Identification of Watershed Soil Erosion Risk Patterns Based on Source-Sink Landscape Units (Postprint)

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Abstract

Land use and its landscape patterns under human activity influences affect, to a certain extent, the occurrence and development of watershed soil erosion. The Qijiang River Basin, located in the Three Gorges Reservoir Area, was selected as the study area. Using 2015 aerial imagery data, a digital elevation model, and a soil database, hydrological response units were delineated to serve as source-sink landscape units for the study area. Integrating the contributions of landscape type, soil, and slope to soil erosion impacts, weights for source-sink landscape units were constructed. Based on this, the landscape spatial load contrast index was modified and soil erosion risk patterns were identified. Finally, the Revised Universal Soil Loss Equation was used to simulate soil erosion, thereby validating the rationality of the risk patterns, and comprehensively analyzing the spatial characteristics of source-sink landscapes: the compositional structure of source-sink landscape units, their weights, and soil erosion risk. The results indicate: (1) Areas with high source-sink landscape unit weights are mainly distributed in the transition zone from mid-low mountainous areas to low hilly gentle slope regions, characterized by relatively steep slopes and high soil erodibility. Source-sink landscape units of paddy fields, dryland, and residential areas are also relatively concentrated in distribution. (2) The landscape spatial load contrast index of each sub-watershed shows a significant positive correlation with the average soil erosion modulus. Therefore, the landscape spatial load contrast index based on source-sink landscape units with assigned weights can effectively reflect soil erosion patterns within watersheds and serve as an effective method for watershed soil erosion risk assessment. (3) Based on the characteristics of the landscape spatial load contrast index of each sub-watershed, the Qijiang River Basin in the reservoir area can be divided into five major soil erosion landscape risk zones: the northern riparian area has relatively concentrated cultivated land distribution in each sub-watershed with relatively short flow paths and less forest-grassland, resulting in high soil erosion risk; the

central hilly region has relatively dispersed source landscape unit distribution with unbalanced spatial landscape distribution, posing certain soil erosion risks; the southern mid-low mountainous area is dominated by forest land sink landscape distribution with relatively small source landscape distribution, resulting in lower soil erosion risk.

Full Text

Identification of Soil Erosion Risk Patterns in a Watershed Based on Source-Sink Landscape Units

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Abstract

Land use and its landscape patterns under anthropogenic influence affect the occurrence and development of soil erosion in watersheds. This study selected the Qijiang watershed in Jiangjin District of the Three Gorges Reservoir Region (TGRR) as the research area. Hydrological response units were delineated as "source-sink" landscape units using 2015 aerial imagery, digital elevation model (DEM) data, and a soil database. The soil erosion weight of the "source-sink" landscape units was assigned by combining landscape type weight, soil erodibility weight, and slope weight. Based on this, the location-weighted landscape index (LWLI) related to relative flow path was calculated to identify soil erosion risk patterns. Finally, the revised universal soil loss equation (RUSLE) was used to simulate the soil erosion modulus and verify the rationality of the risk patterns. The results showed that: (1) Paddy fields and dry land in the source landscape, and woodland in the sink landscape were dominant in the spatial structure of the "source-sink" landscape units, followed by residential areas in the source landscape and grassland in the sink landscape, with distinct area characteristics identified in the Qijiang watershed. (2) Regions with higher soil erosion weight of landscape units were mainly located in the transition zones from low mountainous areas to gentle hilly slopes, where slope and soil erodibility were higher. Source landscape units of paddy field, dry land, and residential area were also concentrated. (3) The soil erosion modulus was positively correlated with the LWLI ($r = 0.92$, $p < 0.05$), indicating that the LWLI could correctly reflect the effect of source and sink landscapes on soil erosion and could be used as a valid tool to evaluate the potential risk of soil erosion. According to the characteristics of the LWLI, five landscape risk zones for soil erosion were delineated in the reservoir area of the Qijiang watershed. In the northern region along rivers, cultivated land was more concentrated than woodland and grassland, with a shorter relative flow path, resulting in greater soil erosion risk. In the central hilly region, the distribution of source landscape units was more decentralized and unbalanced, indicating a certain soil erosion risk in sub-watersheds. In the southern low mountain region, woodland was the dominant landscape, the amount of source landscape was relatively less, and the soil erosion risk was lower.

Keywords: source-sink landscape; hydrological response unit; soil erosion; location-weighted landscape index; Three Gorges Reservoir Region

1. Introduction

Soil erosion is a process triggered by natural factors and intensified by human activities, particularly land use practices [1-4]. Numerous studies have demonstrated that a coupling relationship exists between land use landscapes and soil erosion. Haycock and Muscutt [5] suggested that the effectiveness of buffer strips in mitigating sediment input to rivers depends on landscape type and proper design. Uuemaa et al. [6] argued that landscape metrics are determined by pixel size, terrain scale, and land use classification, making it impossible to isolate the impact of land use patterns on soil erosion from landscape index effects based on FRAGSTATS. This indicates that simple landscape pattern index analysis cannot adequately reveal the coupling relationship between landscape patterns and soil erosion processes [6].

The source-sink landscape theory has been proposed to organically link landscape patterns with ecological processes [7-10]. Based on ecological functions, landscape types are classified into source and sink categories for the soil erosion process. Source landscapes, such as cultivated land and residential areas, promote soil erosion, while sink landscapes like forest land and grassland inhibit it [7-8]. The proposal of source-sink landscapes can effectively integrate areal landscape patterns with point monitoring data, enabling quantitative research on the relationship between watershed landscape patterns and ecological processes [11]. This approach has been applied in water pollution [12-15] and soil erosion studies [9, 16-17].

However, previous research has often assigned soil erosion weights to land use types based solely on subjective experience or the soil erodibility factor in soil erosion equations [18-20]. For landscape units, in addition to land use spatial heterogeneity, terrain and soil also exhibit spatial heterogeneity, affecting the spatial variation of soil erosion risk within landscape units [21]. Therefore, the delineation of source-sink landscape units and their weight assignment must consider not only land use type distribution but also terrain and soil type differences. Hydrological response units (HRUs) are integrated geographic units with similar terrain distribution, soil conditions, and land use patterns [22-23]. Thus, this study introduces HRUs as source-sink landscape units for soil erosion risk identification in the Three Gorges Reservoir watershed.

Using aerial imagery covering the Qijiang watershed in the Three Gorges Reservoir area, this study interprets source-sink landscape types, delineates source-sink landscape units based on HRUs, evaluates unit weights, constructs a modified location-weighted landscape index, and identifies watershed soil erosion risk patterns. The modified universal soil loss equation is then used to simulate soil erosion modulus for validation. This provides a scientific basis for soil erosion prevention and management planning in the reservoir area.

2. Study Area

The study area is the Qijiang watershed in Jiangjin District, Chongqing Municipality, located at the tail end of the Three Gorges Reservoir Region. Qijiang River is a primary tributary of the Yangtze River, with Sunxi River as its first-order tributary. The main rivers include Qijiang, Feilong River, and Fuxing River. Based on the land use master plan of Jiangjin District (2006-2020), land use regional development zoning, and geomorphological characteristics, the area is divided into three zones: northern riverine area, central hilly area, and southern low mountainous area.

The watershed lies in a subtropical monsoon climate zone with an average annual temperature of 18.7°C and average annual precipitation of 1040.1 mm, concentrated in May-September (68.9% of annual precipitation). Vegetation is dominated by subtropical evergreen broadleaf forest, followed by deciduous broadleaf forest and warm coniferous forest. The topography is mainly mountainous and hilly, with terrain gradually transitioning from flat dams and low hills in the north, through low and deep hills in the center, to more mountains and less flat land in the south. Land use problems include scarce per capita land resources, low land productivity, limited reserve resources for agricultural land, difficult development, and large soil erosion areas.

[Figure 1: see original paper] Digital elevation and geographical position of Qijiang watershed in the Three Gorges Reservoir Region

3. Data Sources

Data sources include: 1. **Remote sensing imagery**: 1 m resolution digital orthophoto map from 2015 aerial imagery (black and white) provided by Jiangjin District Land Resources and Housing Administration, with sampling interval of 1 m in GeoTIFF format. Background values were removed and the image was spatially clipped to the study area. 2. **DEM data**: From China Western Data Center, processed using ArcGIS spatial analysis to extract slope. 3. **Soil data**: 1:1,000,000 soil type distribution map from Nanjing Institute of Soil Science, Chinese Academy of Sciences, and soil particle size data from Chongqing' s second soil census. Soil erodibility was calculated using the EPIC model formula from the SWAT2012 user manual [25]. 4. **Hydrological data**: River network database from the Upper Yangtze River (Earth System Science Data Sharing Network Southwest Mountain Sub-center), extracted to obtain the study area' s water system distribution. 5. **Climate data**: Daily dataset (1981-2010) from China Meteorological Data Network and local meteorological station data from

Chongqing Meteorological Bureau. 6. **Enhanced Vegetation Index (EVI)**: 250m resolution monthly composite product from TERRA MODIS (MOD13Q1) via the International Scientific Data Mirror Site of the Chinese Academy of Sciences Computer Network Information Center.

All data were geometrically registered and resampled to a unified 250 m resolution in Albers projection using ArcGIS.

4. Methods

4.1 Source-Sink Landscape Classification and Interpretation Different landscape types have varying effects on water and sediment transport processes. Based on source-sink landscape theory, source landscapes promote soil erosion while sink landscapes inhibit it. In this study, paddy fields, dry land, and residential areas are classified as source landscapes, while forest land and grassland are sink landscapes.

The 2015 source-sink landscape pattern extraction involved: (1) geometric correction and image mosaicking of remote sensing imagery; (2) field surveys and farmer interviews along three routes to establish interpretation keys based on image tone, topography, and place names; (3) human-computer interactive interpretation and patch delineation; and (4) field verification and correction of interpreted patches.

4.2 Source-Sink Landscape Unit Delineation Traditional landscape pattern analysis uses land use patch mosaic units, but single land use units cannot adequately reflect the coupling relationship between landscape patterns and soil erosion processes. The Hydrological Response Unit (HRU) in SWAT model integrates land use, soil, and slope characteristics, representing areas with relatively uniform underlying surface features [22-23]. Therefore, this study uses HRUs as source-sink landscape units.

The delineation process involved: (1) creating SWAT database by matching source-sink landscape types and soil types with SWAT model databases; (2) delineating sub-watersheds and outlets using the Watershed Delineation module in SWAT 2012, with the Qijiang River mouth into the Yangtze as the final outlet; (3) determining watershed area thresholds based on matching with actual river networks, resulting in 25 sub-watersheds; and (4) overlaying source-sink landscape types, soil type raster maps, and reclassified slope to generate source-sink landscape units.

4.3 Location-Weighted Landscape Index (LWLI) The LWLI was developed to measure landscape spatial patterns by considering relative distance, relative height, and slope to the watershed outlet using the Lorenz curve formula. However, this original formulation has limitations as it doesn' t fully incorporate hydrological significance.

4.4 Modified Location-Weighted Landscape Index (MLWLI) Soil erosion involves water and sediment transport along flow paths. Compared to relative distance, elevation, and slope, flow path is more hydrologically meaningful [26]. Therefore, this study modifies the LWLI by using relative flow path to the sub-watershed outlet:

$$MLWLI = \log \left(\frac{\sum_{i=1}^{M} WI_i \cdot dAI_i}{\sum_{j=1}^{N} WJ_j \cdot dAJ_j} \right)$$

where: - $MLWLI$ is the modified landscape spatial load contrast index - WI_i and WJ_j represent the soil erosion weights of the ith unit of landscape type I and jth unit of landscape type J - dAI_i and dAJ_j are the cumulative area proportions - PI and PJ are the total area proportions - M and N are the numbers of units - D represents the flow path length to the watershed outlet, calculated using ArcGIS hydrological analysis tools

The MLWLI indicates that when source landscape contribution to the outlet exceeds sink landscape contribution, the watershed has high soil erosion risk. A balanced contribution yields $MLWLI \approx 0$.

4.5 Landscape Unit Weight Setting Weights integrate three components:

1. **Landscape type weight** (C_i): Reflects vegetation cover and management effects on soil erosion. Based on the C-factor in RUSLE and previous studies [27-28], values were assigned (e.g., residential source: 1.0; forest sink: 0.2).
2. **Soil weight** (E_i): Quantified through soil erodibility factor K:

   $$E_i = \frac{K_i}{\sum K}$$

   where K_i is the soil erodibility factor of HRU i, and $\sum K$ is the sub-watershed average. Higher K indicates greater erodibility and weight.
3. **Slope weight**: Based on slope classification from China' s "Land Use Status Survey Technical Regulations" and Soil and Water Conservation Law, with steeper slopes receiving higher weights.

The integrated landscape unit weight is:

$$W_i = C_i \cdot E_i \cdot S_i$$

4.6 Revised Universal Soil Loss Equation (RUSLE) RUSLE was used to estimate soil erosion for validation:

$$A = R \times K \times LS \times C \times P$$

where: - A = soil erosion modulus ($\mathrm{t \cdot hm^{-2} \cdot a^{-1}}$) - R = rainfall erosivity ($\mathrm{MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}}$), calculated using the simplified half-month algorithm - K = soil erodibility ($\mathrm{t \cdot h \cdot MJ^{-1} \cdot mm^{-1}}$), obtained from soil type data and Wu et al.' s TGRR study [29] - LS = slope length and steepness factor, calculated using Van Remortel' s algorithm - C = vegetation cover factor, estimated from EVI data using Wener' s method - P = conservation practice factor (1.0 for farmland source landscapes, 0.2 for forest/grassland sink landscapes)

The resulting continuous soil erosion raster was used to calculate average erosion modulus for each sub-watershed for correlation analysis with the landscape indices.

5. Results

5.1 Spatial Characteristics of Source-Sink Landscape Units Source Landscapes: - Paddy fields: Uniformly distributed across sub-watersheds (6.74%-33.35% of area), concentrated in northern riverine and central hilly areas. - **Dry land**: Distribution ranged from <20% in southern mountainous sub-watersheds (23, 24, 25) to 20%-36% in central areas, showing a consistent spatial trend with paddy fields. - **Residential areas**: Decreasing trend from north to south (12.89% in north to 2.07% in south), dominated by rural settlements with urban centers at township locations.

Sink Landscapes: - Woodland: Increasing trend from north to south (8.44% to 73.62%), with highest coverage in southern low mountainous sub-watersheds (70.21% in sub-watershed 25). Protected areas like Simian Mountain Scenic Area showed concentrated distribution. - **Grassland**: Drastically reduced in both quantity and spatial extent, with maximum coverage of only 8.76% (sub-watershed 17) and minimum of 0.04% (sub-watershed 15), distributed in scattered patches without spatial dominance.

[Figure 2: see original paper] Source-sink landscape unit pattern and area ratio statistics for the Qijiang watershed

5.2 Spatial Characteristics of Landscape Unit Weights Landscape type weight: Forest sink had the lowest weight (0.2), while residential source had the highest (1.0), consistent with source-sink unit distribution.

Soil weight: Ranged 0-1.08 across the watershed. Areas with forest/grassland cover (southern mountains) had lower weights, while outlets near sub-watersheds with paddy/dry land had higher weights due to soil erodibility.

Slope weight: Ranged 1-4.86. Northern riverine and central hilly areas with gentle slopes had lower weights, while southern mountainous areas had higher weights.

Integrated soil erosion weight: High values (1.24-5.00) occurred mainly in transition zones from mountains to gentle hills (sub-watersheds 13, 17) where soil erodibility was high and source landscape units were concentrated.

[Figure 3: see original paper] Spatial distribution of source-sink landscape unit weight

5.3 Correlation Between Landscape Index and Soil Erosion The modified LWLI showed significant positive correlation with average soil erosion modulus ($r = 0.92$, $p < 0.05$), while the original LWLI correlation was weaker ($r = 0.66$, $p < 0.05$). This demonstrates that HRU-based source-sink landscape units with comprehensive weighting better indicate watershed soil erosion patterns.

[Figure 4: see original paper] Landscape index statistics, correlation with soil erosion modulus, and risk zones

5.4 Watershed Soil Erosion Risk Based on Source-Sink Landscape Units MLWLI values varied significantly among sub-watersheds due to natural constraints and human disturbance. Using natural breaks classification (which minimizes within-class variance [30]), five distinct risk zones were identified:

1. **Extremely low risk zone** (MLWLI: -0.7 to -0.2): Southern low mountainous sub-watersheds (20-25) with concentrated forest sink landscapes and minimal human activity.
2. **Low risk zone** (MLWLI: -0.1 to 0): Central hilly and southern mountainous sub-watersheds (12, 14, 17) with relatively good vegetation cover and dispersed source landscapes.
3. **Moderate risk zone** (MLWLI: 0.2-0.8): Central hilly sub-watersheds (11, 13, 16, 18, 19) transitioning from hills to valleys with moderate vegetation cover and unbalanced source-sink distribution.
4. **High risk zone** (MLWLI: 0.8-1.5): Northern riverine sub-watersheds (1, 3) and central hilly sub-watersheds (6-10, 15) with concentrated paddy fields, dry land, and residential areas, short flow paths, and limited forest/grassland.
5. **Very high risk zone** (MLWLI > 1.5): Sub-watersheds 2, 4, 5 near the watershed outlet where source landscapes dominate and erosion products directly enter water bodies.

6. Discussion

The composition of source-sink landscape units shows distinct spatial regional characteristics. Paddy fields and dry land are relatively uniformly distributed but fragmented due to complex terrain. The HRU-based approach considers not only land use but also soil erodibility and slope contributions, providing better representation of internal soil erosion risk variation compared to subjective weighting methods [10, 17, 20].

The significant positive correlation between MLWLI and erosion modulus (r = 0.92) validates the approach and aligns with Li et al.' s findings [20]. As an ungauged watershed, we used empirical modeling rather than SWAT' s hydrological simulation, but leveraged its HRU delineation capability, expanding the application of source-sink landscape indices in SWAT.

While HRUs have clear attribute characteristics, their spatial positions are not uniquely defined, representing a key weakness of SWAT [34]. Future research should focus on spatially explicit HRU discretization based on flow paths to better couple landscape patterns with erosion processes.

7. Conclusions

This study delineated source-sink landscape units for the Qijiang watershed based on HRUs integrating land use, soil, and slope attributes. Key conclusions are:

1. The source-sink landscape unit composition is dominated by paddy/dry land source landscapes and woodland sink landscapes, with residential source and grassland sink as secondary components.
2. High-weight units are concentrated in transition zones from mountains to gentle hills with high soil erodibility, where source landscape units are clustered.
3. The MLWLI based on weighted source-sink landscape units significantly correlates with soil erosion modulus ($r = 0.92$, $p < 0.05$), effectively reflecting watershed soil erosion patterns and serving as a valuable risk assessment tool.
4. Five soil erosion risk zones were identified, providing scientific reference for erosion control and watershed management planning in the reservoir area.

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