall and average rainfall intensity. Susana et al. [15] used runoff plots and found that roadbed slope engineering and greening can effectively prevent soil erosion.

In order to better understand the effect of grass-planting or shrub-grass planting on reducing runoff and soil erosion and increasing soil water infiltration, this study investigated the rainfall yield and sediment yield using runoff plots for a sloped system with three different treatments and five different rainfall intensities. The objectives of this study were to: (i) explore the law of runoff and sediment yield under different rainfall intensities, and (ii) evaluate which types of planting and vegetation allocation have the best soil and water conservation benefits. In this experiment, we study runoff and sediment losses on a shrub-grass planted, grass-planted, and bare slope under different rainfall intensities. This contrast provides a theoretical reference for further exploring the regulation and control ability of subgrade slope vegetation on runoff and sediment erosion rates, as well as reasons that planning slope greening may be effective in both highway and railway construction.

2. Materials and Methods

2.1. Site Description

The selected observation plot was located in the subgraded section of Jianning Qi Railway in Nantong City, Jiangsu Province (31°53′42″ N, 121°21′47″ E). The subgrade slope is 7.0 m high with a slope of 30°. Each experimental plot was made of three square concrete frames of each railway subgrade. A total of nine plots were selected for this study. The boundary of the experimental plot was brick and concrete smear, with runoff and sediment collection tanks below the sample site. The specific specifications (reference standard runoff plot) of subgrade and sand sink are shown in Figure 1.

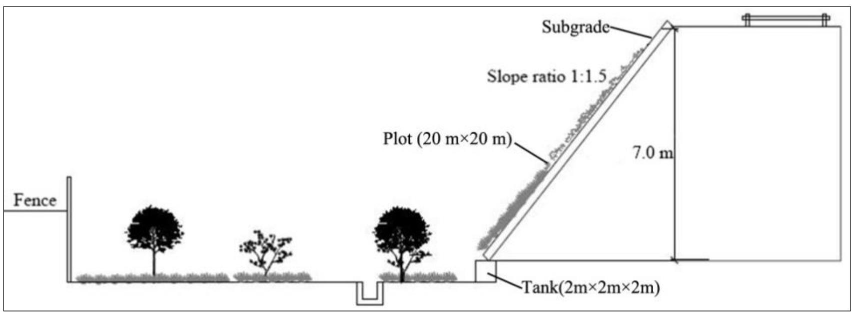

Figure 1. Diagram of the sloped roadbed plot.

2.2. Soil Characteristics

The test soil was a yellow-brown earth from Jiangsu Province. The thickness of the overlying soil was about 30 cm. Before planting and greening, the density of the soil was measured to be 1.50 g/cm^3.

The particle size composition was analyzed by a Nicomp (USA) 380N3000 laser particle size analyzer, and the results are shown in Figure 2.

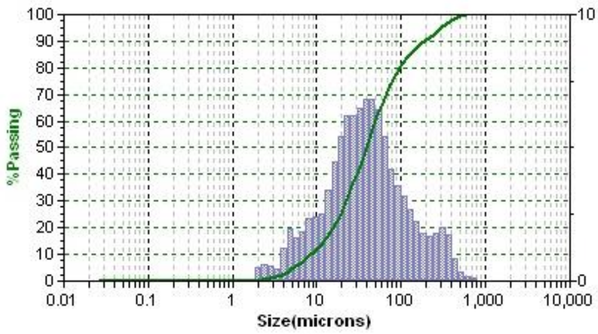

Figure 2. Distribution of the particle sizes of soil used in the experiment.

2.3. Vegetation Characteristics

Grass seeds were sown on the grass slope and allowed to grow for about 120 days until the coverage (VFC) reached 95%, according to the grass square method [16]. The plots with grass cover were planted with *F. elata Keng ex E. Alexeev*. The plots with shrub-grass were planted with *F. elata Keng ex E. Alexeev* and *L. japonicum*. Two rows of trees were planted across a plot of 1 m length. Six trees were planted in each row, for a total of 12 trees/m per plot. The distance between the single slope protection units was about 2.5 m (Figure 3).

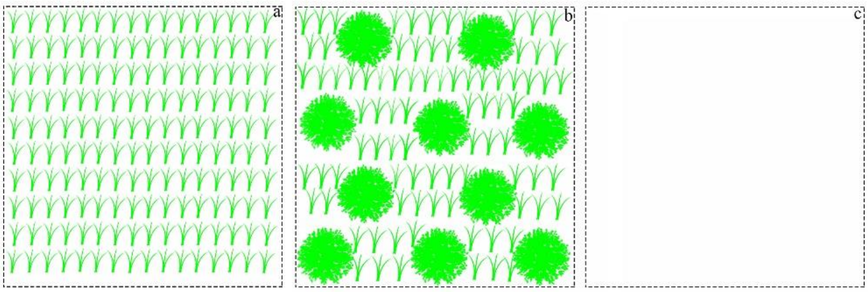

Figure 3. Diagram of the experimental plots: The (**a**–**c**) correspond to the shrub-grass, planted-grass and bare slope, respectively.

2.4. Experimental Design

The experimental area was located in a section of subgrade under a real road. After the subgrade fill was completed and the runoff plot was built to meet the requirements, a stainless-steel rainfall tube was set up to measure rainfall in real time and to calculate the average hourly rainfall intensity (mm/h) of the monitoring site. In order to better control the single variable, the treatments with similar rainfall during the observation period were selected as the effective observational data. There were different amount of rainfall on days with initial soil moisture content. As a result, the soil moisture content was close to the soil holding capacity at the beginning of the experiment (30% ± 1%), and the observations reflected the runoff and sediment load of the selected plots under specified rainfall conditions.

The number of rainfall intensity selected during the observation period is shown on Table 1. The types of underground subgrade surfaces were divided into three types: bare slope, a grass slope, and a shrub-grass slope. There were three replicate plots for each type. The overall rainfall on each subgrade type was 80 ± 4 mm, with rainfall intensities of 15, 28, 40, 63, and 82 mm/h, respectively being tested in each subgrade.

Table 1. Significance test (Friedman Method) of the runoff generation time of the three tested different vegetation types. SS-square of the standard deviation; df-degrees of freedom; MS-mean square.

The Difference of Source	SS	df	MS	*F*-Value	*p*-Value
Between groups	38,568.133	2	5112.29	4.911	0.047
Within the group	94,227.600	12	7852.300	-	-
Total	132,795.733	14	-	-	-

The runoff generation time was recorded with a stopwatch during the rainfall event. After a single rainfall, an (L) event was measured, taking into account the specifications of the collecting tank and the depth of the runoff. After sediment deposition in the sedimentation tank, most of the runoff flowed out through the outlet at the bottom of the collection tank, but some evaporated. The wet sediment was brought back to the laboratory, dried at 105 °C, and its dry weight determined.

2.5. Runoff Reduction Rate

The runoff reduction rate, Q (%), was calculated as follows:

$$Q(\%) = \frac{Q_1 - Q_2}{Q_1} \times 100\% \tag{1}$$

where Q is the runoff reduction rate, Q_1 is the total amount of runoff produced by bare slope, L; Q_2 is the runoff produced by either the planted grass or shrub-grass slopes, L.

2.6. Statistical Analysis

All statistical analyses were performed using the software package SPSS 16.0 (IBM, New York, NY, USA). Descriptive statistics were used to calculate the mean and standard deviations for each set of replicates. All data were tested for normal distribution and homogeneity of the variance analysis to ensure that the data met the requirements of the variance analysis. A two-way ANOVA was used to analyze differences in runoff generation time, runoff and sediment, with treatment type and precipitation as independent factors. The least significant difference method was used to compare the runoff generation time and runoff when necessary.

3. Results and Discussion

3.1. Runoff Generation Time

There were three treatments in the study and three plots in each treatment. Compared with a bare slope, the slopes planted with grass and shrub-grass respectively showed a delaying effect on runoff generation time. The runoff generation time of the three treatments under different rainfall intensities is shown in Figure 4. This was due to the existence of surface vegetation, which increased the surface roughness and prolonged the runoff path, and was also able to increase the soil infiltration intensity via the root system [14,17,18]. In addition, the crown of the shrub-grass impacted the rainfall interception effect, weakening the splash impact of raindrops on surface soil particles [19], enabling the soil to maintain a strong infiltration rate for a long time, thus delaying the initial runoff generation time.

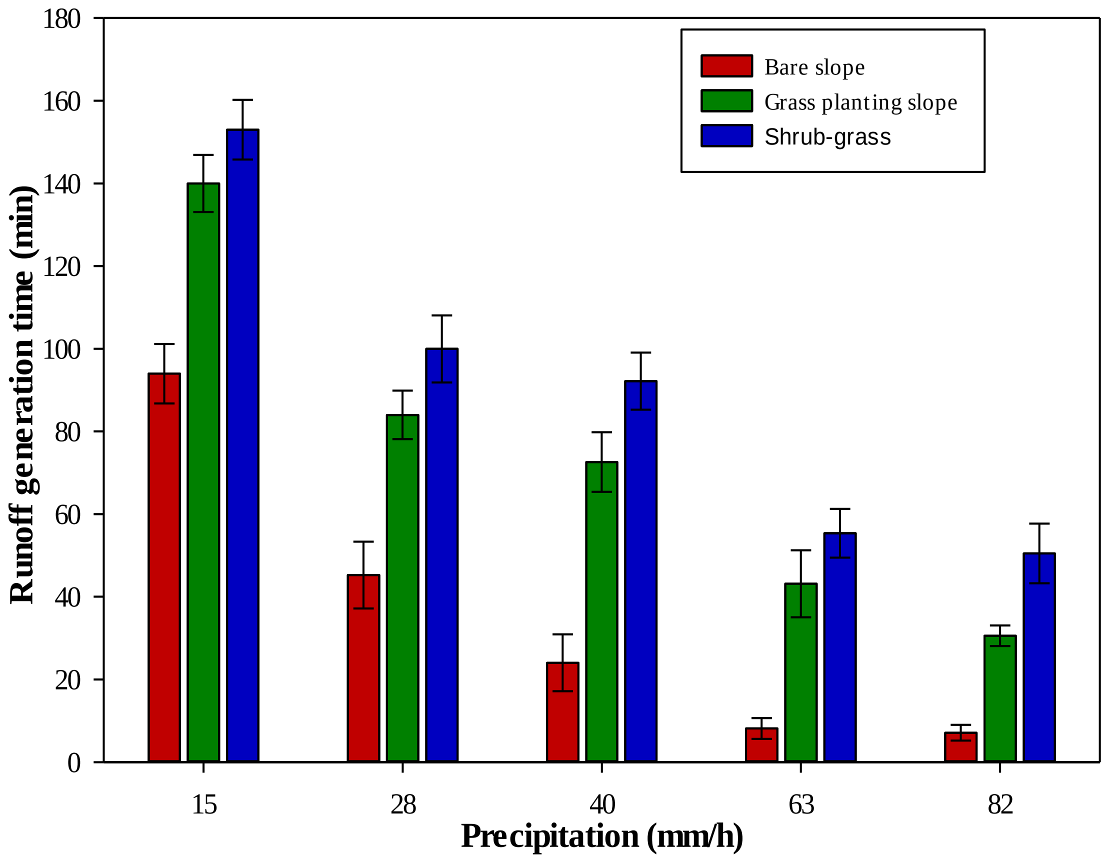

Figure 4. Mean (± SD) runoff generation time (min) under different rainfall intensities and three different vegetation types.

It can be also seen from the figure that as rainfall intensity increases, the generation time for the bare, planted grass, and shrub-grass slopes showed a decreasing trend, with the generation times significantly decreasing above rainfall intensities greater than 28 mm. The runoff generation time in the planted grass and shrub-grass was longer than of the bare slope ($p = 0.047$). Compared to the bare slope, the delay time associated with using a planted grass slope was 38′28″. The delay time associated with using a shrub-grass slope was on average of 54′34″. The delay time on the shrub-grass slopes were 41.2% higher than that of the grass slopes. This showed that a vegetation-covered slope can effectively prevent the formation of runoff, prolonging the time of runoff formation. Previous studies have also found similar results [20].

As rainfall intensity increased, the runoff generation time decreased from 2 h 20′, 30′57″ and 2 h 33′ in 15 mm/h to (82 mm/h), to 50′47″, 1 h 34′ and 7′10″ in 82 mm/h of the planted-grass, shrub-grass and bare slope, respectively. Rainfall intensity had a significant impact on the runoff generation time for all three treatments. The runoff generation time of the slope with shrub-grass and planted grass was significantly different from that of the bare slope ($p < 0.01$). The runoff generation time of the vegetated slope was significantly higher than that of the bare slope ($p < 0.5$). These phenomena were mainly due to the fact that the infiltration capacity of the soil was close to the soil at the start of the experiment. Vegetation such as shrubs and grasses can effectively improve the physical and chemical properties of soil, increase soil space, and increase soil water infiltration capacity [7]. However, different vegetation types had different impacts on the physical and chemical properties of the soil. Some studies have found that grasses provide better results than shrubs in reducing runoff generation time [21].

This was likely due to the existence of surface vegetation, which increased soil surface roughness, lengthened the runoff path, and increased soil infiltration capacity through the root system [19]. In addition, the crown of the shrub-grass changed the interception effect of rainfall by weakening the splash impact of raindrops on the surface soil [22], allowing a higher infiltration for a longer period of time, thus delaying the runoff generation time.

3.2. Total Runoff

The total runoff on the three subgrade types under different rainfall intensities is shown in Figure 5. When rainfall was held constant, increasing rainfall intensity caused the runoff of all types of subgrade to increase. The total amount of runoff on the bare slope was significantly larger than that on the planted-grass and shrub-grass slopes ($p < 0.001$), indicating that the combined effect of planting grass and shrub-grass was able to reduce runoff (42.7%) from the slopes. Compared with the shrub-grass slope, runoff in the planted-grass slope was not significantly different for the different rainfall intensities ($p = 0.196$). This indicated that the runoff was closely associated with each rainfall intensity from the planted grass slope. This was mainly because the flow velocity on the sloped surface was low when there was vegetation coverage and the rainfall intensity was low. Additionally, the shear force of the sloped flow on the soil surface was weak and flow velocity was low, while the runoff generation time spent flowing through the whole surface was long. This increased the infiltration effect of the soil and reduced the runoff and sediment production, weakening soil erosion.

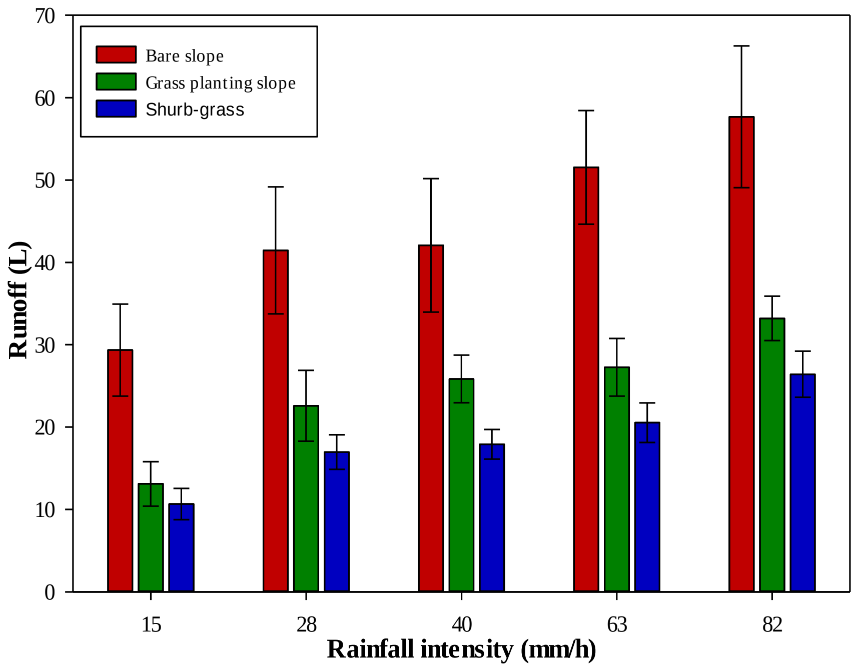

Figure 5. Mean (± SD) runoff for the three different subgrade types under different rainfall intensities.

The mean runoff values for the grass slope were 13.10 L, 22.58 L, 25.84 L, 27.26 L, and 33.20 L under the five rainfall intensities, respectively ($p < 0.05$) (Table 2). The average values of the total runoff were 10.66 L, 16.96 L, 17.91 L, 20.53 L, and 26.41 L for the shrub-grass slope, respectively ($p < 0.05$). The mean value of total runoff was 29.35 L, 41.46 L, 42.08 L, 51.54 L, 57.67 L for the bare slope, respectively. The difference level was also significant ($p < 0.05$). This showed that rainfall intensity has a significant impact on the total runoff of the three subgrade types. This was because rainfall was not only the cause of runoff, but also the source of runoff. A large number of studies have found that the higher the rainfall intensity, the larger the middle diameter of raindrops, which is more conducive to runoff generation [23]. When rainfall intensity and other conditions are fixed, runoff and sediment volume mainly depend on rainfall.

Table 2. Significance test (Friedman Method) amounts on the runoff from three different vegetation types. SS—standard deviation squared; df—degrees of freedom; MS—mean squared value.

The Difference of Source	SS	df	MS	*F*-Value	*p*-Value
Between groups	1846.586	2	923.293	13.558	0.001
Within the group	817.169	40	68.097	4.106	0.093
Total	2663.755	44	-	-	-

Shrub-grass slopes had the greatest impact on total runoff, with average reduction rates of 58.92%. On grass slopes, the runoff reduction rate was 45.81%. The combination of planting and irrigating grass can play a large role in increasing soil and water conservation, regulating and storing rainwater runoff, and increasing soil infiltration in subgrade slopes, such as those used in railways or highways.

Table 3 shows a linear relationship between runoff reduction rate and rainfall intensity. The runoff reduction rate associated with the planted-grass and shrub-grass slopes decreased as rainfall intensity increased. This is partially due to the effect of the canopy interception, coupled with its associated effect on soil infiltration. When rainfall intensity is high, the interception effect is reduced, and the existence of a biological crust on the soil will affect the runoff generation time of the planted-grass and shrub-grass slopes. The existence of vegetation on a slope makes the infiltration rate of soil lower than the slope [24–26]. The combination of these two factors decreases the runoff reduction rate when rainfall intensity is high. The runoff was extremely significantly influenced by rainfall intensity, which is consistent with the results of Polyakov et al. [27]. The runoff generation time in each experimental area was related to the water content of the soil. If the soil moisture content was monitored in real time and the same water content was used, the relationship between rainfall intensity and runoff generation time could be better quantified.

Table 3. Total runoff volume and reducing rate.

Rainfall Density	Bare Slope Runoff Volume/L	Grass Runoff Volume/L	Shrub-Grass Combined Runoff Volume/L	Reducing Rate of Grass Slop/%	Reducing Rate of Shrub-Grass Combined Slop/%
15 mm·h^{-1}	29.35	13.1	10.66	55.37	63.68
28 mm·h^{-1}	41.46	22.58	16.96	45.54	59.09
40 mm·h^{-1}	42.08	25.84	17.91	38.59	57.44
63 mm·h^{-1}	51.54	27.26	20.53	47.11	60.16
82 mm·h^{-1}	57.67	33.2	26.41	42.43	54.20
Average	44.42	24.40	18.49	45.81	58.92

3.3. Sediment Yield

Under different rainfall intensities, the sediment yield from the three subgrade surfaces is as shown in Figure 6. As rainfall intensity increased, the amount of sediment produced by the bare slope increased exponentially ($R^2 \leq 0.98$), especially at intensities above 60 mm. The sediment yield from planted-grass and shrub-grass slopes was significantly lower than that from the bare slope, and the difference in sediment yield between the shrub-grass and planted-grass slopes was very significant ($p < 0.01$). For lower rainfall intensities, the sediment yield from the grass and shrub-grass slopes did not increase significantly with rainfall intensity ($p > 0.05$), but were not significantly different from the bare slope ($p > 0.05$).

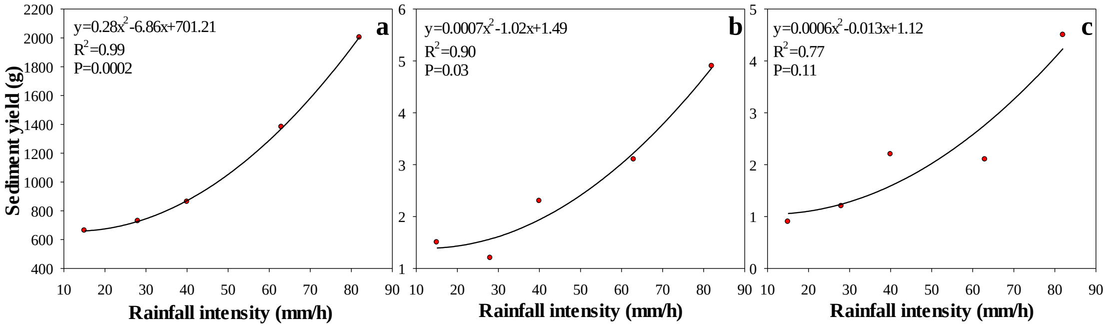

Figure 6. Sediment yield under different rainfall intensities and different vegetation types. The (**a**–**c**) were bare slope, grass planting and shrub-grass planting, respectively.

As rainfall intensity increased, the sediment yield from the bare slope increased sharply from 662.66 g/m^2 (15 mm/h) to 2002.95 g/m^2 (82 mm/h), while the sediment concentration from the planted grass slope was only 1.5–4.9 g/m^2, and the sediment yield from the shrub-grass slope was 0.9–4.5 g/m^2. The difference between the shrub-grass and grass slopes was not significant, and the soil conservation effect was obvious. This was mainly because the vegetation reduced or even prevented splash erosion, thereby being able to reduce runoff.

3.4. Effects of Rainfall Intensity on Runoff Reduction Rate

There is a significant correlation between rainfall intensity and runoff reduction rate. María et al.'s research showed that the relationship between runoff, sediment and rainfall intensity was a power function [28]. Gessesse et al.'s study on land use patterns with vegetative cover showed that the fitting effect between rainfall and runoff by a curtain function was better [29]. Previous studies suggested that runoff generation rate increased as a power function with rainfall intensity and slope [30–33]. It has been found that the relationship of runoff and rainfall intensity is a power function for slopes of 10°, 15°, and 20° [34]. A regression analysis of rainfall intensity, and runoff reduction rate produced the following equation:

$$Q(\%) = (-0.791 \ln I - 0.893) \times 100\% \ (R^2 = 0.90)$$

In the formula above, Q denotes the runoff reduction rate (%) and I denote rainfall intensity (mm/min).

The simulated and measured runoff reduction rates under varying rainfall intensities and treatments were compared with the measured values using the above formula. It can be seen from the table that the reduction rate obtained by the simulation was close to the measured value, and the absolute error between the simulated value and the measured value ranged from 1.0%–6.6%, which indicated that the accuracy of the simulated value obtained by the equation was good. The absolute error between the average value of the simulated value and the average value of the measured value was 5.9%, which indicated that the fitting effect of the above formula was satisfactory. This was mainly because the yellow-brown soil itself was porous and had good infiltration. Infiltration directly determines the amount of runoff. The presence of vegetation cover mainly affects runoff generation by affecting the raindrop kinetic energy and infiltration. With yellow-brown soil, a small vegetated area had a great impact on the production of sediment, while using the shrub-grass combination had a small additional impact on the production of sediment [35–38]. The effects of vegetation cover and rainfall intensity on runoff and sediment were the same. The effects of rainfall duration and soil bulk density on runoff and sediment in different soils were significantly different, especially on yellow-brown soil [39].

4. Conclusions

The runoff generation times from a bare slope, planted-grass slope, and shrub-grass slope were negatively correlated with rainfall intensity. The greater the rainfall intensity, the shorter the initial runoff generation time, and the effect of rainfall intensity on runoff yield was very significant. The effect of planted grass and shrub-grass on the runoff generation time was significant difference. As rainfall intensity increased, the runoff from the three vegetation types tended to increase, and the rainfall intensity had a significant effect on the total runoff amount. The total runoff from the planted-grass slope and the shrub-grass slope was significantly different from that of a bare slope. The total runoff from shrub-grass and grass slopes was reduced compared to a bare slope, but the difference between the treatments was not significant, although the runoff on the shrub-grass slope was slightly higher. This analysis shows that slightly highly runoff reduction effects could be achieved by vegetating sloped subgrade areas, especially when combining of shrub and grass. As rainfall intensity increased, the sediment the bare slope increased exponentially, especially when the rainfall intensity was higher than 60 mm. The difference in sediment yield between the shrub-grass, grass, and the bare slope was very significant, showing that greening had a very significant and positive effect on reducing soil erosion.

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