Experimental Study on Runoff and Sediment Yield Processes from Karst Bare Slopes: Postprint

Authors: Yan Youjin, Dai Quanhou, Fu Wenbing, Peng Xudong, Jin Li

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Abstract

Simulating karst bare slopes using experimental steel flumes with adjustable slope gradients and subsurface pore (fissure) porosity filled with soil and rock materials, this study investigated the runoff and sediment yield processes through artificial rainfall simulation. The results indicated that rainfall intensity, slope gradient, and subsurface pore (fissure) porosity all significantly affected runoff and sediment yield from karst bare slopes. (1) Under rainfall intensities of 30, 50, and 80 mm/h, a critical rainfall intensity existed for surface runoff and sediment yield, which fell between 50-80 mm/h. Both subsurface pore (fissure) runoff yield and sediment yield exhibited a pattern of first increasing then decreasing with increasing rainfall intensity. The order of runoff yield with respect to rainfall intensity was $50 > 30 > 80$ mm/h, while the order of sediment yield with respect to rainfall intensity magnitude was $50 > 80 > 30$ mm/h. (2) As slope gradient increased, the subsurface sediment transport modulus decreased, with its magnitude following the order of $10° < 15° < 20° < 25°$ with respect to slope variation. Within the same rainfall duration, the smaller the slope gradient, the greater the reduction in subsurface sediment transport modulus per unit time, with its magnitude following the order of $10° > 15° > 20° > 25°$ with respect to slope variation. (3) Subsurface pore (fissure) porosity exerted a significant influence on subsurface runoff and sediment yield; increases in subsurface pore (fissure) porosity led to increased subsurface loss. Both the proportion of subsurface runoff yield and the proportion of subsurface sediment yield increased with increasing subsurface pore (fissure) porosity, following the order of $1\% < 3\% < 5\%$. This study contributes to a deeper understanding of soil erosion mechanisms on karst slopes and provides a theoretical basis for karst rocky desertification control and ecological restoration.

Full Text

Experimental Study on Runoff and Sediment Production Processes on Karst Bare Slopes

YAN Youjin[1], **DAI Quanhou**[1], **FU Wenbing**[1],[2], **PENG Xudong**[1], **JIN Li**[1] [1]College of Forestry, Guizhou University, Guiyang 550025, China [2]Guizhou Shengtai Engineering Consulting Co., Ltd., Guiyang 550002, China

Abstract

Artificial rainfall experiments were conducted using a steel tank filled with soil and rock fragments to simulate a karst bare slope with adjustable slope gradient and underground hole (crack) porosity. The study explored runoff and sediment production processes on karst bare slopes, revealing that rainfall intensity, slope gradient, and underground porosity all significantly influenced these processes.

Three key findings emerged: (1) When actual rainfall intensity exceeded the critical threshold of 50–80 mm/h, surface sediment production occurred. Both runoff and sediment yields exhibited an initial increase followed by a decrease with increasing rainfall intensity, with the order of runoff yield being 50 > 30 > 80 mm/h and sediment yield following the same pattern. (2) The underground sediment transport modulus decreased with increasing slope gradient, following the order 10° < 15° < 20° < 25°. During the same rainfall event, smaller slopes showed greater reductions in sediment transport modulus per unit time, with the order being 10° > 15° > 20° > 25°. (3) Increased underground porosity enhanced underground loss, with both underground runoff and sediment production ratios increasing with porosity in the order 1% < 3% < 5%.

These findings provide deeper insights into soil erosion mechanisms on karst slopes and offer a theoretical basis for rocky desertification control and ecological restoration in karst regions.

Keywords: karst soil erosion; dual structure; artificial rainfall; underground holes (cracks); runoff and sediment yield

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1. Introduction

Soil erosion accelerates rocky desertification in karst regions, seriously threatening ecological security [1]. Environmental factors influencing karst soil erosion primarily include climate, slope gradient, and others [2]. The combined action of rainfall kinetic energy and gravitational potential energy constitutes the main driving force of desertification [3]. Tectonic movements since the Tertiary period have provided dynamic potential for karst soil erosion [4-5].

Strong dissolution in karst regions forms underground caves, subterranean rivers, and various fractures in the surface epikarst zone, creating karst underground conduit systems that combine with the surface to form heterogeneous dual structures [6-8]. The existence of these structures results in both surface and subsurface soil loss pathways in karst areas [9-10]. Soil bodies in underground pores often exist in plastic, soft-plastic, or even fluid-plastic states, entering underground karst conduits under rainfall conditions or high moisture content to form the unique "underground soil loss" phenomenon in karst regions [11].

Research on karst underground soil erosion remains relatively limited. Liu Zhigang noted that surface soil in karst areas enters underground karst systems through sinkholes under runoff action [12]. Most studies on karst soil erosion have focused on surface water and soil loss, with underground loss research being extremely weak, limited to mechanisms, universality, and conceptual models of underground erosion. Chen Xiaoping proposed that fracture erosion in karst areas is a hidden form of erosion that is easily overlooked but actively promotes complete slope desertification [13]. Wan Hengsong et al. briefly summarized the characteristics, mechanisms, and influencing factors of underground water and soil loss [14]. Zhou Nianqing et al. comprehensively analyzed the mechanisms of water and soil loss in karst regions based on lithological characteristics and hydrological conditions in Puding County [15]. Zhang Xinbao et al. used ^{137}Cs technology to measure sediment deposition rates in depressions and roughly calculated underground soil loss using a mixing model [17].

Studies integrating surface and underground erosion processes at the slope scale are even rarer, with relevant reports mainly focusing on artificial rainfall simulation experiments examining slope gradient, rock exposure rate, and porosity effects on slope soil erosion [18-19]. This study simulates the microtopography of karst bare slopes and underground pore structures to analyze dynamic soil erosion characteristics in both surface and subsurface directions, providing important theoretical support for soil erosion prevention and ecological restoration in karst regions.

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2. Materials and Methods

2.1 Experimental Equipment

The experimental apparatus primarily consisted of a self-designed variable-slope steel tank [20] and a rainfall simulator. The steel tank measured 4.0 m × 1.5 m × 0.35 m, with a slope adjustment range of 0–45° and porosity adjustment range of 0–8%. The tank bottom comprised two uniformly perforated plates whose overlapping area could be adjusted to control porosity. The tank included surface and subsurface flow collection troughs.

The rainfall simulator (Model QYJY-501) was a portable, fully automatic, downward-spraying artificial rainfall device produced by Xi' an Qingyuan Measurement and Control Technology Co., Ltd., consisting of a water pump and controller. Rainfall height was 6.5 m, effective area 6.5 m × 6.5 m, regulation accuracy >7 mm/h, adjustment response time <30 s, rainfall uniformity >85%, and rainfall duration arbitrarily adjustable.

2.2 Experimental Materials

The test soil was collected in May from Luoping Village, Huaxi District, Guiyang City (26°24 41.4396 N, 106°39 53.4384 E), representing a calcareous clay loam developed from carbonate rocks. The soil was not sieved; only large clods were broken up.

2.3 Experimental Design

The experiment simulated soil erosion and sediment production characteristics under natural karst desertification slope conditions. Three natural factors were selected: rainfall intensity, slope gradient, and underground porosity. A cross-experiment was designed with rock exposure rate fixed at 30%, rainfall intensities of 30, 50, and 80 mm/h, slope gradients of 10°, 15°, 20°, and 25°, and underground porosities of 1%, 3%, and 5%. These parameters were based on field surveys of 9 slope plots and 6 rock profiles in Nanming District, Huaxi District, and Puding County, Guizhou Province. Rainfall intensity settings were based on Zhang Wenyuan et al.' s proposed erosive rainfall indicators for karst yellow soil slopes [21] and local hydrological data showing $ $30% of annual rainfall intensities between 50–120 mm/h.

Limestone blocks were randomly arranged in the steel tank to simulate bedrock exposure. After achieving the designed arrangement, soil was filled in layers (each 10 cm thick) to the target level. Soil compaction for each layer followed field measurements: 410, 760, and 1070 kPa from top to bottom. Each rainfall event lasted 90 minutes. Before each test, a light rain (<30 mm/h) was applied until soil saturation and flow initiation, after which timing began. Water samples were collected at 10-minute intervals for both surface and subsurface flows. Each treatment was replicated twice.

2.4 Measurement Methods

Rock exposure rate: After adjusting the steel tank to the designed slope, carbonate rocks were randomly arranged to occupy 30% of the tank surface area. Rocks protruding >30 cm were adjusted, and vertical photographs were taken and verified using ArcGIS.

Underground porosity adjustment: Porosity was adjusted by controlling the overlapping area of holes between the two bottom plates. Complete overlap gave maximum porosity; complete misalignment gave minimum porosity. The maximum chord length (L) of the overlapping area at designed porosity was calculated, then adjusted using a rocker arm. The porosity calculation formula was:

P = (S_{hole} / S_{bottom}) × 100%

where S_{bottom} is plate area, S_{hole} is overlapping area, L is maximum chord length (m), and R is hole radius (0.025 m).

Soil compaction: After filling the tank, a soil compaction meter measured each 10 cm layer’ s compaction.

Runoff measurement: Plastic containers were placed at surface and subsurface flow outlets before the test. Flow was collected at 10-minute intervals to calculate cumulative runoff volumes.

Sediment measurement: For each 500 mL water sample, sediment was filtered using qualitative filter paper (12.5 m), transferred to a beaker, dried at 105°C, and weighed using an electronic balance (0.0001 g precision).

Cumulative runoff ratio: Calculated as the ratio of surface cumulative runoff to underground cumulative runoff at each time interval.

Underground sediment yield ratio: Calculated as underground sediment yield divided by total sediment yield.

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3. Results and Discussion

3.1 Effects of Rainfall Intensity on Runoff

Rainfall is the primary driver of slope soil erosion, affecting erosion processes through rainfall erosivity and runoff volume. Rainfall intensity significantly influences runoff velocity, erosive force, and raindrop splash [22-23].

At rainfall intensities of 30 and 50 mm/h, no surface runoff occurred, with runoff coefficients of 0.26–0.41. Between 50–80 mm/h, a critical rainfall intensity threshold existed for surface runoff generation. Underground runoff showed an initial increase then decrease with increasing rainfall intensity. Compared with 30 mm/h, underground runoff at 50 mm/h increased by 10.60%, 10.20%, 11.36%, and 17.06% for slopes of 10°, 15°, 20°, and 25°, respectively. At 80 mm/h, underground runoff decreased by 29.37%, 30.87%, 25.08%, and 44.89% compared with 50 mm/h.

At 80 mm/h, surface runoff dominated. At 30 and 50 mm/h, underground flow dominated because rainfall intensity was less than soil infiltration rate, allowing water to infiltrate and flow through underground pores. At 80 mm/h, rainfall exceeded infiltration capacity, generating surface runoff while reducing underground flow.

Analysis of underground runoff variation across rainfall durations showed an increasing relationship with rainfall duration. At 80 mm/h, later-stage runoff exceeded early-stage runoff. At 30 mm/h, underground runoff increased throughout the event because precipitation exceeded infiltration rate, and soil moisture approached saturation. The presence of underground pores allowed more water to exit through subsurface channels. At 80 mm/h, surface runoff exceeded underground runoff in the same time period, but underground runoff increased as rainfall progressed [Figure 2: see original paper].

3.2 Effects of Rainfall Intensity on Sediment Production

At lower intensities (30, 50 mm/h), all sediment production occurred underground. At 80 mm/h, both surface and subsurface sediment production occurred, with surface sediment transport rates (5.51-6.69 g/min) 4.6–5.6 times higher than underground rates (1.19-1.57 g/min), making surface erosion dominant.

Underground sediment yield showed an initial increase then decrease with rainfall intensity, peaking at 50 mm/h. Compared with 50 mm/h, underground sediment yield at 80 mm/h decreased by 23.09%, 23.99%, 19.58%, and 27.91% for the four slopes, while 30 mm/h decreased by 24.15%, 34.58%, 40.69%, and 52.38%.

Underground sediment concentration was highest in early rainfall periods at all intensities, decreasing over time. The range (R) of sediment concentration was 0.16–0.23 at 30 mm/h, 0.34–0.42 at 50 mm/h, and 0.44–0.61 at 80 mm/h. The decreasing concentration over time resulted from soil particles clogging pores during downward movement. Higher rainfall intensity produced more splash-generated particles, giving higher initial sediment concentrations that decreased more rapidly over time [Figure 3: see original paper].

3.3 Effects of Slope Gradient on Surface and Underground Runoff

Comparing surface-to-underground cumulative runoff ratios across slopes revealed dynamic changes. At 10°, the ratio was 1.0–1.8; at 15°, 1.7–2.8; at 20°, 2.0–3.1; and at 25°, 2.8–4.8. The ratio increased with slope gradient in the order 25° > 20° > 15° > 10°, consistent with Li Guifang et al.' s findings [25]. Within the same rainfall period, more runoff flowed as surface runoff at steeper slopes.

At 80 mm/h, the ratio showed distinct temporal patterns by slope. At 10°, the ratio initially increased then stabilized. At 15°, 20°, and 25°, it increased progressively with rainfall duration. At 25°, the ratio was largest at rainfall onset but gradually decreased, differing from lower slopes because raindrop splash filled soil pores, reducing infiltration and increasing surface runoff. At 25°, enhanced runoff scouring capacity removed particles clogging pores, increasing infiltration and reducing the surface-to-underground ratio over time [Figure 4: see original paper].

3.4 Effects of Slope Gradient on Underground Sediment Production

Underground sediment transport modulus showed significant temporal variation, generally decreasing linearly with rainfall duration. Modulus was smallest in early rainfall periods and peaked mid-event. Mean modulus reduction between measurement periods was 1.67\$$\times10^{\{-2\}, 1.56\times10}$\{-2\}, $1.33\times10^{\{-2\}, and 1.15\times10}$\{-2\}\$ for the four slopes, respectively.

Slope significantly affected underground sediment transport modulus, which decreased as slope increased ($10° < 15° < 20° < 25°$). Lower slopes better inhibited soil particle loss with runoff. The reduction occurred because steeper slopes increased friction between particles. When friction exceeded downward movement forces, sediment accumulation increased and transport modulus decreased [Figure 5: see original paper].

3.5 Effects of Underground Porosity on Runoff and Sediment Production

In karst regions, the special surface-subsurface dual structure means water and soil loss is influenced by both topographic and subsurface factors. The surface-to-underground cumulative runoff ratio decreased with increasing porosity. Correlation analysis showed a highly significant negative relationship ($r = -0.903$, $p = 0.000 < 0.01$), indicating porosity significantly affected runoff spatial distribution on karst bare slopes.

At 1% porosity, the runoff ratio was 4.10%-9.60%; at 3%, it was 9.93%-14.87%; and at 5%, it was 4.10%-9.60%. The ratio generally decreased with rainfall duration across all porosities. At 15° slope, the mean difference between porosities was 1.75% (3.33\$±\$0.002)%; at 25°, it was 4.09%. The cumulative runoff ratio showed a decreasing-then-increasing trend with rainfall duration across all porosities [Figure 7: see original paper].

Underground pores are the main channels for subsurface sediment loss in karst areas. Underground sediment yield ratio (underground/total sediment) ranged 10%-30% at 80 mm/h, indicating surface erosion dominated. The ratio increased with porosity ($1\% < 3\% < 5\%$) and was highly significantly correlated with porosity ($r = 0.639$, $p = 0.000 < 0.01$). However, the ratio decreased with rainfall duration (30 min > 60 min > 90 min), showing a highly significant negative correlation ($r = -0.786$, $p = 0.000 < 0.01$) [Figure 8: see original paper].

The decreasing ratio over time occurred because inter-particle friction slowed sediment movement, causing accumulation in pores. Initially, maximum sediment entered pores, but as accumulation increased, downward movement was hindered, reducing transport efficiency. This aligns with Zhang Xingbao' s findings on karst subsurface soil creep and loss [39].

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4. Conclusions

Rainfall is the primary driver of slope erosion. Critical findings include:

1. **Rainfall intensity effects:** A critical threshold of 50–80 mm/h existed for surface runoff initiation. Underground runoff and sediment yields peaked at 50 mm/h, decreasing at both lower (30 mm/h) and higher (80 mm/h) intensities. At intensities <80 mm/h, underground flow dominated. At 80 mm/h, surface flow dominated. Surface erosion only occurred at 80 mm/h, with sediment transport rates 4.6–5.6 times higher than underground rates. Karst erosion research should focus on lower intensity rainfall events.

2. **Slope gradient effects:** The surface-to-underground runoff ratio increased with slope (25° > 20° > 15° > 10°). Underground sediment transport modulus decreased with increasing slope, with lower slopes showing the greatest reduction rates. Low slopes better inhibited particle loss, though more runoff occurred underground.

3. **Underground porosity effects:** Both underground runoff and sediment yield ratios increased with porosity (1% < 3% < 5%). The runoff ratio was highly significantly negatively correlated with porosity (r = -0.903). Underground sediment yield ratio was highly significantly positively correlated with porosity but negatively correlated with rainfall duration (r = -0.786), decreasing over time due to friction and pore clogging.

Karst rocky desertification is an accelerating process once initiated. The presence of underground pores exacerbates desertification. Since karst farmland consists mainly of slope fields, conservation measures should address both surface (terracing, rock removal) and subsurface processes.

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Note: Figure translations are in progress. See original paper for figures.