Effects of "Source-Sink" Landscape Patterns on Spatial Heterogeneity of River Nitrogen and Phosphorus in Urbanized Watersheds: A Case Study of the Yuqiao Reservoir Watershed, Tianjin (Postprint)

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Abstract

With the acceleration of watershed urbanization, the impact of urbanization-driven landscape patterns on water quality is becoming increasingly severe. Taking the Yuqiao Reservoir watershed, which exhibits prominent urbanization trends, as a case study, and based on the watershed "source-sink" landscape characteristic index, combined with water quality data from 33 sub-watersheds in the Yuqiao Reservoir watershed for 2013, 2014, and 2015, this study employs spatial analysis, correlation analysis, and redundancy analysis to investigate the quantitative relationship between landscape characteristic indices and water quality indicators under the influence of urbanization. The results indicate that: from upstream to downstream, the entire watershed shows a trend of decreasing "sink" landscape area and increasing "source" landscape area; the proportion of residential construction land reaches 34.6% in middle and lower sub-watersheds, while forest land accounts for 33.5% of the "sink" landscapes. The global Moran' s I value for the Landscape Spatial Load Contrast Index (LWLI) is 0.637 ($P<0.01$), indicating significant spatial clustering, with LWLI high-high clustering areas coinciding with urbanization concentration zones. LWLI shows highly significant correlations with the spatial distribution of nitrogen and phosphorus in the watershed; the multiple correlation coefficient R^2 between TN and LWLI during the normal flow period is 0.811, while that between LWLI and TP during the wet period is 0.741. All water quality parameters (NH -N, TN, NO -N, TP) and LWLI in the sub-watersheds are concentrated in the same quadrant; compared with other landscape characteristic indices, LWLI exerts the greatest influence on nitrogen and phosphorus in rivers. Urban residential land shows highly significant correlations with water quality indicators and represents an important pollution source contributing to watershed water quality degradation. In the context of watershed urbanization development, it is recommended to enhance landscape connectivity in villages and towns to facilitate centralized pollutant treatment, while simultaneously increasing forest and grassland areas to improve the watershed' s eco-hydrological functions.

Full Text

Preamble

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Impact of a "Source-Sink" Landscape Pattern in an Urbanized Watershed on Nitrogen and Phosphorus Spatial Variations in Rivers: A Case Study of Yuqiao Reservoir Watershed, Tianjin, China

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Abstract

With the acceleration of watershed urbanization, the impact of landscape patterns on river basin water quality has intensified. Using the rapidly urbanizing Yuqiao Reservoir watershed as a case study, this research integrated landscape characteristic indices with water quality data from 33 sub-watersheds to explore quantitative relationships between landscape metrics and water quality indicators under urbanization pressure. Spatial analysis, correlation analysis, and redundancy analysis were employed to examine these relationships across multiple spatial scales during normal-water and high-water periods in 2013-2014.

The results revealed a clear upstream-to-downstream trend: "sink" landscape area decreased while "source" landscape area increased. Residential construction land accounted for 34.6% of area in middle and lower sub-watersheds on average, while forestland comprised 33.5% of the “sink”landscape. The Location-Weighted Landscape Contrast Index (LWLI) exhibited strong spatial clustering, with a Moran’ s I value of 0.637 ($p < 0.01$). LWLI showed the strongest correlation with nitrogen and phosphorus among all landscape indices, with determination coefficients (R^2) of 0.811 for total nitrogen (TN) during the normal-water period and 0.741 during the high-water period. All water quality parameters (NH -N, TN, NO -N, TP) clustered in the same quadrant, indicating that urban residential land surrounding Zunhua City serves as a critical pollution source. The study demonstrates that identifying quantitative relationships between landscape patterns and water quality is theoretically and practically significant for optimizing regional landscape patterns and improving water quality management.

Keywords: landscape pattern; Location-Weighted Landscape Contrast Index (LWLI); urbanized watershed; non-point source pollution

Introduction

Rapid socio-economic development has accelerated watershed urbanization trends, intensifying anthropogenic activities and triggering numerous river ecological environmental problems. Non-point source pollutants migrate and transform across various landscape types, making watershed landscape composition and spatial configuration influential on river water quality at different scales. The Location-Weighted Landscape Contrast Index (LWLI), which integrates landscape spatial structure and characteristics, can quantitatively evaluate landscape pattern impacts on pollution processes. This index has been validated and applied in multiple watersheds including the Yangtze River, Hai River, and Taihu Lake basins, with recent applications extending to estuarine areas and soil erosion regions based on slope indices and hydrological response units.

Urbanization-induced pollution manifests in diverse, random, and highly uncertain forms, rendering traditional agricultural non-point source analyses insufficient for addressing urban water environmental degradation. Consequently, research on urbanized watershed landscape patterns and water pollution has become a focal point. Watershed landscape patterns exhibit high spatial variability and autocorrelation, which is closely related to the spatial heterogeneity of water pollutants. Spatial autocorrelation analysis of landscape patterns can reveal clustering characteristics and aid understanding of pollutant distribution patterns.

While model-based studies offer strong mechanistic foundations, they require extensive spatial data and long-term monitoring series. Statistical methods such as correlation and regression analysis are commonly used to explore landscape-water quality relationships, though uncertainties persist due to pollutant complexity and spatial heterogeneity. Multivariate approaches including multiple linear regression, canonical correspondence analysis, and redundancy analysis have enabled more in-depth investigations of multi-factor relationships.

The Yuqiao Reservoir serves as a critical regulating reservoir for the Luanhe-Tianjin Water Diversion Project, with its water environment directly affecting Tianjin' s industrial, agricultural, and domestic water supply. Recent urbanization has increased residential construction land from 11.7% to 18.1%, with urban settlements expanding significantly from plains to mountainous areas and increasing spatial heterogeneity. This has resulted in severe nitrogen and phosphorus enrichment, threatening the safety of Tianjin' s drinking water source. While previous studies have examined agricultural non-point source pollution in this watershed, research on landscape pattern-water quality coupling relationships under urbanization remains limited. This study addresses this gap by analyzing recent monitoring data using spatial analysis and redundancy analysis to investigate how landscape patterns during normal-water and high-water periods affect water quality, providing scientific support for watershed protection and management.

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1. Study Area

The Yuqiao Reservoir watershed (39°56 -40°23 N, 117°26 -118°12 E) covers 2060 km^2 in Zunhua City, Hebei Province, and is located east of Jixian County, Tianjin. The terrain descends stepwise from northeast to southwest, with hills and low mountains in the northwest, plains in the central region, and a temperate continental monsoon semi-humid climate. Major rivers include the Sha River, Lin River, and Li River, with numerous towns and villages distributed throughout. To comprehensively characterize water environmental conditions, the watershed was divided into 33 sub-watersheds for water quality monitoring and sampling. Annual precipitation exceeds 700 mm. Pollutants from these settlements directly or indirectly affect water quality.

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2. Methods

2.1 Land Use Classification

Land use types were classified into water bodies, forestland, orchard land, grassland, residential construction land, bare land, and cultivated land based on Landsat 8 remote sensing imagery from May 2014. Using ENVI 5.1 and ArcGIS, images underwent atmospheric radiation correction and geometric correction, with field surveys validating interpretation accuracy.

2.2 Water Sample Collection and Analysis

Water quality monitoring data were collected during high-water periods (July-August 2013–2014, sampled after moderate/heavy rainfall) and normal-water periods (mid-monthly sampling). One sampling point was established at each of the 33 sub-watershed outlets, with 500 mL samples collected in sampling bottles and stored in insulated containers. Considering watershed pollution characteristics and related research, total nitrogen (TN), ammonium nitrogen (NH -N), nitrate nitrogen (NO -N), and total phosphorus (TP) were selected as water quality indicators, following GB 3838-2002 standards. Analytical methods included alkaline potassium persulfate digestion-UV spectrophotometry for TN, Nessler’ s reagent spectrophotometry for NH -N, and ammonium molybdate spectrophotometry for TP.

Nitrogen and phosphorus concentrations were generally high across sub-watersheds, with significant seasonal differences (higher in high-water periods than normal-water periods due to rainfall effects). The Sha River, most affected by urbanization, showed the highest concentrations, followed by the Li River and Lin River. TN and NH -N showed smaller seasonal variation than TP and NO -N.

Water Quality Data Descriptive Statistics

2.3 Landscape Pattern Indices

Based on ecological significance and watershed characteristics, the following indices were selected using Fragstats 4.2: Shannon’s Diversity Index (SHDI), Patch Density (PD), Largest Patch Index (LPI), and Area-Weighted Mean Patch Fractal Dimension (AWMPFD). These reflect human impact, patch aggregation, landscape fragmentation, and richness.

Building on “source-sink” landscape theory, Chen Liding et al. proposed the Location-Weighted Landscape Contrast Index (LWLI) to quantitatively describe relationships between landscape patterns and non-point source pollution. Following previous studies and incorporating the vegetation cover-management factor from the Universal Soil Loss Equation, weight values were assigned: forestland (0.4), orchard land (0.5), grassland (0.6), cultivated land (0.8), and residential land (1.0).

The LWLI model based on Lorenz curves is calculated as:

$$LWLI = \frac{\sum_{i=1}^{m} \text{source}_i \times W_i \times AP_i}{\sum_{i=1}^{m} \text{source}_i \times W_i \times AP_i + \sum_{j=1}^{n} \text{sink}_j \times W_j \times AP_j} \times LWLI'_{\text{distance}} \times LWLI'_{\text{elevation}} \div LWLI_{\text{slope}}$$

where source and sink represent different landscape types, W represents weights, AP represents area percentages, and m and n represent the total number of source and sink landscape types, respectively.

2.4 Statistical Analysis

Water quality data from 2013-2014 were analyzed separately for high-water and normal-water periods. Spatial autocorrelation (Moran' s I) and local spatial association (Anselin Local Moran' s I) of LWLI were analyzed using ArcGIS 10.2. Spearman rank correlation analysis between landscape indices and water quality was performed in SPSS 17.0. Redundancy Analysis (RDA) in CANOCO 4.5 was used to reveal contributions of individual landscape variables to water quality variation, while stepwise regression identified the most explanatory environmental or landscape factors.

3. Results

3.1 Landscape Pattern Analysis of Yuqiao Sub-watersheds

Landscape composition varied significantly across the 33 sub-watersheds. Residential construction land and cultivated land proportions increased from upstream to downstream, while forestland showed the opposite trend. Residential land was distributed across all sub-watersheds, with proportions ranging from 0.1% to 56.4%. The average percentage in middle and lower reaches reached 34.6%, with some sub-watersheds exceeding 56.4%. High proportions were concentrated around Zunhua City in the middle-lower reaches. Forestland dominated "sink" landscapes, accounting for 33.5% of total watershed area, primarily distributed in upstream mountainous areas such as the Qingdongling region.

[Figure 2: see original paper] Composition of Landscape Types in Different Watersheds

3.2 Spatial Autocorrelation of LWLI and Correlation with Nitrogen-Phosphorus Distribution

Spatial autocorrelation analysis revealed that LWLI had a Moran' s I value of 0.637 ($p < 0.01$), indicating strong positive spatial autocorrelation and clustering tendency. High-clustering areas were concentrated around Zunhua City in the central region, with residential land proportions of 56.4%, 50.2%, 43.7%, 38.5%, 31.2%, and 11.9% in these sub-watersheds. Low-clustering areas were distributed in the northwestern upstream region of the Lin River basin, where "sink" landscapes (shrubland and forest) dominated with residential land comprising only 0.08%-0.92%.

LWLI showed extremely significant positive correlations with nitrogen and phosphorus spatial distributions. Correlation coefficients were highest during the normal-water period ($R^2 = 0.811$ for TN, 0.797 for TP) and slightly lower during the high-water period ($R^2 = 0.741$ for TN). All water quality parameters (NH -N, TN, NO -N, TP) clustered in the same quadrant, indicating consistent relationships.

Spearman Correlation Analysis Between LWLI and Water Quality Parameters

3.3 Identification of Dominant Landscape Variables Affecting Water Quality

Redundancy Analysis (RDA) of eight landscape indices and water quality data revealed that during both water periods, urban residential land proportion showed the strongest correlation with water quality indicators, while forestland proportion showed significant negative correlations. Landscape Diversity Index (SHDI), Patch Density (PD), and Area-Weighted Mean Patch Fractal Dimension (AWMPFD) were positively correlated with water quality parameters, indicating that higher fragmentation and human disturbance corresponded to poorer water quality. The Largest Patch Index (LPI) was negatively correlated, suggesting that dominant natural landscapes improved water quality.

LWLI demonstrated the greatest influence on nitrogen and phosphorus, with all water quality parameters converging in the same quadrant. Sub-watersheds with high urban residential land proportions (15, 8, 16, 12, 5) showed strong nitrogen and phosphorus impacts, consistent with their landscape composition. Sub-watersheds with high forest coverage were distributed on the left side of the second ordination axis, indicating better water quality.

[Figure 3: see original paper] Local Spatial Autocorrelation of LWLI in Yuqiao Reservoir Watershed
[Figure 4: see original paper] RDA Ordination in Different Water Periods

Stepwise regression analysis showed that most water quality parameters could be explained by 2–3 environmental variables. LWLI was the dominant explanatory variable for all models, with regression coefficients decreasing from normal-water to high-water periods. The highest regression coefficient (0.765) occurred between LWLI and NO -N during the normal-water period. Urban residential land proportion (Red%) and orchard land proportion (Ord%) also significantly contributed to models, while forestland proportion (For%) showed significant negative relationships.

Regression Analysis Between Landscape Pattern Indices and Water Quality Index

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4. Discussion

Numerous studies have identified urban residential land as the primary source of water quality degradation, while forestland effectively controls pollutant concentrations. The RDA ordination clearly demonstrated that urban residential land had the strongest correlation with water quality indicators during both water periods. Urban residential land is widely distributed across all sub-watersheds, and pollutants from impervious surfaces are more readily discharged into rivers, exacerbating water quality deterioration. The area around Zunhua City in the middle-lower reaches, with large proportions of urban residential land, showed relatively poor river water quality due to severe urbanization and human disturbance. In addition to point source pollution from industrial and mining wastewater, domestic sewage and livestock breeding contribute significantly to non-point source pollution.

This study found that urban residential land had a more significant impact on nitrogen and phosphorus than in some other studies, possibly because cultivated land comprises a relatively small and concentrated proportion of this watershed, contributing less to nitrogen and phosphorus output compared to urban land. Orchard land showed uncertain effects on water quality. While primarily composed of chestnut forests with low phosphorus fertilizer application, orchard vegetation can absorb and retain pollutants. The correlation between orchard land and water quality was not significant, suggesting its impact remains uncertain.

Landscape Diversity Index (SHDI), Patch Density (PD), and Area-Weighted Mean Patch Fractal Dimension (AWMPFD) reflect landscape fragmentation and human disturbance intensity. Their positive correlation with water quality indicators indicates that higher fragmentation corresponds to poorer water quality. Conversely, the negative correlation between Largest Patch Index (LPI) and water quality suggests that watersheds with dominant natural landscapes maintain better water quality.

Urbanization-induced pollution exhibits greater randomness and uncertainty. Most landscape indices describe geometric characteristics while neglecting ecological processes. LWLI, developed from "source-sink" theory, effectively integrates spatial position and topographic features, showing significant correlations with nitrogen and phosphorus indicators. This index quantitatively evaluates pollution levels by considering elevation, distance, and landscape type. From normal-water to high-water periods, LWLI' s correlation with phosphorus increased while correlation with nitrogen decreased, reflecting terrain influences on water quality distribution. Under heavy rainfall, higher elevations trigger increased erosion, transporting particulate phosphorus into rivers, while phosphorus fertilizer from orchard lands is also washed into waterways during high-water periods.

LWLI considers both landscape type and distance to watershed outlets. Its significant correlation with water quality indicators in Spearman analysis and stepwise regression demonstrates its effectiveness in reflecting nitrogen and phosphorus export characteristics. The slight differences in correlation strength between methods may arise because most water quality parameters can be explained by 2–3 environmental variables, with variable differences affecting LWLI correlations.

5. Conclusions

1. The watershed exhibited a clear upstream-to-downstream trend of decreasing “sink” landscapes and increasing “source” landscapes. Urban residential land was concentrated around Zunhua City in the middle-lower reaches, averaging 34.6% of sub-watershed area (exceeding 56.4% in some areas). Proportions of urban residential land and cultivated land increased downstream, while forestland showed the opposite pattern.
2. LWLI showed strong spatial clustering (Moran’ s I = 0.637, $p < 0.01$), consistent with urban settlement distribution. High-clustering areas were concentrated around Zunhua City, while low-clustering areas were in the northwestern upstream region where “sink” landscapes dominated.
3. LWLI was significantly positively correlated with nitrogen and phosphorus during both water periods, with higher correlation coefficients during the normal-water period ($R^2 = 0.811$ for TN). LWLI’ s explanatory power far exceeded other landscape indices, with all water quality parameters clustering in the same quadrant.
4. In watershed urbanization development, improving landscape connectivity in towns and villages facilitates centralized pollutant treatment. Increasing forest and grassland patches in downstream areas, optimizing agricultural-forestry patterns, reducing fertilizer and pesticide use, and decreasing landscape fragmentation in mountainous areas can enhance ecological-hydrological functions and improve water quality.

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