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Evaluation of the EUROSEM on soil erosion simulation for loess plateau, northern China

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Abstract

The Loess Plateau region features fragmented landforms, sparse vegetation, and short but intense summer rainstorms that can easily cause severe soil erosion. To evaluate its applicability to a typical Loess Plateau in northern China, an indoor laboratory experimental study was conducted for events with different slope lengths (3, 4, and 5 m) and rainfall intensities (50, 60, 70, 80, 90, 100, 110, and 120 mm/h). EUROSEM (European Soil Erosion Model) was used to simulate the soil erosion process and predict both total runoff and sediment yield. The EUROSEM modeling results were compared with the observed experimental values and analysed to determine the performance of EUROSEM. The results and analysis showed that EUROSEM could effectively simulate the runoff processes. It produced better predictions for the total runoff yield than for the sediment yield, with Nash–Sutcliffe efficiencies of 0.9003 and 0.1820, respectively. The qualified rates of the RE (relative error) between simulated and observed values of the total runoff and sediment yield were 87.5% and 37.5%, respectively. Compared to the sediment yield under rainfall intensities of 50–80 mm/h, those under 90–110 mm/h had lower RE and higher NSE, which increased from −3.9 to 0.5. However, the modeling results deviated more from the experimental data at a rainfall intensity of 120 mm/h. According to this study, EUROSEM is a good fit for simulating the runoff and partial sediment yield processes of the Loess Plateau region's slopes. However, the accurate prediction of sediment yield still requires more research to achieve complete effectiveness using EUROSEM for typical and wide scenarios in China.

KEYWORDS
EUROSEM evaluation, loess plateau, runoff and sediment processes, single rainfall event

1 | INTRODUCTION

Soil erosion modeling is a frontier area of research on soil erosion mechanisms and the simulation of soil erosion processes. It is an effective tool for assessing soil erosion and supports the configuration of soil conservation measures. Researchers worldwide have developed many soil erosion models, such as the CSLE and USLE. However, most models are based on either empirical or statistical approaches. Although they have proven accurate and popular, they are ineffective in providing a theoretical explanation and insight into the physical mechanisms underlying soil erosion processes. Thus far, physical analytical models are still at a relatively early stage and require further improvement and advancing development. For example, the DYRIM model (Wang et al., 2007), which considers climate change and land scenarios, requires large amounts of input data. The other two models, that is, the WaTEM/SEDEM and Yang models, which consider geoeffects such as gully erosion, do not consider river siltation, a key factor in slope soil erosion. On the other hand, the WEPP and EUROSEM (European Soil Erosion Model) are two models developed based on slope runoff observed on plots. Compared to other similar models based on physical hydrological processes, both models demonstrated good performance in soil loss prediction. The two models also have benefits, such as thorough consideration of physical processes. Comparing the two models themselves, the EUROSEM is dynamically event-based. It only needs to specify the initial condition of a single rainfall event as the data input, on which it can predict the peak values of the discharge and sediment and their occurrence time in minutes (Morgan et al., 1998). The modeling prediction was consistent with the rainfall characteristics, and the results met the demand for simulation purposes. Previous research has indicated that, compared with WEPP and MEDRUSH, EUROSEM is the optimal option for estimating soil loss (Centeri et al., 2009).

The EUROSEM, which stands for the European Soil Erosion Model, can be used for predicting the intensity of hydraulic erosion on individual plots and in small watersheds. Folly et al. (1999) and Mati et al. (2006) analysed watersheds in the Netherlands and Kenya, respectively, and found that EUROSEM accurately predicted the peak values of runoff rate and total runoff under different environmental and rainfall characteristics. Audu et al. (2001) simulated runoff for a rainfall experiment using bare soil from degraded lands in northeastern Nigeria and showed that EUROSEM predicted surface runoff. EUROSEM was adopted to simulate both runoff and infiltration in the northern Kanto Plain in Japan, and the results were compared with the observed data. It produced a better prediction for surface runoff than for infiltration because the infiltration rates were lower than those of indoor tests (Ikeda et al., 2019). Furthermore, because soil macropores and fractures influence the infiltration rate and determine vertical water infiltration in addition to surface runoff, EUROSEM was unable to accurately estimate the ‘absolute value’ of the infiltration rate (Artabe Ibarreche, 2011).

EUROSEM has been widely used to simulate runoff and soil loss. A study on an artificial rainfall field test in Hungary found that runoff prediction is unstable, but good for soil loss prediction (Centeri et al., 2009). Another study in the UK for runoff and soil loss adopted two approaches to reduce parametric variation: one improved the selection of the set of parameters and the other derived physical parameters from observed hydrographs. The simulation results were in good agreement with the observed data (Quinton, 1997). EUROSEM is also unsatisfactory for hydrograph and sediment simulations. However, it produced reasonable predictions for annual soil loss in two case studies in Costa Rica and Mexico (Veihe et al., 2001). Meanwhile, a study in Iran (Khaleghpanah et al., 2016) demonstrated that EUROSEM accurately predicted the total sediment yield on steep stony slopes under most rainfall events, whereas occasional unsatisfactory predictions were mainly due to insufficient estimation of runoff sediment content.

In summary, up-to-date modeling activities and results have highlighted that EUROSEM exhibits different performances in different geographical and climatic scenarios. To date, only a few studies have evaluated the EUROSEM against erosion data from scenarios in China. A study of steep slope soil erosion in the area of the Three Gorges Reservoir (Cai et al., 2005) showed good performance in runoff prediction but relatively less effect on sediment yield. To gain further knowledge of these scenarios in China, this study used EUROSEM to simulate slope soil erosion in a typical hilly-gully region of the Chinese Loess Plateau. The study site was in the middle reaches of the Yellow River Basin in northern China. This area has a fragmented geomorphological landscape with sparse vegetation. Its climate is characterized by several intense rainstorms of short duration in the summer. Geographical and climatic features make slopes prone to serious soil and water loss. The main objective of this study is to use single rainfall event data from experiments at the plot scale to evaluate the results of the EUROSEM simulation and assess its application in a specific scenario.

2 | METHODOLOGY AND METHODS

Both experiments and modeling were conducted in this study. The experiment involved a single rainfall event at a plot scale. Thereafter, the rainfall, soil, and topography data were input into EUROSEM for modeling to predict runoff and sediment yield. Finally, the experimental data and the EUROSEM predictions were contrasted. To assess the model's accuracy, two analytical parameters were used: the relative error (RE) and the Nash–Sutcliffe efficiency coefficient (NSE).

2.1 | Experiment setup

The soil for the experiment was collected from the slopes in the region of Wangjiagou small watershed (37°31′ N, 111°11′ E), Shanxi Province, China (Figure 1). The average annual rainfall is 490.3 mm, with a maximum of 711.5 mm and a minimum of 240.2 mm. Nearly 80% of the annual precipitation occurs from July to September. The average annual temperature is 8.9°C. The research area has sparse vegetation, mainly consisting of barren slopes and sloping farmland, with slopes exceeding 25° accounting for 56.93% of the total. The measured multiyear sediment transport modulus was 7651 t/km^2. According to the ‘International Standard for soil texture classification’, the slope soil is typical sandy loam soil composed of clay (1.75%), silt (14.2%), and the sand (84.05%). The soil bulk density in the natural state is 1.35 g/cm^3, the organic matter content is 13.42 g/kg, pH is 8.15, the initial volumetric water content is 13.99%, and the total porosity is 49.05%.

An open space with an area of 2 × 4 m was selected locally. Soil was collected from 10 cm deep layers, each up to a total of 50 cm. The soil samples collected from the individual layers were bagged separately and labelled. Upon returning to the laboratory, the soil was air-dried, and impurities were removed. Soil erosion tests were conducted using runoff flumes. Before being loaded into the collected field soil, at the bottom of the runoff flumes was first laid a layer of

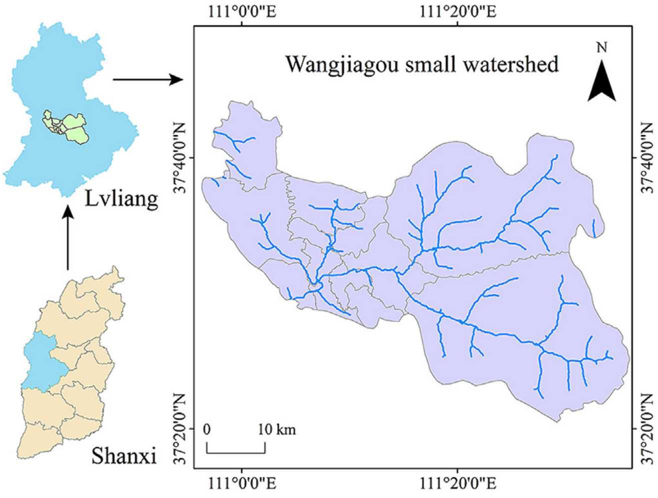


FIGURE 1 Location of the study area.

fine sand of 5 cm thickness. Thereafter, the top of the sand was covered using permeable gauze to guarantee the free flow of air and water at the bottom, so that it was close to the state in the field. Finally, the prepared field soil was loaded into flumes on top of the permeable gauze. To effectively restore the original state in the field, soil was added layer-by-layer, following the exact order when taking them in the field, up to a total of five layers. Each layer was 9 cm thick, resulting in a total soil height of 45 cm. Prior to the soil being loaded into the flume, the soil moisture content was determined by weighing and drying the soil. To strictly control the bulk density of the added soil in accordance with the field conditions, each layer was meticulously compacted. Before adding a new layer, the top surface of the compacted soil in the flumes was ploughed slightly using a tooth rake to ensure contact and integration at the interface between the soil layers. Finally, the loaded flumes were left to stand for 1 month before performing the experimental tests. They were regularly watered and monitored using the cutting ring method to determine the soil bulk density. At the runoff flume wall, the soil bulk density was increased to a suitable level in order to mitigate the edge effect on the slope runoff and sediment yield in the subsequent tests.

2.2 | Rainfall simulation

The experimental tests were conducted in the Water Flow Experiment Hall at Taiyuan University of Technology on three runoff flumes with designed slope lengths of 3, 4, and 5 m and a width of 0.5 m. The flumes were installed on a 20° slope and loaded with bare soil without vegetation growth. With reference to data from the Institute of Geographic Sciences and Natural Resources Research, CAS (http://www.igsnrr.cas.cn/cbkx/kpyd/zgdl/cndm/202009/t20200910_5692372.html), the maximum rainfall intensity on the Loess Plateau was 144 mm/h. To cover the highest intensities of rainfall events occurring in the Loess Plateau, eight rainfall intensities were implemented in this study: 50, 60, 70, 80, 90, 100, 110, and 120 mm/h. Rainfall was simulated using an artificial rainfall device installed 10 m above the ground. The rainfall device used was the advanced FULLJET rotating down spray nozzle head (FR/11, FR/13, and FR/15) produced by SPAYING SYSTEMS CO. It can produce a continuous rainfall intensity in the range of 15–200 mm/h and covers an area of 5×5 m^2. The raindrop size can be adjusted in the range of 0.3–5.7 mm. A total of 35 self-registering rain gauges with a diameter of 85 mm and a height of 200 mm were placed evenly around the runoff flumes. The rainfall intensity was calibrated using rain gauges before the tests. The rainfall uniformity, which is generally defined by the coefficient of uniformity (CU), was set above 85% (Figure 2). The water used for rainfall is tap water with an electrical conductivity of 128 μs/cm and a salt content of 82 mg/L.

The soil moisture content in the flumes was measured before each rainfall event to ensure that the initial soil moisture content (absolute moisture content) was consistent across all tests. Each rainfall event lasted for 30 min, the time of runoff occurrence was recorded, and runoff samples were collected at time intervals of 2 min using the plastic bottles of 1 L capacity marked with a volume scale. For every rainfall event test, three distinct lengthened runoff flumes were positioned side by side, and each test was carried out in duplicate. A total of 16 tests were conducted. After each test, the collected runoff samples were left to rest for 24 h before measuring the runoff volume by the depth of water in the bottles and the sediment, which was weighed after the collected samples were drained and oven-dried for 12 h at 105°C. The final results were the averages of the values from two duplicate tests.

2.3 | EUROSEM

EUROSEM is a process-based single-event model for the erosion process at a plot or small watershed scale. It describes the soil erosion process under individual rainstorms in a minute manner (Morgan et al., 1998), and considers the major underlying physics, such as rainfall retention by vegetation, infiltration, raindrop splash, runoff erosion, runoff transport, and sediment deposition. The runoff and soil loss were computed based on the following dynamic mass balance equation (Morgan et al., 1998):

Surface runoff continuity equation:

$$\frac{\partial A_W}{\partial t}+\frac{\partial Q}{\partial x}=w[r_i(t)-f(t)] \tag{1}$$

where A_W is the cross-sectional area of the flow (m^2), t is the time (s), x is the horizontal distance (m), w is the flow width (m), $r_i(t)$ is a rainfall rate less than the interception rate (m/s), and $f(t)$ is the local infiltration rate (m/s).

Sediment continuity equation:

$$\frac{\partial (A_W q_s)}{\partial t}+\frac{\partial (Q q_s)}{\partial x}-e(x,t)=q_s(x,t) \tag{2}$$

where q_s is the sediment concentration (m^3/m^3) and e is the net detachment rate or rate of erosion of the bed per unit length of flow(m^3/s/m).

The model uses a set of interconnected homogeneous geo-elements, such as slope planes and channels, that are parameterized to describe the movement of water and sediment over the land surface.

This study primarily focused on slope runoff and erosion; therefore, only the slope elements were considered. The pycnometer method was used to determine the specific gravity of the sediment particles (RHOS) for the input data; the drying and weighing method was used to determine the soil porosity (POR), and the combined pycnometer and cutting ring method was used to determine the initial volumetric moisture content (THI) of the soil. Soil erodibility (EROD), soil cohesion (COH), and recession factor (RECS) were determined with reference to both measured data on the Loess Plateau (Geng et al., 2015; Zhang et al., 2004) and the EUROSEM user manual (Morgan et al., 1998). The other parameters, such as the effective net capillary drive (G), saturated hydraulic conductivity (FEIN), and surface roughness (RFR), were determined based on trial and error by adjusting their input values by comparing the simulation results with the experimental measurements.

The EUROSEM is ineffective in coping well with complex hydrological conditions, such as large and sharp variations in soil properties during rainfall (Mati et al., 2006). Heavy rainfall in general is more likely to increase raindrop splash, which could result in the blockage of soil pores, the collapse of soil pore structure, and soil crusting (Rahma et al., 2017). On the other hand, the parameter FEIN not only

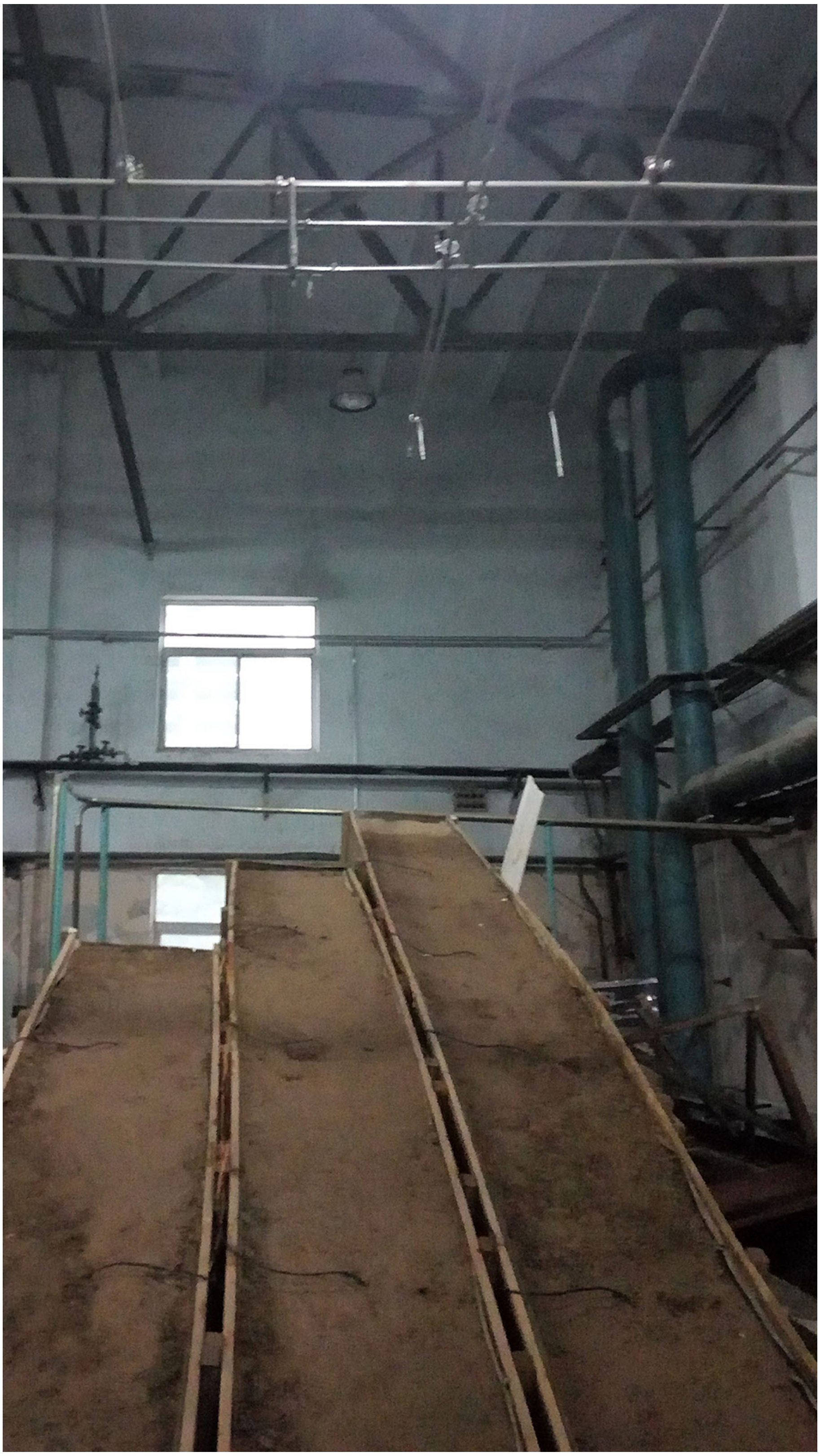


FIGURE 2 Artificial simulated rainfall experiment.

depends on the soil pore structure but also plays an important role in runoff (Folly et al., 1999). In this study, to effectively address the drastic changes in soil properties under different rainfall conditions, two separate values of FEIN were set for rainfall intensities in the ranges of 50–80 and 90–120 mm/h. The values of the other parameters, except RFR, were strictly set in the range recommended by Morgan et al. (1998), as listed in Table 1.

2.4 | Data processing method and model simulation accuracy evaluation

To analyse the runoff and sediment yield, the correlation between rainfall intensity, slope length, total runoff, and sediment yield, the Nash-Sutcliffe efficiency coefficient (NSE), and relative error (RE) were employed to evaluate the model accuracy. The higher the

TABLE 1 Main parameters of the EUROSEM.

Modified parameters		Parameters provided in model brochure			
FEIN[a] (mm/h)	RFR[b] (cm/m)	G[c] (mm)	EROD[d] (g/J)	COH[e] (kPa)	RECE[f] (mm)
8 (90–120 mm/h), 20 (50–80 mm/h)	0.1	350	3	3	15

Abbreviation: EUROSEM, European Soil Erosion Model.

[a] Saturated hydraulic conductivity.

[b] Surface roughness.

[c] Effective net capillary drive.

[d] Soil erodibility.

[e] Soil cohesion.

[f] Recession factor.

NSE and the smaller the RE, the better the modeling results and applicability of the model.

3 | RESULTS

3.1 | Simulation of runoff process under different rainfall intensities

Figure 3 compares the runoff results of the EUROSEM with those of the experiments. This shows that the simulated runoff over time exhibited a trend similar to that observed in the experiments. The observed runoff rate shows oscillation, but in a similar trend to the simulation at all rainfall intensities for the slope lengths of 3 and 4 m. However, for the slope length of 5 m, the simulation prediction is considerably greater than that observed in the tests under rainfall intensities of 50, 60, and 100 mm/h and considerable smaller than that observed at rainfall intensities of 120 mm/h. Moreover, under different conditions of rainfall intensity and slope length, 87.5% of the simulated values had an RE within 20%. For a slope length of 4 m under all rainfall intensities and for a slope length of 3 or 5 m under 110 mm/h of rainfall, the model yielded a better estimate. Both modeling and experiments showed that the runoff rate generally increased with rainfall duration. The heavier the rainfall, the earlier the runoff starts. For instance, runoff started at 4 min under a rainfall intensity of 50 mm/h but started at 9 s under 100 mm/h. When the rainfall intensity was less than 80 mm/h, the runoff increased sharply within the first 4 min but slowed down thereafter. When the rainfall intensity exceeded 80 mm/h, the runoff almost reached a stable state within 3 min of the start. However, the heavier the rainfall intensity and the longer the slope length, the higher the growth rate of the runoff and peak value.

3.2 | Simulation of sediment yield processes under different rainfall intensities

Figure 4 compares the sediment yield predicted by EUROSEM with that of the experiments. This indicates that the sediment yield in the experimental tests initially exhibited a smooth increase. When the rainfall intensity exceeded 80 mm/h, the sediment yield rate exhibited increasing fluctuation with increasing slope length. In contrast, the EUROSEM modeling results at rainfall intensities of 50–80 mm/h present a steep increase in sediment yield before reaching a significant peak value, which is several orders of magnitude higher than that observed. Thereafter, the curves quickly fell back and flattened at the level about one fourth of their peak values. The greater the rainfall intensity and slope length, the steeper the peak wave of the EUROSEM curves. After passing the initial steep peak wave for the flat part, the difference between the predicted sediment and the value observed in the experiment decreased as the rainfall continued. The comparison indicates that the performance of EUROSEM on sediment prediction is ineffective for the initial yield at the start stage but improves when the sediment yield has stabilized. The results show that the model is unstable and inaccurate under certain rainfall intensity conditions, including scenarios of 50–80 mm/h, where rainfall and runoff erosion lead to large amounts of sediment yield in the initial phase.

3.3 | Evaluation of EUROSEM performance

The results (Figures 3 and 4) indicate that the EUROSEM performs better in the runoff process simulation than in the sediment yield process. High-performance simulations of the runoff process play a key role in erosion and sediment yield prediction (Morgan et al., 1998). In the sediment yield simulation, the predicted values were higher than those observed for all slope lengths at rainfall intensities of 50 and 60 mm/h. However, in the rainfall intensity range of 70–100 mm/h, the predicted values were higher than the observed values within the first 10 min; thereafter, the two values became similar. The observed values for the 3- and 4-m slope lengths oscillated around the predicted values when the rainfall intensity increased to 110 and 120 mm/h, respectively; in the meantime, they were significantly higher than those observed for the 5-m slope. These results show that the model is particularly unstable and inaccurate for rainfall intensity scenarios of 50–80 mm/h, which lead to a large amount of sediment yield at the initial stage.

A relevant comparison between the prediction and observation in Figure 5 shows that for the total runoff, the modeling and experiment demonstrated a good linear correlation ($R^2 > 0.87$). The NSE is 0.9003, and the Res for all the cases are in the range of -30.36% to 38.93%. If we give 20% tolerance for the potential inaccuracy of the total runoff measurements, the RE pass rate was 87.5%. These results justify the good performance of EUROSEM in runoff simulations for typical slopes on the Loess Plateau in China. On the other hand, for the total sediment yield, a good linear correlation between prediction and observation was found for the 5-m slope only ($R^2 = 0.96$). For all

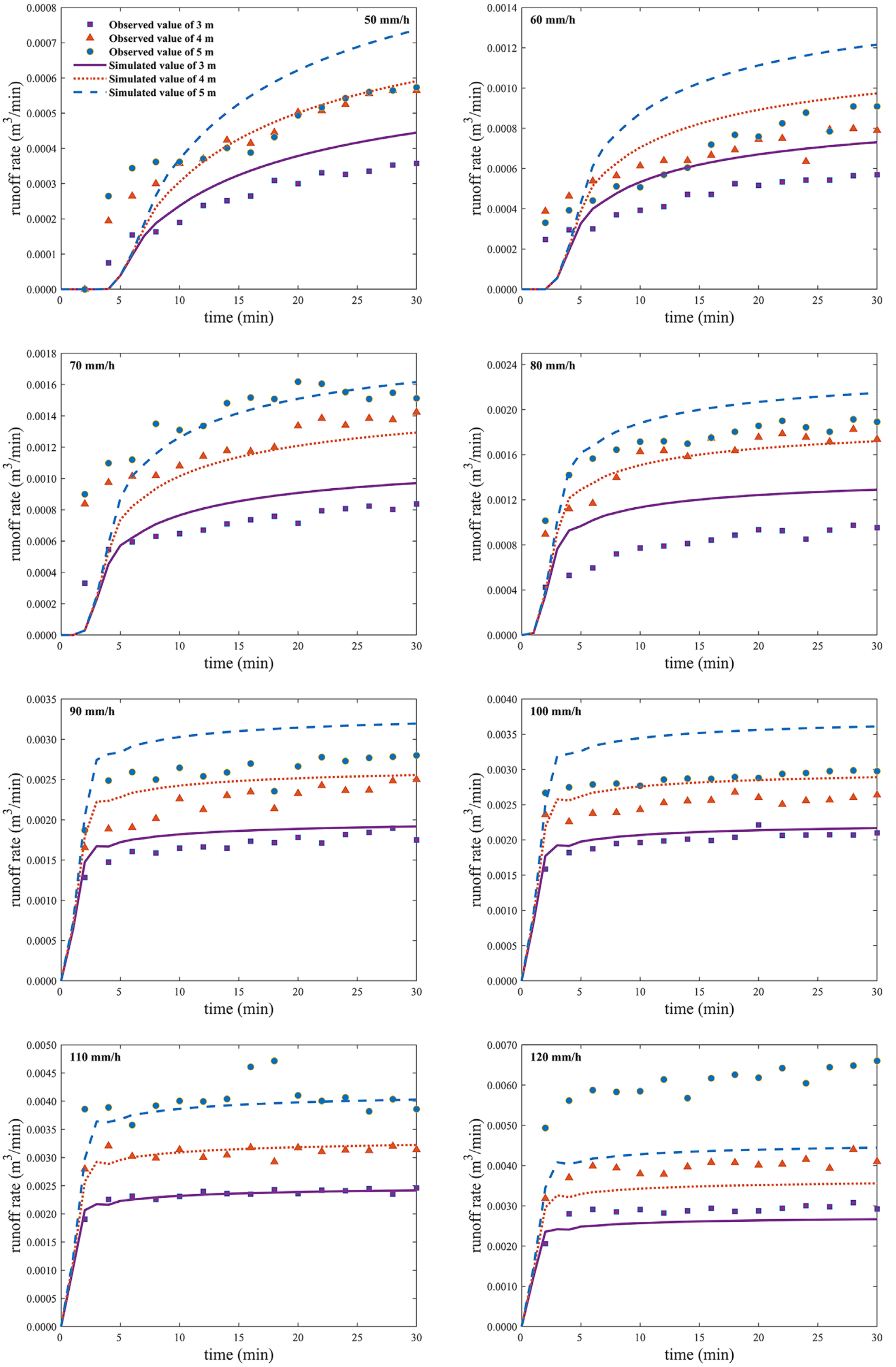


FIGURE 3 Simulated versus observed runoff rates over time.

slope lengths, the model NSE was 0.182. If the allowable error was set at 20% of the actual total sediment yield, the RE pass rate was only 37.5% with the same 20% tolerance.

Figure 6 compares the modeling and experimental results for rainfall intensities for all slope lengths (3, 4, and 5 m). It can be noticed that the difference between the predicted and observed total runoff is relatively high at 120 mm/h, while the average absolute error of the prediction against the experimental value for all three slope lengths is -0.002 m^3, and the standard error of average value is 0.014. Under a rainfall intensity of 50–110 mm/h, the absolute error of the simulated values fluctuated around zero, and the standard errors of the average values were less than 0.004 (Figure 7).

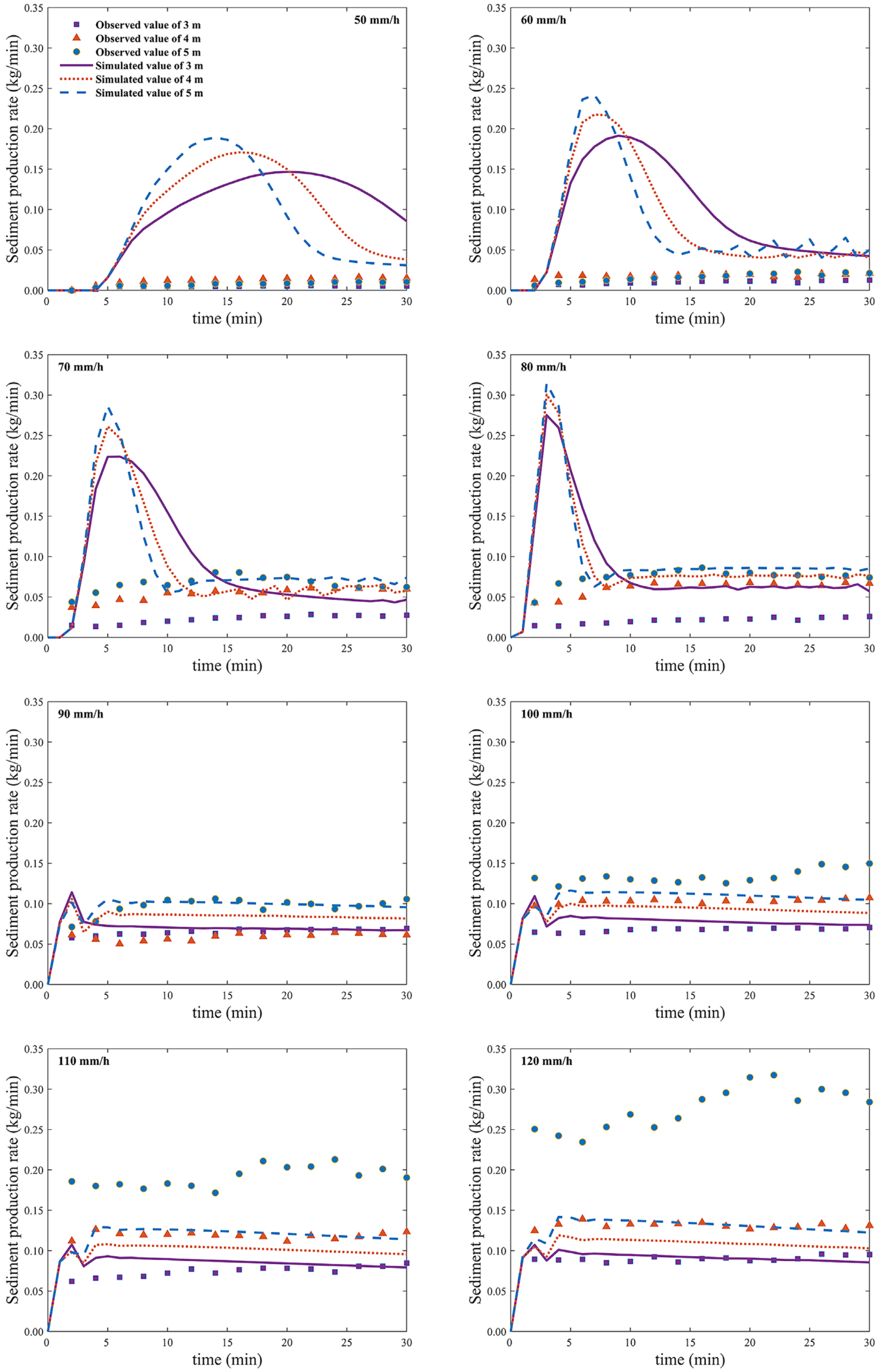


FIGURE 4 Comparison of simulated and observed values of sediment yield rate.

The predicted and experimental results showed a significant difference in total sediment yield (Figure 6). The experimental results showed a steady increase in sediment yield aligned with the increase in rainfall intensity, whereas the model simulation results showed much less variation at different rainfall intensities. When the intensity of the rainfall is less than 120 mm/h, the analysis indicates that EUROSEM can be used with reliability to predict the total runoff yield.

In general, the results thus far show that the EUROSEM can simulate the runoff rate variation process well and predict the total runoff

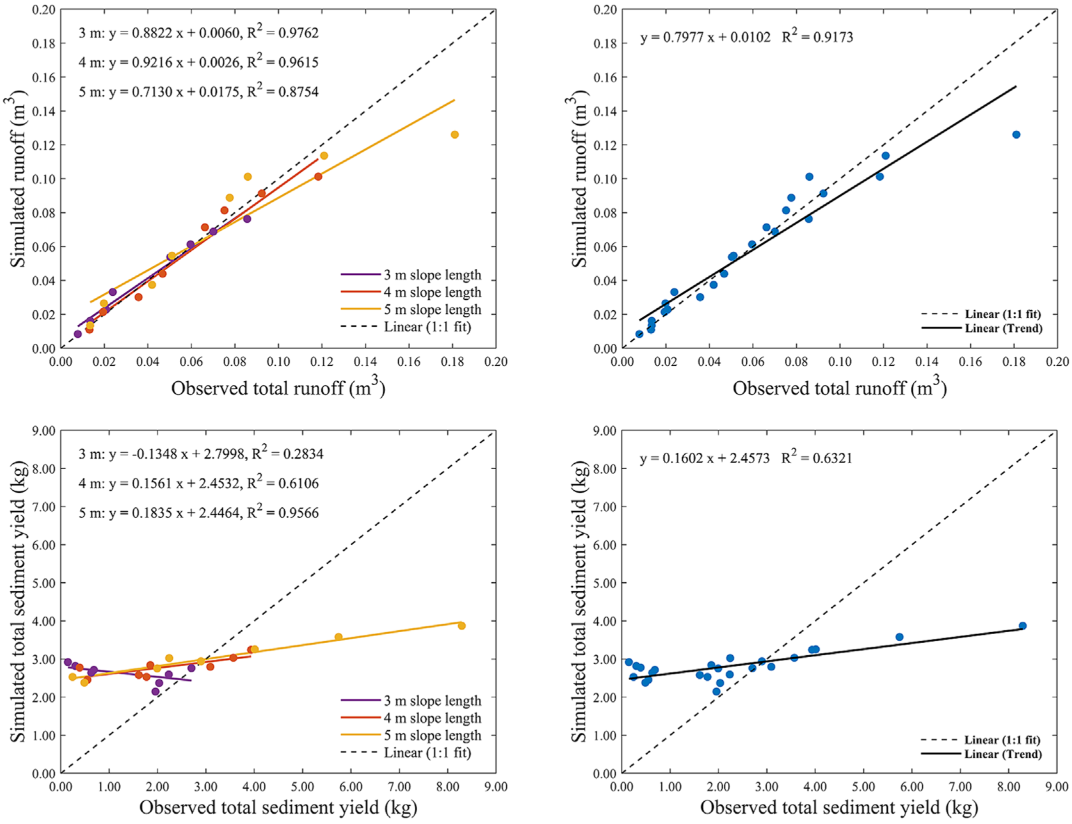


FIGURE 5 Relationship between simulated and observed values of total runoff and sediment yield under different slope lengths.

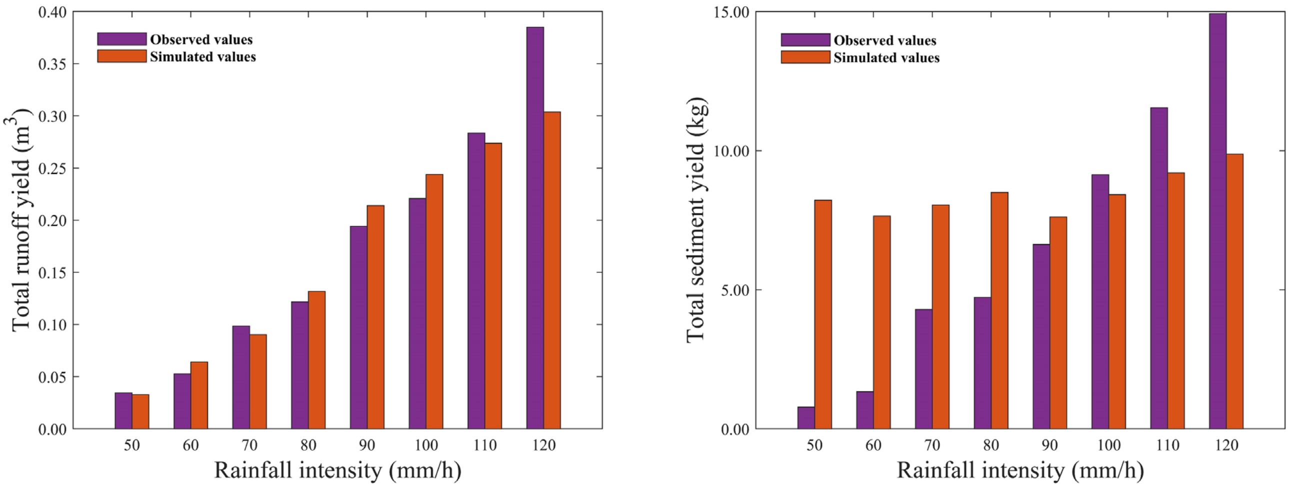


FIGURE 6 Varies of simulated and observed total runoff and sediment yield with rainfall intensities under test slope lengths.

for Loess Plateau soils under indoor test conditions, given a simulation NSE greater than 0.90. However, it only presented a good simulation for the variation in sediment yield rate under the scenarios of 90–120 mm/h rainfall intensities and 3- and 4-m slope lengths.

4 | DISCUSSION

The discussion section mainly analyses the reasons why the observed runoff and sediment yield data change with rainfall, slope length, and other conditions and discusses the reasons why the EUROSEM has poor simulation performance for sediment yield under some specific conditions.

4.1 | Runoff analysis

As shown in Figure 8, runoff increased with slope length and rainfall intensity, and the relationship between runoff and rainfall intensity under different slope lengths could be well described using the power function (R^2 > 0.97). Specifically, at a rainfall intensity of 60 mm/h for a slope length ranging from 3 to 5 m, the runoff increased by

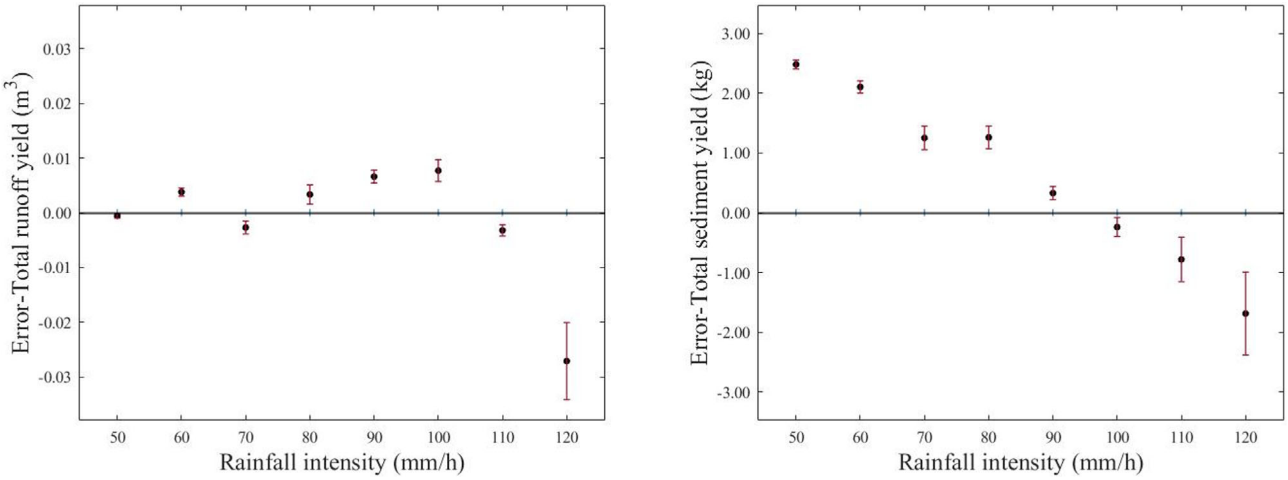
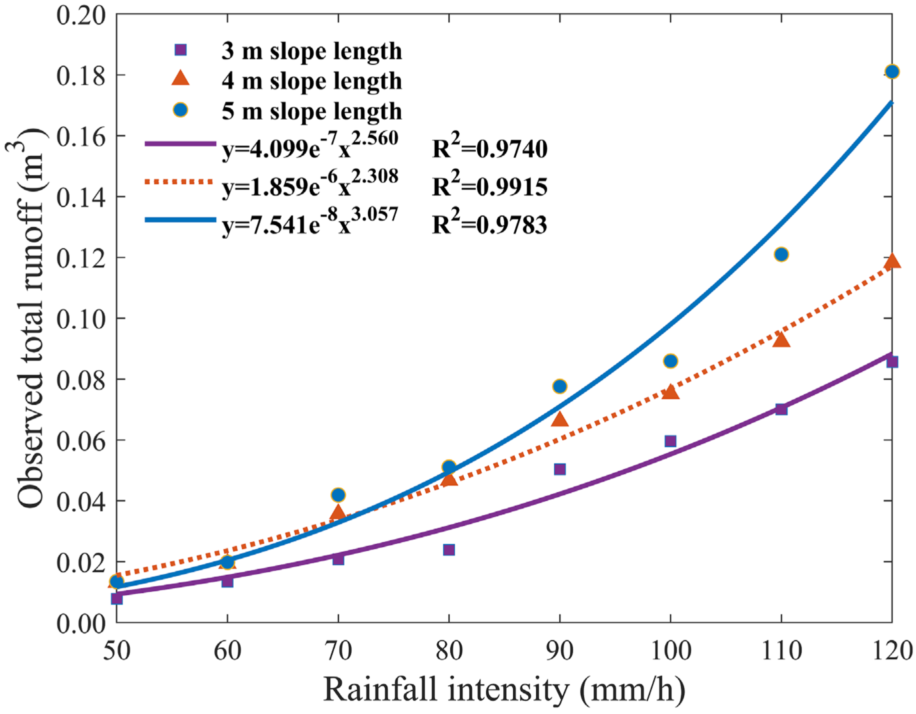


FIGURE 7 Absolute error of each rainfall intensity simulation. (note: the data used for absolute error of each rainfall intensity is the average value of the 3-m slope lengths, and the vertical line segment represents the standard error of the average value.)

FIGURE 8 Variation of runoff with slope length and rainfall intensity.



0.0063 m^3. For higher rainfall intensities of 90 and 120 mm/h, the runoff increments were 4.3272 and 15.1273 times those at 60 mm/h, respectively, indicating a positive correlation between the effects of slope length and rainfall intensity on runoff.

However, under a certain rainfall intensity, the runoff did not show a proportional trend with slope length. For instance, under 60 mm/h rainfall intensity, the runoff increments are 0.0059 m^3 and 0.0003 m^3 when the slope length changes from 3 to 4 m and 4 to 5 m, respectively; under 90 mm/h, the increments are 0.0158 and 0.0114 m^3; and under 120 mm/h, they are 0.0326 and 0.0627 m^3. These results indicate that the effect of slope length on runoff is strengthened at high rainfall intensities.

The observed runoff rates increased with the rainfall duration (Figure 3). The analysis of the experimental tests identified two major causes. First, it was observed that at the beginning of rainfall, the raindrops falling on the plot seeped rapidly, showing little surface runoff because the initial soil infiltration rate was greater than the rainfall intensity. Thereafter, with an increase in the slope soil moisture content, the infiltration rate decreased, and surface runoff started and steadily increased (Carey & Woo, 2000) (Figure 9). Second, in the initial 3 min of runoff, the slope surface and slope moisture content undergo a large transformation and change before reaching a relatively steady state when the infiltration and runoff vary less rapidly. In addition, as the water kinetic potential energy accumulated on the slope surface increased with rainfall intensity, the time to reach a steady infiltration state and the runoff to reach its peak value were shortened. This analysis agrees with the conclusions of Dunkerley (2012).

The observed increase in runoff with slope length and rainfall intensity might be attributed to two main reasons: (i) the increased slope surface area with the increase in slope length leads to an increase in the amount of water per unit time on the slope. Meanwhile, it was observed that rills with different scouring degrees appeared at the lower part of the slope (Figure 10), where the runoff gathered in too short a period of time, infiltrated downwards, and was discharged rapidly at the slope outlet, leading to an increase in total runoff. (ii) The splash erosion of topsoil increased with slope length and rainfall intensity (Figure 11). It changes the topsoil pore structure and the form of the surface crust (Tackett & Pearson, 1965) and therefore significantly reduces the soil infiltration rate (Fattah & Upadhyaya, 1996) and accordingly leading to an increase in slope runoff. In addition, the kinetic potential energy of raindrops affects the hardening of the soil crust on the slope surface (Morrison et al., 1985), and can result in a disproportionate increase in runoff yield, which is aligned with the increase in rainfall intensity and slope length.

4.2 | Sediment yield analysis

Slope length and rainfall intensity are two key factors that significantly affect sediment yield (Defersha & Melesse, 2012; Sun et al., 2019). Figure 12 illustrates that the observed sediment yield increased sharply with rainfall intensity, and the trend can be represented using a power function with a coefficient of determination greater than 0.90. Given the same increase in slope length, the greater the rainfall intensity, the greater the sediment increment. These results are in agreement with those reported by Mathier et al. (1989). For example, when the slope length increased from 3 to 5 m, the sediment yield increased by 0.1878 kg under a rainfall intensity of 60 mm/h. However, under rainfall intensities of 90 and 120 mm/h, the sediment yield increased by 0.9399 and 5.5872 kg, respectively, which were 5.0051 and 29.7508 times that under 60 mm/h.

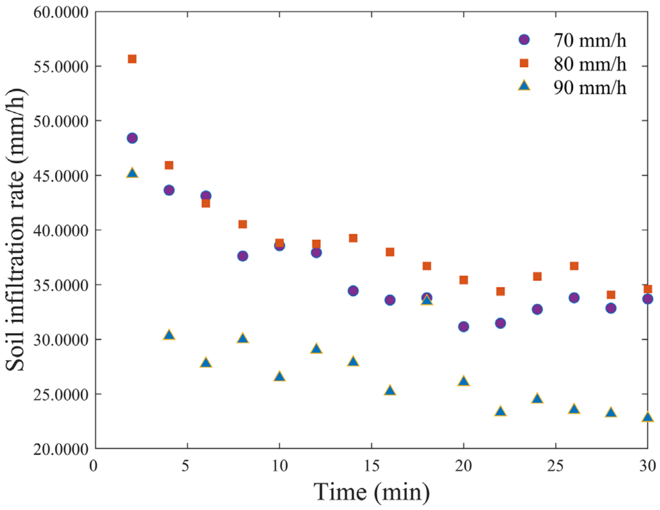


FIGURE 9 Soil infiltration rate following the onset of runoff under a slope length of 5 m.

At the start of a rainfall event, raindrops, with their kinetic energy, disperse and strip off loose soil particles from the slope surface (An et al., 2012). Although a thin layer of water may develop on the slope surface, a considerable number of soil particles could still be splashed off and woven with runoff downwards on the slope. In addition, the rapid increase in the runoff rate at the beginning of the runoff (Figure 3) adds to runoff erosion and further enhances the sediment yield (DiBiase & Whipple, 2011). As runoff flow builds up on the slope surface, the splash and proportion of raindrop-mobilized particles can decline; however, the proportion transported by the runoff flow increases (Moss & Green, 1983).

Following the initial abrupt increase in sediment yield, the growth of the runoff rate gradually slowed and became stable over time, as did the sediment yield rate. However, as the runoff builds up on the slope surface, a driving force exists for the momentum downstream. When the shear strength of the soil is exceeded, rills are created on the slope. Rill formation increases runoff turbulence, resulting in an abrupt increase in the sediment yield rate. This analysis is consistent with that reported by Berger et al. (2010). Moreover, the distribution of kinetic energy, which is constantly changing (Gut et al., 1990), causes the sediment yield rate to fluctuate within a certain time range determined by factors such as rainfall intensity and slope length (Deng et al., 2020).

The observed sediment yield increased sharply with rainfall intensity and slope length (Figure 5). When the slope length increases, runoff erosion and rill erosion increase because of an

FIGURE 10 Scouring of the lower part of the slope.

FIGURE 11 Observed splash erosion under different conditions. ((a) 3-m slope length and 60 mm/h rainfall intensity; (b) 3-m slope length and 100 mm/h rainfall intensity; (c) 5-m slope length and 60 mm/h rainfall intensity; (d) 5-m slope length and 100 mm/h rainfall intensity).

increase in the exposure of the slope surface to raindrops (Yair & Raz-Yassif, 2004). However, the overall gravitational potential energy of the runoff increased accordingly. When transformed into kinetic energy, it strengthens the runoff shear force and ultimately enhances scouring capability (Yang et al., 2022). In addition, the formation and development of rills on the plot directly affect sediment yield (Schiettecatte et al., 2008), resulting in a rapid increase in sediment yield (Rejman & Brodowski, 2005). This study demonstrated that in the range of rainfall intensity from 90 to 120 mm/h, slope length increased from 3 to 5 m; rill density increased by 0.2375 m/m^2 or 53.7%.

Table 2 indicates that there were significant positive correlations between runoff, sediment yield, and rainfall intensity at the 0.01 level, with correlation coefficients of 0.8864 and 0.8022. The correlation coefficients between runoff, sediment yield, and slope length were 0.3199 and 0.4166. A larger correlation is found between runoff and rainfall intensity than runoff and slope length when both factors are present. Particularly, the partial correlation analyses of rainfall intensity and slope length on runoff and sediment yield have shown that the correlation between runoff, sediment yield, and rainfall intensity remain highly significant (correlation coefficient 0.9356, 0.8802); meanwhile, there is significant positive correlation between runoff, sediment yield, and slope length at the 0.01 level, given that the correlation coefficients increase to 0.6914 and 0.6895, respectively. The results suggest that when both rainfall intensity and slope length jointly affect the runoff and sediment yield, they constrain each other,

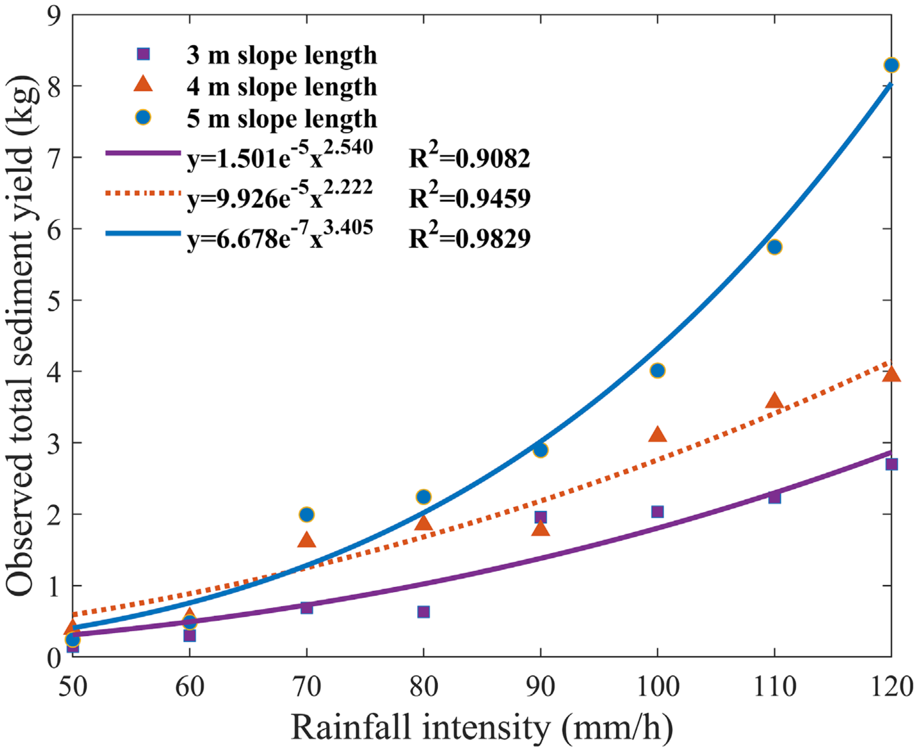


FIGURE 12 Variation of sediment yield with slope length and rainfall intensity.

TABLE 2 Correlation of runoff, sediment yield and rainfall intensity, and slope length.

		Slope length	Rainfall intensity
Simple correlation analysis	Runoff	0.3199	0.8864**
	Sediment yield	0.4116*	0.8022**
Partial correlation analysis	Runoff	0.6914**	0.9356**
	Sediment yield	0.6895**	0.8802**

**denotes $p < 0.01$.*denotes $p < 0.05$.

while the impact of slope length on runoff and sediment yield is largely covered up by rainfall intensity.

4.3 | Analysis of the performance of EUROSEM

Smets et al. (2011) improved the EUROSEM to address the constantly changing soil properties during runoff processes in a dynamic manner. However, because the development of the EUROSEM was based on soil experimental observation data from Europe (Morgan et al., 1998), the variation trends and ranges of the observed sediment yield in this study are inconsistent with the EUROSEM modeling results. In particular, in the rainfall intensity range of 50 to 80 mm/h, the EUROSEM had a much higher peak sediment yield rate at the initial stage of runoff than the observed value. This inaccuracy could be attributed to the EUROSEM-overestimated soil erosion by raindrop splashes at the initial stage. Furthermore, EUROSEM cannot effectively address erosion under saturated surface runoff (Morgan et al., 1998). Additionally, some key parameters, such as the number and morphology of rills, which were assumed to be constant by EUROSEM, are variable and constantly evolving during the actual runoff processes. It has also been noticed that when the rainfall intensity is greater than 100 mm/h, for the 5-m slope, EUROSEM underestimates the sediment yield rate and has poor predictions of runoff and sediment yield. The reason for this underperformance could be that the experimental slope's surface roughness is not accurately described by the EUROSEM's corresponding model (Smets et al., 2011).

In summary, EUROSEM could effectively predict runoff processes during single rainfall events and sediment yield processes during partial rainfall events in the study area. However, because this study is based on laboratory experiments, despite various measures taken to simulate the real conditions of the Loess Plateau as closely as possible, it cannot fully replicate the actual outdoor conditions. Therefore, inevitable differences existed between the indoor and outdoor erosion and sediment yield experiments. The data and results of this study can provide data support and a scientific basis for the conversion of indoor and outdoor runoff and sediment yield experimental data in the next step of research on Loess Plateau slopes, enabling the accurate application of indoor model experimental results to field soil erosion prediction and ultimately achieving the prediction of field soil erosion using EUROSEM. In the future, we hope to obtain more experimental data from on-site and in situ experiments to achieve this goal.

5 | CONCLUSIONS

When both rainfall intensity and slope length jointly affect the total runoff and sediment yield, there is a constraining relationship between them, and the influence of slope length on runoff and sediment is largely covered by rainfall intensity. The observed runoff process increased rapidly in the early start stage and then tended to stabilize as the rainfall duration increased. Comparable to the observed process was the runoff process that the EUROSEM simulated. When rainfall intensity was higher and the slope was longer, the observed sediment yield rate increased more quickly during the first runoff stage before varying around a certain value. Compared to the sediment yield process and yield, the model was more accurate in simulating the runoff process and total runoff. The qualified rate of the RE between simulated and observed values of the total runoff was 87.5%, and the NSE is up to 0.9003. When the rainfall intensity changed from 50 to 80 mm/h, the model could not accurately simulate the rapid increase in sediment in the early stage of sediment yield, and the simulation performance improved after the sediment yield process stabilized. When the rainfall intensity was 70–100 mm/h, the model simulated a rapid increase followed by a small decline in the sediment yield rate, which was similar to the observed values. However, the difference between the simulated and observed values was significant under rainfall intensities of 110 and 120 mm/h, and the longer the slope length, the greater the difference.

AUTHOR CONTRIBUTIONS

Chang Su: Methodology; software; writing—initial draft. **Yu Wang:** Writing-reviewing and grammar editing. **Xingtao Fu:** Conceptualization; investigation; writing—reviewing and editing. **Zhiyuan Wang:** Writing—reviewing and editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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