Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-12
DOI: *10.15244/pjoes/220060* ONLINE PUBLICATION DATE: 2026-07-28

Original Research

Scale-Dependent Effects of Land Use on Water Quality and Source-Sink Mechanisms in Plain River Network Regions: A Case Study of the Wenruitang River Basin

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Received: 23 December 2025
Accepted: 26 March 2026

Abstract

In highly urbanized plain river network regions, the effects of land use on water quality exhibit pronounced scale dependence, yet the characteristic response scale and associated source–sink mechanisms remain insufficiently understood. Taking the Wenruitang River Basin as a case study, this research integrates high-resolution land-use data with multi-site water quality monitoring to explore scale-dependent land use–water quality relationships. Circular buffer zones of 100 m, 300 m, and 500 m were delineated around monitoring sites, and Spearman correlation analysis and RDA were applied. The results indicate that land-use explanatory power follows a clear inverted U-shaped pattern with increasing scale, peaking at the 300 m buffer, where land-use composition explained 96.56% of the variation in water quality. This scale represents the characteristic response distance of water quality to landscape structure in plain river networks. At this scale, built-up land shows significant positive correlations with NH_4^+–N, TP, and COD_{Mn}, acting as the dominant pollution source, whereas forest and grassland exhibit significant sink functions. However, the strong dominance of built-up land relative to limited ecological land creates a source-dominated and sink-deficient configuration, constraining water quality improvement. These findings emphasize the importance of scale-aware management and suggest that water quality control should extend beyond narrow riparian buffers to the 300 m core influence zone through impervious surface regulation and low-impact development measures.

Keywords: land use, scale effects, rda, source-sink landscape, plain river network region

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Introduction

Aquatic ecological conditions provide a fundamental basis for sustainable watershed development [1], and river water quality directly reflects the dynamic balance between human activities and natural systems [2]. With rapid urbanization, land use has continuously shifted from natural landscapes toward built-up land. This transition can profoundly affect riverine water quality by increasing impervious surface cover and altering runoff generation, nutrient cycling pathways, and pollutant transport processes [3]. Compared with mountainous or plateau basins, plain river network regions are typically characterized by low relief, high drainage density, sluggish flow conditions, and complex land–water interfaces, which together render water quality more sensitive to land-use change and often lead to stronger spatial heterogeneity [4].

The Wenruitang River Basin is one of the key areas targeted by the "Beautiful Rivers and Lakes" initiative in Zhejiang Province, China. It exhibits a typical high-density urban–agricultural mosaic landscape. Built-up land accounts for more than 40% of the basin area [5]. Under continued urban expansion, the basin has long suffered from eutrophication, primarily manifested as exceedances of NH_4^+–N and total phosphorus (TP) [6, 7]. However, existing studies have largely focused on statistical associations between land-use structure and water quality at a single spatial scale, and the process-based understanding of how landscape patterns regulate water quality through scale effects remains insufficient. This gap constrains the development of refined, zoned water environment management strategies [8-10]. Therefore, identifying the characteristic spatial scale at which land use most strongly influences water quality, and further extracting key regulatory thresholds, is of both theoretical importance and practical relevance for watershed restoration and riparian landscape planning in plain river network settings.

Recent research on land use–water quality relationships has gradually formed a three-dimensional analytical framework emphasizing "composition–configuration–scale". In terms of land-use composition, numerous studies have shown that cropland and built-up land often function as major "source" landscapes of nitrogen and phosphorus, whereas forest and grassland can act as "sink" landscapes by intercepting runoff and promoting sedimentation and retention processes [11, 12]. For example, Xie et al. [11] reported a significant positive relationship between cropland proportion and total nitrogen (TN) in the Chongqing section of the Yangtze River Basin, and further found that this source–sink relationship varied seasonally, with substantially higher explanatory power in the dry season than in the wet season.

At the landscape configuration level, metrics such as edge density (ED), aggregation index (AI), and interspersion and juxtaposition index (IJI) have been widely used to quantify how spatial arrangement influences water quality. Previous studies suggest that the fragmentation and aggregation patterns of built-up land can significantly regulate pollutant generation and transport pathways [13, 14]. Xu et al. [15] found in the Qingshan Lake Basin that when the edge density of built-up land exceeded 31.69 $m \cdot hm^{-2}$, the risk of water-quality deterioration increased markedly, whereas higher forest aggregation enhanced pollutant interception and buffering capacity.

Scale effects have become a core topic in land use-water quality research. Due to differences in topography and hydrological processes, the spatial scale at which land use most strongly explains water quality variability differs substantially among watershed types. In mountainous or large-river basins (e.g., the Chongqing section of the Yangtze River Basin [11] and the Dongjiang River Basin [16]), the strongest explanatory power commonly occurs at larger extents (e.g., ~1000 m reaches or sub-basin scales), which is closely related to long-distance, gravity-driven convergence under steeper slopes. In contrast, in plain or small watersheds (e.g., the Taihu Basin [17] and the Suzhou Creek catchment [18]), smaller buffer scales (typically within 500 m) often exhibit stronger explanatory performance. Nevertheless, systematic investigations at fine scales below 300 m remain limited, and the coupled mechanisms linking "urbanization–river-network structure–water-quality response" have not been sufficiently elucidated. From a theoretical perspective, these gaps indicate that existing studies have not yet fully integrated spatial scale theory with the source–sink landscape framework in highly urbanized plain river network systems. In particular, the mechanisms through which urbanization-induced landscape patterns interact with hydrodynamic constraints to produce scale-dependent water-quality responses remain insufficiently conceptualized. Addressing this issue requires a more explicit linkage between landscape structure, transport processes, and scale-dependent ecological responses.

Although the scale dependence of land-use impacts on water quality has been widely recognized, several gaps remain for highly urbanized plain river network systems. First, many studies emphasize relatively coarse scales (e.g., sub-basin, 500 m, or 1000 m) while paying insufficient attention to fine-scale gradients within 100-500 m (e.g., 100 m, 300 m, and 500 m), limiting the ability to characterize "short-distance, high-intensity" pollutant transport in dense river networks. Second, the geographic mechanisms underlying why characteristic response scales in plain river networks are often much smaller than those in mountainous basins (e.g., slope conditions, stormwater drainage density, and hydrodynamic regimes) have not been adequately explored. Third, few studies identify source–sink landscape regulatory thresholds at the characteristic scale, which restricts the provision of quantitative guidance for riparian spatial management and intensity control of built-up land (e.g., maximum allowable built-up proportion).

Accordingly, this study applies multi-scale redundancy analysis (RDA) and threshold identification to systematically reveal how land-use patterns affect water quality and how such effects depend on spatial scale in the Wenruitang River Basin. Specifically, we aim to: (i) quantify the relationships between the proportions of built-up land, cropland, forest, and other land-use types and key water quality indicators (e.g., NH_4^+–N, TP, and DO) across three buffer scales (100 m, 300 m, and 500 m); (ii) identify the characteristic scale at which land use best explains water quality variability and, through comparison with representative mountainous and large-river basins, elucidate the mechanisms responsible for scale differences in plain river network regions; and (iii) determine key regulatory thresholds for source–sink landscape patterns at the characteristic scale (e.g., an upper limit for built-up land proportion), thereby providing quantitative support for refined watershed water environment management and spatial planning.

Materials and Methods

Study area

The Wenruitang River Basin is located in Wenzhou City, Zhejiang Province, eastern China, and represents a typical plain river network system characterized by extremely low topographic relief and a dense, highly interconnected channel network. The region is situated in a subtropical monsoon climate zone, with abundant precipitation and pronounced seasonal variability. The river system plays multiple roles, including flood control, drainage, irrigation, navigation, and urban landscape enhancement.

In recent decades, rapid urban expansion has substantially increased the proportion of built-up land and intensified human activities along river corridors, imposing growing pressure on the aquatic environment [19]. To ensure adequate spatial coverage and representativeness, a total of 236 water quality monitoring sites distributed across the core area of the basin were selected for analysis (Fig. 1).

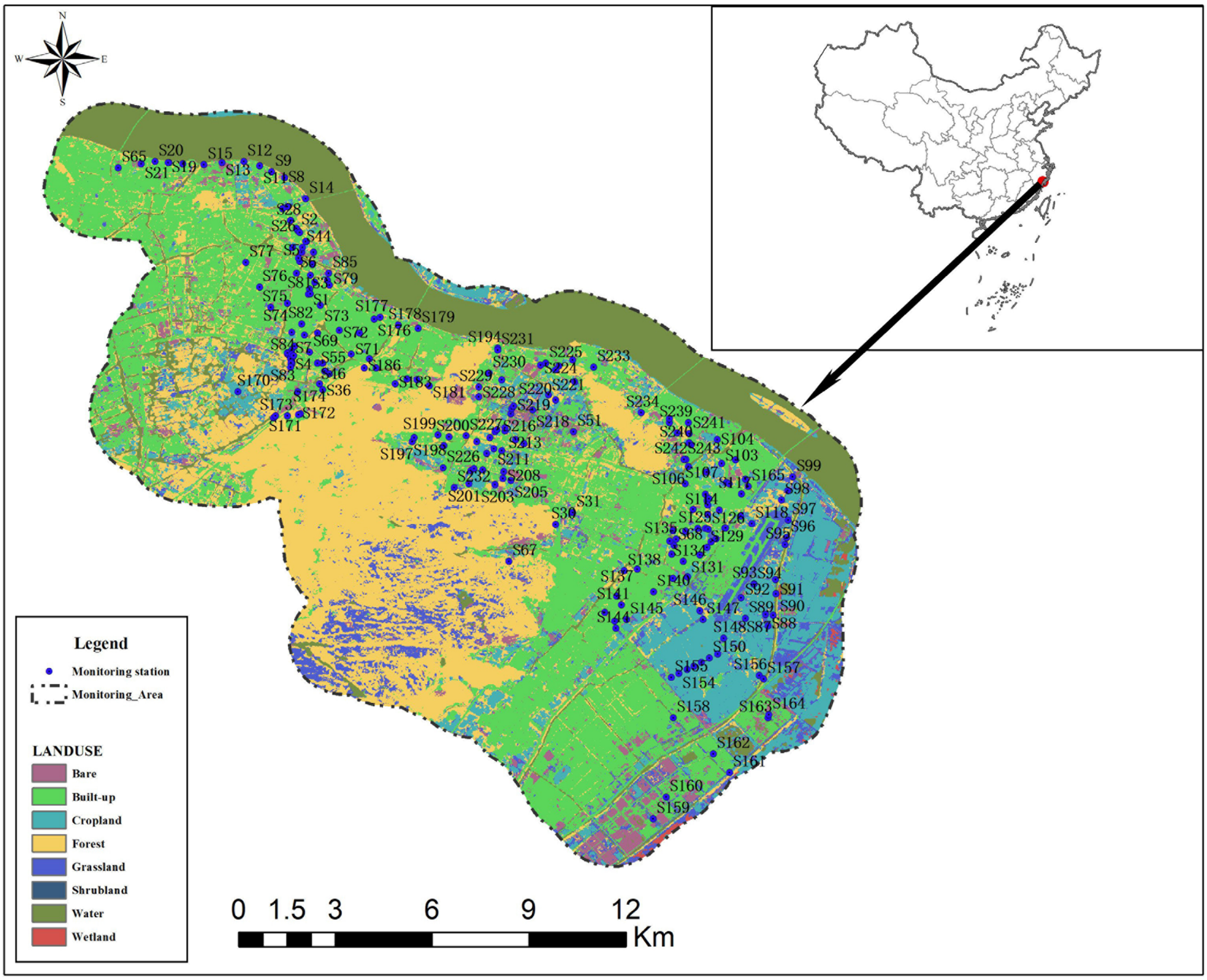

Fig. 1. Location of the study area.

Water Quality Data

Water quality data were obtained from the Wenzhou Municipal Ecological Environment Monitoring Authority and consisted of monthly observations collected throughout 2024. Based on the dominant pollution characteristics of the Wenruitang River and data availability, four key indicators were selected: dissolved oxygen (DO), permanganate index (COD_{Mn}), ammonium nitrogen (NH_4^+–N), and total phosphorus (TP). These indicators collectively reflect oxygen conditions, organic pollution, and nutrient enrichment status.

Based on regional hydrological and climatic characteristics and previous studies, April to September was defined as the wet season, while October to March of the following year was classified as the dry season. After removing duplicate records and abnormal values, seasonal mean concentrations of each indicator were calculated for every monitoring section. This processing approach minimizes the influence of short-term measurement noise and enhances the robustness of seasonal-scale comparisons.

Land Use Data and Classification

Land use data were derived from the ESA WorldCover 2024 land cover product with a spatial resolution of 10 m. The dataset was projected and clipped to the study area using ArcGIS 10.5. Land use classes were then reclassified according to the Land Use Classification Standard of China (GB/T 21010-2017) and local landscape characteristics [20].

The original land cover types were aggregated into six categories: built-up land, cropland, forest, grassland, water bodies, and bare land. For each spatial analysis unit, the proportional area of each land use type was calculated for subsequent statistical analyses.

Buffer Construction

Considering the complex structure of plain river networks and the high density of monitoring sites in urbanized areas, a multi-scale buffer approach was adopted to characterize the spatial extent within which surrounding land use potentially influences water quality [21, 22].

Using each monitoring section as the center, circular buffers with radii of 100 m, 300 m, and 500 m were delineated in a GIS environment. These buffer sizes were selected to represent a gradient from immediate riparian influence to broader landscape context. Specifically:

The 100 m buffer represents the near-riparian zone, which is strongly affected by direct pollutant discharge, shoreline hardening, and short-distance disturbances;

The 300 m buffer represents the core zone of intensive human activities surrounding river channels;

The 500 m buffer characterizes the broader landscape background and potential contributing areas.

Within each buffer, the proportional area of each land use category was extracted to quantify land-use composition at different spatial scales.

Statistical Analyses

Given that water quality variables generally do not satisfy normal distribution assumptions, Spearman's rank correlation analysis was applied to examine relationships between land-use proportions and water quality indicators across different seasons and buffer scales. Correlation results were visualized using heatmaps, with statistical significance defined at $P<0.05$ and $P<0.01$.

To identify dominant patterns of covariation among water quality indicators and to infer potential pollution processes, principal component analysis (PCA) was conducted. Prior to PCA, all variables were standardized using Z-score normalization to eliminate dimensional effects. Principal components with eigenvalues greater than 1 were retained, and Varimax rotation was applied to enhance interpretability. PCA and related visualizations were performed using OriginPro 2025.

To quantify the explanatory capacity of land use composition for spatial variability in water quality, redundancy analysis (RDA) was conducted, with water quality indicators treated as response variables and land use proportions as explanatory variables at each buffer scale. Before RDA, detrended correspondence analysis (DCA) was applied to assess gradient lengths. As gradient lengths were less than 3, linear ordination (RDA) was deemed appropriate. RDA was implemented in Canoco 5.0, and biplots were generated to illustrate the relationships between land use types and water quality indicators.

Results

Seasonal Statistics of Water Quality

Seasonal descriptive statistics of the major water quality indicators in the Wenruitang River Basin are summarized in Table 1. Overall, water quality exhibited pronounced seasonality, with higher concentrations of nutrient and organic pollution indicators in the dry season than in the wet season.

Clear seasonal contrasts were observed for nutrient and organic pollution indicators. The mean dry-season NH_4^+–N concentration reached 3.538 $mg \cdot L^{-1}$, substantially exceeding the wet-season mean of 2.522 $mg \cdot L^{-1}$. A similar pattern was observed for TP, with mean concentrations of 0.356 $mg \cdot L^{-1}$ in the dry season and 0.294 $mg \cdot L^{-1}$ in the wet season. The permanganate index (COD_{Mn}) also exhibited higher values during the dry season (5.942 $mg \cdot L^{-1}$) compared with the wet season (5.274 $mg \cdot L^{-1}$).

In contrast, dissolved oxygen (DO) displayed an opposite seasonal pattern. The mean DO concentration

Table 1. Seasonal statistical characteristics of major water quality indicators.

Indicator	Season	Min	Max	Mean	Std	CV (%)
NH_4^+–N	Dry	0.069	41.5	3.538	3.496	98.81
	Wet	0.036	25.1	2.522	2.536	100.55
TP	Dry	0.020	4.00	0.356	0.411	115.48
	Wet	0.020	3.46	0.294	0.239	81.24
CODMn	Dry	0.8	33.9	5.942	3.741	62.95
	Wet	0.6	20.4	5.274	2.235	42.38
DO	Dry	0.82	15.88	5.986	2.145	35.84
	Wet	1.98	16.01	5.170	1.927	37.28

Table 2. Principal component loading matrix of water quality indicators.

Indicator / Parameter	PC1 (Pollution factor)	PC2 (Environmental factor)	PC3	PC4
NH_4^+-N	0.585	−0.043	−0.496	−0.641
TP	0.604	0.080	−0.261	0.748
COD_{Mn}	0.497	0.355	0.774	−0.169
DO	−0.215	0.930	−0.296	−0.030
Explained variance (%)	55.36	24.57	13.44	6.63
Cumulative variance (%)	55.36	79.93	93.37	100.0

was higher in the dry season (5.986 mg·L^{-1}) and lower during the wet season (5.170 mg·L^{-1}).

Overall, nutrient and organic pollution indicators tended to accumulate under low-flow conditions in the dry season, whereas DO was reduced during the wet season.

Coefficients of variation (CV) indicate strong spatial heterogeneity for most water quality indicators (Table 1). NH_4^+–N exhibited CV values close to 100% in both the dry (98.81%) and the wet (100.55%) seasons, while TP showed extremely high variability during the dry season (CV = 115.48%). These results indicate pronounced spatial contrasts in nutrient pollution levels among monitoring sections.

COD_{Mn} also showed notable spatial heterogeneity, particularly in the dry season (CV = 62.95%), whereas spatial variability was substantially lower in the wet season (CV = 42.38%). By comparison, DO exhibited relatively moderate spatial variability, with CV values of 35.84% in the dry season and 37.28% in the wet season.

Overall, nutrient indicators displayed the strongest spatial heterogeneity, followed by organic pollution, whereas DO was comparatively more spatially homogeneous.

Spearman Correlations among Water Quality Indicators

Spearman's rank correlation analysis was conducted to characterize relationships among water quality indicators (Fig. 2). A strong and highly significant positive correlation was observed between NH_4^+–N and TP ($r = 0.706$, $P<0.01$), indicating synchronized variation of nitrogen and phosphorus across monitoring sites.

COD_{Mn} exhibited positive correlations with NH_4^+–N ($r = 0.358$) and TP ($r = 0.453$), although these relationships were weaker than the NH_4^+–N–TP correlation. This suggests partial coupling between organic and nutrient pollution.

DO was negatively correlated with NH_4^+–N, TP, and COD_{Mn}, with moderate correlation coefficients for NH_4^+–N ($r = -0.294$) and TP ($r = -0.322$). However, none of the negative correlations exceeded $|r| = 0.5$, indicating that DO was only moderately associated with pollutant concentrations.

Overall, the correlation structure reveals strong coupling between nutrient indicators, partial coupling between nutrients and organic matter, and relatively weak associations between DO and pollution indicators.

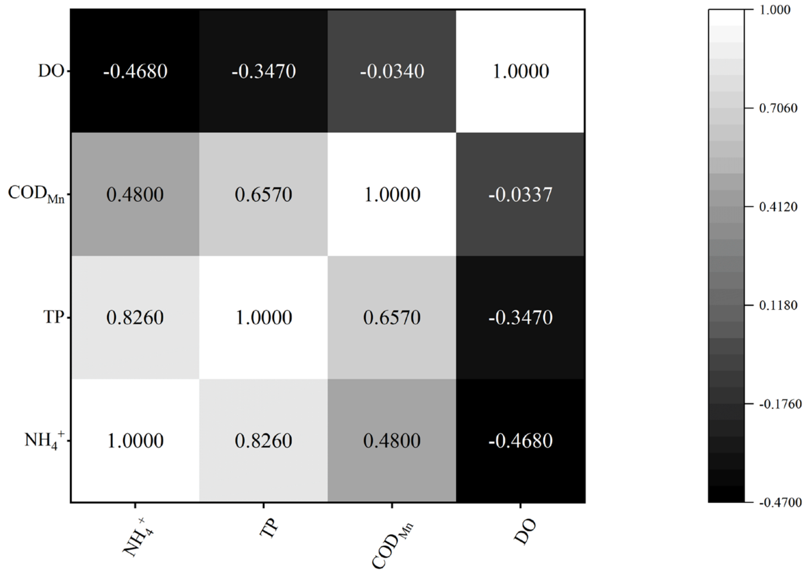

Fig. 2. Spearman correlation coefficient matrix of major water quality indicators.

Table 3. Statistical composition of land use under different buffer scales (%).

Buffer Scale	Built-up	Cropland	Forest	Grass	Water	Dominant Type
100 m	45.2	20.5	8.3	5.1	20.9	Built-up
300 m	42.8	23.1	9.7	6.3	18.1	Built-up
500 m	38.5	27.4	12.2	7.8	14.1	Built-up

PCA-Based Interpretation of Dominant Water Quality Processes

PCA was applied to NH_4^+–N, TP, COD_{Mn}, and DO to identify major gradients in water quality variation [23, 24]. The first two principal components (PC1 and PC2) accounted for 79.93% of the total variance (Table 2).

PC1 explained 55.36% of the variance and exhibited high positive loadings for TP (0.604), NH_4^+–N (0.585), and COD_{Mn} (0.497). This component represents a combined gradient of nutrient enrichment and organic pollution.

PC2 explained 24.57% of the variance and was dominated by DO, with a very high positive loading (0.930), whereas NH_4^+–N, TP, and COD_{Mn} showed low loadings. PC2, therefore, represents an oxygen-related gradient largely independent of nutrient and organic pollution.

COD_{Mn} also showed a high loading on PC3 (0.774; 13.44% variance explained), suggesting that organic pollution exhibited additional variability not fully aligned with nutrient enrichment.

In summary, water quality variability in the Wenruitang River Basin is primarily structured by two dominant gradients: a nutrient–organic pollution gradient (PC1) and an oxygen condition gradient (PC2).

Spatial Characteristics of Land-Use Composition across Buffer Scales

Land-use composition exhibited strong urbanization characteristics and distinct scale dependence across buffer zones (Table 3). Built-up land was the dominant land-use type at all scales, accounting for 45.2% within the 100 m buffer and remaining above 38% even within the 500 m buffer. Although its proportion declined with increasing buffer radius, built-up land consistently dominated the riparian and near-riparian landscape.

Cropland proportion increased with buffer size, rising from 20.5% at 100 m to 27.4% at 500 m, reflecting a transition from highly urbanized river corridors to surrounding agricultural landscapes.

Forest and grassland remained limited across all scales, together accounting for only 13.4% within the 100 m buffer and increasing modestly to 20.0% at the 500 m scale. Ecological land uses were therefore scarce close to river channels.

Overall, the land-use structure of the Wenruitang River Basin can be characterized by a predominance of source-type landscapes and a deficit of sink-type landscapes.

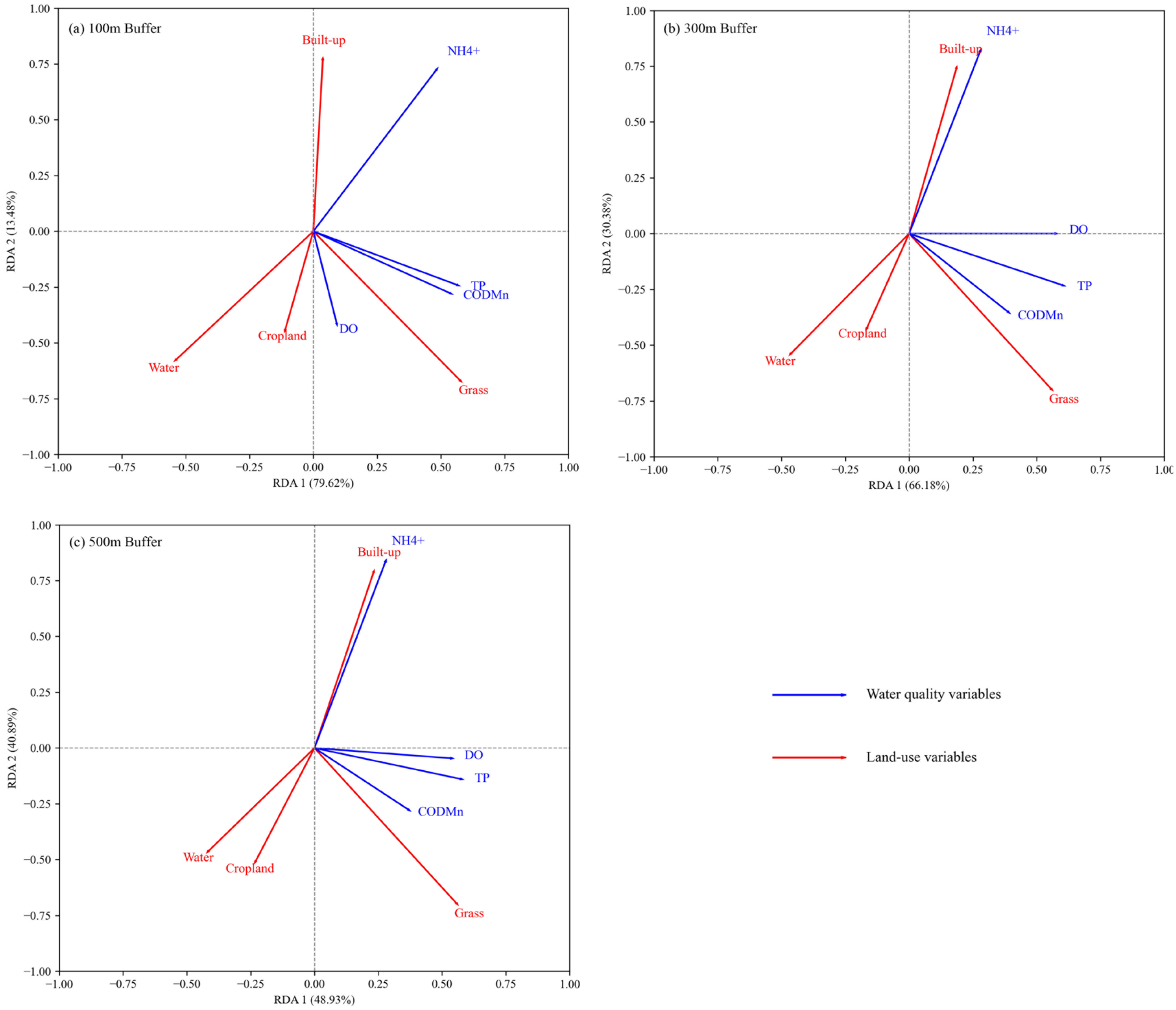

Fig. 3. Multiscale redundancy analysis (RDA).

Scale Effects of Land Use on Water Quality (RDA)

RDA revealed clear scale dependence in the ability of land-use composition to explain spatial variability in water quality (Fig. 3). The cumulative variance explained by the first two RDA axes increased from 93.10% at the 100 m scale to a maximum of 96.56% at the 300 m scale, before declining to 89.82% at the 500 m scale.

This inverted U-shaped pattern indicates that land-use explanatory power does not increase monotonically with spatial extent. Instead, the 300 m buffer represents the scale at which land-use patterns exert the strongest influence on water quality.

Accordingly, the 300 m buffer was identified as the characteristic scale for subsequent interpretation of land-use drivers.

Identification of Key Driving Factors at the Characteristic Scale

At the 300 m characteristic scale, RDA biplots were further examined to identify dominant land-use drivers and source–sink relationships (Fig. 3).

In the RDA ordination, the arrow representing built-up land formed acute angles and showed strong directional consistency with the pollution indicators NH_4^+–N, TP, and COD_{Mn}, indicating significant positive associations. This clearly identifies impervious-dominated built-up land as a major source landscape contributing to nutrient and organic pollution.

Mechanistically, extensive impervious cover increases runoff generation efficiency, and rainfall events rapidly mobilize pollutants accumulated on roads and urban surfaces. In addition, discharges routed through stormwater and combined drainage networks can deliver domestic wastewater and other contaminants directly to the river, intensifying nutrient and oxygen-demanding loads and deteriorating water quality.

In contrast, forest and grassland exhibited arrow directions opposite to NH_4^+–N, TP, and COD_{Mn}, forming obtuse angles and indicating negative associations with pollutant concentrations. This suggests that forest and grassland function as sink landscapes, attenuating pollutant delivery through multiple ecological processes, including runoff slowing, particulate settling, adsorption, and retention in soil–vegetation systems, microbial transformation, and plant uptake of nutrients.

At the characteristic scale, water quality in the Wenruitang River Basin is governed by a clear source–sink contrast: built-up land acts as the dominant pollution source, while forest and grassland serve as pollution sinks. However, this source–sink system is highly imbalanced, with built-up land accounting for 42.8% of the landscape at 300 m, whereas forest and grassland together comprise only 16.0%. This pronounced imbalance characterizes a typical "source-dominated, sink-deficient" configuration.

Discussion

Characteristic-Scale Water-Quality Responses in Plain River Network Systems

This study demonstrates a clear scale-dependent relationship between land-use patterns and water quality in the Wenruitang River Basin, with the strongest response occurring at the 300 m buffer scale. At this scale, the first two RDA axes explained 96.56% of the cumulative variance, indicating that land-use composition within a ~300 m near-river neighborhood provides the most effective representation of spatial differences in water quality. This characteristic scale differs markedly from patterns commonly reported for mountainous or canyon-type large-river basins, where broader extents often yield greater explanatory power. For instance, Xie et al. [11] found that the land use-water quality relationship peaked at a 1000 m reach scale in the Chongqing section of the Yangtze River.

Such discrepancies in characteristic scale reflect fundamental heterogeneity in hydrological processes and pollutant transport pathways across geomorphic settings. In mountainous and hilly basins, steeper terrain and clearly gravity-driven routing facilitate rapid overland transport and longer effective influence distances, allowing landscape patches farther from the channel to affect water quality through hillslope–channel connectivity [19, 25, 26]. In contrast, the Wenruitang River is a low-lying, tidal-influenced plain river network characterized by dense channel connectivity, slow flow, frequent flow reversals, and overall weak hydrodynamic conditions. Under these conditions, lateral transport distances are strongly constrained, and land-water interactions are expected to be concentrated within an "effective drainage radius" adjacent to the river corridor [27]. This geomorphic–hydrodynamic setting provides a plausible basis for why the land-use signal peaks at a relatively fine scale (300 m), rather than continuing to increase with larger buffer extents.

Urbanization further strengthens the relevance of the 300 m hinterland scale. The basin contains extensive impervious surfaces along river corridors, and rainfall events can trigger a pronounced first-flush effect, in which pollutants accumulated on road surfaces and within stormwater/sewer systems are mobilized and rapidly conveyed into the river over short time periods [28, 29]. This short-distance, high-efficiency transport pathway implies that a buffer that is too narrow (e.g., 100 m) may not fully capture the functional "pollution source–pipe network–river channel" linkage, whereas a larger buffer (e.g., 500 m) may introduce additional land-use information that is less directly connected hydraulically, thereby diluting the explanatory signal.

From a management perspective, these results suggest that strategies relying solely on narrow riparian buffers may be insufficient for highly urbanized plain river networks. In this study, forest and grassland together accounted for only 13.4% within the 100 m buffer, indicating limited sink capacity in the immediate riparian zone. In comparison, controlling impervious expansion and implementing source-control runoff management within the ~300 m characteristic zone appear more consistent with the scale at which water quality most strongly responds to land-use patterns.

Mechanisms of Water-Quality Deterioration Driven by Source–Sink Landscape Imbalance

The multi-scale RDA results further indicate that built-up land functions as the primary source landscape for nitrogen and phosphorus pollution in the Wenruitang River Basin, whereas forest and grassland act as sink landscapes that provide attenuation and buffering effects [30]. Importantly, within the characteristic scale (300 m), the pronounced imbalance in both the extent and functional configuration of these source and sink landscapes likely represents a key reason why water quality improvement remains challenging [31].

Land-use statistics show that impervious built-up land accounts for 42.8% within the 300 m buffer, while forest and grassland together comprise only 16.0%. This "high source–low sink" configuration implies that, even if sink landscapes exhibit interception, adsorption, and retention capacity on a per-area basis, their limited areal extent and potentially fragmented spatial arrangement are unlikely to offset the runoff-driven pollutant loads generated by extensive impervious cover. As a result, pollutants can be delivered to the river persistently and at high intensity [32].

Moreover, consistent with the "rainfall-driven concentration increases" reported by Xie et al. [11] in the Yangtze River Basin, a high proportion of hardened surfaces in the Wenruitang River Basin can amplify the first-flush effect, producing pulsed pollutant inputs over short time windows during rainfall events. Such dynamics further weaken the regulating effectiveness of narrow vegetated riparian strips and help explain why, in highly urbanized plain river network systems, increasing limited vegetation cover only within the immediate near-riparian zone (e.g., within 100 m) is unlikely to reverse deteriorating water quality trends [33].

Overall, these findings suggest that water-quality degradation in plain river networks is not driven by a single strengthened pollution source alone, but rather by a structural coupling of "strong sources–weak sinks–short-distance, high-efficiency transport". Substantial improvement in water environment quality is therefore more likely to require integrated interventions at the characteristic scale, including limiting impervious surface coverage, optimizing land-use composition, and enhancing both the extent and connectivity of ecological sink landscapes within the ~300 m core influence zone.

Implications for Water Environment Management and Spatial Planning

The identification of a 300 m characteristic scale has important implications for water environment management in highly urbanized plain river network regions. Traditional river restoration strategies often prioritize narrow riparian buffers (e.g., ≤100 m), under the assumption that pollutant interception and ecological restoration within the immediate river corridor are sufficient to achieve water-quality improvement. However, the results of this study indicate that land use within a broader near-river hinterland exerts a stronger and more coherent influence on water quality than the immediate riparian zone alone.

Specifically, the peak explanatory power of land use at the 300 m scale suggests that effective management units should be redefined from a narrow "riparian strip" to a wider "core influence zone" encompassing both river-adjacent land and surrounding urban infrastructure. Within this zone, priority should be given to controlling impervious surface expansion, reducing pollutant generation at the source, and disconnecting hardened surfaces from direct drainage pathways to river channels.

Moreover, the pronounced source–sink imbalance identified at the characteristic scale highlights the limited effectiveness of relying solely on small, fragmented vegetated patches for pollution mitigation. Instead of only increasing vegetation cover along the immediate riverbank, management efforts should focus on enhancing both the extent and spatial connectivity of ecological sink landscapes – such as forested patches, grassed areas, and multifunctional green–blue infrastructures – within the 300 m buffer. The integration of low-impact development (LID) measures, including permeable pavements, rain gardens, green roofs, and decentralized stormwater retention systems, could substantially reduce runoff generation and pollutant delivery efficiency in this core influence zone.

Overall, these findings support a shift from linear, river-centered management toward a spatially integrated, scale-aware approach that coordinates land-use regulation, urban drainage design, and ecological restoration at the landscape level in plain river network systems.

Uncertainties and Limitations

Several uncertainties and limitations should be acknowledged when interpreting the results of this study. First, the analysis was based on seasonal mean water-quality data, which effectively capture general seasonal patterns but may not fully reflect short-term pollution pulses associated with extreme rainfall events, tidal fluctuations, or accidental discharges. Such episodic processes can be particularly important in urbanized plain river networks and warrant finer temporal resolution analysis.

Second, the buffer-based approach adopted in this study assumes isotropic influence around monitoring sites and does not explicitly account for directional hydrological connectivity, stormwater pipe networks, or tidal backwater effects. In highly engineered urban river systems, pollutant transport pathways may deviate substantially from simple Euclidean distance assumptions, potentially leading to under- or overestimation of land-use influence in specific areas.

Third, this study focused primarily on land-use composition, while landscape configuration metrics (e.g., fragmentation, connectivity) and detailed point-source discharge data were not explicitly incorporated into the RDA framework. Although the strong explanatory power observed at the characteristic scale suggests that composition plays a dominant role, incorporating additional spatial and infrastructural variables could further refine source attribution and process understanding.

Finally, the results are derived from a single plain river network basin and may not be directly transferable to all low-relief watersheds, particularly those with different degrees of tidal influence, drainage engineering intensity, or land-use history. Nevertheless, the methodological framework and scale-based interpretation developed here provide a transferable reference for similar urbanized plain river systems.

Directions for Future Research

Future research should focus on integrating higher-frequency water quality monitoring data with rainfall, water-level, and tidal observation data, especially extreme precipitation events, to better analyze short-term transport processes and initial runoff dynamics in plain river networks. Incorporating hydrological connectivity indicators, such as drainage network density, flow directionality, and residence time, would allow for more mechanistic linking of land use and water-quality responses.

In addition, combining land-use composition with landscape configuration metrics and ecological function indicators may help clarify how spatial arrangement modulates source–sink efficiency at the characteristic scale. Finally, comparative analyses across multiple plain river network basins with different urbanization intensities would facilitate broader generalization of characteristic scales and support the formulation of region-specific water environment management guidelines.

Conclusions

This study investigated the scale-dependent effects of land use on river water quality and the underlying source–sink mechanisms in a highly urbanized plain river network, using the Wenruitang River Basin as a representative case. By integrating multi-site water quality monitoring data with high-resolution land-use information, the following conclusions can be drawn.

1) Water quality in the Wenruitang River exhibits pronounced seasonal variability. Concentrations of NH_4^+–N, TP, and COD_{Mn} were consistently higher during the dry season, whereas dissolved oxygen was lower during the wet season. These seasonal patterns reflect the combined effects of hydrological conditions, temperature-dependent biogeochemical processes, and anthropogenic pollutant inputs in a low-gradient, densely urbanized river network.

2) Nutrient pollution is highly synchronized and predominantly anthropogenic in origin. Spearman correlation analysis and principal component analysis revealed strong coupling between NH_4^+–N and TP, with both variables dominating the primary pollution-related principal component. This indicates that external inputs associated with urban wastewater discharge and mixed urban-agricultural runoff remain the principal drivers of water quality degradation in the basin.

3) The influence of land use on water quality displays a clear scale dependence, with a characteristic response scale of approximately 300 m. Redundancy analysis revealed an inverted U-shaped relationship between explanatory power and buffer size, with land-use composition within the 300 m buffer accounting for the highest proportion of spatial variability in water quality. This characteristic scale reflects the shortened land–water interaction distance typical of plain river networks with low relief, dense drainage systems, and limited effective transport pathways.

4) A pronounced source–sink imbalance at the characteristic scale constitutes a key structural driver of persistent water quality stress. Built-up land functions as the dominant pollution source, exhibiting strong positive associations with NH_4^+–N, TP, and COD_{Mn}, whereas forest and grassland act as sink landscapes with evident pollutant attenuation effects. However, the overwhelming dominance of built-up land (42.8%) relative to ecological sink land uses (16.0%) forms a strongly source-dominated, sink-deficient landscape configuration that constrains water quality improvement.

5) These findings have direct implications for water-environment management in urbanized plain river networks. Effective water quality control should move beyond narrow riparian buffers and instead target the characteristic scale landscape. Expanding management units to the 300 m core influence zone, restraining further impervious surface expansion, and enhancing sink functions through low-impact development practices and ecological land-use restoration are critical for achieving spatially precise and effective water quality management.

Overall, this study demonstrates that water quality degradation in plain river networks is primarily driven by short-distance, high-intensity source–sink imbalances. Identifying characteristic spatial response scales provides a crucial link between landscape structure and targeted water-environment governance, offering both theoretical insight and practical guidance for improving water quality in rapidly urbanizing low-relief regions.

Furthermore, although this study is based on the Wenruitang River Basin, the identified scale-dependent mechanisms and source–sink landscape patterns are not site-specific but reflect fundamental processes inherent to highly urbanized plain river network systems. The concept of a characteristic response scale, particularly the identification of the ~300 m core influence zone, provides a transferable analytical framework for similar low-relief, high-density river networks. Therefore, the findings of this study can be extended to support water environment management, spatial planning, and ecological restoration in other urbanized plain river regions undergoing comparable land-use transitions, enhancing their broader applicability and theoretical significance.

Funding

This research was supported by the 2026 Henan Provincial Science and Technology Research Project (No. 262102230122).

Acknowledgements

The authors express their gratitude for the support provided by the Wenzhou Water Resources Bureau.

AI Usage Disclosure Statement

Doubao and ChatGPT 5.2 were adopted merely for English language polishing and grammar revision after the completion of the original manuscript draft. No artificial intelligence tools were involved in experimental design, data collection and analysis, figure generation, or the drafting of core research content and conclusions. All text revised by AI was thoroughly reviewed, examined and validated by all authors. Every experimental parameter, numerical data and academic statement was manually cross-checked to guarantee the authenticity and reliability of the manuscript content. All research work was independently accomplished by the authors, who take full responsibility for all arguments and results presented in this article.

Conflict of Interest

The authors declare no conflict of interest.

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