

Runoff and Sediment Yield Characteristics of Individual Rainfall Events under Different Vegetation Restoration Patterns in the Longzhong Loess Plateau Hilly and Gully Region (Postprint)

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Abstract

Based on observation data from 2015–2017 at the Tangyu River runoff plot in Qingshui County, Gansu Province, this study investigates the characteristics of hillslope infiltration, runoff and sediment yield during individual rainfall events under different vegetation restoration patterns. The results show that: Under different vegetation restoration patterns, soil infiltration exhibits a quadratic functional relationship with rainfall intensity, and there exists a critical rainfall intensity at which infiltration reaches its maximum value. The relationship between infiltration rate and rainfall duration can be expressed by a power function, conforming to the Kostiakov infiltration model. Under different vegetation restoration patterns, the runoff yield rate ranges between 0.0033–0.0036 mm · min⁻¹, with a flow reduction rate of 54%–58% relative to bare land. The relationship between runoff yield rate and rainfall intensity follows a quadratic function ($R^2 > 0.88$), with rainfall intensity being the primary influencing factor of runoff yield rate. The average sediment concentration in runoff follows the order: tree-shrub mixed area (3.13 g · L⁻¹) > shrubland (2.95 g · L⁻¹) > forestland (2.79 g · L⁻¹) > grassland (2.58 g · L⁻¹), and sediment concentration exhibits a linear increasing functional relationship with rainfall intensity. Sediment yield from bare land is significantly higher than that from vegetated plots ($P < 0.05$), being 43–57 times greater; the sediment reduction rate in vegetated plots ranges between 93%–94%, indicating that sediment reduction benefits exceed flow reduction benefits. Soil loss from vegetated slopes exhibits a linear increasing functional relationship with rainfall erosivity; there exists a highly significant positive correlation between runoff yield rate and erosion-sediment yield rate ($P < 0.01$), which can be expressed by a quadratic function. The findings of this study can provide a theoretical basis for the optimal allocation

of soil and water conservation measures in the hilly and gully regions of the Loess Plateau.

Full Text

Characteristics of Slope Runoff and Sediment Yield Under Individual Rainfall Events for Different Vegetation Restoration Patterns in the Hilly and Gully Loess Region of Central Gansu

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Abstract

Based on three years of observational data (2015–2017) from the Tangyuhe runoff plot in Qingshui County, Gansu Province, this study investigated the characteristics of slope infiltration, runoff, and sediment yield under individual rainfall events across different vegetation restoration patterns. The results demonstrate that soil infiltration amount exhibits a quadratic relationship with rainfall intensity, with a critical rainfall intensity at which infiltration reaches its maximum. The relationship between infiltration rate and rainfall duration can be expressed by a power function, consistent with the Kostikov infiltration model. Runoff rates under different vegetation restoration patterns ranged from $0.0033 \text{ mm} \cdot \text{min}^{-1}$ to $0.0036 \text{ mm} \cdot \text{min}^{-1}$, achieving runoff reduction rates of 54%–58% compared with bare land. Runoff rate and rainfall intensity followed a quadratic relationship ($R^2 > 0.7$), indicating that rainfall intensity is the primary influencing factor. Average sediment concentration in runoff ranked as follows: arbor-shrub mixed area ($3.13 \text{ g} \cdot \text{L}^{-1}$) > shrub forest ($2.95 \text{ g} \cdot \text{L}^{-1}$) > arbor forest ($2.79 \text{ g} \cdot \text{L}^{-1}$) > grassland ($2.58 \text{ g} \cdot \text{L}^{-1}$). Sediment concentration showed a linear increasing relationship with rainfall intensity. Sediment yield from bare land was significantly higher than from vegetated plots ($P < 0.05$), reaching $2.558 \text{ t} \cdot \text{hm}^{-2}$ —43–57 times that of vegetated plots. Sediment reduction rates for vegetated plots ranged from 93% to 94%, demonstrating greater sediment reduction benefits than runoff reduction benefits. Soil loss from vegetated slopes exhibited a linear increasing relationship with rainfall erosivity, while runoff rate and sediment yield rate showed an extremely significant positive correlation ($P < 0.01$), which can be expressed by a quadratic function. These findings provide a theoretical basis for optimizing soil and water conservation configurations in the hilly and gully regions of the Loess Plateau.

Keywords: hilly and gully loess region; runoff plot; vegetation restoration

pattern; runoff and sediment yield

The hilly and gully region of central Gansu in the Loess Plateau represents one of the most severely eroded areas, characterized by extreme ecological vulnerability and harsh natural conditions. This region is also among the driest areas in Gansu Province and across China, resulting in unstable and low agricultural productivity that has created a nationally recognized concentrated poverty zone. Consequently, vegetation restoration and ecological reconstruction are fundamental requirements for achieving sustainable regional development. To combat soil erosion and improve ecological conditions, the area has implemented comprehensive small watershed management programs since the 1980s, including ecological restoration projects such as the Grain for Green initiative.

Rainfall serves as the driving force behind soil erosion, with rainfall intensity, amount, and duration representing key characteristic factors that influence slope erosion. In the Loess Plateau hilly and gully region, where vegetation cover is relatively low, runoff and sediment yield show positive correlations with rainfall intensity, making rainfall intensity the primary factor controlling erosion. Vegetation redistributes rainfall through canopy interception, reducing effective rainfall reaching the ground surface and decreasing the erosive energy of runoff. Plant roots improve soil properties, enhance infiltration capacity, and increase soil resistance to erosion through their complex network structures. Near-surface vegetation cover is a sensitive factor controlling and accelerating soil erosion. Previous studies have consistently demonstrated that grassland, shrubland, and forest vegetation provide significantly better soil and water conservation benefits than sloping cropland.

Common plant species in the Loess Plateau hilly and gully region include *Hippophae rhamnoides* (sea buckthorn), *Caragana korshinskii* (peashrub), *Robinia pseudoacacia* (black locust), and *Pinus tabulaeformis* (Chinese pine). While numerous studies have investigated the soil and water conservation functions of these vegetation types, research on specific combinations such as clover, willow, and purple-leaf plum under different restoration patterns remains limited. The Tanguye runoff plot monitoring station, established in 2015 as part of China's national soil and water conservation monitoring network, provides an opportunity to address this research gap. This study utilizes three years of rainfall and sediment data from the Tanguye runoff plots to compare runoff and sediment yield characteristics under individual rainfall events across different vegetation types and restoration patterns, aiming to identify optimal vegetation configurations for soil and water conservation in the Loess Plateau hilly and gully region.

1. Study Area Overview

The Tanguye runoff plots are located in Nuanwan Village, Yongqing Town, Qingshui County, Gansu Province (105°15'42" E, 34°42'50" N), approximately 3

km east of Qingshui County seat. Situated within the Tangyuhe River basin, a secondary tributary of the Wei River, the site represents one of 34 newly established runoff plots in Gansu Province in 2015. The watershed features cinnamon soil, loess soil, and red soil with a clay loam texture. Dominant vegetation includes *Robinia pseudoacacia*, *Pinus massoniana*, poplar, *Hippophae rhamnoides*, and Artemisia species. The region has an annual sunshine duration of 2,076.9 hours, average annual temperature of 9.3°C, \$10°C accumulated temperature of 2,894°C, frost-free period of 180 days, and annual precipitation of 584 mm.

Five runoff observation plots were established, each measuring 5 m × 20 m (horizontal projection) with a 20° slope. The plots represent different vegetation restoration patterns: bare land, grassland (clover), arbor forest (purple-leaf plum), shrub forest (willow), and arbor-shrub mixed area (willow and purple-leaf plum). Specific plot parameters are detailed in .

2. Materials and Methods

Rainfall Observation: A tipping-bucket digital rain gauge recorded rainfall processes at 5-minute intervals, enabling calculation of total rainfall amount and rainfall intensity for individual events.

Runoff and Sediment Measurement: After runoff generation, water depth in each plot's collection tank was measured using a staff gauge. Total runoff volume was calculated based on tank bottom area and water depth. Sediment concentration was determined using the specific gravity bottle method: the sediment-water mixture was thoroughly stirred, and 500 mL samples were collected from different tank areas, filtered, dried, and weighed to obtain average sediment concentration.

Vegetation Coverage Measurement: Vegetation coverage was measured every 15 days using direct visual estimation.

The monitoring period spanned 2015–2017, during which 34 rainfall events generated runoff (defined as effective rainfall events). Following meteorological classification, these events were categorized as light rain (\$10mm, 3events), moderaterain(10–25mm, 13events), andheavyrain(>25mm, 18events).Rainfallamountrangedfrom5.2mmto68.4mm, withaveragerainfallintensityof10.1mm·h⁻¹ and duration of 0.5–46.1 hours. Moderate and heavy rains represent the primary runoff-generating rainfall types in the Loess Plateau hilly and gully region, consistent with previous findings.

Calculation Methods: Since rainfall duration was relatively short and intensity relatively low, canopy interception, soil evaporation, and depression storage could be considered negligible. Infiltration amount was calculated as:

$$R_i = R - R_u$$

where R_i is infiltration amount (mm), R is rainfall amount (mm), and R_u is runoff depth (mm).

Runoff reduction rate for each vegetation plot was calculated as:

$$\text{Runoff reduction rate} = \frac{\text{Runoff rate of bare plot} - \text{Runoff rate of vegetated plot}}{\text{Runoff rate of bare plot}} \times 100\%$$

Sediment reduction rate was calculated as:

$$\text{Sediment reduction rate} = \frac{\text{Soil loss of bare plot} - \text{Soil loss of vegetated plot}}{\text{Soil loss of bare plot}} \times 100\%$$

Rainfall erosivity was calculated using the standard formula:

$$Re = E \times I_{30}$$

where E represents total rainfall kinetic energy and I_{30} represents maximum 30-minute rainfall intensity.

Data processing was performed using Excel 2016 and SPSS 20.0 software packages.

3. Results and Analysis

3.1 Rainfall Infiltration Characteristics of Different Plots During the 34 effective rainfall events, rainfall intensity was relatively small (average $10.1 \text{ mm} \cdot \text{h}^{-1}$). The scatter plot of soil infiltration amount versus rainfall intensity ([Figure 1: see original paper]) reveals that infiltration amount increased with rainfall intensity following a quadratic relationship:

$$R_i = aR_p^2 + bR_p + c$$

where a , b , and c are constants, and R_p is rainfall intensity ($\text{mm} \cdot \text{h}^{-1}$). The determination coefficient (R^2) exceeded 0.7 for all plots. At low rainfall intensities, increasing intensity enhanced infiltration capacity. However, beyond a critical threshold, intensified rainfall erosivity destroyed soil structure, causing infiltration to decrease. The first derivative of the regression curve identified the critical rainfall intensity: approximately $12 \text{ mm} \cdot \text{h}^{-1}$ for vegetated slopes and $11 \text{ mm} \cdot \text{h}^{-1}$ for bare slopes. Infiltration amounts under bare land were consistently lower than under vegetation across all rainfall intensities.

Soil infiltration rate (R_v), calculated as the ratio of infiltration amount to rainfall duration, showed similar patterns across vegetated plots during initial rainfall stages, all exceeding the bare plot rate. However, differences diminished as rainfall continued. The relationship between infiltration rate and rainfall

duration followed a power function:

$$R_v = at^b$$

where a and b are constants. This relationship, with $R^2 > 0.7$, aligns well with the Kostikov infiltration model, consistent with previous research on common vegetation types in the Loess Plateau hilly and gully region.

3.2 Plot Runoff Rates Statistical analysis of average runoff rates showed minimal variation among grassland, arbor forest, shrub forest, and arbor-shrub mixed plots, ranging from $0.0033 \text{ mm} \cdot \text{min}^{-1}$ to $0.0036 \text{ mm} \cdot \text{min}^{-1}$. The bare plot runoff rate averaged $0.0079 \text{ mm} \cdot \text{min}^{-1}$, approximately 2.2 times higher than vegetated plots. Mean comparison revealed no significant differences among the four vegetated plots ($P > 0.05$), yet all vegetation restoration patterns demonstrated clear runoff reduction benefits, with rates of 54%-58% compared to bare land.

Correlation analysis indicated an extremely significant positive relationship between runoff rate and rainfall intensity ($P < 0.01$). The scatter plot ([Figure 3: see original paper]) shows an increasing trend, with runoff per unit area and time rising as rainfall intensity increases. Regression analysis revealed a quadratic relationship:

$$R_r = aR_p^2 + bR_p + c$$

with $R^2 > 0.7$, confirming rainfall intensity as the dominant factor controlling runoff rate.

3.3 Plot Sediment Concentration Sediment concentration in slope runoff represents a critical indicator of erosion processes, reflecting flow sediment-carrying capacity. Average sediment concentration ranked as: arbor-shrub mixed area ($3.13 \text{ g} \cdot \text{L}^{-1}$) > shrub forest ($2.95 \text{ g} \cdot \text{L}^{-1}$) > arbor forest ($2.79 \text{ g} \cdot \text{L}^{-1}$) > grassland ($2.58 \text{ g} \cdot \text{L}^{-1}$). Grassland, with the highest near-surface vegetation coverage, exhibited the lowest sediment concentration. Although the arbor forest canopy coverage was only 45% during the monitoring period, the understory vegetation (*Artemisia*, wheatgrass) reached 85% coverage, effectively reducing rainfall kinetic energy and maintaining low sediment concentrations.

Correlation analysis showed an extremely significant positive relationship between sediment concentration and rainfall intensity ($P < 0.01$), with correlation coefficients exceeding 0.7. The scatter plot ([Figure 4: see original paper]) demonstrates a linear increasing relationship, where slope a reflects the rate of increase. The bare plot a value was 6-8 times higher than vegetated plots, with the ranking: bare land > arbor-shrub mixed area > shrub forest > arbor forest > grassland, consistent with sediment concentration rankings. This indicates

that grassland and arbor forest most effectively reduce rainfall kinetic energy and sediment production intensity, while shrub forest and arbor-shrub mixed areas are less effective due to vegetation gaps that concentrate rainfall energy.

3.4 Plot Soil Loss Rainfall erosivity reflects the potential of rainfall to cause soil erosion and represents a fundamental factor in the Universal Soil Loss Equation (USLE). During the monitoring period, 34 effective rainfall events were classified by erosivity: $<50 \text{ MJ} \cdot \text{mm} \cdot \text{hm}^{-2} \cdot \text{h}^{-1}$ (low erosivity, 13 events), $50\text{--}200 \text{ MJ} \cdot \text{mm} \cdot \text{hm}^{-2} \cdot \text{h}^{-1}$ (moderate erosivity, 15 events), and $>200 \text{ MJ} \cdot \text{mm} \cdot \text{hm}^{-2} \cdot \text{h}^{-1}$ (high erosivity, 6 events). While high-erosivity events were less frequent, they contributed the most to total sediment yield (52.6%). Moderate-erosivity events, though more frequent, accounted for 38.2% of cumulative sediment yield.

Soil loss increased with rainfall erosivity following a linear relationship for all vegetation types:

$$SL = aRe + b$$

where SL is soil loss and a , b are fitted parameters ($P < 0.01$), with $R^2 > 0.7$. Mean soil loss was highest for bare land ($2.558 \text{ t} \cdot \text{hm}^{-2}$), 43–57 times greater than vegetated plots. Sediment reduction rates for vegetated plots ranged from 93% to 94%, demonstrating highly significant sediment reduction benefits. Among vegetated plots, soil loss did not differ significantly ($P > 0.05$), but followed the trend: shrub forest $>$ arbor-shrub mixed area $>$ arbor forest $>$ grassland. During the initial establishment phase, grassland's high coverage provided the strongest erosion resistance, followed by arbor forest with understory vegetation, while shrub forest and arbor-shrub mixed areas lacking ground cover showed relatively weaker erosion resistance.

3.5 Relationship Between Runoff and Sediment Yield The relationship between runoff and sediment yield serves as an indicator of soil erodibility, typically linear under net detachment conditions and quadratic under deposition conditions. Results ([Figure 6: see original paper]) show an extremely significant positive correlation between runoff rate and sediment yield rate under natural rainfall ($P < 0.01$), following a quadratic function:

$$E_r = aR_r^2 + bR_r + c$$

where E_r is sediment yield rate ($\text{g} \cdot \text{L}^{-1} \cdot \text{min}^{-1}$), R_r is runoff rate ($\text{mm} \cdot \text{min}^{-1}$), and $R^2 > 0.7$. This differs from some simulated rainfall studies, likely due to natural rainfall variability.

The Universal Soil Loss Equation (USLE) quantitatively predicts average annual soil loss:

$$A = R \times K \times L \times S \times C \times P$$

where A is average annual soil loss, R is rainfall erosivity, K is soil erodibility, L and S are slope length and steepness factors, C is vegetation cover and management factor, and P is conservation practice factor. For these experimental plots with fixed slope, length, and soil properties, soil loss depends primarily on rainfall erosivity when vegetation cover and conservation measures are similar. The linear relationship between soil loss and rainfall erosivity ([Figure 5: see original paper]) confirms this dependency.

4. Conclusions

1. Slope runoff generation follows the infiltration-excess mechanism, occurring when rainfall intensity exceeds soil infiltration rate. Soil infiltration amount exhibits a quadratic relationship with rainfall intensity, increasing initially but decreasing beyond a critical threshold where rainfall erosivity destroys soil structure. The critical rainfall intensity is approximately $12 \text{ mm} \cdot \text{h}^{-1}$ for vegetated slopes and $11 \text{ mm} \cdot \text{h}^{-1}$ for bare slopes. Infiltration rate decreases with rainfall duration following a power function relationship that aligns well with the Kostiakov infiltration model.
2. Bare land runoff rate is approximately 2.2 times higher than vegetated slopes. Runoff rates for grassland, arbor forest, shrub forest, and arbor-shrub mixed plots remain stable at $0.0033\text{-}0.0036 \text{ mm} \cdot \text{min}^{-1}$, demonstrating clear runoff reduction benefits of 54%-58%. Runoff rate shows a quadratic relationship with rainfall intensity ($R^2 > 0.7$), with rainfall intensity as the dominant controlling factor.
3. Bare land sediment concentration is significantly higher than vegetated plots ($P < 0.05$), approximately 6-8 times greater. Average sediment concentration ranks as: arbor-shrub mixed area ($3.13 \text{ g} \cdot \text{L}^{-1}$) > shrub forest ($2.95 \text{ g} \cdot \text{L}^{-1}$) > arbor forest ($2.79 \text{ g} \cdot \text{L}^{-1}$) > grassland ($2.58 \text{ g} \cdot \text{L}^{-1}$). Sediment reduction benefits are significant, with reduction rates of 93%-94% exceeding runoff reduction benefits. Grassland and arbor forest most effectively reduce rainfall kinetic energy and sediment production, while shrub forest and arbor-shrub mixed areas are less effective due to vegetation gaps.
4. Soil loss from vegetated slopes increases linearly with rainfall erosivity, while runoff rate and sediment yield rate follow a quadratic relationship. Different vegetation types and combinations yield varying soil and water conservation benefits. Vegetation establishment is a gradual process, and runoff-sediment characteristics vary across development stages. This study focused on initial-stage vegetation restoration patterns; long-term monitoring is needed to comprehensively evaluate soil and water conservation efficacy across different development phases.

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