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RESEARCH ARTICLE

SEASONAL VARIATIONS OF NITROGEN AND PHOSPHORUS IN URBAN AND NON-URBAN RIVER REACHES: A CASE STUDY OF THE NANCHONG SECTION OF THE JIALING RIVER, CHINA

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ABSTRACT

The process of urbanization exerts an increasingly pronounced impact on river water quality; however, existing studies have predominantly focused on large cities, with insufficient attention devoted to small and medium-sized cities (SMCs) undergoing rapid development. This study targeted the Nanchong Segment of the Jialing River as the research subject. Water samples were collected from 12 sampling sites in summer (August) and winter (January of the subsequent year) 2024 to analyze the spatial distribution and seasonal variation characteristics of nitrogen, phosphorus, and dissolved oxygen (DO) in urban versus non-urban reaches. Additionally, the trophic state index (TSI) and nutrient pattern classification method were employed to identify pollution source types. Results indicated that total phosphorus (TP) concentrations in urban reaches were significantly higher than those in non-urban reaches across both seasons (64% ~ 79% higher), while total nitrogen (TN) concentrations were 25% ~ 35% higher—suggesting that phosphorus exhibits a more sensitive response to urbanization. TP concentrations in urban reaches were 0.076 mg/L in summer and 0.078 mg/L in winter, consistently maintaining a eutrophic state (mean TSI: 52.8 ~ 53.4), whereas non-urban reaches remained in a mesotrophic state (TSI: 47.5 ~ 48.0). Regarding seasonal variations, DO in non-urban reaches displayed typical natural fluctuations (significantly higher in winter than in summer), whereas DO recovery in urban reaches was inhibited in winter, indicating continuous input of oxygen-consuming substances. Nutrient pattern classification further revealed that TP in urban reaches presented a "non-seasonal" pattern, dominated by point source inputs; in contrast, TP in non-urban reaches exhibited a "phase-synchronous" pattern, with non-point source (NPS) control as the primary driver. This study demonstrates that urbanization fundamentally alters the seasonal dynamics of river nutrients, shifting the dominant pollution source from seasonal NPS to continuous point sources. For rapidly developing SMCs, it is recommended to prioritize the strengthening of point source control (especially phosphorus removal) and implement a seasonal management strategy that integrates targeted supervision during the winter low-flow period with NPS interception in summer.

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INTRODUCTION

Urbanization ranks among the most severe anthropogenic disturbances to river ecosystems. With the acceleration of global urbanization, urban land use continues to expand, and the intensity of industrial and agricultural activities escalates. Consequently, surface runoff, domestic sewage, and industrial wastewater exert an increasingly prominent impact on river water quality, driving the persistent deterioration of water quality in urban river reaches. Extensive research has demonstrated a significant correlation between urbanization level and river water quality indicators[1], and the urban expansion index exhibits long-term consistency with the variation trends of multiple pollution metrics[2]. Additionally, seasonal hydrological conditions (e.g., rainfall, runoff, and water temperature) strongly influence dissolved oxygen (DO) and nutrient concentrations in river water; neglecting seasonal differences may compromise the practical efficacy of water body management. Zhang et al[3] further revealed in their study of tidal rivers in the Pearl River Delta that hydrological processes regulate the spatiotemporal variation of water retention time, thereby affecting DO concentrations. Notably, the impacts of point source pollution and non-point source (NPS) pollution on DO vary significantly across seasons and regions. In temperate and subtropical monsoon climate zones, summer rivers are characterized by high discharge, which may either dilute pollutants or transport them into NPS via surface runoff. In winter, however, reduced discharge leads to the concentration of point source pollutants, while lower temperatures slow biological uptake and transformation processes[4]. Based on the relationship between nutrient concentrations and river discharge, Meter et al[5] identified three distinct patterns: the in-phase pattern, the out-of-phase pattern, and the non-seasonal pattern. The establishment of these patterns provides clear guidance for identifying dominant river pollution sources and formulating targeted mitigation measures. Against the backdrop of rapid urbanization, water environment management of rivers in SMCsin China faces widespread challenges. Urban river reaches typically exhibit characteristics of elevated nitrogen and phosphorus concentrations and high organic matter loads[6], with significant spatiotemporal variations across seasons—posing higher demands for water quality assessment and management.

Currently, systematic studies have been conducted on the water quality of large rivers (e.g., the Yangtze River, Yellow River, and Pearl River) and urban reaches in megacities (e.g., Beijing, Shanghai, and Guangzhou), revealing the response relationship between urbanization indices and water quality indicators. Li et al[1] found through a national-scale study that the high aggregation of urban land exacerbates spatial inequality in water quality. Huang et al[7] analyzed the Yangtze River Basin and concluded that the proportion of urban built-up area is a key factor influencing river nutrient concentrations. Zhang et al[6] further confirmed in their study of the Pearl River Delta urban agglomeration that the proportion of construction land contributes over 46% to the explanation of water quality variations. However, these studies are predominantly focused on rivers in large cities, with insufficient attention paid to rivers in medium-sized cities—the mainstay of urban growth in China. As the largest tributary of the upper Yangtze River, the Jialing River spans multiple cities in Sichuan Province and serves as a critical water source[8]. Nanchong City, located in the middle reaches of the Jialing River, is a typical medium-sized city in China. In recent years, accelerated urbanization and intensified coupling of industrial and agricultural development have rendered the Nanchong Segment of the Jialing River a representative study area for exploring the impact of urbanization on river water quality. Previous studies have confirmed water quality issues in this segment: Ren et al[9] found that the water quality of the Jialing River Basin exhibited a clear threshold around 2017, with pH, DO, permanganate index, and ammonia nitrogen as key distinguishing factors. However, most of these studies rely on continuous-time-series routine monitoring data, lack dedicated comparative analysis of summer and winter, and fail to elaborate on differences in nutrient seasonal patterns between urban and non-urban reaches. Thus, this study aims to provide a reference for sustainable water quality management under rapid urbanization by comparing summer and winter water quality in the Nanchong Segment of the Jialing River and clarifying the nutrient patterns in these two seasons.

MATERIALS AND METHODS

Overview of the study area: The Nanchong Segment of the Jialing River is situated in northeastern Sichuan Province, China (105°57′26″E ~ 106°23′32″E, 30°28′41″N ~ 31°36′57″N). The Jialing River enters the region via Langzhong City and exits at Lidu Town, with a total length of approximately 300 km within the segment. This area is characterized by a subtropical monsoon climate: summers (June–August) are hot and humid, with an average temperature of 26 ~ 28 °C; winters (December–February of the subsequent year) are mild, with an average temperature of 5 ~ 6 °C. The annual average precipitation is approximately 987 mm, of which70% occurs during the summer monsoon period [10].

Deployment of sampling points: A total of 12 sampling sites were established along the mainstream of the Jialing River (Figure 1.1). Among them, sites S1–S4 and S11–S12 were located in urban reaches, distributed in the urban areas of Langzhong City, Nanbu County, and Nanchong City; sites S5–S10 were set as non-urban reference reaches, situated in the natural and agricultural reaches within the Nanchong Segment of the Jialing River.

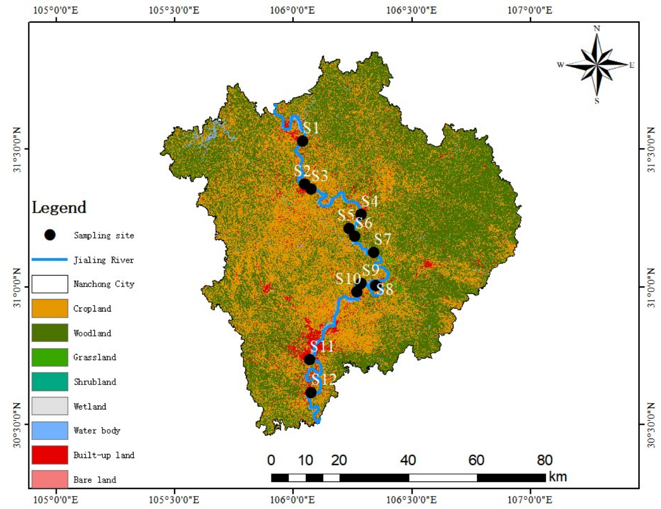


Fig. 1.1. Study area and sampling points

Collection and determination of samples

Sample collection: Field sampling will be conducted in August 2024 (summer) and January 2025 (winter) respectively. Collect water samples from 0 to 0.5m below the water surface and store them in acid-washed polyethylene bottles.

Determination of the sample

On-site determination of indicators: water temperature (WT), dissolved oxygen (DO), pH. The three on-site measurement indicators were measured using a Doha water quality meter (Hach 30d), with three measurements at each sampling point to minimize error.

Determination of TN and DTN: Both were determined using alkaline potassium persulfate digestion ultraviolet spectrophotometry. For the determination of DTN, the water sample was filtered through a 0.45μm filter membrane before the determination.

Determination of NO_3^--N: Nitrate ultraviolet spectrophotometry

Determination of NO_3^--N: Determination using Nessler's reagent spectrophotometry.

Determination of TP and DTP: Determination using ammonium molybdate spectrophotometry. For the determination of DTP, the water sample was filtered through a 0.45μm filter membrane before the determination.

PO_4^{3-}-P determination: The determination shall be carried out in accordance with the method for the determination of phosphate in the analytical method for boiler water and cooling water.

Data Analysis: Calculate descriptive statistics for each parameter by season and point type. Normality was tested using the Shapiro-Wilk test. Statistical analysis, correlation analysis and principal component analysis of the data were performed using SPSS 26.0 software; The distribution map of sampling points and the spatial analysis map of sampling points were plotted using ArcGIS 10.8 software; The data analysis results were visualized using Origin 2022 software.

Eutrophication assessment: The nutritional status index was calculated using the modified Carlson index[11]. The specific calculation formula is as follows:

$$\mathrm{TSI}_{(\mathrm{TP})}=10*(6-(\ln\frac{48}{\mathrm{TP}}/\ln 2))\# \quad (1)$$

$$\mathrm{TSI}_{(\mathrm{TN})}=10*(6-(\ln\frac{48}{\mathrm{TN}}/\ln 2))\# \quad (2)$$

In the formula: TSI(TP) and TSI(TN) are nutritional status indices based on TP and TN respectively, and TP and TP are measured values of each parameter respectively. Classification criteria: $TSI < 40$ Oligotrophic; $40 < TSI < 50$ Mesotrophic; $50 < TSI < 60$ Eutrophic; $TSI > 60$ Hypertrophic[11].

Nutrient pattern classification[5]: Seasonal patterns are classified based on the relationship between concentration and flow. The study area is located in the monsoon climate zone, with high flow in summer and low flow in winter.

- The "in-phase" model, where concentration increases with flow, indicates that the surface source is dominant;
- "anti-phase" mode, where concentration decreases with flow rate, indicating point source dominance;
- "non-seasonal" mode, with very little seasonal variation in concentration, reflecting the characteristics of mixed or urbanized sources.

RESULTS

Overview of water quality parameters and differences in temporal and spatial distribution: Descriptive statistics of water quality parameters in the study area were conducted by season and river section type, and the results are shown in Table 2.1. Independent sample t-tests were used to compare water quality differences among different river sections in the same season.

Table 2.1. Water quality indicators for the entire section in different seasons

Water quality indicators	Season	Urban segment		Non-urban segment		P value
		M±SD	Range	M±SD	Range	
TP (mg/L)	Summer	0.076±0.022	0.052 ~ 0.110	0.037±0.009	0.029 ~ 0.051	< 0.01
	Winter	0.078±0.017	0.061 ~ 0.104	0.042±0.008	0.034 ~ 0.054	< 0.01
DTP (mg/L)	Summer	0.026±0.004	0.023 ~ 0.032	0.022±0.003	0.019 ~ 0.027	< 0.05
	Winter	0.031±0.005	0.027 ~ 0.040	0.028±0.003	0.023 ~ 0.030	-
PO_4^{3-}-P (mg/L)	Summer	0.020±0.006	0.017 ~ 0.031	0.019±0.004	0.015 ~ 0.023	-
	Winter	0.024±0.006	0.020 ~ 0.036	0.024±0.003	0.019 ~ 0.027	-
TN (mg/L)	Summer	0.708±0.106	0.592 ~ 0.891	0.563±0.053	0.486 ~ 0.630	< 0.01
	Winter	0.637±0.090	0.533 ~ 0.795	0.474±0.067	0.399 ~ 0.564	< 0.01
DTN (mg/L)	Summer	0.513±0.095	0.395 ~ 0.595	0.354±0.048	0.287 ~ 0.429	< 0.01
	Winter	0.502±0.100	0.330 ~ 0.591	0.327±0.052	0.277 ~ 0.415	< 0.01
NO_3^--N (mg/L)	Summer	0.284±0.087	0.141 ~ 0.365	0.216±0.058	0.131 ~ 0.292	-
	Winter	0.213±0.056	0.130 ~ 0.291	0.168±0.033	0.133 ~ 0.224	-
NH_4^+-N (mg/L)	Summer	0.257±0.047	0.201 ~ 0.301	0.209±0.053	0.130 ~ 0.271	-
	Winter	0.227±0.041	0.191 ~ 0.277	0.192±0.051	0.125 ~ 0.259	-
DO (mg/L)	Summer	8.66±0.71	7.58 ~ 9.49	8.78±1.30	7.85 ~ 11.38	-
	Winter	9.60±0.58	8.97 ~ 10.49	11.86±1.49	9.49 ~ 13.50	< 0.01
WT (℃)	Summer	30.0±2.2	27.4 ~ 33.0	29.3±1.7	26.7 ~ 31.2	-
	Winter	12.08±0.67	10.83 ~ 12.61	13.36±1.17	11.98 ~ 15.20	< 0.05
pH	Summer	7.93±0.13	7.76 ~ 8.15	8.48±0.42	8.07 ~ 8.92	< 0.05
	Winter	8.62±0.08	8.56 ~ 8.77	8.93±0.09	8.84 ~ 9.06	< 0.01

Note:P<0.05 indicates a significant difference; P<0.01 indicates an extremely significant difference; - indicates no significant difference.

Table 2.2. Evaluation Results of water quality nutritional status in the study area

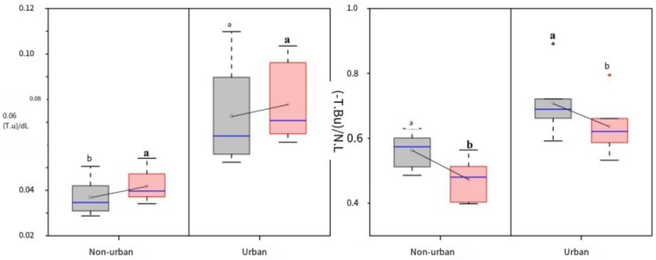
River section	Seasons	TSI(TP)	TSI(TN)	TSI(Mean)	Grading
Urban	Summer	55.8	51.0	53.4	Eutrophic
Urban	Winter	56.0	49.6	52.8	Eutrophic
Non-urban	Summer	47.5	48.4	48.0	Mesotrophic
Non-urban	Winter	48.9	46.0	47.5	Mesotrophic

In terms of phosphorus, the TP concentration in urban river sections was significantly higher than that in non-urban river sections in both seasons (summer: urban river section 0.076 mg/L> non-urban river section 0.037 mg/L, $p<0.01$; winter: urban river section 0.078 mg/L> non-urban river section 0.042mg/L, $p<0.01$). The TP concentration in urban river sections was 64% to 79% higher than that in non-urban sections. DTP was also higher in urban river sections in summer ($p<0.05$), while the difference was not significant in winter. PO_4^{3-}-P showed no significant difference between the two types of river sections, suggesting that the increased phosphorus in urban areas was mainly in granular or organic form. In terms of nitrogen content, TN in the urban section was significantly higher than that in the non-urban section in both seasons (summer: $0.708 mg\cdot L^{-1}$in the urban section > 0.563 mg/L in the non-urban section, $p<0.01$; winter: 0.637 mg/L in the urban section > 0.474 mg/L in the urban section, $p<0.01$). The distribution pattern of DTN was similar to that of TN. NO_3^--N and NH_4^+-N have higher average concentrations in urban river sections, but not significantly. The urban/non-urban ratio of TN was approximately 1.25 to 1.35, which was less than the ratio of total phosphorus, indicating that phosphorus was more sensitive to urbanization in the river sections of the study area. The dissolved oxygen levels in urban and non-urban river sections were comparable in summer. However, in winter, the dissolved oxygen in non-urban sections was significantly higher than that in urban sections ($p<0.01$). In winter, both WT and pH showed significant differences between the two types of river sections ($p < 0.05$), while in summer only pH showed significant differences ($p < 0.05$).

Eutrophication assessment: The modified Carlson Trophic Status Index (TSI) was used to assess eutrophication in the study section, and the results are shown in Table 3.2. According to the table, the urban river section was in a eutrophic state in both seasons, with mean TSI values of 53.4 (summer) and 52.8 (winter) respectively, both exceeding the eutrophic threshold ($TSI \geq 50$). The non-urban sections were in mesotrophic condition in both seasons, with TSI averages of 48.0 (summer) and 47.5 (winter) respectively, close to the lower limit of the eutrophic threshold. Consistent with the urban-rural differences in TP and TN concentrations in Section 2.1, the risk of eutrophication in urban sections was significantly higher than that in non-urban sections.

In terms of evaluation indicators, the TSI (TP) in the urban river section was 55.8 in summer and 56.0 in winter, respectively, both higher than TSI (TN) in the same period (51.0 and 49.6), indicating that phosphorus contributed more to eutrophication in the region than nitrogen. The TSI (TP) and TSI (TN) in non-urban river sections are relatively close, indicating that phosphorus and nitrogen contribute equally to eutrophication.

Classification of nutrient salt patterns: Combining the significant differences in nutrient concentration in urban and rural river sections and the assessment results of eutrophication risk in the previous text, the distribution patterns of nutrients in urban and non-urban river sections were further revealed from the perspective of seasonal variation. Based on the seasonal concentration model, urban and non-urban river sections presented different nutrient characteristics (Figure 3.2). TP shows a "non-seasonal" pattern in urban river sections, with little difference in concentration between summer and winter (0.076 mg/L in summer and 0.078 mg/L in winter), indicating that point source pollutant input continues to dominate. The non-urban sections show a "phase in phase" pattern, with concentrations in winter (0.042 mg/L) slightly higher than in summer (0.037 mg/L), indicating that they are controlled by non-point source pollutants. TN showed an "anti-phase" pattern (higher concentrations in summer than in winter) in both types of river sections. In urban river sections, TN was 0.708 mg/L in summer and 0.637 mg/L in winter, with a seasonal variation of 11.1%; For non-urban river sections, it was 0.563 mg/L in summer and 0.474 mg/L in winter, with a seasonal variation of 18.8%, and the seasonal variation was more significant for non-urban river sections.



Note: The black box represents summer and the pink box represents winter

Figure 2. Distribution characteristics of total nitrogen and total phosphorus in different river sections

DISCUSSION AND ANALYSIS

The driving effect of urbanization on nutrient enrichment: In this study, the TP concentration in the urban river section was significantly higher than that in the non-urban section (64% to 79% higher), and the urban river section remained eutrophic (TSI 52.8 to 53.4), while the non-urban section was only mesotrophic (TSI 47.5 to 48.0), which is consistent[12] with the conclusions of studies on the impact of urbanization on water quality worldwide. Phosphorus is more sensitive to urbanization than nitrogen, similar [13]to the findings in developed regions such as the Yangtze River Delta in China, suggesting that phosphorus remains the most indicative pollutant in urban river basins at different levels of development. However, there is no significant difference in PO_4^{3-}-P between urban and non-urban river sections. This suggests that phosphorus from urban sources mainly exists [14]in granular or organic form and may originate from particulate [15]matter in urban surface runoff and effluent from sewage treatment plants. This suggests that particulate phosphorus may settle in reservoirs and downstream river sections, forming legacy pollution [16]sources that persist even after the external load is reduced. The total nitrogen concentration is higher in urban river sections, but the ratio of total phosphorus is lower in urban to non-urban river sections. This may be due to the diverse sources of nitrogen input in non-urban areas, such as agricultural fertilizer application and livestock breeding. Research shows that agricultural activities (fertilizers and livestock manure) contribute 60% to 64%[17] of nitrogen sources in U.S. river basins, with fertilizers being the largest source of nitrogen in most basins around the world. These agricultural processes not only directly input nitrogen, but also form long-term "nitrogen legacies[18]" in soil and groundwater, where historically accumulated nitrogen can persist for decades within the basin and continue to affect water quality even after external inputs have decreased. In the Jialing River Basin, livestock farming is also a significant source [19]of total nitrogen, and agricultural inputs significantly increase nitrogen background levels in non-urban areas, thereby reducing the contrast in nitrogen concentrations between urban and non-urban river sections.

Seasonal variations and urbanization impact on water quality: The DO in non-urban river sections shows typical natural seasonal variations, that is, significantly higher in winter (11.86 mg/L) than in summer (8.78 mg/L), in line with the natural law[20] that lower water temperature leads to higher DO solubility and weakened biological oxygen consumption. However, in the urban section, this natural recovery mechanism is greatly weakened, with no significant difference in winter DO (9.60 mg/L) compared to summer do (8.66 mg/L), indicating a sustained input of oxygen-consuming substances in the urban section. These oxygen-consuming substances mainly come from organic matter in domestic sewage, industrial wastewater, etc. In the context of the incomplete coverage of sewage treatment plants in Nanchong City, even in low-temperature winter conditions, a considerable amount of dissolved oxygen is still needed. In addition, the classification of nutrient salt models further explains the fundamental differences in the structure of pollution sources. Total phosphorus in urban river sections shows a "non-seasonal" pattern (with almost equal concentrations in summer and winter), indicating that point sources continue to dominate and the annual discharge load is relatively constant; Total phosphorus in non-urban sections shows a "same-phase" pattern (slightly higher in winter than in summer), reflecting the dominance of non-point sources, consistent with the agricultural runoff activated by monsoon rainfall; Total nitrogen in both types of river sections showed an "anti-phase" pattern (higher in summer than in winter), which may reflect the strong solubility and high mobility of nitrogen, as well as the continuous input of nitrogen [21]from groundwater in agricultural areas during low flow periods. This suggests that urbanization has changed the seasonal variation [22]of nutrients in rivers, transforming the dominant source of pollution from a seasonal point source to a continuous point source. For small and medium-sized cities that are developing rapidly, this indicates that instead of simply following the water quality management measures of natural river basins, a year-round control mechanism that ADAPTS to the characteristics of urban point sources should be established. Similar conclusions have been drawn in other river basins. In a study of the tributaries of Lake Ontario, it was noted that highly urbanized rivers exhibit non-seasonal or counter-phase nutrient patterns, while rural and mixed-use river basins exhibit typical co-phase patterns of point source control. This is due to the "fast landscape" created by urbanization, which has changed the way and content [23]of nutrient input.

Suggestions for Water Quality Management Measures and Research Limitations: Based on the findings of this study and the above discussion, management suggestions for river governance in the context of rapid urbanization are proposed:

(1) Point source control remains crucial in urban river sections. Point sources are the dominant source of pollution throughout the year based on the "seasless" nutrient pattern of urban river sections. The current TP concentration in the urban river section (0.076-0.078 mg/L) has exceeded the eutrophication threshold of the flowing water (0.05 mg/L). The point source emissions of phosphorus can be reduced through measures such as strengthening the phosphorus removal process in sewage treatment plants, accelerating the diversion transformation of combined sewer networks, and reducing overflow pollution during the rainy season to achieve the effect of water quality treatment.

(2) Seasonal management strategies should be considered. The impact of point source inputs on rivers is particularly prominent in winter due to the reduced flow and weakened dilution capacity of rivers, and pollutant inputs in winter can be controlled by strengthening point source regulation; In summer, urban runoff is the main source of non-point pollutants, which can be reduced by intercepting and purifying the runoff before it enters the river.

CONCLUSIONS

This study, through water quality analysis of 12 sampling points in the Nanchong section of the Jialing River during summer and winter, revealed the differences in temporal and spatial distribution of nitrogen, phosphorus and dissolved oxygen between urban and non-urban river sections, and identified the types of pollution sources using the nutrient salt pattern classification method. The main conclusions are as follows:

(1) The concentration of nutrients in urban river sections is significantly higher than that in non-urban river sections. The total phosphorus (TP) concentration in urban river sections is 64% to 79% higher, and the total nitrogen (TN) concentration is 25% to 35% higher. Phosphorus is more sensitive to urbanization. The average TP in urban river sections was 0.076 mg/L in summer and 0.078 mg/L in winter, both exceeding the eutrophication threshold of the flowing water.

(2) There are fundamental differences in the seasonal variation of dissolved oxygen in urban and rural river sections. In non-urban sections, dissolved oxygen shows typical natural variations (significantly higher in winter than in summer), while in urban sections, the recovery of dissolved oxygen is inhibited in winter and there is no significant difference between summer and winter, indicating the continuous input of oxygen-consuming substances in urban sections.

(3) The risk of eutrophication in urban sections is significantly higher than that in non-urban sections. The average TSI of urban river sections is at the eutrophic level, while that of non-urban river sections is at the mesotrophic level. Urban river sections have higher TSI (TP) than TSI (TN), further suggesting that phosphorus is a key driver of eutrophication in the region.

(4) Nutrient pattern classification reveals essential differences in the structure of pollution sources in urban and rural river sections. Total phosphorus in urban river sections shows a "non-seasonal" pattern, indicating that point sources continue to dominate; Total phosphorus in non-urban river sections shows a "phase in phase" pattern, indicating the characteristics of point source control; Total nitrogen in both types of river sections showed an "anti-phase" pattern, possibly due to the strong solubility and high mobility of nitrogen.

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