

Article

Runoff and Sediment Response to Rainfall Events in China's North-South Transitional Zone: Insights from Runoff Plot Observations

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Abstract

China's North-South Transition Zone is a critical ecological transition region, marked by complex environments, climatic sensitivity, and transitional characteristics. To investigate the effects of individual rainfall events on runoff generation and sediment yield across different slopes and land uses within this zone, the study collected data from slope runoff plots (20 m in length and 5 m in width, measured as horizontal projection) at three monitoring stations (Luoshan, Lushan, Shanzhou) between 2014 and 2023. Rainfall events were classified via K-means clustering. Regression and correlation analyses were applied to reveal the effects of rainfall characteristics, slope gradient and land use type (grass land, dry land, forest land, bare land and natural vegetation) on runoff and sediment. The results indicate that: (1) The most frequent rainstorms were Type C (short, low-intensity, low-volume, low-erosivity events). (2) The runoff depth of bare land is 3.6, 2.3, and 2 times that of forest land, dry land, and natural vegetation, respectively. Similarly, its sediment concentration is 134, 13, and 16 times higher, respectively. Grassland, however, showed markedly lower levels of both runoff and sediment. (3) Rainfall intensity was significantly correlated with runoff and sediment across slopes. Runoff depth depended mainly on rainfall amount. While Type A (prolonged, high-intensity) caused peak runoff, Type D (moderate but intense and erosive) yielded the highest sediment. (4) Sediment reduction efficiency (sediment reduction compared to bare land under identical conditions) consistently surpassed runoff reduction across all land types, with grassland showing the highest efficiency for both. For soil and water conservation, grass-planting was the most effective measure on 10° and 15° slopes, whereas both afforestation and grass-planting were optimal on the 25° slopes.

Keywords: runoff plot; soil erosion; runoff and sediment; land use type



Academic Editor: Tin Lukic

Received: 19 August 2025

Revised: 17 October 2025

Accepted: 17 October 2025

Published: 18 October 2025

Citation: Gu, Z.; Ji, K.; Xu, G.; Rehemam, M.; Feng, D.; Shen, Y.; Yi, Q.; Kang, J.; Zhang, X.; Pan, S. Runoff and Sediment Response to Rainfall Events in China's North-South Transitional Zone: Insights from Runoff Plot Observations. *Atmosphere* **2025**, *16*, 1207. <https://doi.org/10.3390/atmos16101207>

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1. Introduction

China's North-South Transition Zone is a critical ecological transition region characterized by high environmental complexity and climatic sensitivity [1]. It is divided from west to east into the western mountainous valley area, the central plain and hilly area, and the

eastern rivers, lakes, and marshes area [2]. Human and natural drivers have altered runoff and sediment dynamics, worsening erosion and pollution. Rainfall patterns variably affect erosion: light rain causes gradual soil erosion, heavy rain triggers immediate loss. While rainfall and conservation effects are known, the combined impacts of land use, rainfall, and slope remain unclear [3].

The effects of rainfall characteristics on soil erosion were investigated using both simulated experiments and natural observation. Simulations are controllable, repeatable, and data-rich but costly, scale-limited, and unrepresentative of natural rain [4]. The runoff plot method, fundamental for quantifying soil erosion, was pioneered by Ewald Wollny [5]. Advanced by Miller et al. at the University of Missouri in 1917 [6], it is now widely used globally, with 826 monitoring stations in China alone. This method is widely applied in Europe, Australia, Africa, and beyond [7,8]. This method underpins soil erosion model development and mechanistic studies [5,9], enabling long-term research and established models such as the Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (RUSLE) [10–12]. It allows for the quantitative evaluation of erosion rates under major land uses and the effectiveness of conservation measures in China, Europe, Australia, Brazil, and Africa [13]. Based on extensive monitoring, China has developed regional soil loss equations and the Chinese Soil Loss Equation (CSLE) [10].

The runoff plot method is a key approach for analyzing small-scale rainfall-runoff-sediment relationships. Rainfall directly drives surface runoff and sediment yield [14], causing splash erosion and transporting particles via runoff, resulting in soil loss [15,16]. Furthermore, different underlying surfaces significantly affect runoff and sediment yield; the influence of different land use types varies [17,18]. Studies show that runoff and sediment consistently follow land-use-dependent patterns: grazing > burned > cropland > mixed vegetation > young forest [19], bare land > wild grassland > shrubland [20], slope cropland > planted grassland > arbor forest > natural grassland > shrubland [21], and slope cropland > orchard > forest land [22]. Current research on rainfall-runoff-sediment processes emphasized Northeast China's black soil region, the Loess Plateau, and southwest China's karst areas [23]. In contrast, the ecologically significant North-South Transition Zone remains understudied. Quantitative assessments of conservation measures using runoff plots are especially limited, complicating accurate soil and water loss evaluation in this region.

Investigating soil and water erosion dynamics under varying rainfall conditions and erosion patterns on typical slopes in China's North-South Transition Zone is essential for designing effective conservation measures. This study utilizes data from three automated monitoring stations (Luoshan, Lushan, Shanzhou), which provide standardized, networked observations crucial for hydrological and erosion research. Based on rainfall-runoff-sediment data (2014–2023), our objectives are to (1) analyze runoff and sediment responses across different land use types (grass land, dry land, forest land, bare land and natural vegetation) and slopes, and (2) quantify the relationships between rainfall characteristics, slope, land use, and sediment yield in the region.

2. Materials and Methods

2.1. Study Area

The North-South Transition Zone is located in the border area between northern and southern China (31°12'–35°30' N, 102°24'–144°06' E), with its main scope covering the Qinling-Daba Mountains and the Han River Valley between them (Figure 1). The southern part has a northern subtropical humid monsoon climate, while the northern part has a warm temperate semi-humid monsoon climate. The annual average temperature is 15.2 °C, and the annual precipitation ranges from 400 to 1300 mm. The landform types

are diverse, mainly including the Qinling Mountains, Daba Mountains, and the Han River Valley Basin, with mountainous and hilly terrain being predominant. Summer rainfall is concentrated, with high rainfall intensity, and significant seasonal variations in runoff and sediment yield. The soil types are varied, with yellow-brown soil and cinnamon soil dominating most areas. The main land use types in this area are forest land, grassland and dry land. The region features complex vegetation composition, high forest coverage, rich biodiversity, and distinct transitional zone characteristics. As the dominant vegetation type in the North-South Transition Zone, the evergreen deciduous broad-leaved mixed forest exhibits extremely complex structural dynamics and geographical differentiation, granting it ecological status equivalent to that of warm-temperate deciduous broad-leaved forests and subtropical evergreen broad-leaved forests. In terms of physical geography, it belongs neither to the warm-temperate zone nor to the subtropical zone, but rather constitutes a distinct independent physio-geographical zone.

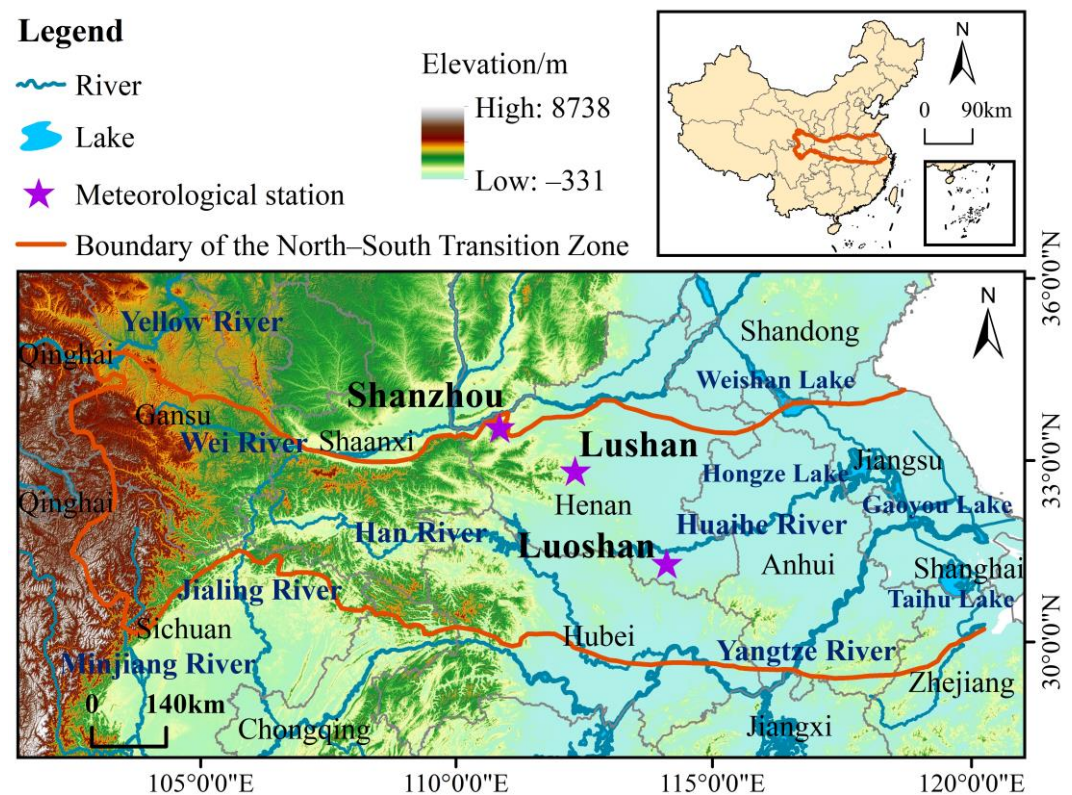


Figure 1. Location of the study area.

2.2. Data Source

This study focuses on 24 standard runoff plots (with a horizontal projected slope length of 20 m and a horizontal vertical width of 5 m) at three soil and water conservation monitoring stations—Luoshan (eight runoff plots), Lushan (four runoff plots), and Shanzhou (twelve runoff plots), located in the central part of the study area. Three monitoring stations—Luoshan, Lushan, and Shanzhou—cover key geomorphic units, slope gradients (10° , 15° , 25°), and two major river systems (Huai and Yellow Rivers), reflecting north-south hydrological contrasts. The land use types of runoff plots are grassland (mainly used for growing herbaceous plants), forest land (shrubland and soil and water conservation forests), dry land (cultivated land primarily dependent on natural rainfall for the cultivation of arid-resistant crops), natural vegetation (vegetation that develops under natural conditions without human influence) and bare land (vegetation coverage is less than 5%). Standardized methods controlled non-experimental variables, clarifying interactions between slope,

rainfall, and land use. The results offer localized parameters for erosion models (e.g., CSLE) and support tailored soil water conservation.

The Luoshan Soil and Water Conservation Monitoring Station is located at 114°11'54" E, 31°58'10" N. The monitoring station is located in the Wanhe small watershed of the Xiaohuang River system, which belongs to the Huaihe River Basin. It comprises two runoff plots with a total of eight standard runoff sub-plots and eight collecting tanks. These include four standard runoff sub-plots at each of the 10° and 15° slopes. Each standard sub-plot is equipped with one collecting tank and covers an area of 100 m² (20 m in length and 5 m in width, measured as horizontal projection). The station primarily conducts observations of precipitation, runoff, and sediment, as well as monitoring soil erosion processes.

The Lushan Soil and Water Conservation Monitoring Station is situated at 112°42'49" E, 33°54'16" N, with two standard runoff plots each at 10° and 15° slopes. Runoff plot No. 5 consists of a natural 10° slope afforested with soil conservation trees *Platycladus orientalis*. Plot No. 6 is a 10° sloping farmland planted with peanuts; Plot No. 7 is a 15° sloping farmland, also cultivated with peanuts; Plot No. 8 features a natural 15° slope planted with shrubs (local name: Zha Dun). Flow measurement was conducted using a two-stage split-flow pool system.

The Shanzhou Soil and Water Conservation Monitoring and Experimental Station is positioned at 111°11'07" E, 34°43'35" N. The monitoring station is located within the Huoshaoyang gully watershed, situated in a loess terrace region. It belongs to the Yellow River water system and serves as a first-order tributary of the Qinglongjian River. There are four standard runoff plots at each of the 10°, 15°, and 25° slopes. Each standard plot is equipped with two collecting tanks, each with a capacity of 3 m³, and covers an area of 100 m² (20 m long by 5 m wide horizontally). The 10° and 15° plots are designated for crops, while the 25° plots are designated for shrub and grass vegetation (there is little crop cultivation on slopes exceeding 25°). Based on the existing manual observation infrastructure of the slope runoff field, necessary standardized equipment enhancements were implemented.

Complete time-series data of rainfall, runoff, and sediment from experimental runoff plots were collected for the period 2014–2023, with incomplete records from 2019, 2020, and 2021 excluded from analysis due to pandemic-related data gaps. The individual rainfall dataset included rainfall frequency, duration (T , min), rainfall amount (P , mm), maximum 30-min rainfall intensity (I_{30} , mm·h^{−1}), and rainfall erosivity (R_c , MJ·mm·ha^{−1}·h^{−1}), while runoff and sediment data comprised runoff depth, runoff coefficient, sediment concentration, and soil loss amount. Runoff and sediment monitoring was performed using a manual sampling method involving stirring and scooping: after manually stirring the muddy water in the collection barrel to achieve homogeneity, samples (usually more than 3) were collected using a spoon and entirely transferred to sample bottles. The samples were then poured into sedimentation boxes (aluminum container), and the bottles were rinsed to ensure complete sediment transfer. The corresponding sedimentation box number was documented. After each rainfall event, the sediment yield and runoff depth were calculated based on the total volume of sediment and runoff collected in the collection barrel. The contents in the beaker were allowed to settle for 3–5 days. Then, the supernatant was decanted, allowed to air-dry, and then weighed to obtain the slope sediment yield.

2.3. Methods

2.3.1. K-Means Clustering of Rainfall

K-Means clustering is an algorithm that automatically groups data based on similarity. This study employed it to analyze rainfall data because it can simultaneously consider multiple factors to objectively identify different rainfall types, thereby avoiding potential

biases introduced by manual classification. Additionally, its computational efficiency and strong representativeness of categories (with clear cluster centroids) help reveal the unique distribution patterns of rainfall types in the North-South Transition Zone and provide structured input for subsequent analysis of slope-land-use-erosion-response relationships. In the study area, individual rainfall events were classified into four categories (A, B, C, D) using K-Means clustering [24] in IBM SPSS 23, with rainfall duration (T), rainfall amount (P), rainfall erosivity (R_c), and maximum 30-min rainfall intensity (I_{30}) as characteristic indicators [25].

The formula for calculating rainfall erosivity (R_c) is as follows:

$$R_c = E \cdot I_{30} \quad (1)$$

$$E = \sum_{r=1}^n (e_r \cdot P_r) \quad (2)$$

$$e_r = 0.29[1 - 0.72 \exp(-0.082i_r)] \quad (3)$$

where R_c represents the individual rainfall erosivity ($\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1}$); I_{30} represents the maximum 30-min rainfall intensity ($\text{mm} \cdot \text{h}^{-1}$); E represents the total kinetic energy of individual rainfall events ($\text{MJ} \cdot \text{ha}^{-1}$); $r = 1, 2, \dots, n$, denotes that a rainfall event is divided into n segments based on breakpoint rainfall intensities; P_r represents the rainfall amount for the r -th time period (mm); e_r represents the unit rainfall kinetic energy for each time period ($\text{MJ} \cdot \text{ha}^{-1} \cdot \text{mm}^{-1}$); i_r represents the breakpoint rainfall intensity during the r -th time interval ($\text{mm} \cdot \text{h}^{-1}$) [25].

2.3.2. Effects of Individual Rainfall Events on Runoff and Sediment Yield

Through a stratified linear regression analysis of rainfall amount with soil erosion rates and runoff depth at different slopes, this study quantified the linear interactions between rainfall characteristics and topography on soil erosion, providing locally calibrated parameters for predictive models and thus formulating targeted soil and water conservation strategies for the ecologically sensitive North-South Transition Zone. The impacts of rainfall events on runoff and sediment yield across various slopes were examined through linear regression in Origin 2021 and Pearson correlation analysis [18] in IBM SPSS 23. Vegetation coverage was measured using the visual estimation method (through the visual observation and experience to estimate the vegetation coverage), routinely conducted on the 1st and 16th of each month, with an additional measurement taken after each runoff event. Land use types were obtained from field observations (Figure 2).

Compared to bare land plots, the relative reduction in runoff and sediment yield under the same slope conditions can be used to evaluate the soil and water conservation benefits of different land use types. The calculation of runoff and sediment reduction efficiency is shown in Equations (4) and (5):

$$R_W = \frac{W_O - W_I}{W_O} \times 100\% \quad (4)$$

$$R_S = \frac{S_O - S_I}{S_O} \times 100\% \quad (5)$$

R_W denotes the runoff reduction efficiency (%), where W_O represents the runoff depth from bare soil plots (mm) and W_I indicates the runoff depth from other treatment plots (mm); R_S signifies the sediment reduction efficiency (%), with S_O referring to the soil loss from bare land plots ($\text{t} \cdot \text{ha}^{-1}$) and S_I representing the soil loss from other treatment plots ($\text{t} \cdot \text{ha}^{-1}$).

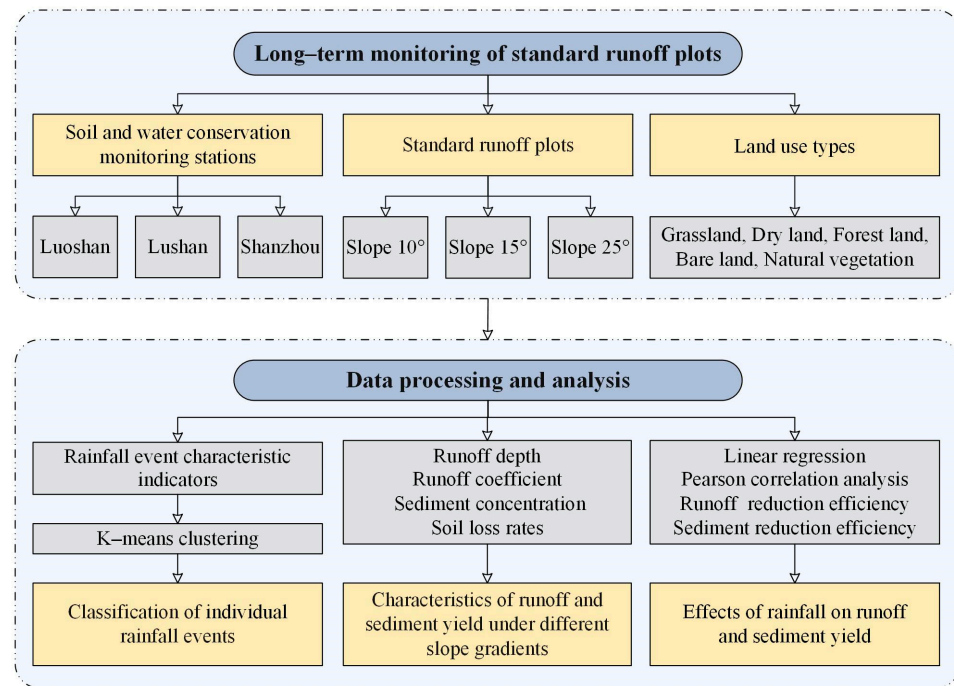


Figure 2. The research framework.

3. Results

3.1. Rainfall Event Characteristics

From 2014 to 2023, precipitation in the North-South Transition Zone was concentrated primarily between April and October. The region experienced approximately 29 rainfall events per year on average, and the mean annual rainfall erosivity per event reached $306.86 \text{ MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$. The maximum rainfall erosivity was recorded in 2014 at $440.63 \text{ MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$, while the minimum occurred in 2015 at $173.78 \text{ MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$. The I_{30} ranged from $11.74 \text{ mm}\cdot\text{h}^{-1}$ to $30.36 \text{ mm}\cdot\text{h}^{-1}$, with an average of $21.17 \text{ mm}\cdot\text{h}^{-1}$. Although rainfall and rainfall erosivity generally exhibited similar trends, an exception was observed in 2022. During this year, high rainfall amounts with short durations enhanced the kinetic energy of raindrop impacts on soil, leading to an increase in rainfall erosivity to $416.42 \text{ MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$ (Figure 3a).

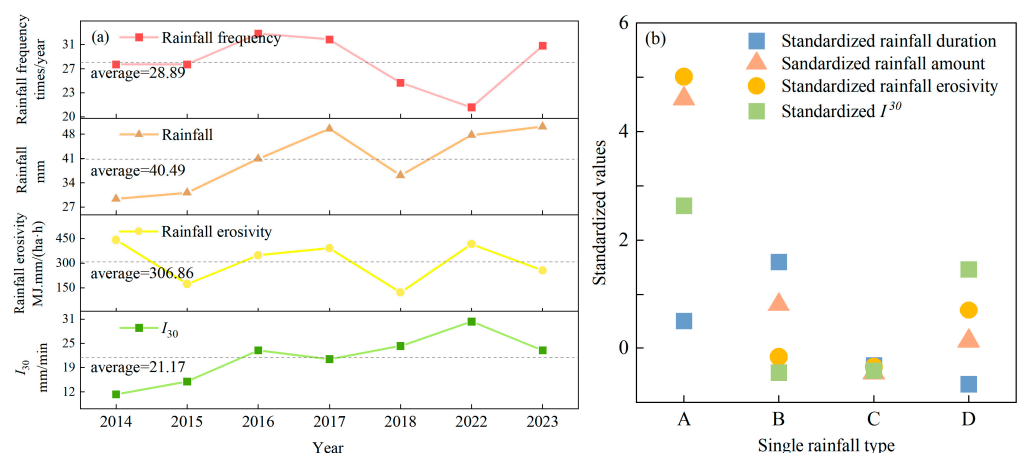


Figure 3. Annual variation in rainfall events (a) and final cluster centers of rainfall event types (b).

Based on the individual rainfall indicators obtained in this study, four rainfall types in the research area were identified through K-Means clustering analysis, labeled as Type A

(long duration, high precipitation amount, as well as high intensity and erosivity), Type B (high precipitation amount but low intensity and erosivity, coupled with long duration), Type C (low precipitation amount, low intensity, and low erosivity, with short duration), and Type D (low precipitation amount, high intensity and erosivity, along with short duration). Figure 3b presents the final cluster centers of these four rainfall types. As shown in Table 1, Type C rainfall events predominated, characterized by a low precipitation amount, low intensity, and low erosivity, with a short duration. These events occurred 118 times, accounting for 60% of the total frequency. Type B and Type D rainfall events were secondary in occurrence. Type B events exhibited a relatively high precipitation amount but low intensity and erosivity, coupled with a long duration. In contrast, Type D events showed the opposite characteristics: a low precipitation amount but high intensity and erosivity, along with a short duration. Type A rainfall events were the least frequent, with only four occurrences during the study period. They were primarily characterized by a long duration, a high precipitation amount, and high intensity and erosivity.

Table 1. The four rainfall types in China's North-South Transition Zone exhibit distinct features.

Rainfall Types	Frequency	Rainfall Characteristic Variables	Minimum	Maximum	Standard Deviation	Mean	Coefficient of Variation
A	4	T/min	870.00	2030.00	645.97	1477.50	0.44
		P/mm	170.00	233.00	17.77	206.13	0.09
		$R_c/\text{MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$	2143.23	4353.81	72.92	3694.99	0.02
		$I_{30}/\text{mm}\cdot\text{h}^{-1}$	43.30	98.69	7.16	72.12	0.10
B	38	T/min	1250.00	5090.00	937.97	2472.87	0.38
		P/mm	22.50	156.00	25.34	69.60	0.36
		$R_c/\text{MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$	0.00	975.00	777.37	196.51	3.96
		$I_{30}/\text{mm}\cdot\text{h}^{-1}$	0.00	35.30	9.59	12.01	0.80
C	118	T/min	15.00	1970.00	836.86	736.56	1.14
		P/mm	5.90	79.50	41.30	24.19	1.71
		$R_c/\text{MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$	0.00	340.80	731.52	75.11	9.74
		$I_{30}/\text{mm}\cdot\text{h}^{-1}$	0.00	39.30	21.13	12.72	1.66
D	38	T/min	25.00	2110.00	1042.08	422.97	2.46
		P/mm	6.90	106.00	26.77	45.30	0.59
		$R_c/\text{MJ}\cdot\text{mm}\cdot\text{ha}^{-1}\cdot\text{h}^{-1}$	9.57	3587.00	340.09	784.97	0.43
		$I_{30}/\text{mm}\cdot\text{h}^{-1}$	26.80	82.57	19.88	49.30	0.40

3.2. Characteristics of Runoff and Sediment Yield Under Different Slope Gradients

Within the study area, runoff and sediment yield exhibited significant variations across slope gradients and land cover types (Table 2). Bare land demonstrated the highest runoff and sediment production, with slopes of 15° being particularly prominent, while grassland showed minimum values. Runoff decreased in the following order: bare land > natural vegetation > dry land > forest land > grassland, with average depths of 3.91 mm (15°), 3.27 mm (10°), and 2.99 mm (25°), corresponding to average runoff coefficients of 0.075 (15°), 0.054 (10°), and 0.053 (25°).

Sediment yield ranked as follows: bare land > dry land > natural vegetation > forest land > grassland, with average soil loss rates per rainfall event of $5.83 \text{ t}\cdot\text{ha}^{-1}$ (25°), $3.86 \text{ t}\cdot\text{ha}^{-1}$ (15°), and $2.79 \text{ t}\cdot\text{ha}^{-1}$ (10°). Bare land and natural vegetation consistently showed the highest runoff, followed by dry farmland, forest land, and grassland. Although natural vegetation produced more runoff than dry land, its sediment yield was lower due to soil-stabilizing roots. Bare land at 25° exhibited the highest sediment yield, while grassland remained no soil erosion.

Table 2. Runoff and sediment yield characteristics across slope gradients in the study area.

Land Use Type	Runoff Depth (mm)			Runoff Coefficient			Sediment Concentration (g·L ⁻¹)			Soil Loss Rates (t·ha ⁻¹)		
	10°	15°	25°	10°	15°	25°	10°	15°	25°	10°	15°	25°
Grassland	0.00	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Dry land	3.49	4.22	2.32	0.05	0.06	0.03	20.67	29.21	6.02	2.18	3.22	0.87
Forest land	1.54	2.44	0.00	0.03	0.04	0.00	0.66	1.20	0.00	0.09	0.48	0.00
Bare land	6.45	7.48	7.43	0.13	0.14	0.14	102.12	135.97	183.78	11.12	14.94	22.42
Natural vegetation	4.89	5.35	2.18	0.07	0.15	0.04	7.09	7.52	0.57	0.54	0.68	0.03

Natural vegetation shows “high runoff but low sediment yield” due to its uneven canopy—which reduces rainfall interception—and a robust root network that resists erosion. Although runoff is higher than in dry land (tilling occurs in dry land), sediment remains low thanks to the roots of natural vegetation. Compared to dry land, natural vegetation generates higher runoff but lower sediment yield.

3.3. Effects of Rainfall on Runoff and Sediment Yield

3.3.1. Effects of Rainfall Characteristics on Runoff and Sediment Yield

During the entire observation period, plots were generated with rainfall duration as the x-axis and soil loss (runoff depth) and rainfall amount as the y-axis (Figure 4). Overall analysis reveals that runoff and sediment yield exhibit a consistent fluctuation trend with rainfall amount. Under shorter rainfall durations, runoff and sediment yield are generally higher compared to prolonged rainfall events. The combination of a short duration and high rainfall intensity leads to more severe soil erosion. Conversely, during extended rainfall durations, runoff and sediment yield decrease.

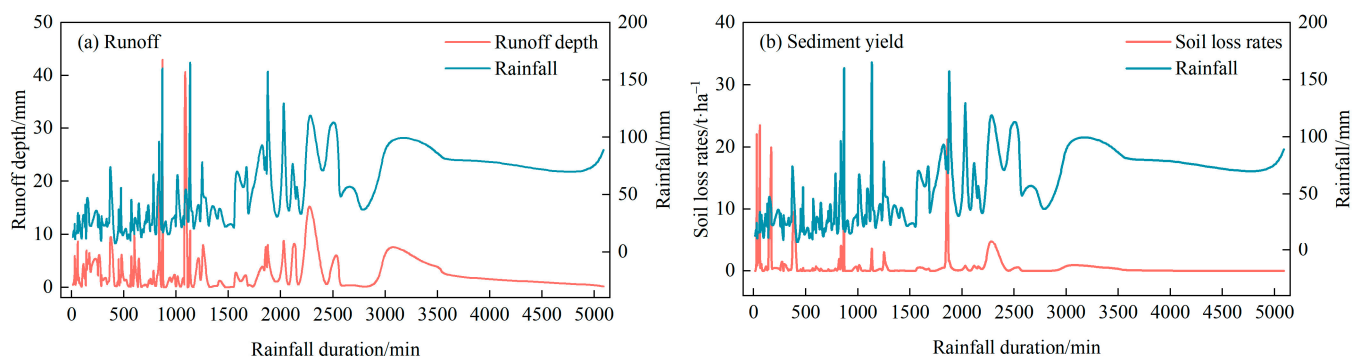


Figure 4. The relationship between rainfall duration and runoff depth (a) and rainfall duration and sediment yield (b).

Figure 5 demonstrates a linear correlation between rainfall and runoff/sediment yield across different slope gradients, where y_1 represents the mean annual runoff depth, y_2 denotes the mean annual soil loss, and x stands for the mean annual rainfall. The runoff depth exhibits a relatively high goodness-of-fit with rainfall, whereas the soil loss shows a lower fitting accuracy. The coefficient of determination (R^2) for runoff depth is 0.40 ($p > 0.05$) (10°), 0.55 ($p > 0.05$) (15°), and 0.40 ($p > 0.05$) (25°), while that for soil loss rates is 0.73 ($p < 0.05$) (10°), 0.90 ($p < 0.01$) (15°), and 0.12 ($p > 0.05$) (25°). These results indicate that rainfall exerts a stronger influence on runoff generation than on sediment yield.

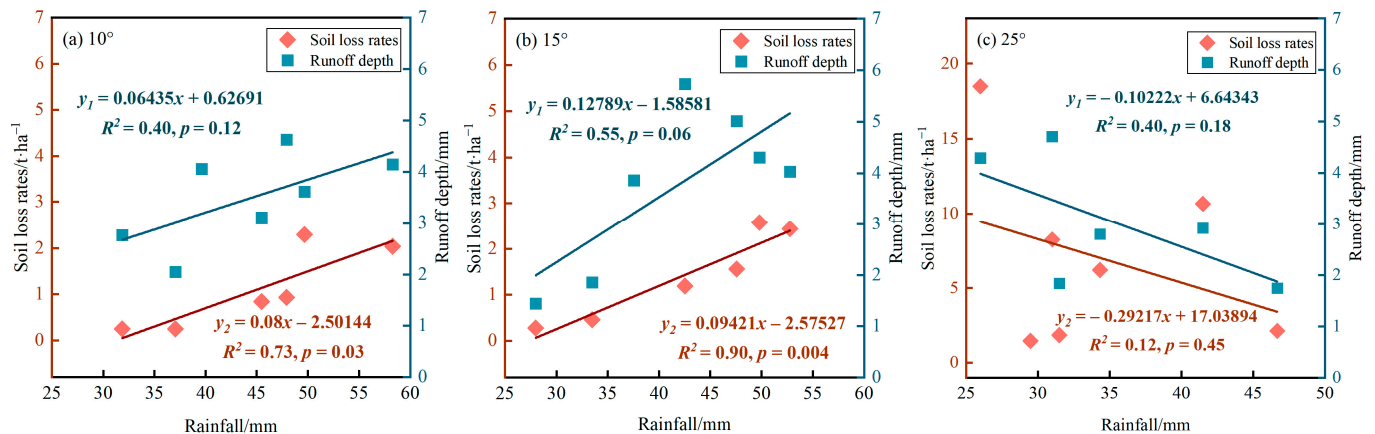


Figure 5. Fitting and regression analysis of rainfall with runoff depth and soil loss rates at 10° slope (a), 15° slope (b) and 25° slope (c).

In addition to rainfall amount, other factors including rainfall characteristics, vegetation coverage (V_c), and land use types (L) also significantly influenced runoff and sediment transport processes within the study area (Table 3). Based on Pearson correlation analysis, soil loss (runoff depth) across all slope gradients exhibited statistically significant correlations with rainfall-related indicators during the entire study period. The dominant influencing factors were rainfall intensity (highly significant positive correlation, $p < 0.01$), followed by vegetation coverage (extremely significant negative correlation, $p < 0.01$) and total rainfall amount (significant positive correlation, $p < 0.05$). For the 15° and 25° slopes, soil loss demonstrated extremely significant positive correlations with rainfall erosivity, while runoff depth displayed highly significant (or significant) positive correlations with rainfall erosivity.

Table 3. Pearson correlation analysis between rainfall characteristics and runoff/sediment yield across slope gradients in the study area.

Variables	10°		15°		25°	
	Soil Loss Rates (t·ha ⁻¹)	Runoff Depth (mm)	Soil Loss Rates (t·ha ⁻¹)	Runoff Depth (mm)	Soil Loss Rates (t·ha ⁻¹)	Runoff Depth (mm)
I_{30}	0.124 **	0.393 **	0.195 **	0.364 **	0.214 **	0.333 **
V_c	−0.234 **	−0.187 **	−0.213 **	−0.130 **	−0.273 **	−0.174 **
P	0.108 *	0.499 **	0.137 **	0.474 **	0.108 **	0.459 **
R_c	0.053	0.409 **	0.118 **	0.441 **	0.142 **	0.498 **
L	−0.029	0.143 **	−0.038	0.080 *	0.033	0.094 *
T	−0.055	0.017	−0.091 *	0.002	−0.099*	0.014

** indicates a highly significant correlation at the 0.01 level (two-tailed). * indicates a significant correlation at the 0.05 level (two-tailed).

In the North-South Transition Zone, rainfall intensity dominates runoff and sediment yield due to frequent short, high-intensity storms (e.g., Type D) impacting vulnerable soils and slopes. The results confirm an extremely significant positive correlation between rainfall intensity and erosion, with Type D events producing the highest sediment yield despite moderate total rainfall-highlighting its role as the primary driver of soil loss.

A noteworthy observation is that runoff depth and soil loss on 25° slopes exhibit a negative correlation with rainfall amount, which appears inconsistent with the Pearson correlation results. This discrepancy does not imply unreliable findings. The Pearson correlation, analyzed across the entire study period while incorporating multiple factors, demonstrates an overall positive correlation between rainfall amount and runoff/sediment yield. In contrast, the linear regression employed annual average data from different slope gradients, thereby accentuating the underlying variation trends. The observed negative

correlation can be attributed to two primary mechanisms. First, when the slope reaches the critical gradient for soil erosion, although runoff velocity increases, the runoff layer becomes thinner with reduced residence time on the soil surface, ultimately decreasing actual soil loss. Second, the 25° slope exhibits diverse natural vegetation types (e.g., *Medicago sativa*, *Vitex negundo*, and *Astragalus adsurgens*), complemented by implemented biological measures such as forage grasses and shrubs. This vegetation significantly intercepts rainfall; as precipitation increases, the unimpeded portion rapidly forms surface runoff, consequently reducing both runoff depth and soil erosion.

3.3.2. Effects of Rainfall Types on Runoff and Sediment Yield

Different rainfall types exerted distinct impacts on runoff and sediment yield in the study area (Table 4). Among them, Type D rainfall generated the highest sediment yield, while Type A produced the greatest runoff volume, followed by Types B and C. The mean runoff depth (runoff coefficient) for rainfall Types A, B, C, and D measured 25.91 mm (0.12), 2.94 mm (0.02), 1.21 mm (0.04), and 6.87 mm (0.10), respectively. Corresponding sediment concentrations (soil loss rates) averaged 17.13 g·L⁻¹ (4.31 t·ha⁻¹), 10.13 g·L⁻¹ (1.33 t·ha⁻¹), 6.73 g·L⁻¹ (0.30 t·ha⁻¹), and 34.67 g·L⁻¹ (4.18 t·ha⁻¹). Although Type D events occurred less frequently, their combination of high rainfall intensity, significant erosive power, and short duration resulted in disproportionately severe sediment production, ultimately causing greater soil erosion than the more frequent Type C rainfall.

Table 4. The influence of different rainfall types on runoff and sediment yield.

Rainfall Types	Runoff Characteristic Variables	Minimum	Maximum	Mean
A	Runoff Depth/mm	11.13	64.39	25.91
	Runoff Coefficient	0.06	0.30	0.12
	Sediment Concentration/g·L ⁻¹	2.9	32.13	17.13
	Soil Loss Rates/t·ha ⁻¹	1.11	8.36	4.31
B	Runoff Depth/mm	0	21.00	2.94
	Runoff Coefficient	0	0.14	0.02
	Sediment Concentration/g·L ⁻¹	0	174.78	10.13
	Soil Loss Rates/t·ha ⁻¹	0	31.81	1.33
C	Runoff Depth/mm	0	15.48	1.21
	Runoff Coefficient	0	2.01	0.04
	Sediment Concentration/g·L ⁻¹	0	204.94	6.73
	Soil Loss Rates/t·ha ⁻¹	0	8.74	0.30
D	Runoff Depth/mm	0.42	61.00	6.87
	Runoff Coefficient	0	0.40	0.10
	Sediment Concentration/g·L ⁻¹	0	312.69	34.67
	Soil Loss Rates/t·ha ⁻¹	0	34.91	4.18

3.4. Comparison of Soil and Water Conservation Benefits

All land types showed greater sediment reduction than runoff reduction. Grassland demonstrates the highest efficiency in both runoff and sediment reduction. On 10° slopes, the runoff reduction efficiency ranks as: grassland (100%) > forest land (76.14%) > dry land (43.55%) > natural vegetation (24.24%). For sediment reduction, grassland remains the most effective, while dry land exhibits the lowest efficiency at 80.40%. On 15° slopes, grassland exhibits the highest efficiency in both runoff and sediment reduction, followed by forest land, with corresponding reduction rates of 67.35% (runoff) and 96.79% (sediment). Dry land demonstrates higher runoff reduction efficiency (43.55%) than natural vegetation (28.50%), but its sediment reduction efficiency (78.48%) is lower than that of natural vegetation (95.46%). On 25° slopes, sediment reduction is most pronounced in grassland, forest land, and natural vegetation, indicating that vegetation effectively mitigates runoff and

sediment yield. Table 5 further reveals that dry land consistently achieves a higher runoff reduction than sediment reduction across all slope gradients.

Table 5. Runoff and sediment reduction amounts and efficiencies across land-use types under different slope gradients.

Land Use Types	Runoff Reduction/mm			Sediment Reduction/t·ha ^{−1}			Runoff Reduction Efficiency/%			Sediment Reduction Efficiency/%		
	10°	15°	25°	10°	15°	25°	10°	15°	25°	10°	15°	25°
Grassland	6.45	7.45	7.39	11.12	14.94	22.42	100	99.58	99.51	100	100	100
Dry land	2.97	3.26	5.11	8.94	11.73	21.55	45.99	43.55	68.76	80.40	78.48	96.14
Forest land	4.91	5.04	7.43	11.03	14.46	22.42	76.14	67.35	100	99.21	96.79	100
Natural vegetation	1.56	2.13	5.25	10.58	14.26	22.39	24.24	28.50	70.66	95.11	95.46	99.88

4. Discussion

4.1. Effects of Slope Gradient on Runoff and Sediment Yield

Under given rainfall conditions, the variation in slope sediment yield with gradient constitutes a complex process, primarily governed by rainfall intensity fluctuations, rain-drop splash erosion, and the movement of sediment-laden surface flow [26]. Slope gradient influences both runoff and sediment production, with distinct critical slope gradient for sediment yield emerging under varying soil types, rainfall patterns, and vegetation conditions. Liu et al. [27] investigated slope runoff and sediment yield under natural rainfall events, identifying a critical slope range between 15 and 20°. Zhang et al. [28] conducted simulation experiments under specific rainfall intensities with varying vegetation coverage and slope gradients, revealing that the runoff rate decreased with increasing slope gradient, while the erosion rate peaked at 15°. In the study of China's North-South Transitional Zone, both runoff and sediment yield rates reached their maximum at 15°, exhibiting a linear correlation with rainfall amount, but shifted to a negative correlation at 25°, indicating a critical slope of 15° for runoff and sediment yield. The influence of slope gradient on runoff and sediment yield is complex—once the gradient exceeds a certain threshold or critical value, the relationship may reverse. Further investigation is required to account for regional rainfall characteristics and environmental factors.

4.2. Effects of Different Land Use Types on Runoff and Sediment Yield

Land use change exerts significant impacts on runoff and sediment yield [29]. Increased land cover leads to marked reductions in both runoff volume and sediment production, demonstrating a strong inverse relationship between sediment yield and land cover [30]. This study further confirms this conclusion, revealing a statistically significant negative correlation between vegetation coverage and runoff-sediment yield in China's North-South Transitional Zone. Soils under different land cover types possess distinct microenvironments characterized by vegetation composition, soil crust development, and surface roughness, resulting in varied erosion behaviors [31,32]. Vegetation cover serves as a protective buffer that intercepts raindrop impact, effectively suppressing both splash erosion and concentrated flow erosion [33]. Grassland demonstrates the most efficient buffering effect, as grass root systems form soil-root composites within the surface layer, substantially enhancing soil strength and erosion resistance while delivering optimal runoff and sediment reduction benefits [34]. This study reveals that forestland in China's North-South Transitional Zone exhibits the second highest runoff and sediment reduction efficiency after grassland. Natural vegetation types, primarily dominated by *Medicago sativa* (alfalfa), *Vitex negundo* (vitex), and *Astragalus adsurgens* (standing milkvetch), also play a significant role in reducing runoff and sediment. As proposed by Liu et al. [35],

this phenomenon primarily results from the buffering effect of forest litter layers, which effectively dissipate raindrop kinetic energy. Additionally, the remarkable water-retention capacity of forest ecosystems intercepts substantial rainfall [36], while simultaneously increasing surface roughness and consequently reducing soil erosion potential.

4.3. Runoff and Sediment Generation Responses to Single Rainfall Events

The transport of water and sediment is influenced by multiple factors, among which land use and rainfall are frequently cited as two primary determinants [37–39]. Rainfall affects surface runoff concentration as well as runoff and sediment generation processes through its characteristics, including intensity, type, and duration. Studies indicate that rainfall intensity is one of the most critical parameters governing runoff and sediment yield. Specifically, when the peak rainfall intensity reaches 6.25 mm/min, the runoff rate is maximized, whereas a reduction in intensity to 5.82 mm/min leads to a corresponding decrease in runoff rate [40]. Rainfall itself affects runoff and sediment yield primarily through its intensity, with slope sediment production increasing as rainfall intensity rises [41,42]. In this study, I_{30} exhibited the highest correlation with runoff and sediment yield, followed by vegetation coverage and total rainfall. From a holistic slope perspective, aside from rainfall intensity, vegetation coverage is another key factor influencing runoff and sediment generation. Rainfall type also plays a role: short-duration, high-volume events (e.g., Type D in this study) generate significantly higher runoff and sediment yields compared to other types (e.g., Type C), despite their lower frequency of occurrence, warranting particular attention.

5. Conclusions

1. From 2014 to 2023, Type C rainfall was the dominant type in China's North-South Transition Zone, marked by low precipitation, intensity, erosivity, and short duration. These events occurred mainly between April and October, with an annual frequency of approximately 29.
2. Runoff and sediment yield varied significantly across slopes and land use types in the study area. Bare land exhibited the highest values, especially at 15° slope, while grassland showed the lowest.
3. Rainfall amount demonstrated a positive correlation with runoff and sediment yield. Soil loss rates (runoff depth) across all slopes showed significant correlations with rainfall indices, with rainfall intensity being the dominant factor. Among rainfall types, Type D generated the highest sediment yield, while Type A produced the greatest runoff volume, followed by Type B and Type C.
4. All land types showed greater sediment reduction than runoff reduction. On 15° slopes, grassland remained most effective, followed by forest. On 25° slopes, forest and grassland maximized runoff reduction. Grass-planting was the most effective measure on 10° and 15° slopes, whereas both afforestation and grass-planting were optimal on the 25° slopes.

This study investigated the effects of rainfall characteristics on runoff and sediment under different underlying surfaces, as well as their interrelationships, to provide references for soil erosion control in the region. The processes influencing slope runoff and sediment yield are highly complex. In addition to rainfall, factors such as different crop planting methods, soil physicochemical properties, and human activities are also significant contributors to runoff and sediment. However, the current methods and contents of this study are rather limited. Therefore, further research into the mechanisms by which these influencing factors affect runoff and sediment yield, along with improving the effectiveness of soil and water conservation measures, will help prevent and reduce regional soil erosion.

Author Contributions: Conceptualization, Z.G. and K.J.; methodology, Z.G.; software, K.J.; validation, G.X., M.R. and D.F.; formal analysis, Q.Y. and Y.S.; investigation, J.K.; resources, X.Z.; data curation, S.P.; writing—original draft preparation, K.J.; writing—review and editing, Z.G.; visualization, G.X.; supervision, M.R.; project administration, Z.G.; funding acquisition, Z.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Key Scientific and Technological Research Project of Henan Province, grant number 252102320245, Key Research Projects of Higher Education Institutions in Henan Province, grant number 25A170004 and Nanhu Scholars Program for Young Scholars of XYNU, grant number 2019046.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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