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RESEARCH ARTICLE

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Vegetation pattern and topography determine erosion characteristics in a semi-arid sandstone hillslope-gully system

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Abstract

The hillslope-gully system serves as the primary contributor to both runoff and sediment yield. The WEPP (Water Erosion Prediction Project) model is often applied to investigate erosion characteristics at hillslope scale, demonstrating a high level of accuracy in simulating water erosion. In this study, according to in situ field monitoring (2014–2020) at a Pisha sandstone hillslope on the Loess Plateau, China, a total of 50 rainfall events' data were used as climatic data to calibrate the soil parameters, and 11 different vegetation patterns and four slope gradients of hillslope-gully systems were installed as inputs for the management and slope data, respectively. In systems A, B, C and D, the hillslope gradients were defined as 5°, 8°, 10° and 12° and the gully gradients as 15°, 20°, 25° and 30°, respectively. The results showed that the steeper the slope, the more severe the erosion. However, there was a critical value for the effect of slope on runoff. When the slope exceeded 8° and the gully exceeded 20°, the runoff no longer increased further and even decreased. The reduction in runoff in hillslope-gully systems was in the following order (in mm): system D (3.4 ± 0.14) > system C (3.4 ± 0.14) > system B (3.39 ± 0.14) > system A (3.12 ± 0.13). Increasing vegetation cover could reduce erosion. Differences in runoff between vegetation patterns were not significant ($p > 0.05$) and ranged from 8% to 26%. However, there were significant differences in the sediment yield reduction benefits of different vegetation patterns ($p < 0.05$), ranging from 17% to 66%. It was observed that vegetation located in the lower slope produced a more pronounced effect in mitigating sediment when the degree of cover was the same. We conclude that implementing watershed management strategies based on the vegetation and topographic attributes of hillslope-gully systems within the Loess Plateau, especially on Pisha sandstone hillslopes, serves as the fundamental approach to achieving sustainable watershed management.

KEYWORDS

hillslope-gully system, slope gradient, sustainable watershed management, the Loess Plateau, vegetation coverage, WEPP model

1 | INTRODUCTION

Highlights

- Vegetation pattern and slope gradient condition runoff and sediment yield in hillslope-gully system.
- Runoff and sediment yield increase as vegetation is distributed at the bottom of hillslopes.
- As the slope becomes steeper, the runoff volume increases.
- Various vegetation patterns show sediment yield reduction benefits ranging from 17.1% to 66%.

Soil erosion is one of the most influencing processes affecting land degradation and defeating the quality in fragile ecosystems of arid and semi-arid areas (Li et al., 2021). The Loess Plateau, an area in northwest China, is one of the most severely eroded areas in the world (Li et al., 2023). In this region, it is well-known that soil erosion seriously affects local agricultural production and economic development (Yu et al., 2021). During the last decades, many authors confirmed losses of soil structure, reduction in soil fertility and agricultural yield, increases in geological hazard risks and disturbances of ecosystem services (Zhang et al., 2022). However, the environmental variability and large extension of this region mean that general control measures are impossible to be designed.

Due to many factors that affect water and soil loss related to climate change and human activities, only specific strategies can be applied, for example terraces, Grain for Green Project, and Gully Land Consolidation Project (Cao et al., 2023; Zhu, 2012). In recent years, with the design of a large number of conservation measures and the application of several vegetation restoration strategies, the environment the Loess Plateau has been significantly improved (Yuan et al., 2022). Extensive research has been conducted on the water and soil conservation functions pertaining to vegetation restoration on the Loess Plateau. The accurate planification of vegetation can decrease runoff erosion power and promote soil erosion resistance (Liang et al., 2020). The benefit of revegetation increases parallel to the coverage degree and tended to stabilize beyond 60% (Liu et al., 2020). However, high density and large area plantations can also have negative effects on soil moisture content in semi-arid and arid areas (Jia et al., 2017). In limited water availability regions, it is imperative to carefully determine the degree of vegetation coverage and strategically optimize its spatial distribution based on climate and topography (Deblauwe et al., 2008; Huang et al., 2016). This approach is crucial for promoting soil and water conservation, enhancing the ecological environment and fostering sustainable development.

Hillslope morphology is another crucial factor that affects runoff generation and soil detachment, such as slope gradient, length or position (Chen et al., 2021; Li, Jiang, et al., 2020). The effects of slope gradient on water and soil erosion have been evaluated by different methods (Ziadat & Taimeh, 2013). For example, research results with models have shown that the greater the slope gradient was, the earlier the runoff occurred and the greater the runoff amount produced (Liu & Singh, 2004). When the gradient reaches a threshold value, the runoff and soil loss tend to stabilize (Zhang, Hu, et al., 2018). In contrast, the presence of slope form exerts a substantial influence on soil erosion, which has been demonstrated under laboratory conditions (Mombini et al., 2021). Convex hillslopes typically consist of a hillslope with a relatively gentle gradient and a gully with a steeper gradient. The erosion mechanism and hydrological attributes of a convex slope exhibit notable distinctions when compared with those of a single slope (Shi et al., 2023). In recent years, researchers have come to recognize the interconnectedness of hillslopes and gullies in the hydrological processes of rainfall, runoff generation and sediment yield within a watershed (Fan et al., 2022; Poeppl et al., 2023). Consequently, studies focusing solely on either hillslope or gully features fail to capture the comprehensive erosion dynamics of the entire erosion system (Conti et al., 2019). The hillslope-gully system could be considered as a basic topographic unit of the Loess Plateau and plays an important role in soil and water conservation and ecological restoration (Yu et al., 2020). Previous studies have examined the characteristics of runoff and sediment yield in the context of hillslope-gully systems. In the Loess Plateau, Chen and Zhang (2022) explored the characteristics of sediment yield and hydrodynamic parameters in hillslope-gully systems on natural hillslopes and found that vegetation distribution had an obvious effect on the benefits of runoff power and sediment yield reduction. Scouring experiments using soil boxes with two different gradients showed that the sediment yield decreased with the increase in the degree of grass coverage (Li et al., 2009). Zhang, Li, et al. (2018) used a physical model of convex hillslope and simulated rainfall experiment to analyse the characteristics of runoff and sediment under five different grass strip patterns and came to similar conclusions.

Soil erosion research methods based on modelling must include field observations and measurements, or laboratory experiments to train the models (Borrelli et al., 2021). Precisely, soil erosion models are important tools for simulating and predicting soil erosion process and the main approaches to evaluate soil and water conservation measures and impact at larger scales. The Water Erosion Prediction Project (WEPP) is a continuous simulation erosion prediction model and widely used to simulate the erosion process at slope scale. The model depends on a large number of parameters involving climate, soil, management and topography factors (Flanagan et al., 2012). The applicability of the WEPP model in different study areas has been extensively researched. The model was calibrated and validated in Dal catchment to simulate sediment yield and concluded that the accuracy of the model is satisfactory (Kumar et al., 2021). In North China, the results of a study on terracing found that the model is a reliable tool for characterizing the changes in micro-topography and specific protective measures for soil and water conservation (Liu et al., 2013). On the Loess Plateau, the WEPP model was used to predict runoff and soil loss at various time scales and topographic conditions, and in most cases, the model accuracy was satisfactory (Zheng et al., 2020). These results indicate that the WEPP model can reproduce the trend and variations in runoff and soil loss among different conditions at hillslope scale in different study areas.

The Pisha stone area on the Loess Plateau is one of the most severely eroded and difficult to manage areas in the world (Zhu et al., 2023). The Pisha stone gully-hillslope systems are characterized by less rainfall volume, terrain fragmentation, lower vegetation coverage degree, and fragile ecological environment (Liang et al., 2019). The extreme severity of erosion and poor vegetation coverage are related to the mineral, chemical, lithologic, and particle size composition in this region (Xiao et al., 2018). Water erosion is the main erosion type in the area. The intensity of erosion is influenced by topographical conditions and vegetation measures (Chen et al., 2022). Nowadays, although many studies have simultaneously considered the effects of vegetation patterns and topographic conditions on soil erosion (Li & Pan, 2018), few studies have been conducted on Pisha stone slopes.

In this study, in order to assess the impact of topography and vegetation cover, we calibrated the WEPP model to create a total of 11 distinct vegetation patterns and four hillslope-gully systems. Additionally, we incorporated a long-term precipitation events dataset as input for our predictions. The main objectives of this study were to (1) analyse the effect of grass cover on soil erosion in hillslope-gully systems, (2) explore the response of runoff and soil erosion to vegetation patterns and slopes, and (3) detect the critical value of slopes in hillslope-gully systems. We assume that topography and vegetation pattern jointly affect the runoff and sediment yield of hillslope-gully system, with a threshold effects. Our study can provide a basis for the vegetation restoration and sustainable management of small watersheds in fragile regions.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area considered to perform this scenario analysis is located in the Getuodian watershed in the Junggar Banner, the Inner Mongolia Autonomous Region of China (40°18′40–40°23′00 N and 111°12′00–111°14′40 E) (Figure 1). The watershed has an area of about 7 km^2 and an elevation of 1183–1361 m a.s.l. and inclination range from 5° to 30°. The climate is mainly semi-arid continental, with an average annual precipitation of 400–600 mm. Most rainfall events are concentrated from July and September, accounting from 60% to 80% of the total annual precipitation. On average, the wind speed is 2.2 m/s, the annual evaporation is 2234.4 mm and annual temperature is 7.3°C (https://data.cma.cn/). The study area is characterized by interlaced hills and gullies with exposed bedrock and low vegetation cover, with a gully density of 7 km/km^2. The bedrock is extremely hard when it is dry but rapidly disintegrates when it is wet. The soil erosion modulus is 30,000–40,000 t/km^2·a in the area, representative of a typical soil-covered Pisha sandstone area. The dominant plant species are sea-buckthorn (*Hippophae rhamnoides*), alfalfa (*Medicago sativa*), apricot (*Prunus armeniaca*), and bunge needlegrass (*Stipa bungeana*).

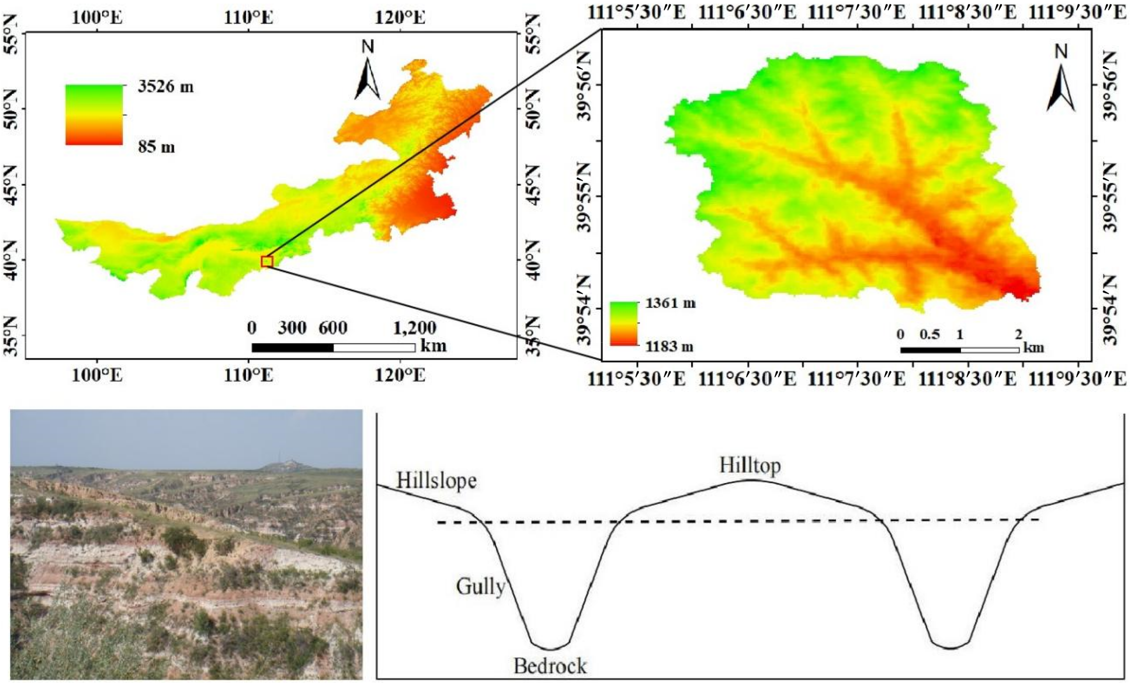


FIGURE 1 Localization and topography of the hillslope-gully system in the Loess hilly watershed.

2.2 | Hillslope-gully system model design

The results of the DEM (Digital Elevation Model)-based terrain analysis show that that most of the landscape slopes in the region are between 5° and 30°. Therefore, the four different hillslope-gully systems using the WEPP model were designed (Table 1). The slope gradient for the studied hillslopes were 5°, 8°, 10° and 12°, and the slope gradient for the gully walls were 15°, 20°, 25° and 30°. Su et al. (2022) suggested that the length ratio of the hillslope and gully was 1.6:1. In order to restore the topographic characteristics of the hillslope where the plots are located, the horizontal projection length of the hillslope and gully-side were 30 and 18 m, respectively.

According to previous investigation (Wang et al., 2022), native grassland can significantly reduce water erosion and maintain soil moisture; therefore, the experiment design involved five different degrees of grassland coverage (0, 25, 50, 70, and 100%) for the hillslope surface. Each degree of coverage manifests different spatial distribution patterns of grassland (Figure 2). On the other hand, the gully-side was not covered by grassland for each scenario.

2.3 | Input data for the WEPP model

The WEPP model is a widely used computer software for soil erosion prediction and describes most parameters related to water erosion. As shown in Figure 3, the WEPP model requires the establishment of four databases: climate, soil, inclination and management and can export runoff, soil loss, and sediment yield.

TABLE 1 Gradients of hillslopes with different degrees of grassland and gully-sides with bare surfaces.

	Hillslope gradients	Gully gradients
System A	5°	15°
System B	8°	20°
System C	10°	25°
System D	12°	30°

In this study, climate data were obtained from measured data from meteorological stations for the period 2014–2020. A tipping bucket rain gauge installed outside the observatory automatically measures precipitation every 2 min. The depth, duration, and intensity of each precipitation event were recorded. During the monitoring period, a total of 50 erosive rainfall events were monitored. Rainfall characteristic parameters were entered using the climate generator, CLIGEN (v4.2), provided by the WEPP model (Zhang, 2004). The slope and management information were based on the hillslope-gully system model and slope grassland coverage designed in Table 1 and Figure 2.

Soil samples were collected at four soil layers and three times repetition in fields plots and transported into the laboratory for determination of soil texture. The particle size was measured with the Malvern Mastersizer 3000

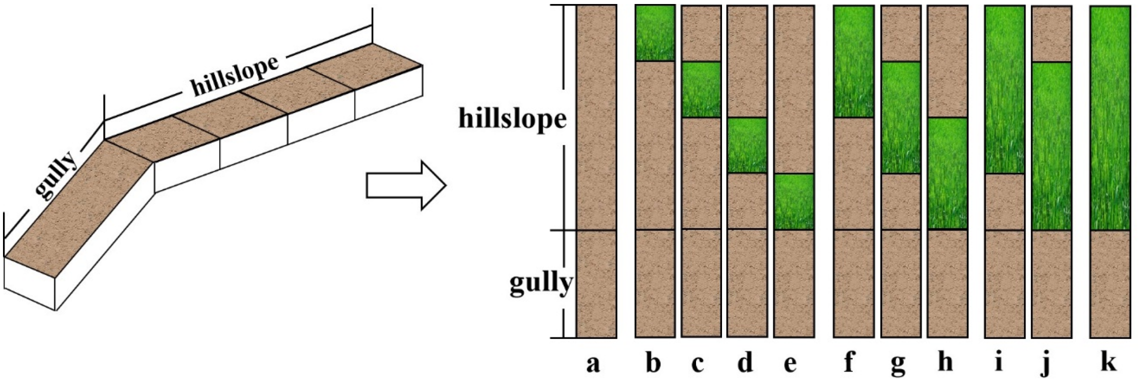
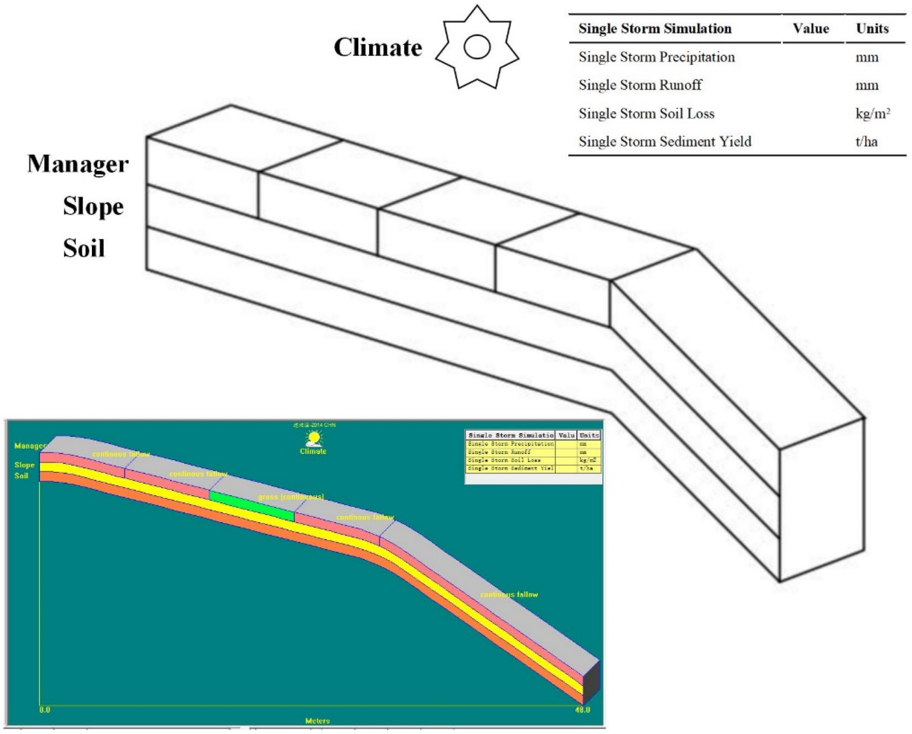


FIGURE 2 Degree of grassland coverage and spatial distribution patterns. The green areas indicate native grassland.



Single Storm Simulation	Value	Units
Single Storm Precipitation		mm
Single Storm Runoff		mm
Single Storm Soil Loss		kg/m²
Single Storm Sediment Yield		t/ha

FIGURE 3 Hillslope-gully system model designed and WEPP model input and output data.

laser particle size analyser. Soil organic matter was analysed by bichromate dilution heat colorimetric (Metson, 1957). The soil property parameters and formulas were included in Table 2. The formulas in WEPP model allows us to estimate albedo, initial saturated hydraulic and inter-rill erodibility as a base value. The final parameters such as rill erodibility, critical shear stress, and hydraulic conductivity were obtained by manual calibration. Soil parameters are calibrated by comparing observed and simulated data. The 50 erosive rainfall events were ranked in descending order of precipitation depth, and every two rainfall events were divided into groups (Flanagan et al., 2012). One randomly selected rainfall event in each group was used for calibration and the other for validation. According to the results of sensitivity analysis, the effective hydraulic conductivity mainly affects runoff and sediment yield, the rill erodibility and critical shear stress mainly affect sediment yield (Nearing et al., 1990). These could be seen by either the

TABLE 2 Soil properties required for the WEPP model.

Soil depth (cm)	Sand content (%)	Clay content (%)	Organic content (%)	Rock content (%)
0–10	43.4	10.8	0.59	0
10–20	40.7	12.3	0.41	0
20–40	40.3	12.8	0.29	0
40–60	39.9	12.8	0.23	0

increase or the decrease in hydraulic conductivity by ±25%, ±50% and ±75%, respectively. The adjusted hydraulic conductivity was substituted into the model. The predicted runoff values were recorded and compared with observed values. The final parameter was used the hydraulic conductivity value that was closest between the predicted and observed values. After completion of hydraulic conductivity, rill erodibility, and critical shear stress were calibrated by the same steps with sediment yield.

2.4 | Model performance evaluation and statistical analysis

The calculation formula of runoff yield and sediment yield reduction benefits was estimated as follows in Equations 1 and 2:

$$R_W = \frac{W_a - W_X}{W_a} \times 100\% \tag{1}$$

$$R_S = \frac{S_a - S_X}{S_a} \times 100\% \tag{2}$$

where R_W and R_S are the runoff and sediment yield reduction benefits under each scenario (%); W represents the runoff (mm); S means the sediment yield (t/ha); a and X corresponds the pattern a without vegetation and other scenarios.

The performance of WEPP model for estimating runoff and sediment yield in this study was assessed by applying the coefficient of determination (R^2), Nash–Sutcliffe model efficiency (E), root mean square error (RMSE) and coefficient of residual mass (CRM) and were described as follows in Equations 3, 4 and 5:

$$\mathrm{E} = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2} \tag{3}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{n}} \tag{4}$$

$$\mathrm{CRM} = \frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i} \tag{5}$$

where n is number of observations, O_i means observed values, P_i represents predicted values and $\overline{O}$ is mean of observed values.

Finally, the average and standard deviation were used to represent runoff and sediment yield data. One-way ANOVA was used to compare differences with different vegetation patterns and slope gradients and were statistically significant at $p < 0.05$. The statistical analyses were made with R software v.4.1.1.

3 | RESULTS

3.1 | Performance validation of model validity

The results showed that the model accuracy was highest when the soil parameters were as shown in Table 3.

Figure 4a shows that the R^2 for runoff during the calibration process reached 0.92, E was 0.9, RMSE was 2.3 and CRM was 0.07, respectively. Figure 4b indicates that the R^2, E, RMSE, CRM for sediment yield were 0.86, 0.85, 2.97, 0.2, respectively. During the validation process, the R^2 for runoff and sediment yield were 0.82 and 0.56, E were 0.77 and 0.54, RMSE obtained 3.06 and 5.14 and CRM were 0.09 and 0.4, respectively (Figure 5). The result indicates that the WEPP model could accurately predict the actual conditions of runoff and sediment yield on slopes ($R^2 > 0.5$, $E > 0.5$ and CRM close to 0).

TABLE 3 Results of soil parameter.

Soil parameter	Calibration results	Unit
Albedo	0.6	
Initial saturated hydraulic	57.06	%
Inter-rill erodibility	2,804,840	kg/(s·m^4)
Rill erodibility	0.06	s/m
Critical shear stress	1.365	Pa
Hydraulic conductivity	6.075	mm/h

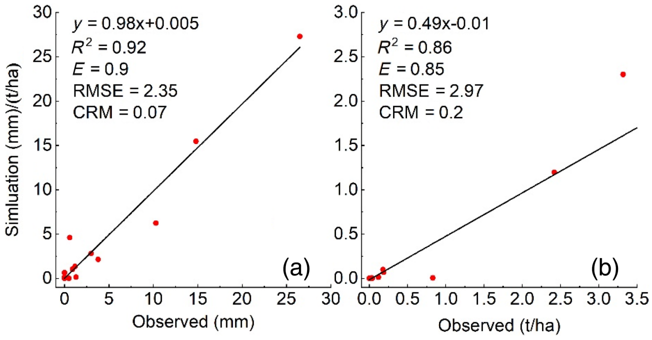


FIGURE 4 Relationships between observed and simulated runoff and sediment yield for WEPP model calibration by regression equations.

3.2 | Effects of different scenarios on runoff

Figure 6 shows the change in runoff for different coverage degrees and spatial distribution patterns. The general trend of runoff shows a decrease with the increase in grassland coverage. Pattern a (without grassland cover) obtained the highest runoff (3.94 ± 0.25 mm). When hillslopes registered the same grassland cover, runoff decreased as the distance between the vegetation and the top of the slope increased. For the scenarios with 25% grass cover, runoff in the four patterns decreased in the following sequence: b (3.63 ± 0.22 mm) > c (3.47 ± 0.21 mm) > d (3.27 ± 0.22 mm) > e (3.24 ± 0.22 mm). With the grass cover of 50%, the runoff was in order of f (3.37 ± 0.2 mm) > g (3.17 ± 0.19 mm) > h (3.06 ± 0.18 mm). The reduction of runoff in vegetation patterns was in the following order: a > b > c > f > d > e > g > i > h > j > k.

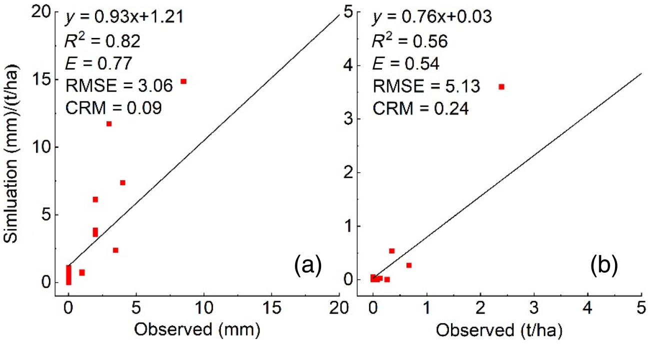


FIGURE 5 Relationships between observed and simulated runoff and sediment yield for WEPP model validation by regression equations.

The runoff differed among different gradients of hillslope-gully systems. The result demonstrated that runoff increases as gradients increases from 3.12 ± 0.13 mm to 3.4 ± 0.14 mm (Figure 7). The role of slope on runoff differed when grassland cover varied. The critical slope under different coverage degrees on hillslope differed. The critical slope for most patterns was system B. For pattern a, however, the critical slope was system C. Runoff remained constant for hillslopes more than 10° and gullies greater than 25°. In the patterns with greater grassland cover (patterns j and k), values of runoff were unchanged with increasing

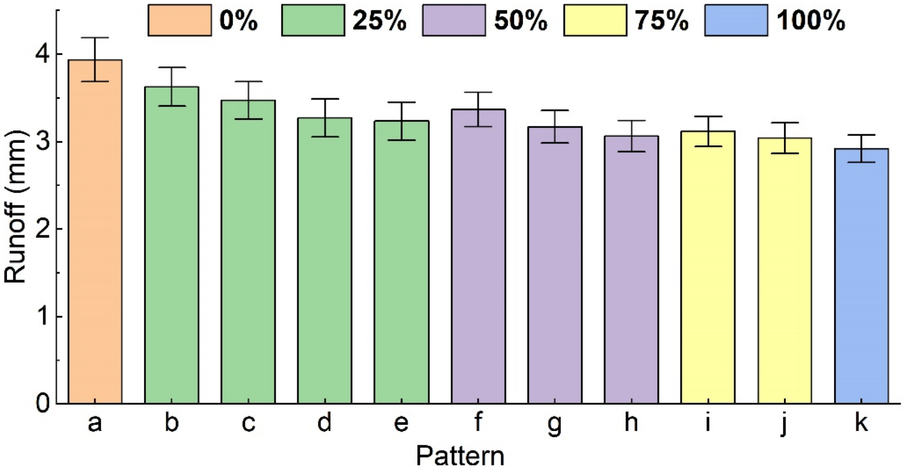


FIGURE 6 Runoff of different vegetation cover and distribution patterns.

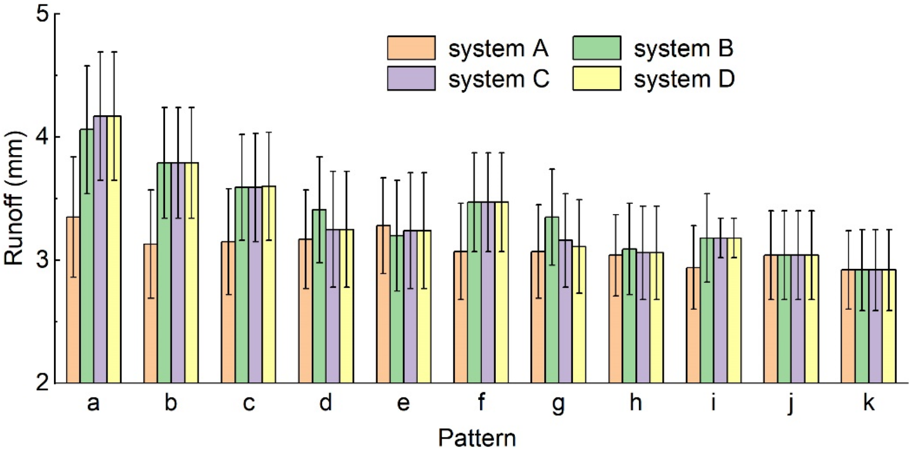


FIGURE 7 The effect of different vegetation patterns on critical slopes.

slope (3.04 ± 0.36 mm and 2.92 ± 0.33 mm). However, patterns d and g were exceptions. System B had the higher runoff of 6.92 ± 0.62 mm and 6.19 ± 0.59 mm. Instead, runoff decreased when the gradient exceeded a critical value (Figure 7).

3.3 | Effects of different scenarios on sediment yield and soil loss

Different coverage degrees affected sediment yield. The greater the grassland cover, the smaller the sediment yield. The sediment yield of non-grass cover scenario reached the highest (18.92 ± 1.0 t/ha). The lowest sediment yield scenario, where the hillslope was fully covered by grassland, obtained 6.45 ± 0.61 t/ha coming from the bare gully-side. For the scenarios with 25% grass cover, spatial distributions of grassland had a significant effect on the sediment yield. The patterns with vegetation at the top of the hillslope produced the highest sediment yield (15.68 ± 1.09 t/ha). The reduction of sediment yield in vegetation patterns was as follows: pattern b (15.68 ± 1.09 t/ha) > pattern c (14.25 ± 1.08 t/ha) > pattern d (13.29 ± 1.08 t/ha) > pattern e (12.09 ± 1.01 t/ha). For the scenarios with 50% grass cover, the sediment yield of pattern f, which the grassland was distributed at the top position of the hillslope, was significantly higher than in other scenarios (12.49 ± 0.91 t/ha). When the grassland is spread at the middle and low of the hillslope, these values showed slight variation (10.78 ± 0.88 t/ha and 9.01 ± 0.86 t/ha, respectively). In addition, sediment yield was influenced by a combination of vegetation patterns and slope gradient. Figure 8 shows that the higher the slope gradient, the greater the effect of degree of grassland coverage on the sediment yield.

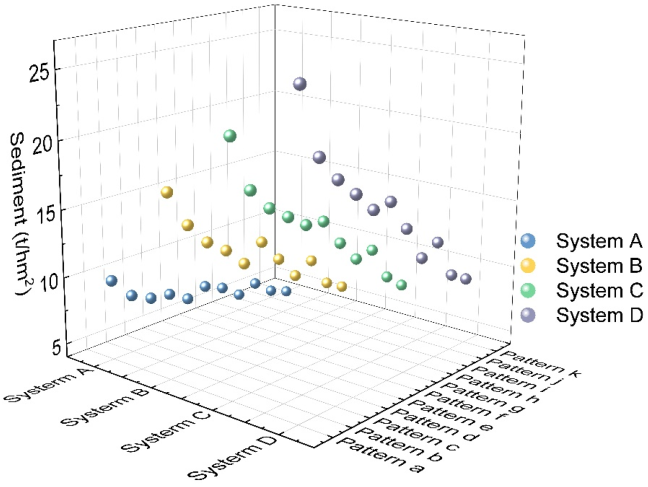


FIGURE 8 Effect on combination of vegetation patterns and slope gradient.

Figure 9 shows the effect of gradient on sediment yield and soil loss. The sediment yield increased with the increase in slope gradients. The system with the hillslope gradient of 5° and the gully gradient of 15° produced the lowest sediment. The value was significantly lower than other system with greater gradients. The decrease in sediment yield for different hillslope-gully systems was in the following order: D (16.73 ± 0.84 t/ha) > C (14.24 ± 0.73 t/ha) > B (11.17 ± 0.59 t/ha) > A (6.76 ± 0.4 t/ha). The gap between sediment yield and soil loss increased with slope gradient.

3.4 | Runoff and sediment yield reduction benefit

The runoff and sediment yield reduction benefits can be found in Figure 10. There were a few differences in the

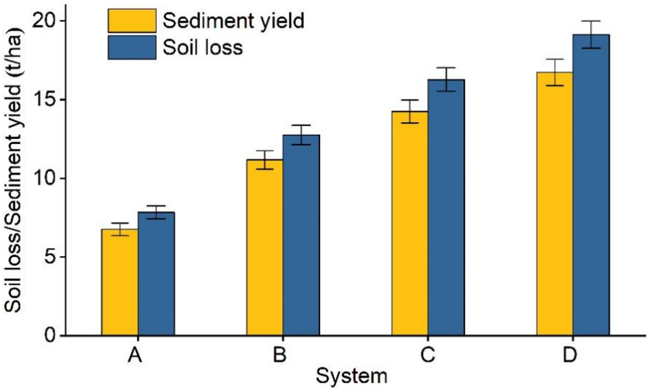


FIGURE 9 Influence of slope gradients and vegetation patterns on sediment yield and soil loss.

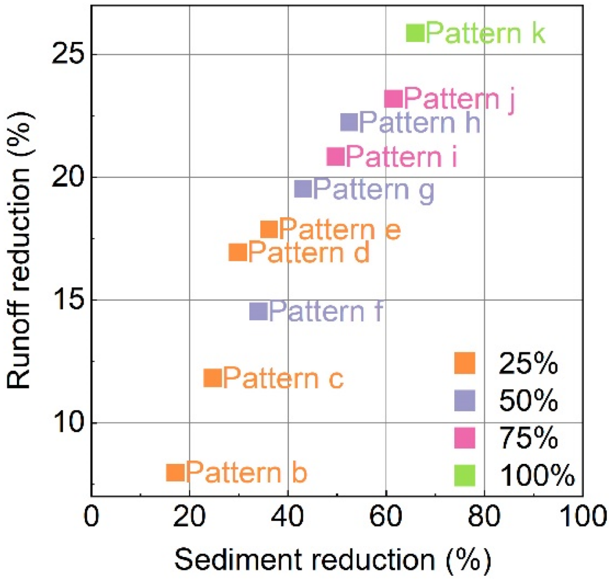


FIGURE 10 Relative positions of benefits of runoff and sediment reduction.

runoff reduction benefits of the different grassland patterns. The lowest runoff reduction benefit is found in pattern b (8%). The runoff reduction benefit of pattern k, full grassland cover, was only 26%.

Different vegetation patterns had significant differences in sediment yield reduction benefits. In the patterns with 25% grassland cover, the benefits ranged from 17.11% to 36.1%. Spatial distribution of grassland cover had the greatest impact in sediment yield reduction at 50% vegetation cover. The reduction of benefits per pattern was as follows: h (52.36%) > g (43.03%) > f (33.99%). Patterns j and k showed the greatest benefits, at 61.5% and 65.9% respectively.

4 | DISCUSSION

In the Loess Plateau, planned revegetation can be considered an effective measure to reduce surface runoff and sediment as in other fragile environments with similar characteristics. Previous studies pointed out different vegetation types significantly influence soil and water conservation benefits (Yu et al., 2022). Compared with shrublands and forestlands, grasslands have lower water requirements and help to retain soil moisture (Chen et al., 2010; Wang et al., 2019). Native grass species are adapted to the local arid environment and saline soil. Therefore, considering the balance between water storge and soil conservation, native grassland was used as a research object. Grasslands are widely used to reduce soil erosion in Loess Plateau (De Baets et al., 2007; Wei et al., 2007). Although increasing the degree of vegetation coverage is a helpful tool to reduce soil and water loss, excessive vegetation planting can exacerbate water deficits and cause more serious environmental problems in water-limited ecosystems. The effects of vegetation on reducing soil loss remain stable when the coverage rate reaches a threshold value. Liu et al. (2020) reported that vegetation cover showed low efficiencies in soil and water conservation when the coverage rate was lower than 40%. The runoff and sediment reduction benefit tended to be stable when the coverage rate was more than 70% in the Loess Plateau (Zhao et al., 2014).

In our study, five different degrees of coverage and 11 patterns were tested (Figure 2), and the results showed that the greater the degree of coverage, the lower the runoff and sediment yield. However, it is worth noting that an exception exists whereby the soil erosion observed in pattern i, characterized by a 75% coverage, is more severe compared with pattern h, which exhibits a 50% coverage. Grassland in pattern h is distributed at bottom of hillslope and planted at the top of the slope in pattern i. This outcome underscores the significance of considering the spatial distribution of vegetation as an influential factor in soil erosion (Liu et al., 2018). The same conclusion was found for Liu et al. (2013).

In this study, the sediment yield and soil loss varied significantly between vegetation patterns (Figure 8). In general, the sediment yield was lowest when vegetation was established at bottom of the hillslope. Spatial variations in vegetation cover result in spatial variations in soil erosion. In particular, the scenarios with 50% grassland cover showed the largest difference in sediment yield reduction benefits between vegetation patterns (Figure 10). Grasslands reduce sediment yield mainly through a combination of above ground and below ground components. The above ground component of grassland can decrease the hydrological connectivity of hillslope-gully systems and effectively intercept water and soil from upslope. The sediment transport and detachment of gully parts in the hillslope-gully system are significantly influenced by the inflow of runoff from the upper hillslope and the concentration of sediment inflow (Zhu et al., 2021). The sediment will be alleviated greatly if the runoff from upper hillslopes is intercepted by grassland. The role of the root component is mainly in improving the soil structure, such as reducing soil shear stress and increasing the erosion resistance. The reduction in shear stress varied widely across vegetation patterns. At the slope scale, shear stress increases and then decreases as the distance between the grassland and the top of the slope increases.

Slope gradient also played a key role in sediment yield (Jourgholami et al., 2020; Wu et al., 2018). Previous studies found that slope has a considerable impact on erosion (Koulouri & Giourga, 2007). Our results indicated that sediment yield increased significantly with increasing slope. The main erosion types on hillslopes include splash erosion, inter-rill and rill erosion. However, gravitational erosion and ephemeral gully erosion induced by precipitation and runoff is the dominant in gully (Qin et al., 2019). Increase in slopes can lead to soil particles being separated more easily, which will affect soil stability and induce landslide or collapse. The phenomenon of increased slopes results in a heightened propensity for soil particles to undergo separation, thereby exerting an influence on the stability of the soil and potentially instigating occurrences of landslides or collapses. As the slope escalates, the rate at which sediment yield augments experiences a decline (Figure 9). This phenomenon can be attributed to the impact of slope on sediment concentration. The effect of different slope gradients on soil loss is similar to sediment yield, with the greater the gradient, the higher the soil loss. When the surface slope is gentle, the soil loss increases rapidly with increasing slope. As the slope increases, the rate of increase in soil loss decreases.

Our findings indicate that an increase in slope gradient is positively correlated with an augmented runoff yield. The presence of steeper gullies results in reduced rain infiltration durations, thereby amplifying both runoff volume and dynamic energy. For most vegetation patterns, when the hillslope gradients increased from 8° to 12°, runoff remained almost constant, increasing only from 3.39 ± 0.14 to 3.4 ± 0.14 mm. The result indicated that the system B, with a hillslope gradient of 8° and gully gradient of 20°, was close to the critical slope. The results show that when the slope was less than in system B, the runoff increased rapidly with increasing slope. However, when the slope exceeded that in system B, the runoff no longer increased with increasing slope., In the patterns d and g, runoff yield decreased with increasing slope gradient when the hillslopes had gradients over 8° and gullies had gradients over 20°. Therefore, it is inferred that system B is near the critical slope in this study area. It is probably because the rain bearing area decreased with increasing slope gradient (Shen et al., 2016). When the slope exceeds the threshold, most of the rainfall falls to the bottom without passing through the convex hillslope. Zhao et al. (2015) found that sediment yield increased significantly as slope gradients increased from 5° to 15°, but in contrast, there was no difference between sediment yield on 15° slope and 25° slope. Therefore, moderate slope (15°) should be closer to the threshold. The critical slope depended on rainfall characteristics, soil bulk density, soil surface roughness, and runoff length (Liu et al., 2001). Li, Zhao, et al. (2020) analysed the interaction between surface roughness and slope and revealed the existence of a critical slope gradient that effected the interaction on soil erosion. If the gradients were less than the threshold, an increase in surface roughness would decrease soil erosion. Otherwise, the soil surface roughness would be ineffective for controlling soil erosion. Grassland can increase infiltration and soil surface roughness through the root system, litter layer, and canopy (Mongil-Manso et al., 2021). In addition, the increased slope promotes rill development (Fang et al., 2015). Rills became denser with increasing slope, which increased sediment concentrations and decreased the cumulative runoff. The form of slope erosion is gradually changing from denudation to accumulation. Thus, increased slope affects runoff in two major ways: (1) it leads to lower infiltration rates and higher runoff depth, and (2) it results in less rain bearing area on slopes and less runoff. The trend for runoff to increase with slope is weaker under the combined effect of both influences (He et al., 2012). On the contrary, the increase in slope will affect runoff parameters such as runoff velocity, which in turn increases runoff erosivity.

Most studies conclude that vegetation coverage degree and different spatial distributions exert different effects on runoff reduction (Zhu et al., 2021). However, there are a few studies that stated that different vegetation locations have no effect on runoff reduction (Ding & Li, 2016). Actually, in our study, there was a little difference in terms of runoff reduction benefit of different vegetation patterns. This may be associated with characterization of grasslands that have shorter canopies and less litter, resulting in grasslands being less able to intercept rainfall and reduce runoff (Zhou et al., 2019). In contrast to prior research, our study reveals significantly higher gully gradients. The presence of steeper gullies diminishes the effect of vegetation cover. Although vegetation cover does not directly reduce the amount of runoff, it can alter soil hydrologic conditions (reducing soil moisture), which leads to a decrease in the contribution of slope to water and soil erosion. Therefore, runoff trends with slope are different when the vegetation pattern is different.

In addition, it is interesting to note that under extreme rainfall conditions, the vegetation pattern had no effect on either runoff or sediment yield. On the one hand, it may be attributed to the internal qualities of the Pisha sandstone and environment factors of the area that extreme rainfall can lead to geological hazards such as slope collapse. It shows that a single grass cover cannot effectively respond to the effects of extreme rainfall (Shao et al., 2016). In arid and semi-arid regions, the hazards caused by extreme precipitation are more severe. It is because the ecosystems in this region are more fragile and more responsive to extreme climate change (Zhang et al., 2017). Extreme rainfall is susceptible to disasters such as landslides, floods, and mudslides, as well as causing changes in hydrological elements directly related to water resource (Bhardwaj et al., 2019). Single grass cover has poor or even negative soil and water conservation benefits in the presence of extreme climatic events, and the combination of multiple soil and water conservation measures has a runoff and sediment yield reduction benefit of 80%. Therefore, subsequent studies should consider the effects of other land use types such as shrubland and forestland. Moreover, because of the special characteristics of Pisha sandstones and the unique climatic features of the region, our results can only be applied to similar study areas.

A marginal discrepancy might exist between the outcomes of the model simulation and the observed data. However, it continues to effectively demonstrate the positive impact of grassland coverage and topographic conditions on soil erosion within a hillslope-gully system. Vegetation and topography conditions are key factors influencing runoff and sediment in Pisha stone area. In the unique topographical conditions of the Loess Plateau region, the effect of hillslope-gully systems on soil erosion process is complex.

This study shows the soil and water conservation role of natural grassland in hillslope-gully system.

5 | CONCLUSIONS

A total of five degrees of grassland coverage, 11 patterns of grassland and four hillslope-gully systems were formulated and inputted into the WEPP model. Our findings indicate that an increase in vegetation cover leads to a decrease in runoff yield, albeit the effect is minimal. Sediment yield and soil loss were significantly reduced by increasing coverage rate. The lowest runoff and sediment yield were found in the pattern where vegetation was planted in the downslope position. The slope gradients significantly affect soil erosion. Critical slopes exist for the effect of slope on runoff (system B). The greater the gradient, the greater the runoff when the slope is less than the critical slope. For systems with slopes exceeding the critical slope, runoff remains the same or even decreases. When slopes are gentle, soil loss and sediment yield increase rapidly with increasing slope. At larger slopes, the rate of increase slows down. The effect of slope gradients on erosion decreases as vegetation coverage degree increases. Under topographic conditions with a slope gradient of 8°and a gully gradient of 20°, a vegetation cover of 25% spread over the bottom of the hillslope would be a more appropriate revegetation strategy for the study area. This study provides theoretical support for the development of suitable vegetation restoration measures for different topographic conditions in the Pisha sandstone area of the Loess Plateau.

AUTHOR CONTRIBUTIONS

Yang Yu: Conceptualization; investigation; methodology; validation; software; formal analysis; supervision; funding acquisition; writing – review and editing; writing – original draft; visualization. **Ruipeng Zhu:** Data curation; formal analysis; writing – original draft; visualization. **Dianjun Liu:** Methodology; data curation. **Jingxue Wang:** Methodology; data curation; supervision. **Zhiqiang Gao:** Methodology; data curation. **Jing Liu:** Methodology; data curation. **Francisco Serrano-Bernardo:** Writing – review and editing. **Jesús Rodrigo-Comino:** Writing – review and editing; visualization.

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DATA AVAILABILITY STATEMENT

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

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