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*Original Paper*

# Research Progress and Outlook on Soil Erosion and Leakage in Karst Regions of Southwest China

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**_Abstract_**

*As the world's largest and most fully developed karst distribution zone, the karst regions of Southwest China possess an extremely fragile ecological environment. Their unique surface-subsurface dual three-dimensional hydrogeological structure results in a distinctive feature of concurrent surface runoff and subsurface seepage, posing a major constraint to regional ecological governance and sustainable socioeconomic development. This paper systematically reviews research progress on soil erosion/leakage in the Southwest Karst region, focusing on the core characteristics of the regional natural environment (poor soil, karst development, concentrated rainfall) and human activities (overcultivation, vegetation destruction, engineering disturbances). It summarizes the primary pathways of soil erosion (surface slope runoff migration, subsurface fissure/pipeline transport) , research methodologies (traditional runoff plot observation, erosion line method, ground-penetrating radar, and application of new techniques like radionuclide tracers), and fundamental findings (contribution quantification, driving factors, relationships with rock desertification and nutrient loss). It also categorizes control technologies including engineering, agricultural, biological measures, and agroforestry models. Building on this foundation, it delves into critical challenges in current research: Controversy persists over primary pathways for subsurface leakage - Multiscale coupling mechanisms of driving factors remain unclear - Proportions of surface-subsurface loss lack consensus - Mechanisms linking soil erosion/leakage to nutrient cycling are understudied Finally, future research directions are proposed, including clarifying leakage pathways, quantifying coupling relationships between drivers, standardizing proportion estimation criteria, and deepening understanding of nutrient* *impact mechanisms. These findings provide scientific references for precise soil erosion control, karst desertification management, and ecosystem restoration in the karst regions of Southwest China.*

***Keywords***

*Southwest karst, soil erosion, subsurface leakage, karst desertification*

## 1. Introduction

The karst regions of southwest China represent the world's largest contiguous distribution zone characterized by the most complete development and the most fragile ecological environment [1]. The unique environmental characteristics of this region have led to deteriorating environmental conditions, ecological fragility, and intensified soil erosion, severely constraining local economic development. Soil erosion has become a global ecological challenge. According to the 2023 national soil erosion dynamic monitoring results, the total area affected by soil erosion in China reached 2.6276 million square kilometers[2]. The karst regions of Southwest China remain among the most severely affected areas in the country. Unlike non-karst regions, the unique hydrological structure of karst areas results not only in surface runoff but also in subsurface seepage. This subsurface soil loss exhibits complexity, concealment, and strong spatio-temporal variability[3], making monitoring and prevention exceptionally challenging. Research on soil erosion in China's karst regions began as early as the 1960s. By the 1990s, the concept of rock desertification was proposed and refined, drawing widespread attention to the erosion status in the Southwest karst area. Entering the 21st century, scholars conducted in-depth studies on the mechanisms and spatiotemporal patterns of soil erosion in karst regions. Subsequently, the mechanisms of karst soil erosion, the causes and hazards of rock desertification, and its management approaches became research hotspots[4-5]. The karst regions of Southwest China represent a key and challenging area for ecological environment governance and government poverty alleviation efforts[6-7] Therefore, clarifying the current state of soil erosion research in these karst regions holds significant scientific importance for rock desertification management, socioeconomic sustainable development, and ecological environment protection in the area.

## 2. Characteristics of Karst Environmental Media in Southwest China

### *2.1 Natural Environmental Features*

China's karst terrain is primarily concentrated in the Southwest Karst Region centered on Guizhou Province, one of the world's three major karst-dominated areas. Soil erosion and water loss in this region are closely linked to its natural environmental characteristics. Firstly, the region possesses a fragile ecological environment. Soils are predominantly calcareous soils formed by the weathering and residual accumulation of carbonate rocks, with clay minerals primarily consisting of kaolinite and vermiculite. Soil formation occurs slowly. There is no transitional C horizon between the soil layer and bedrock, resulting in poor cohesion and affinity between parent rock and soil. The shallow soil profile, low soil volume, weak water retention capacity, and high permeability lead to rapid hydrological processes, frequently causing droughts and floods[8] Second, the southwestern karst region features extensive contiguous areas of exposed carbonate rocks, covering approximately 510,000 km². These hard rocks are susceptible to dissolution during hydrochemical processes, exhibiting the most typical karst development. Furthermore, the region experiences simultaneous rainfall and heat in the southwest, with uneven spatiotemporal distribution of precipitation. Heavy rainfall events occur frequently and intensely, with a high proportion of torrential and extreme downpours[9]. While exacerbating soil erosion, this also promotes the development of underground systems such as karst fissures, sinkholes, dolines, and underground rivers. This unique surface-subsurface -subsurface dual-three-dimensional hydrogeological structure. This dual-pathway soil erosion occurs both at the surface and underground. The highly permeable surface allows nearly all rainfall to infiltrate, entering subterranean karst fissures to join underground rivers or become part of the groundwater system[10]. Finally, the severe rock desertification, vegetation degradation, low productivity, sparse vegetation cover, inherent fragility, high heterogeneity, and distinctive yet markedly variable hydrological processes characteristic of karst regions collectively constitute major factors contributing to soil erosion in the karst areas of Southwest China.

### *2.2 Characteristics of Human Activities*

Soil erosion/leakage in the karst regions of Southwest China results from the combined effects of human activities and natural factors[11], with human activities being the primary driver of accelerated karst erosion. First, since the Ming and Qing dynasties, the Southwest has experienced rapid population growth and increased demands. High land reclamation rates and soil degradation have trapped karst regions in a vicious cycle of population growth → overexploitation → soil degradation → economic hardship[12]. Second, extensive land management practices—including indiscriminate logging, excessive cultivation, and overgrazing—have caused soil fertility decline, poor crop growth, low vegetation coverage, Topsoil erosion, rock exposure, and increased karstification damaged ecosystems, triggering soil erosion and impoverishment. This erosion and impoverishment further accelerated rock desertification, which in turn disrupted soil structure, reduced organic matter and nutrient content, and diminished soil water retention capacity. Finally, the karst regions of Southwest China are rich in mineral resources. Activities such as open-pit mining and road construction have destroyed vegetation. Without the protection of forests and grasses, rainfall directly impacts the soil, causing soil particles to disperse, clog pores, and form crusts. This reduces soil infiltration capacity, intensifies runoff erosion, and weakens the soil's resistance to erosion. This further accelerates ecosystem degradation and soil quality decline[7], intensifying soil erosion and water loss in the karst regions of Southwest China.

## 3. Research Progress

### *3.1 Soil and Water Loss Pathways in Karst Regions of Southwest China*

Soil and water loss refers to the degradation and depletion of soil resources and land productivity caused by natural forces such as hydrological, wind, gravitational, and freeze-thaw processes, as well as human activities. This includes surface soil erosion and water loss [13]. Soil and water leakage represents a unique form of soil and water loss specific to karst regions.

Early studies on soil erosion in karst regions primarily drew upon methodologies from the Loess Plateau, focusing mainly on factors, mechanisms, monitoring, and assessment of surface soil erosion[14], while neglecting the hazards of subsurface loss. Subsequently, scholars both domestically and internationally began to identify groundwater seepage phenomena in karst areas, recognizing subsurface soil loss as a significant component of karst soil erosion. Foreign scholar Jones[15] observed that few lichens attached to limestone surfaces near dissolution gullies, and that limestone surfaces devoid of lichen growth were distributed along the soil-rock boundary. Using lichen-based dating methods, he confirmed that soil subsides and disappears along dissolution gullies. Gosden[16], through studies of lichens and pollen, observed discontinuities in lichen and pollen deposits on rock surfaces, attributing this to soil subsidence along karst fissures. Bell[17] and colleagues, during archaeological research in Ireland, found mineral soils on terraces within limestone regions but not in surrounding areas, confirming soil loss phenomena in limestone areas. In 1963, Chinese scholar Liu Zhigang[18] pointed out that surface soil in karst regions enters underground karst systems via sinkholes under the influence of runoff. Throughout the 1980s and 1990s, only a few researchers continued to focus on groundwater-induced soil erosion in karst areas. It was not until after 2000 that research on karst groundwater soil erosion entered an explosive phase. Jiang Zhongcheng et al.[19], Li Dewen et al.[20], and Zhang Xinbao et al. [21] began investigating evidence, mechanisms, and prevalence of karst groundwater soil erosion, filling some gaps in the field. Subsequently, an increasing number of researchers have successively conducted studies on the mechanisms[22], pathways[23], and conceptual models[24] of groundwater-induced soil erosion.

The dual-dimensional three-dimensional network structure of the soil-water system endows soil erosion with the unique characteristics of both surface runoff and subsurface seepage. Surface soil erosion primarily migrates with slope runoff formed by rainfall. High-intensity rainfall is more likely to cause surface soil erosion. Rainwater from concentrated downpours with high intensity is more readily converted into soil water, altering soil structure and rapidly forming slope runoff. This creates soil erosion channels, leading to sediment loss carried by slope runoff. A portion of slope runoff infiltrates vertically through soils in the karst vadose zone, surface karst zones, and conveyor belts[25]. In low-lying areas, it enters the groundwater system via vertical shafts, conduits, and sinkholes[8]. Primary pathways for subsurface loss include karst fissures or pores formed by chemical dissolution, as well as underground cavities and subterranean rivers created by conduit erosion. Chen Hongsong et al.[26] propose that well-developed fissures in karst regions constitute a significant pathway for subsurface water and soil loss. Surface water and soil resources are susceptible to erosion and migration along these fissures, ultimately entering subsurface spaces and causing soil erosion. Zhang Xinbao[27] argues that subsurface soil loss is the primary factor in the formation of rocky slopes, with relatively high loss rates occurring through fissures (or pores) in the soil. The extent of fissure development and connectivity at their bases influence the magnitude of soil and water loss along fissures. When fissure bases are closed or disconnected from underground spaces, loss is minimal, with fissures largely filled by soil or weathered rock fragments. Conversely, significant loss occurs when connectivity exists[28]. Wei Xingping et al.[29] suggest that at the watershed scale, losses via this pathway are relatively minor. Surface soil rarely infiltrates vertically through fissures to reach the soil-rock interface. Most sediment primarily enters underground river systems through short-distance slope transport, entering via sinkholes and funnels in low-lying areas. Geissen[30] also proposes that significant soil loss underground occurs primarily within sinkholes. The pathways of groundwater-soil leakage are diverse and complex, and remain a subject of ongoing debate.

### *3.2 Soil Erosion Research Methods*

Soil erosion monitoring serves as an effective means for quantitatively assessing erosion conditions within study areas. Conventional monitoring methods employed domestically and internationally primarily include: runoff plot observation, erosion line (pin) method, landform observation, and artificial simulation experiments. These conventional methods involve substantial workload, low efficiency, and lengthy cycles, gradually failing to meet the modern demands for high timeliness, automation, and systematization in soil erosion monitoring. With scientific and technological advancements, soil erosion research methods have continuously evolved, with monitoring precision advancing from qualitative to semi-quantitative, quantitative, and precise quantitative levels. Advanced techniques such as ground-penetrating radar, underground river outlet monitoring, radionuclide tracers, and magnetic susceptibility measurements enable researchers to conduct more precise and efficient studies.

Given the multitude of soil erosion research methods, selecting an appropriate approach requires comprehensive consideration of the study area's specific characteristics—such as spatial scale, climate, hydrology, topography, vegetation, and land use patterns—alongside task requirements including time constraints, cost, and precision.

#### 3.2.1 Traditional Methods

Runoff Plot Observation: This is a classic method for measuring soil loss. However, constructing plots in rocky desertification areas with numerous bedrock outcrops faces certain limitations, and some sites may be unsuitable for construction. By measuring soil loss in each runoff plot after every rainfall event and summing the losses from all rainfall events within a year, the annual soil erosion rate for the study plot can be determined.

Erosion Line (Pin) Method: Primarily applied in plots with high bare rock coverage, this method involves installing 6–9 erosion lines (pins) per plot. It is operationally convenient and fully utilizes exposed bedrock. The erosion line method involves carving reference lines on rock surfaces, while the erosion pin method involves placing calibrated iron pins on slopes, rills, or gullys. Regular observations of the height difference between the reference lines/pins and the soil surface measure the vertical depth of soil erosion or deposition. By monitoring erosion thickness at different times throughout the year across each plot, the soil erosion volume for representative plots can be calculated. The formula for converting soil erosion depth to loss volume is:

$$\Delta \mathrm{h}=\frac{0.001M}{\gamma.(1-\mathrm{k})} \tag{1}$$

$\Delta h$ = Soil erosion depth (mm)

$M$ = Soil loss volume per unit area (t/km²)

$\gamma$ = Soil bulk density (g/cm³), based on the average value across all demonstration areas during the monitoring year

$k$ = Bare rock ratio of the sample plot

Landform Observation Method: Utilizing differences in soluble rock surface and subsurface dissolution patterns, this method provides a rough calculation of average annual soil erosion thickness. The soil erosion modulus for a sample plot is determined through runoff sub-basin and erosion line (pin) methods. The formula for converting this to a regional soil erosion modulus is as follows:

$$\mathrm{M_s}=M_{si}f_i\frac{M_{si}A_i}{\mathrm{A}} \tag{2}$$

$$f_i=\frac{A_i}{\mathrm{A}}\mathrm{M_s M_{si} F_i} \tag{3}$$

$M_s$ = Regional soil erosion modulus

$M_{si}$ = Soil erosion intensity at each level within the region

$f_i$= Area proportion of soil erosion intensity at each level within the region

$A_i$= Area of erosion at each level

$A$ = Total area of the region

Artificial Simulation Experiment Method: Artificial simulation experiments are conducted in test steel channels with adjustable slopes and underground pore (fracture) spaces. These channels are filled with soil and rocks are arranged at specific intervals to simulate karst exposed slope farmland. By simulating rainfall, the impact of rainfall intensity on nutrient loss in slope runoff is studied. The effects of rainfall intensity, slope gradient, rock exposure rate, and fissure density on subsurface runoff and sediment generation were analyzed[31].

Conventional methods, characterized by high labor intensity, low efficiency, and lengthy cycles, are increasingly unable to meet the demands of modern soil erosion monitoring for high timeliness, automation, and systematization.

### 3.2.2 Detection and Application of New Technologies

Ground Penetrating Radar (GPR): Currently, the application scope of GPR has expanded from relatively homogeneous geological environments, such as ice layers and salt layers, to fields including road defect inspection, underground pollutant detection, soil moisture content measurement, shallow groundwater level depth assessment, and soil thickness determination. Terrestrial Laser Scanning (TLS) employs close-range observation and static data collection [32], generating higher-resolution and more accurate 3D models[33], making it more suitable for monitoring small-scale plots or point locations[34].

Continuous Monitoring Method for Underground River Outlet Cross-Sections: Monitoring at underground river outlets involves installing automated sampling equipment—such as water level gauges, turbidity meters, water quality analyzers, and samplers—or conducting on-site collection and analysis of river water's hydrochemical characteristics[35] to reflect sediment transport patterns. Sediment carried in underground river water originates from underground leakage, and the hydrochemical characteristics of the water can partially reveal the leakage process.

Nuclear Tracer Method: In the 1960s, the United States began employing$^{137}$ Cs tracer technology for soil erosion research. This technique was introduced to China in the 1980s. Zhang Xinbao et al. [36] applied $^{137}$Cs tracer technology to measure soil erosion rates in cultivated land, demonstrating that the $^{137}$Cs tracer method effectively reflects erosion levels in agricultural soils. The $^{137}$Cs nuclear dust in the surface environment primarily originates from atmospheric nuclear tests conducted between the 1950s and 1970s, with a half-life of 30.1 years. This $^{137}$Cs nuclear dust mainly settles onto the surface with precipitation and is subsequently adsorbed by soil particles. After adsorption, the migration of $^{137}$Cs primarily occurs alongside the movement of the adsorbing soil particles. Beyond single-nuclide tracing techniques, most scholars employ combined multi-nuclide tracing to monitor soil erosion processes, thereby mitigating the impact of variability in single nuclides on tracing results [37]. In larger watersheds, multi-nuclide composite tracing facilitates a clearer understanding of current soil erosion conditions and the identification of sediment sources, ultimately enhancing research accuracy.

Rare Earth Element Tracer Technique: Rare earth element tracers are deployed on the upper surfaces of typical fractures. Under natural rainfall conditions, this method investigates the transformation characteristics of fractured soil at the rock-soil interface and within fractured soil profiles. This approach holds significant potential for revealing the migration patterns of fractured soil particles within profiles. Since the dissolution of fractured rock provides space for the loss of overlying soil, measuring the annual dissolution rate of circular carbonate rock specimens of known area and mass allows direct estimation of the annual loss rate per fracture[38].

Magnetic susceptibility: Since the introduction of soil magnetism at the Fifth International Soil Congress in the mid-20th century, research on its principles has increased. Generally, undisturbed soil profiles exhibit enhanced surface magnetic susceptibility, and soil magnetic susceptibility levels correlate significantly with pedogenic environments[39]. On eroded slopes, soil magnetic susceptibility changes due to particle erosion, transport, and deposition. Therefore, by leveraging the heterogeneity of soil magnetic susceptibility across slopes and profiles, it is possible to reconstruct long-term temporal sequences and large-spatial-scale processes of soil erosion and redistribution.

### *3.3 Advances in Fundamental Research on Surface Erosion and Subsurface Seepage*

#### 3.3.1 Quantitative Studies on Contributions to Surface and Subsurface Seepage

Subsurface seepage in karst regions is difficult to observe directly, and existing research cannot yet precisely determine the contribution rates of surface runoff and subsurface seepage to total water loss in these areas. Utilizing multiple techniques including field monitoring, isotope tracing, and monitoring of sediment sections in underground rivers, scholars have investigated the contribution rates of surface runoff and subsurface seepage in karst regions. Although some research results exist, the conclusions reached vary significantly. Some scholars argue that subsurface seepage dominates soil loss in karst areas, while others contend that subsurface seepage accounts for only a small proportion of water and soil loss in karst regions.

**Table 1. Contribution Rates of Surface Loss/Underground Leakage (Surface Loss as the Main Body)**

| Researchers | Region | Method | Contribution Results |
|---|---|---|---|
| He Yongbin [40] et al. | Typical small watershed of Maolan Engineering Monument grassland, Guizhou | $^{137}$Cs ratio method | Surface: 70.13%Underground: 29.87% |
| Wei Xingping [29] et al. | Karst trough valley area, Chongqing | $^{137}$Cs ratio method | Surface: 75%Underground: 25% |
| Wei [41] et al. | Mudu watershed, Chongqing | $^{137}$Cs ratio method | Underground leakage rate: 4.5% |
| Li Jin [42] et al. | Wangjiazhai small watershed, Guizhou | Observation of river discharge and sediment concentration at the outlet section of underground river | Surface: 99.19%Underground: 0.81% |
| Li [43] et al. | Huanjiang Karst Monitoring Station, Guangxi | Composite fingerprint identification technology combined with multivariate mixing model calculation | Surface: 77.9%Underground: 22.1% |

**Table 2. Contribution Rates of Surface Loss/Underground Leakage (Underground Leakage as the Main Body)**

| Researchers | Region | Method | Proportion Situation |
|---|---|---|---|
| Peng Xudong [44] | Karst plateau slope, Guizhou | Artificial simulated rainfall | Leakage rates under different conditions: 53.1%~100%, 58.1%~89.6%, 32.1%~58.9%, 50.8%~85.33% |
| Wang Kelin [45] et al. | Reservoir of Huanjiang Karst Station, Guangxi | $^{137}$Cs ratio method | Surface: 12%Underground: 88% |

| | | | |
|---|---|---|---|
| Luo Weiqun [46] et al. | Slope of Longhe Shangfengcong depression, Guangxi | Mathematical model method | Underground leakage accounts for more than 75% in 4 geomorphic positions (peak top, mid-slope, gentle slope and slope foot); surface soil loss accounts for 61.32% at the depression bottom |
| Luo [47] et al. | Two typical karst areas (Puding and Zhenfeng), Guizhou | Anatomy and age determination of exposed tree roots and buried tree roots | Surface: 33.33%Underground: 66.67% |
| Cheng [48] et al. | Chenqi small watershed, Puding, Guizhou | Composite fingerprint identification technology combined with $^{137}$Cs and magnetic susceptibility | Contributions of underground soil to suspended sediments at the outlets of surface rivers and underground rivers account for 62% and 68% respectively |
| Zhang Xinbao [49] et al. | Maolan Karst Forest Reserve | Material balance relationship of silicate minerals in soil | Surface: 20%Underground: 80% |
| Yang Qian [50] | Sahaxi plateau mountain, Bijie, Guizhou | Field monitoring of runoff plots | Surface: 16.42%Underground: 83.58% |

Previous studies have failed to reach a unified understanding regarding the extent of underground seepage and its pathways. Differences in methodologies for studying soil erosion have yielded varying results for both surface runoff and underground seepage volumes. Compounded by the complexity and high heterogeneity of karst's dual-flow erosion structure, along with the immaturity of monitoring techniques, these factors have led to significant discrepancies in findings. To date, the question of whether underground seepage dominates soil erosion in karst regions remains unresolved.

### 3.3.2 Drivers of Surface and Subsurface Runoff

Precipitation, fissures, soil aggregates, rock desertification intensity, and land use practices significantly influence surface-subsurface soil erosion. Multi-factor interactions can amplify the impact of individual factors on soil erosion.

Rainfall: Under natural conditions, rainfall is the primary driver of runoff and sediment generation. Rainfall is initially intercepted by forest vegetation, then absorbed by surface soil and litter layers upon reaching the ground. As surface soil infiltration rates decrease, rainwater either percolates through soil layers into groundwater or forms surface pools. Liu Bingzheng et al. [51] noted that surface soil only generates seepage flow through over saturation when rainfall intensity exceeds soil infiltration rates. Due to soil water-holding capacity, a certain lag exists between runoff and sediment generation [52]. Li Yanqiu et al. [53] observed that under heavy rainfall conditions, underground runoff increases initially and then stabilizes across different slopes. Furthermore, the inflection point of underground runoff typically occurs during the early rainfall phase. They also noted that under light rainfall conditions (less than 30 mm/h), no surface runoff forms on bare slopes, with underground runoff being the primary component. Gan Yixian et al. [54] observed that at fixed rainfall intensity and slope gradient, underground runoff volume increased initially and then stabilized over rainfall duration across different fissure degrees, while underground sediment yield increased initially and then decreased over rainfall duration. Fu Wenbing et al. [55] observed that at a rainfall intensity of 80 mm/h, the underground runoff process at five fissure degrees all showed a slow increase trend with rainfall duration. At a rainfall intensity of 50 mm/h, the underground runoff process at five fissure degrees all showed a trend of first increasing and then decreasing with rainfall duration.

Fissures and Soil Aggregates: Due to their unique geological structure and karstification processes, carbonate rocks develop fissures of diverse morphologies that provide migration pathways for water and soil leakage. Slope erosion coupled with fissure soil creep or collapse constitutes the primary mechanism of soil loss in karst regions. Existing research indicates that soil and water loss rates in karst regions are closely correlated with the development and connectivity of karst fissures. Soil and water loss volumes show a positive correlation with karst fissure width or density. Additionally, soil aggregate stability or shear strength also influences soil and water loss volumes. YAN et al. [56] suggest that reducing underground fissure density is a direct method to control soil loss. Influence of Water Pressure: Under rainfall conditions, soil becomes saturated and saturated, reducing its shear strength and gradually approaching a flow-plastic state [57]. This causes soil overlying karst fissures to creep under gravity and enter the underlying fissures. Influence of Fissure Width: Wider fissures facilitate the fall of larger soil aggregates, more readily forming stable interconnected pathways. The shorter the time required to penetrate the soil layer, the lower the corresponding water pressure needed, and the soil loss rate more readily approaches its steady state. Furthermore, the greater the peak soil loss rate and cumulative loss volume, the earlier the peak occurs. Influence of Soil Aggregate Particle Size: When the overlying soil layer remains intact, finer soil aggregates are more readily eroded by water flow [58], resulting in higher soil loss rates and cumulative losses. Additionally, soils with smaller aggregate particles exhibit smaller pore diameters and greater hydraulic resistance, making the overlying layer more susceptible to penetration under hydrostatic pressure. and the karst fissure width required to penetrate the soil layer is smaller. Smaller soil aggregate particle size also results in a relatively longer time required for the soil loss rate to stabilize.

Intensity of Rock Desertification: Karst vegetation is dominated by lithophytic communities that exhibit poor growth and weak water retention capacity within the soil system. Once degraded, this vegetation struggles to recover, readily accelerating soil erosion. Human activities such as deforestation and slope cultivation are primary drivers of modern soil loss and increased rock exposure[59]. Bare bedrock exposure causes uneven distribution of runoff and sediment both on the surface and underground, making it a key factor in the complex soil erosion processes and mechanisms in karst regions. Surface water and sediment yield exhibit a fluctuating pattern with increasing bedrock exposure—initially increasing then decreasing—while underground water and sediment yield first decrease and then increase with increased bedrock exposure[60].

Land Use: Zhang Yushan's[61] research indicates that soil erosion rates under different land uses follow the sequence: cultivated land > grassland > other forested land > sparse forest land > shrubland > forested land. Soil erosion rates on cultivated land and grassland are significantly higher than other land types. Overall, forested land exhibits low soil erosion rates. However, compared to forested, shrub, and sparse woodland areas, other forested land shows markedly higher erosion rates. Construction land and unutilized land possess negligible soil for erosion, resulting in near-zero erosion rates. Findings indicate that cultivated land and grassland are the most erosion-prone land types in Guizhou, with other forested land also exhibiting relatively high erosion rates.

### 3.3.3 Relationship Between Soil Erosion and Rock Desertification

In terms of rock desertification intensity, soil erosion intensity increases with the progression of rock desertification, indicating a mutually reinforcing relationship between soil erosion and rock desertification. Yang Qian's[50] research reveals that under identical land use patterns, the soil erosion modulus in areas with potential rock desertification is lower than that in mildly rock-desertified areas, whether considering surface runoff or subsurface seepage. The surface erosion modulus and subsurface erosion modulus in mildly rock-desertified runoff sub-basins are 1.18 times and 1.05 times higher, respectively, than those in potential rock-desertified runoff sub-basins. reflecting that the degree of karst desertification is a key factor influencing soil erosion in karst regions. Research by Luo Weiqun et al.[62] indicates that both the erosion modulus of surface erosion and the contribution rate of subsurface seepage in mildly karstified areas exceed those in potentially karstified areas. This suggests a synergistic relationship between soil erosion intensity and desertification severity within the study region, where soil loss increases with intensifying desertification. Moreover, karst regions feature extensive areas of exposed bedrock and desertified surfaces, directly manifesting as drought, flooding, and soil erosion/leakage. Soil erosion/leakage is the most direct factor influencing karst desertification, while desertification itself represents the ultimate outcome of soil erosion/leakage—progressing to the point where no soil remains to erode. Soil erosion influences the occurrence and development of rock desertification, while the progression of rock desertification similarly impacts the outcomes of soil erosion.

#### 3.3.4 Soil Erosion and Nutrient Loss

Soil nutrients influence soil structure formation, regulate soil water retention capacity, and suppress the occurrence of soil erosion/leakage[63]. In karst regions, soil erosion is accompanied by nutrient loss, and soil stability is significantly influenced by soil nutrients. Under the disturbance of soil erosion, variations and losses in soil nutrient content occur, leading to changes in soil stability [64]. In karst regions, slope runoff generated by rainfall serves as the primary vehicle for soil nutrient loss. Soil nutrients typically enter runoff in two forms: dissolved nutrients, which dissolve into soil solution and enter surface runoff through processes like water exchange; and adsorbed nutrients, which bind to soil particle surfaces and enter surface runoff via desorption or entrainment with eroded sediment. Loss pathways are generally categorized into three types: first, soluble nutrients transported via runoff; second, nutrients contained within eroded sediment; and third, nutrients lost through subsurface seepage. For example, nitrogen: soil total nitrogen, representing the sum of all nitrogen forms, exhibits a strong response to soil erosion. Its loss occurs primarily through two pathways: first, nitrogen in sediment is transported via surface runoff; second, nitrogen dissolves into runoff and subsurface flow, causing significant soil nitrogen depletion. Research by Wang Zhangwen et al. indicates that long-term soil and water conservation measures increase soil nitrogen content by 34%–65%. Organic Carbon: Soil represents the largest carbon reservoir in terrestrial ecosystems. Surface organic carbon (SOC) in karst calcareous soils is particularly susceptible to loss, typically transported alongside sediment. Soil organic carbon loss in sediment accounts for 85% of total losses[65]. Soil erosion triggers the migration and redistribution of soil organic carbon (SOC), altering its spatial distribution. This occurs as erosion detaches SOC from its original location, directly causing loss. During migration, eroded carbon may undergo mineralization and decomposition. Once deposited, the nature of the carbon and sedimentary environment further influence carbon budget changes.

### *3.4 Soil and Water Erosion/Loss Control Technologies and Models*

Effective control measures not only prevent soil and water erosion and loss in karst regions but also enhance water resource utilization efficiency, facilitate vegetation restoration, and promote ecosystem recovery in rock desertification areas. The primary forms of erosion/loss control involve water interception and nutrient retention. Existing control technologies mainly fall into three categories: engineering measures, cultivation practices, and biological methods.

Engineering control measures primarily involve terraced slope conversion, check dams, fish-scale pits, small-scale water storage and drainage projects, and sedimentation ponds. Their principle is to alter terrain to prevent slope erosion and increase infiltration by intercepting and storing surface runoff, or directly storing surface runoff for utilization.

Terrain cultivation control measures include contour farming, level-trench planting, contour strip intercropping, ridge-furrow farming with reduced tillage, and no-till farming. These alter surface roughness and microtopography to reduce rainfall runoff, enhance soil permeability, water retention, and erosion resistance, thereby improving soil quality.

Biological control measures primarily involve returning farmland to forests and grasslands, mountain closure for afforestation, artificial vegetation restoration, and other soil and water conservation forestry and grassland measures. Examples include expanding green manure cultivation, exposed rock outcrop vegetation barrier techniques, and staggered slope vegetation barrier techniques. These methods work by leveraging vegetation's role in redistributing rainfall, reducing raindrop kinetic energy, and, crucially, improving soil properties. This manifests as enhanced soil permeability, water retention capacity, and resistance to erosion and dispersion, thereby reducing surface soil and water loss.

Integrated management models include: ecological resettlement-mountain closure-natural vegetation restoration; farmland-to-forest conversion-water retention-soil conservation-artificial afforestation-vegetation restoration; and intercropping techniques for medicinal-grain-oil crops.

Research on agroforestry retention techniques has been extensive in karst regions of Southwest China. Jing Jiansheng's[28] findings indicate that plant water retention technology in agroforestry systems enables plant root systems to effectively improve soil structure, increase soil porosity, enhance soil water-holding capacity, and achieve plant water retention effects. The spatial interception technology of agroforestry vegetation can be combined with locally suitable plants to form diverse vertical spatial structures through tall tree layers, medium-to-tall shrub or crop layers, and low herbaceous layers. This causes rainfall to sequentially pass through tree, shrub or crop, and herbaceous layers during descent, prolonging the time it takes for rain to reach the soil and slowing the rate of soil moisture replenishment. This reduces rainfall's impact on soil erosion and splash erosion. Intercropping of agroforestry plants enables rational and efficient spatial utilization. Different plant types effectively improve fissured soil structure, absorb and utilize fissured soil moisture, and enhance soil erosion resistance. Gu Xing[66] proposed three optimized structural configurations for agroforestry plant communities to mitigate soil and water loss, demonstrating their effectiveness through field trials. Findings indicate that increasing surface vegetation cover, combining deep- and shallow-rooted plants, and rationally utilizing soil space can fully absorb soil moisture, improve soil structure, and enhance water retention and soil stability. Wu Chenxu[67] revealed the mechanism by which soil cover in karst agroforestry systems controls soil erosion and water loss. The study clarified that soil cover suppresses karst desertification primarily by increasing coverage to reduce soil erosion, thereby achieving the goal of controlling soil erosion and water loss.

## 4. Issues and Outlook

### *4.1 Primary Pathways for Underground Leakage*

Current understanding of water and soil leakage mechanisms and pathways in karst regions remains limited. Despite significant scholarly attention, substantial controversy persists. Feng Teng et al.[68], analyzing the distribution of $^{137}$Cs in fissure profiles of typical peak cluster slopes in northwest Guangxi, concluded that downward migration of soil particles within fissures is minimal. In contrast, Peng Xudong [44] posits that soil loss primarily occurs through subsidence and bulk creep within pores (fissures) and underground conduits. Luo Weiqun et al.[46] employed mathematical modeling to determine that soil loss in the upper peak cluster depressions of the Long River in Guangxi primarily occurs through sinkholes converting into underground river conduits; Xiong Kangning et al.[69] and Cao Jianhua et al.[70] proposed that soil primarily migrates downward through sinkholes and funnels into subterranean rivers, with only a minor portion lost through rock fissures, conduits, and cavities into the subsurface. Yang et al.[71] and Dai et al.[31], through field monitoring and laboratory simulations, demonstrated that underground pipeline leakage constitutes the primary mode of soil loss in karst desertification areas, surpassing surface runoff in severity. In summary, numerous scholars have conducted research on the primary pathways of underground soil loss in karst regions of Southwest China, achieving certain results. However, the debate over whether sinkholes, fissures, or other mechanisms dominate underground soil loss in karst areas remains ongoing, and the underlying mechanisms of underground soil loss are still unclear. Therefore, future research requires further in-depth investigation.

### *4.2 Driving Factors of Soil and Water Loss*

Current research has identified rainfall, fissures, soil aggregates, karstification intensity, and land use patterns as key drivers of soil and water loss in karst regions of Southwest China. Interactions among multiple factors amplify the erosion effects, yet research remains incomplete. Existing studies predominantly focus on the isolated effects of single or dual factors, lacking quantitative analyses on complex multi-factor interactions. The contribution weights and coupling relationships of various factors across different spatiotemporal scales remain unclear; for instance, the synergistic impact of rainfall and fissure development has not been systematically validated.

Research predominantly addresses short-term factor responses, while studies on long-term factor evolution and cumulative effects remain weak. Dynamic driving mechanisms under global climate change and human interventions remain poorly understood. Additionally, potential factors such as karst hydrochemical processes and soil microorganisms have not been incorporated into research frameworks, resulting in incomplete understanding.

Future research should integrate long-term fixed-site monitoring, laboratory simulations, and modeling to quantify multi-factor coupling mechanisms and their relative contributions. It should track the dynamic evolution of driving factors, broaden research scope, and establish a more comprehensive framework of driving mechanisms.

### *4.3 Proportion of Surface Runoff vs. Groundwater Seepage*

The complex three-dimensional hydrogeological structure of karst regions renders the proportion of surface runoff versus groundwater seepage highly intricate, with current studies failing to reach a unified conclusion. Significant discrepancies exist among different studies: some indicate surface runoff dominates, with underground seepage accounting for only 0.81%–29.87%; others suggest underground seepage is the primary pathway, reaching up to 100%.

These divergences stem from regional heterogeneity, methodological limitations, and inconsistent definitions of underground seepage. Existing estimation methods all have shortcomings and are mostly concentrated at the small watershed or slope scale, with a lack of regional-scale studies and insufficient understanding of the dynamic changes in the proportion.

Future efforts should first standardize the definition of subsurface seepage, develop estimation techniques that integrate multiple methods, strengthen comparative studies at different scales, and conduct long-term dynamic monitoring to reveal the proportional relationships and evolution trends, thereby providing support for differentiated prevention and control measures.

### *4.4 Impact of Soil Erosion/Leakage on Nutrients*

Soil nutrient deficiency is prevalent in karst regions of Southwest China, where soil erosion/leakage exhibits a close coupling relationship with nutrient loss. However, systematic research on the underlying mechanisms remains limited. Existing research confirms that rainfall runoff is the primary vehicle for nutrient loss, with nutrients being lost in dissolved and adsorbed states through three pathways: surface runoff, sediment transport, and subsurface leakage. However, investigations into nutrient migration efficiency and transformation patterns across different pathways remain insufficient. For instance, the effects of fissure characteristics and karst hydrochemical environments on nitrogen and phosphorus transformation remain unclear.

Current research predominantly focuses on the unidirectional loss effects of soil erosion/leakage on nutrients, with insufficient quantification of feedback mechanisms where nutrient depletion leads to soil structure degradation and subsequent erosion intensification. Additionally, systematic studies on the spatial variation of nutrient loss at regional scales and its long-term ecological effects are lacking. The regulatory mechanisms of nutrient retention by different soil and water conservation measures also remain fragmented.

Future research should integrate techniques like isotope tracing to uncover nutrient migration patterns, quantify bidirectional feedback mechanisms, and conduct optimization trials for soil conservation measures. This will provide essential support for achieving synergistic soil erosion control and soil fertility enhancement.

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