Postprint: Effects of Landscape Pattern on Surface Water Quality in the Liyuan River Basin

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Abstract

Investigating the influence degree and mechanism of landscape patterns on water quality in inland rivers is of great significance for water environment protection in inland river basins of arid regions. This study takes the Liyuan River in Linze County as the research object, and employs redundancy analysis and correlation analysis to explore the relationship between landscape patterns and water quality under different buffer zones, based on landscape pattern data and measured water quality data. The results show that the water bodies in the study area generally meet the Class II water quality standard, except that the mean concentration of chemical oxygen demand (CODCr) is at the Class III water quality standard, while the mean concentrations of dissolved oxygen (DO), total phosphorus (TP), permanganate index (CODMn), and ammonia nitrogen (NH3-N) satisfy the Class II water quality standard; the landscape composition in the buffer zones is dominated by cropland, followed by construction land; analysis of landscape indices reveals that human activities are unevenly distributed within the buffer zones, with the 100 m buffer zone experiencing the greatest degree of human disturbance. The proportion of cropland area shows significant positive correlations with DO, TP, electrical conductivity (EC), total dissolved solids (TDS), TP, and salinity, while construction land exhibits significant positive correlations with TP and NH3-N; the Largest Patch Index (LPI) and Contagion Index (CONTAG) are positively correlated with water quality indicators, whereas Patch Density (PD), Edge Density (ED), Landscape Shape Index (LSI), and Shannon's Diversity Index (SHDI) are negatively correlated with water quality indicators; redundancy analysis demonstrates that the explanatory power of landscape composition and landscape indices for variations in water quality indicators is highest within the 300 m buffer zone, establishing the 300 m buffer as the optimal scale at which landscape patterns influence water quality indicators. Therefore, optimizing the landscape structure within the 300 m buffer zone can enhance the landscape' s capacity to intercept and adsorb pollutants, thereby

achieving improvements in water quality in the Liyuan River basin.

Full Text

Impact of Landscape Pattern on Surface Water Quality in the Liyuan River Basin

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Abstract

Investigating the degree and mechanism by which landscape patterns influence water quality in inland rivers is crucial for water environment protection in arid inland river basins. This study examines the Liyuan River in Linze County, utilizing landscape pattern data and measured water quality data to explore the relationship between landscape patterns and water quality across different buffer zones through redundancy analysis and correlation analysis. The results indicate that water bodies in the study area generally meet Class II water quality standards, except for the average chemical oxygen demand (CODCr) concentration, which falls under Class III standards. Dissolved oxygen (DO), total phosphorus (TP), permanganate index (CODMn), and ammonia nitrogen (NH3-N) concentration averages all meet Class II standards. Landscape composition in the buffer zones is dominated by cultivated land, followed by construction land. Analysis of landscape indices reveals unevenly distributed human activities within the buffer zones, with the greatest degree of human interference occurring in the 100 m buffer zone. The proportion of cultivated land area shows significant positive correlations with DO, TP, electrical conductivity (EC), total dissolved solids (TDS), and salinity, while construction land area is significantly positively correlated with TP and NH3-N. The largest patch index (LPI) and contagion index (CONTAG) are positively correlated with water quality indicators, whereas patch density (PD), edge density (ED), landscape shape index (LSI), and Shannon' s diversity index (SHDI) are negatively correlated. Redundancy analysis demonstrates that the explanatory power of landscape composition and indices for water quality variation is highest in the 300 m buffer zone, identifying it as the optimal scale at which landscape patterns influence water quality indicators. Consequently, optimizing landscape structure within the 300 m buffer zone can enhance pollutant retention and adsorption capacity, thereby improving water quality in the Liyuan River Basin.

Keywords: correlation analysis; landscape pattern; water quality; Liyuan River

Introduction

Surface water resources are essential for maintaining social stability and ecological security, representing a critical foundation for human survival and development. However, rapid population growth, urbanization, and socioeconomic development have made surface water pollution a serious environmental challenge. Pollution sources can be categorized as either point source or non-point source pollution. Through long-term supervision and management, point source pollution has been effectively controlled in many regions. In contrast, non-point source pollution, characterized by its wide distribution, random occurrence, long incubation period, and difficulty in management, has become a major pollution source affecting river water quality. Landscape pattern is a key factor influencing the input, migration, transformation, and output of non-point source pollutants.

Landscape pattern refers to the composition and spatial configuration of landscape elements within a given area. Landscape composition reflects the makeup of various "source"and "sink"landscape types resulting from natural activities and human actions, while spatial configuration determines material cycling and energy flow processes, creating differences in pollutant generation, migration, and transformation. Research has shown that nitrogen and phosphorus nutrients not absorbed by crops in cultivated land, along with wastewater from industrial production and residential life in construction land, enter rivers through surface runoff, causing water quality deterioration. Conversely, increased forest and grassland area can retain pollutants and purify water. For instance, Hu et al. analyzed the relationship between landscape pattern and water quality in the Longchuan River tributary of the Yangtze River, finding positive correlations between water quality indicators and both cultivated and construction land, while forest and grassland exerted positive regulatory effects on water quality. Furthermore, landscape aggregation, fragmentation, and connectivity affect the diffusion capacity of substances between patches. Lü et al. demonstrated that in the upstream Dongjiang Basin, dominated by forest and grassland, higher landscape aggregation and connectivity enhanced the retention and adsorption capacity for total nitrogen and phosphorus.

In arid inland regions, however, forest and grassland occupy relatively low proportions and landscape fragmentation is high. Such patterns can alter surface runoff, material cycling, and other hydrological activities, thereby affecting pollutant concentrations in water bodies. Additionally, agricultural irrigation return water in arid inland areas exacerbates river water quality degradation. Therefore, studying the relationship between landscape pattern and river water quality in arid inland regions provides important guidance for water environment protection and rational landscape configuration.

The Liyuan River, part of the Heihe River system in northwestern arid regions, is the largest first-order tributary of the Heihe River and the most important water source for Linze County and the Liyuan River irrigation district. The basin features developed irrigation agriculture, limited forest and grassland area, and high landscape fragmentation, making the impact of landscape pattern on river water quality particularly pronounced. Moreover, the relatively dense river network makes water quality response to land use patterns more sensitive and complex. This study investigates the Liyuan River, analyzing the relationship between landscape pattern and river water quality across multiple circular buffer zones using remote sensing interpretation and correlation analysis to identify the optimal response scale for water quality to landscape patterns, thereby providing scientific references for landscape optimization and water quality improvement in arid inland river basins.

Data and Methods

1.1 Study Area Overview

The Liyuan River originates from Guogaigou and Maquan' gou on the northern slope of the Qilian Mountains. As an inland river in the Hexi Corridor, it has a total length of 2240 km and a drainage area of 169 km^2, with an average annual runoff of 2.37×10^{8} m^3, primarily supplied by ice and snow meltwater from the Qilian Mountains and precipitation during flood seasons. The river ultimately flows into the main Heihe River at Yegouwan, Yaguan Town, Linze County. The Liyuan River Basin has a continental arid climate, with average annual precipitation of 100–500 mm and average annual evaporation of 900–1500 mm. Altitude significantly affects precipitation, evaporation, and temperature. From upstream to downstream, as altitude decreases, evaporation and temperature show clear upward trends while precipitation decreases significantly, demonstrating distinct vertical zonation.

Flowing from south to north through Linze County, the Liyuan River traverses a total county area of 79 km^2. Land use types within the county primarily include cultivated land, grassland, water bodies, desert, and Gobi, with a total irrigation area of 7.38×10^{3} hm^2, of which farmland accounts for 3.85×10^{3} hm^2, making it an important agricultural region in the Hexi Corridor.

1.2 Data Sources and Processing

Based on the spatial distribution characteristics of the Liyuan River system and field investigations, we established 10 representative water quality sampling points along the Linze section of the Liyuan River, as shown in [Figure 1: see original paper]. Sampling was conducted monthly from May to October 2023, collecting a total of 60 water samples. On-site measurements of dissolved total solids (TDS), water temperature, salinity, pH, and electrical conductivity (EC) were performed using a Hach portable water analyzer. At each monitoring point, 1000 mL water samples were collected in polyethylene bottles, stored in a 4°C incubator, and transported to the laboratory for determination of chemical oxygen demand (CODCr), ammonia nitrogen (NH3-N), and permanganate index (CODMn) concentrations (see for analytical methods). The final analysis used the average values from six months of monitoring data.

The data source for this study was Landsat 9 imagery obtained from the United States Geological Survey (USGS) (http://www.usgs.gov/). High-quality imagery from June 15, 2023 was selected. Preprocessing included radiometric and atmospheric correction. Using ENVI 5.6 software, supervised classification was performed with the maximum likelihood algorithm. Following the national standard "Current Land Use Classification" (GB/T 21010), land use types were classified as sand, grassland, water body, cultivated land, and construction land. Classification accuracy was verified through field surveys using a confusion matrix, yielding a Kappa coefficient of 0.86, which meets the requirements of this study.

Using ArcGIS 10.2, we created buffer zones for the 10 monitoring points. Based on previous research [18-19], buffer radii of 100 m, 200 m, 300 m, 400 m, 600 m, 800 m, and 1000 m were selected and overlaid with the interpreted land use data to obtain land use data for each buffer zone. These data were then imported into Fragstats 4.2 software to calculate landscape pattern indices.

1.3 Methods

1.3.1 Landscape Index Method Landscape indices are commonly used in landscape ecology to quantify landscape patterns and characteristics [20]. This study selected indices that measure landscape diversity, fragmentation, aggregation, and dominance: patch density (PD), edge density (ED), largest patch index (LPI), contagion index (CONTAG), landscape shape index (LSI), and Shannon' s diversity index (SHDI). The ecological implications of each index are detailed in .

1.3.2 Statistical Analysis We performed initial data processing in Excel and conducted correlation analyses using IBM SPSS Statistics 20. Canoco 5 software was used for detrended correspondence analysis (DCA). Since the maximum gradient length of the ordination axis was less than 3, redundancy analysis (RDA) was selected. In this study, water quality indicators served as response variables, while landscape pattern data acted as explanatory variables to reveal the contribution of landscape composition and indices to river water quality variation across different buffer zones and to identify the optimal response scale of water quality to landscape patterns.

Results and Analysis

2.1 Water Quality Characteristics

According to the national "Environmental Quality Standards for Surface Water" (GB 3838-2002), water bodies in the study area generally meet Class II water quality standards. The mean and variation ranges of water quality parameters in the Liyuan River show that pH values are distributed between 7.95–9, indicating weakly alkaline water. DO concentrations fall within standard limits, with average TP, CODMn, and NH3-N concentrations of 0.077 mg/L, 2.70 mg/L, and 0.23 mg/L, respectively, meeting Class II standards. The average CODCr concentration of 18.20 mg/L meets Class III water quality standards.

Water quality indicator concentrations vary across sampling points. NH3-N and CODCr concentrations near farmland are significantly higher than at other sampling points ([Figure 2: see original paper]), likely because agricultural activities in Linze County involve substantial fertilizer and pesticide use. Unabsorbed nitrogen, phosphorus, inorganic substances, and pesticides enter water bodies through surface runoff during rainfall, increasing pollutant concentrations. CODMn concentrations are higher at other points ([Figure 2: see original paper]), possibly due to the presence of abundant aquatic plants in the river channel that enhance self-purification capacity.

2.2 Land Use Characteristics Across Buffer Scales

Statistical analysis of land use type proportions across different spatial scales ([Figure 3: see original paper]) reveals that the study area is dominated by cultivated land, followed by construction land. Proportions vary across buffer scales: construction land and water body percentages decrease with increasing buffer radius, with maximum proportions of 14% and 6%, respectively, in the 100 m buffer zone. Sand area proportion increases with buffer radius but remains below 2%. Grassland proportion does not exceed 5%, while cultivated land proportion first increases then decreases, stabilizing at approximately 52–56%.

2.3 Landscape Characteristics Across Buffer Scales

Differences in landscape indices across buffer zones in the Liyuan River Basin are shown in [Figure 4: see original paper]. PD values gradually decrease with increasing buffer radius, reaching maximum median, maximum, and minimum values in the 100 m buffer zone, indicating the highest degree of landscape fragmentation, human interference intensity, and interaction between patches in this zone. LPI values also decrease with increasing buffer radius, reaching their maximum in the 100 m buffer zone, suggesting that human activity intensity is greatest at this scale. ED and LSI values decrease with increasing buffer radius, indicating that landscape shape complexity and spatial heterogeneity are highest in the 100 m buffer zone. In contrast, CONTAG values increase with buffer radius, while SHDI values first increase then decrease, reaching their maximum in the 1000 m buffer zone. This indicates high landscape type richness and equilibrium, as well as strong aggregation and connectivity between different patch types at this spatial scale.

2.4 Correlations Between Landscape Composition and Water Quality

Pearson correlation analysis of landscape composition area and water quality indicators in the Liyuan River Basin ([Figure 5: see original paper]) reveals significant positive correlations between cultivated land proportion and DO, EC, TDS, and salinity across all buffer scales, with significant correlations in the 200 m and 400 m buffer zones. This suggests that as cultivated land area increases, DO content also increases, likely because forest and grassland areas along inland river banks in arid regions are limited, and crops in cultivated land provide some dissolved oxygen to the river. TP shows significant positive correlations with cultivated land in the 300 m and 400 m buffer zones and with construction land in the 400 m and 600 m buffer zones. NH3-N is significantly positively correlated with cultivated land in the 300 m buffer zone and with construction land in the 300 m and 400 m buffer zones, indicating that nitrogen-containing pollutants from domestic and industrial activities on construction land enter water bodies through rainwater runoff, increasing NH3-N concentrations. CODCr is significantly positively correlated with cultivated land in the 200 m, 300 m, and 400 m buffer zones and with construction land in the 300 m buffer zone. These results demonstrate that increases in cultivated and construction land negatively affect water quality by increasing pollutant loads.

2.5 Correlations Between Landscape Indices and Water Quality

Landscape indices show no significant correlations with water quality indicators in the 600 m, 800 m, and 1000 m buffer zones, so these results are not presented. Correlation analysis results for the 100 m, 200 m, 300 m, and 400 m buffer zones are shown in . In the 100 m buffer zone, LPI is significantly negatively correlated with NH3-N. In the 200 m buffer zone, LPI is significantly positively correlated with CODCr, while SHDI is significantly negatively correlated with CODCr. In the 300 m buffer zone, LPI is significantly positively correlated with CODCr and CODMn, while SHDI is significantly negatively correlated with CODCr and NH3-N. In the 400 m buffer zone, LPI is significantly positively correlated with CODCr and CODMn, while SHDI is significantly negatively correlated with CODCr. These results indicate that LPI and CONTAG are positively correlated with water quality indicators, whereas PD, ED, LSI, and SHDI are negatively correlated. The correlation analysis also reveals that the degree of correlation between landscape indices and water quality indicators varies across buffer zones, but overall, correlations are strongest in the 300 m buffer zone, where landscape diversity, connectivity, and aggregation most significantly influence water quality.

Discussion

3.1 Impact of Landscape Types on River Water Quality

Different landscape types affect water quality by influencing surface runoff and the migration, transformation, and input-output of pollutants. Correlation analysis can quickly predict water quality indicators [27]. Results show that in the 300 m and 400 m buffer zones, NH3-N is significantly positively correlated with cultivated land area (r = 0.680, $P < 0.01$; r = 0.650, $P < 0.01$). This is because Linze is an agricultural county with extensive irrigation (7.38$×10^{3}$ hm^{2}) and heavy fertilizer and pesticide use. Unabsorbed nutrients and chemicals enter water bodies through surface runoff, increasing pollutant concentrations [28]. Construction land is also significantly positively correlated with NH3-N, with the strongest correlation in the 300 m buffer zone (r = 0.561, $P < 0.05$; r = 0.570, $P < 0.05$). Construction land hosts numerous human activities, including domestic sewage discharge, industrial production, and waste accumulation, making it a significant pollution source [29]. Additionally, increased impervious surfaces shorten runoff formation time and increase flow volume, facilitating pollutant transport [30]. Sand land shows negative correlations with water quality indicators, likely because sand land in arid inland regions carries fewer human activities and pollutants, and can act as a filter material to purify water through adsorption and filtration [31]. Water body area shows lighter impacts on inland river water quality, mainly because scarce precipitation in arid inland regions fails to dilute pollutants effectively. These findings align with results from the Wuding and Yanhe River basins [32], indicating that in arid regions, cultivated and construction land have negative effects as primary "source" landscape types, while sand land can purify water.

3.2 Impact of Landscape Pattern on Water Quality in the Liyuan River Basin

River water quality is influenced not only by landscape composition but also constrained by landscape spatial configuration. Landscape pattern indices effectively condense landscape pattern information and explain pollutant loads in water bodies, enabling water quality prediction through their associations [33]. This study shows that in the 300 m buffer zone, landscape indices have the strongest correlations with water quality indicators. Specifically, SHDI is significantly negatively correlated with NH3-N (r = -0.702, $P < 0.01$) and CODCr (r = -0.730, $P < 0.01$), while CONTAG is significantly positively correlated with CODCr (r = 0.606, $P < 0.05$). SHDI reflects landscape diversity and heterogeneity from both patch type richness and distribution equilibrium perspectives, while CONTAG reflects landscape connectivity and aggregation. Higher landscape diversity and heterogeneity during runoff processes lead to more balanced distribution of various patch types, reducing the dominance, aggregation, and leading role of construction and cultivated land, thereby decreasing threats from "source" landscapes to water quality [34]. In contrast, in the Qinling Mountains southern foothills where forest coverage exceeds 80.15% [35], increased CON-

TAG enhances forest aggregation and pollutant interception. However, in the arid inland Liyuan River Basin dominated by cultivated and construction land, higher CONTAG increases connectivity between these land types and surrounding areas, facilitating pollutant collection pathways. Higher SHDI reduces the dominance and aggregation of "source" landscape types, thereby decreasing pollutant output.

3.3 Characteristic Scale of Landscape Pattern Impact on Surface Water Quality

The explanatory power of landscape composition and indices for water quality variation across different buffer zones is shown in , which was used to identify the spatial scale with the greatest impact on water quality indicators. Redundancy analysis results indicate that landscape composition has less explanatory power than landscape indices. The explanatory power of landscape composition for water quality variation follows the order: 300 m > 100 m > 200 m > 1000 m > 800 m > 600 m > 400 m, with the strongest explanatory power (26.7%) in the 300 m buffer zone. The explanatory power of landscape indices follows: 300 m > 200 m > 400 m > 600 m > 800 m > 1000 m > 100 m, with the strongest explanatory power (60.9%) also in the 300 m buffer zone. Both landscape composition and indices show highest explanatory rates in the 300 m buffer zone, confirming it as the characteristic scale where landscape patterns most strongly influence water quality indicators.

compares characteristic scales from different regions. The characteristic scale in the Qingyijiang Basin and southeast hilly region, dominated by forest land, is larger than that in basins dominated by cultivated land, primarily due to differences in dominant land types within buffer zones. In the southeast hilly region, forest proportion exceeds 80% [36], controlling pollutant types and reducing pollution loads during runoff-driven sediment and pollutant transport [37]. In contrast, the Liyuan River Basin, dominated by cultivated and construction land, has limited forest and grassland coverage within the 300 m buffer zone (18.20%) and more fragmented landscapes ($\mathrm{PD} = 22.32\ \mathrm{n} \cdot \mathrm{km}^{-2}$). The lack of forest and grassland interception during rainfall facilitates surface runoff formation and nutrient export [38]. Therefore, in arid inland regions dominated by cultivated and construction land, special attention should be paid to landscape patterns within the 300 m buffer zone. Increasing forest and grassland planting within 300 m of river banks can enhance pollutant retention and blocking capacity, reduce the aggregation and connectivity of cultivated and construction land, and play a vital role in protecting surface water quality in arid inland regions.

Conclusions

1) Except for the CODCr indicator, the Liyuan River meets Class II water quality standards for CODMn, NH3-N, DO, and TP. Landscape composition varies across buffer scales but is dominated by cultivated land (52–

56%). Landscape fragmentation, human interference degree, and interaction between patches decrease with increasing buffer size, while landscape diversity, connectivity, and aggregation show opposite trends.

2) In the arid inland Liyuan River Basin, cultivated land is significantly positively correlated with DO and salinity, while construction land is significantly positively correlated with NH3-N. Water body area shows no significant correlation with water quality indicators. Landscape pattern indices LPI and CONTAG are positively correlated with water quality, while SHDI is negatively correlated.
3) Cultivated and construction land are the primary "source" landscape types in arid inland regions, negatively impacting surface water quality. Increased proportions and connectivity of these land types lead to greater pollutant generation and export. Higher landscape diversity and heterogeneity reduce the dominance and aggregation of "source" landscape types, thereby purifying water quality.
4) Redundancy analysis and comparison with other studies identify the 300 m buffer zone as the optimal scale for landscape pattern impacts on water quality indicators in arid inland regions. Landscape planning and configuration within this buffer zone should be prioritized. Increasing forest and grassland planting density, enhancing their aggregation and connectivity, and controlling urban sewage discharge and centralized waste treatment can improve aquatic ecological functions in arid inland regions.

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