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ORIGINAL RESEARCH ARTICLE

Trend analysis of water quality variation in the estuarine reach of the Xiaojiang River, a tributary of the Three Gorges Reservoir Area

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Abstract

Based on measured water quality data from 2010 to 2025, the water quality of the estuarine reach of the Xiaojiang River, a tributary of the Three Gorges Reservoir Area, was analyzed using the comprehensive water quality index method. Pearson correlation analysis and principal component analysis were further employed to reveal the major sources of pollution in the Xiaojiang River. The results showed that the water quality in the Xiaojiang estuary from 2010 to 2025 was mainly Class I. Significant seasonal variation was observed within each year, with more severe pollution in summer. Biochemical oxygen demand over five days, total nitrogen, total phosphorus, permanganate index, and fecal coliform were identified as the main pollution indicators. Principal component analysis showed that the estuarine reach of the Xiaojiang River was mainly affected by organic pollution, eutrophication, and fecal contamination. In response to these pollution problems, source control should be strengthened, and the discharge of major pollutants should be reduced to improve water quality. This study can provide a reference for water environment management in the tributaries of the reservoir area.

Keywords: Water quality assessment; Comprehensive water quality identification index; Principal component analysis; Pollution source apportionment

1. Introduction

Globally, human activities such as urbanization, industrialization, and agriculture, together with natural factors such as precipitation and soil erosion, have placed enormous pressure on rivers. The combined effects of these pressures have led to widespread and serious deterioration in water quality.[1,2] Improving aquatic environmental quality is an important component of the United Nations Sustainable Development Goals (SDGs). In particular, SDG 6 focuses on the sustainable management of water resources and sanitation, with Target 6.3 aimed at reducing pollution, improving water quality, and enhancing wastewater treatment.[3] Since the impoundment of the Three Gorges Dam, China has made remarkable progress in navigation, hydropower generation, flood regulation, and irrigation, making outstanding contributions to the development of the Yangtze River Economic Belt and social progress. However, as a complex ecosystem, the Yangtze River Basin also faces new environmental challenges, including soil erosion, deteriorating water quality, and frequent eutrophication.[4,5] Reservoir impoundment has disrupted river connectivity, causing rising water levels, reduced flow velocity, sediment retention within the reservoir area, obstruction of material transport processes, and weakening of the natural assimilative capacity of the aquatic environment.[6-8]

The Xiaojiang River is one of the most representative tributaries in the Three Gorges Reservoir Area. Located in the reservoir's hinterland, its downstream tributary section forms the largest backwater area in the Three Gorges Reservoir. After the impoundment of the Three Gorges Dam, the backwater zone of the Xiaojiang River extended to 60 km, and the degree of eutrophication intensified. As the aquatic ecosystem of the Three Gorges Reservoir Area is still evolving, investigating the characteristics and trends of recent changes in surface water quality of the Xiaojiang River is helpful for assessing the ecological health of the reservoir area and for providing a scientific basis for water environment management and protection.[9]

Previous studies on water quality issues in rivers and reservoirs have mainly focused on the spatiotemporal variation of water quality, eutrophication characteristics, identification of major pollution indicators, and source apportionment. These studies have shown that nutrient, organic pollutant, and pathogenic microorganism inputs are important factors contributing to the deterioration of river water quality. In particular, excessive inputs of nitrogen and phosphorus can promote abnormal algal proliferation, thereby inducing eutrophication, dissolved oxygen depletion, and degradation of aquatic ecological functions.[10] In tributary backwater areas affected by reservoir regulation, elevated water levels and reduced flow velocities can prolong water residence time and weaken pollutant transport and dispersion capacity. As a result, external pollutant inputs, internal loading, and algal growth are more likely to jointly influence water quality variation.[11] Therefore, identifying long-term trends in water quality and the major pollution indicators is essential for understanding the mechanisms underlying water environmental changes in tributaries of the Three Gorges Reservoir Area and for developing effective pollution control strategies.

At present, commonly used water quality assessment methods include the single-factor method, principal component analysis (PCA), and the comprehensive water quality identification index method. In previous studies, the single-factor assessment method has commonly been used to determine water quality classes and identify the main indicators exceeding standard limits, while PCA has been widely applied to extract the dominant factors influencing water quality variation. In contrast, the comprehensive water quality identification index (WQI) can characterize both the degree of water pollution and the water quality class through a multi-indicator comprehensive assessment. Compared with single-indicator assessment approaches, comprehensive evaluation methods are more effective in reflecting the overall status of regional aquatic environmental quality.

In this study, the WQI method was used to evaluate aquatic environmental quality in the study area, and the entropy weight method was applied to determine the weights of each assessment indicator, thereby improving the objectivity and scientific robustness of the comprehensive evaluation results. On this basis, a correlation analysis was used to investigate temporal variation in the aquatic environmental quality of the Xiaojiang River basin over more than a decade, and PCA was then employed to identify the major pollution indicators and their effects on changes in aquatic environmental quality. The findings of this study may provide a scientific basis for water environment management, pollution prevention and control, and ecological restoration in the Xiaojiang River basin.

2. Materials and methods

2.1. Study area

The Xiaojiang River is located in the central part of the Three Gorges Reservoir Area. It originates in Kaizhou District, Chongqing, flows through Yunyang County, and finally discharges into the Yangtze River. The basin covers an area of 5,173 km^2, and the river is 182 km long, making it the largest first-order tributary on the northern bank of the Three Gorges Reservoir Area. The Xiaojiang River is also known as the Pengxi River, a name dating back to the Western Jin dynasty, derived from the ancient Peng people who once lived in the area. The basin topography is generally characterized by higher elevation in the north and lower elevation in the south. Seasonal variation is evident, with abundant summer precipitation and an annual runoff of 3.41×10^9 m^3.

2.2. Sample collection and analysis

The dataset analyzed in this study was obtained from compiled water-quality records for 2010–2025 provided by the Upper Yangtze River Hydrology and Water Resources Survey Bureau, Bureau of Hydrology, Changjiang Water Resources Commission. The monitoring section is located at the Xiaojiang River estuarine reach beneath Shuangjiang Bridge in Yunyang County, Chongqing, approximately 2 km upstream from the confluence of the Xiaojiang River and the Yangtze River, as shown in Figure 1.

Water samples were collected once per month from 2010 to 2020 and once every two months from 2021 to 2025. Two water samples were collected during each sampling campaign, yielding a total of 330. Based on the sampling month, March–May was defined as spring, June–August as summer, September–November as autumn, and December–February of the following year as winter. Thus, the sampling period covered different seasons and intra-annual hydrological variations.

Sample collection, transportation, and laboratory analysis were conducted in accordance with relevant national, water resources, or environmental protection industry standards. The analytical methods for selected water quality indicators are listed in Table 1.

2.3. Data analysis

2.3.1. Single-factor water quality identification index method

The single-factor water quality identification index method is an intuitive approach for classifying water quality and can evaluate it both qualitatively and quantitatively. The single-factor water quality index P_i consists of one integer and two decimal places, and is calculated as follows:[12]

$$P_i = X_1.X_2X_3 \tag{1}$$

where X_1 represents the water quality class, X_2 indicates the midpoint of the interval corresponding to that class, and X_3 represents the comparison result between the monitored water quality class and the functional zoning class.

2.3.2. Comprehensive water quality identification index method

The comprehensive water quality identification index consists of one integer and three decimal places, and is expressed as follows:[13]

$$I_{wq} = X_1.X_2X_3X_4 \tag{2}$$

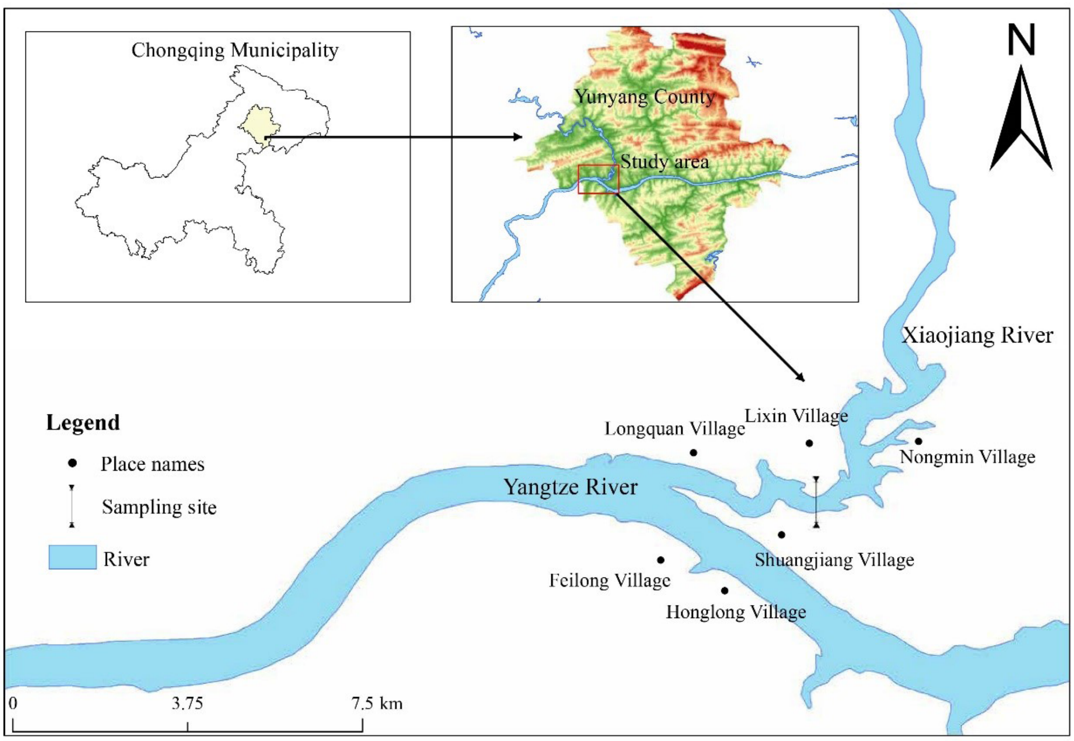

Figure 1. Sampling site of water quality monitoring at the Xiaojiang estuary

Table 1. Analytical methods for water quality monitoring parameters

Parameter	Standard analytical method	Detection limit
Water temperature	Water quality—determination of water temperature by thermometer or the reversing thermometer method.	–
pH	Determination of water quality pH—glass electrode method (GB6920-1986).	–
Dissolved oxygen	Water quality—determination of dissolved oxygen by electrochemical probe method (HJ506-2009).	–
Biochemical oxygen demand over five days	Water quality—determination of five-day biochemical oxygen demand by dilution and seeding method (HJ505-2009).	0.5 mg/L
Permanganate index	Water quality—determination of permanganate index (GB11892-1989).	0.5 mg/L
Total nitrogen	Water quality—determination of total nitrogen by alkaline potassium persulfate digestion UV spectrophotometric method (HJ636-2012).	0.05 mg/L
Total phosphorus	Water quality—determination of total phosphorus by ammonium molybdate spectrophotometric method (GB11893-1989).	0.01 mg/L
Fecal coliform	Water quality—determination of fecal coliform by multiple-tube fermentation method (SL355-2006).	20 MPN/L
Arsenic	Determination of arsenic in water quality—atomic fluorescence spectrometry (SL327.1-2005).	0.2 µg/L
Cadmium	Determination of copper, zinc, lead, and cadmium in water quality—atomic absorption spectrophotometry (GB7475-1987).	0.005 mg/L
Lead	Determination of copper, zinc, lead, and cadmium in water quality—atomic absorption spectrophotometry (GB7475-1987).	0.02 mg/L
Copper	Determination of copper, zinc, lead, and cadmium in water quality—atomic absorption spectrophotometry (GB7475-1987).	0.005 mg/L

where X_1 and X_2 are the water quality index values obtained by weighted calculation of the single-factor indices, and X_3 and X_4 are the identification codes. Since no water function zoning data were available, and the coding part does not affect the results, the identification codes were omitted in this study.[14]

The calculation formula for $X_1.X_2$ is:

$$X_1.X_2 = \sum_{i=1}^{n} \omega_i P_i \quad (3)$$

where X_1 indicates the water quality class, X_2 is the midpoint of the corresponding water quality interval, ω_i is the weight of the i-th indicator, and P_i is the single-factor water quality identification index. As water temperature (WT) is not included in the single-factor identification index analysis, the comprehensive water quality identification index in this study was calculated using biochemical oxygen demand over five days (BOD_5), dissolved oxygen (DO), total nitrogen (TN), total phosphorus (TP), permanganate index (COD_{Mn}), and fecal coliform (FC) (Table 2).

Table 2. Water quality classification standard based on the comprehensive water quality identification index

Criterion	Comprehensive water quality class
$1.0 < X_1.X_2 \le 2.0$	I
$2.0 < X_1.X_2 \le 3.0$	II
$3.0 < X_1.X_2 \le 4.0$	III
$4.0 < X_1.X_2 \le 5.0$	IV
$5.0 < X_1.X_2 \le 6.0$	V
$6.0 < X_1.X_2 \le 7.0$	Worse than V but not black-odorous
$X_1.X_2 > 7.0$	Worse than V and black-odorous

Different weighting methods may yield different evaluation results and, in turn, affect subsequent analyses. In this study, the entropy weight method was used.

The entropy weight method introduces information entropy and standardizes water quality indicators to distinguish the degree of dispersion among indicators and to objectively reflect the amount of information they contain.[15] The main steps are as follows:

(i) Construct the evaluation matrix, where m represents the evaluation objects and n represents the indicators:

$$X = \left(x_{ij}\right)_{mn} \tag{4}$$

where $1 \le i \le m$, $1 \le j \le n$

(ii) Standardize the data:

$$R_{ij} = \left(X_{ij} - X_{min}\right) / \left(X_{max} - X_{min}\right) \tag{5}$$

$$R_{ij} = \left(X_{max} - X_{ij}\right) / \left(X_{max} - X_{min}\right) \tag{6}$$

$$B_{ij} = R_{ij} + 1 \tag{7}$$

Equation 5 applies to positive indicators, and **Equation 6** applies to negative indicators. X_{min} and X_{max} are the minimum and maximum values of each indicator, respectively. **Equation 7** ensures a non-negative transformation.

(iii) Normalize the matrix:

$$P_{ij} = B_{ij} / \sum_{i=1}^{m} B_{ij} \tag{8}$$

(iv) Calculate the entropy value of each indicator:

$$H_j = -k \sum_{i=1}^{m} P_{ij} ln P_{ij} \tag{9}$$

where $k = 1/\ln m$.

(v) Calculate the entropy weight:

$$\omega_i = \left(1 - H_j\right) / \left(n - \sum_{i=1}^{n} H_j\right) \tag{10}$$

2.3.3. Multivariate statistical analysis

SPSS 25.0 was used for correlation analysis and PCA. Pearson correlation coefficients were used to analyze linear relationships among water quality indicators. The correlation coefficient ranges from −1 to 1, with positive values indicating positive correlation and negative values indicating negative correlation.[16]

Principal component analysis is a multivariate statistical method that transforms multiple variables into a smaller number of important variables through linear combinations. It can quantitatively analyze different water quality indicators while retaining most of the original information, and group indicators based on their correlations to more clearly identify the key driving factors affecting changes in the water environment.[17-19] The data for WT, pH, BOD_5, DO, TN, TP, COD_{Mn}, and FC were standardized to eliminate dimensional effects. Kaiser–Meyer–Olkin (KMO) and Bartlett's sphericity tests were conducted before PCA. PCA was considered appropriate when the KMO value exceeded 0.5, and the significance level of Bartlett's test was less than 0.05. Factors with eigenvalues greater than 1 were selected as principal components, ranked by contribution rate, and used to calculate comprehensive water quality scores.

3. Results and discussion

3.1. Water quality assessment of the Xiaojiang estuary

Monthly data for BOD_5, DO, TN, TP, COD_{Mn}, and FC from 2010 to 2025 were selected for evaluation using both the single-factor water quality index method and the comprehensive water quality identification index method. Changes in water quality indices at the Xiaojiang estuary are shown in Figure 2.

As shown in Figure 2, the single-factor water quality identification index was relatively high, averaging 5.41 during 2010–2025, corresponding to Class V water quality. In particular, during the flood season, values greater than six were observed each year, indicating water quality worse than Class V. The highest value was observed in July 2021. Because the monthly single-factor index is represented by the maximum value among the five indicators, i.e., the worst indicator, the results are highly variable.

Compared with the single-factor index method, the comprehensive water quality identification index method simultaneously considers all indicators involved in the evaluation, and therefore provides a more comprehensive and scientific reflection of water quality.[20] Different weighting methods may yield different evaluation results. In previous studies, the equal-weight method was commonly used, assigning the same weight to all indicators and failing to reflect differences in their impacts on water quality.[21] Therefore, the entropy weight method was introduced in this study to improve the scientific reliability of the evaluation results. By calculating entropy values to

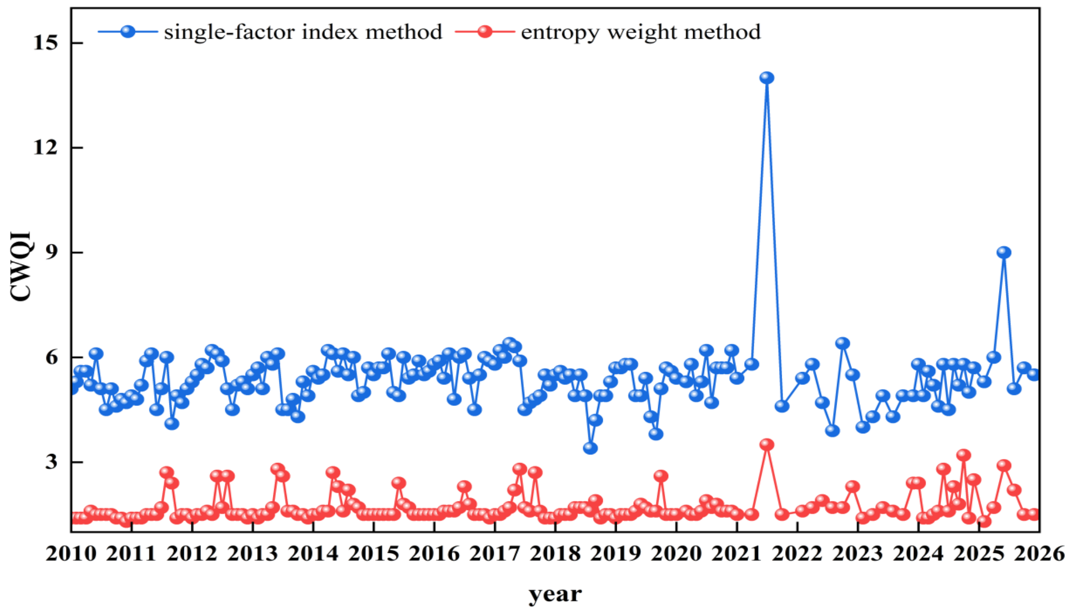

Figure 2. Monthly variation of water quality identification index at the Xiaojiang estuary
Abbreviation: CWQI: Comprehensive water quality identification index.

measure the degree of dispersion and information content of each indicator, the entropy-weight method adjusts indicator weights and effectively reduces the influence of outliers.[22]

When the comprehensive water quality identification index method was applied, Class V and worse-than-Class V conditions no longer appeared. Considering all indicators together, the water quality of the Xiaojiang estuary mainly ranged between Class I and Class II. Compared with traditional methods, the entropy weight method identified 140 months as Class I, 23 months as Class II, and 2 months as Class III. Its distribution pattern was closer to that of the single-factor method and better reflected the actual temporal patterns of water quality variation. Therefore, the entropy weight method can more objectively represent the integrated effects of various indicators and produce more representative results.

Using the entropy weight method, the comprehensive water quality index ranged from 1.3 to 3.5 during 2010–2025, corresponding to Class I–III. Among these, Class I accounted for 84.85% of the total months, and the best water quality period generally occurred from October to February of the following year. Class II accounted for 13.94%, Class III accounted for 1.21%. Overall, the water quality in the Xiaojiang River estuarine reach was dominated by Class I, with Class II accounting for a relatively small proportion and Class III occurring only for a few months, indicating that the water quality of this reach was generally favorable.

In terms of temporal variation, the comprehensive water quality index was mostly concentrated between 1.3 and 1.9, with only a few months exceeding 2.0. The maximum value of 3.5 was observed in July 2021. Overall, the water quality of the Xiaojiang River estuarine reach exhibited certain monthly fluctuations from 2010 to 2025, but months with relatively high index values were limited, and no clear trend of continuous deterioration was observed.

3.2. Temporal variation characteristics of water quality indicators

The monthly mean concentrations of the 12 water quality indicators from 2010 to 2025 were compared to analyze the temporal variation characteristics of water quality at the Xiaojiang estuary, as shown in Figure 3 and Table 3. In this study, four heavy metal indicators, namely arsenic (As), cadmium (Cd), lead (Pb), and copper (Cu), were statistically summarized. The results showed that the mean concentrations of As, Cd, Pb, and Cu were 0.003, 0.002, 0.009, and 0.003 mg/L, respectively, indicating generally low concentration levels. Since these four heavy metals were below the method detection limits in most samples, reliable analysis of their temporal trends and pollution characteristics was difficult. Therefore, the subsequent results and discussion mainly focus on conventional water quality indicators, including WT, pH, DO, COD_{Mn}, BOD_5, TN, TP, and FC. Heavy metal indicators are only presented as background statistical results in Table 3. Most indicators exhibited clear seasonal patterns: WT, BOD_5, TN, TP, COD_{Mn}, and FC increased during the flood season and reached peak values, whereas they remained relatively low during the non-flood season. In contrast, DO showed lower concentrations in summer and recovered to peak levels in winter.

Table 3. Statistical summary of water quality indicators in the Xiaojiang River estuarine reach

Parameters	Mean value	SD	Maximum	Minimum
WT (°C)	19.95	5.46	32.3	10.5
pH	8.08	0.28	8.78	6.57
DO (mg/L)	8.64	1.22	15.43	5.46
BOD_5 (mg/L)	1.51	1.14	10.35	0.5
COD_{Mn} (mg/L)	2.54	1.09	7.35	1.1
TN (mg/L)	1.62	0.36	2.72	0.64
TP (mg/L)	0.08	0.04	0.29	0.02
FC (MPN/L)	12,380	31,254.85	350,000	400
As (mg/L)	0.003	0.002	0.004	0.001
Cd (mg/L)	0.002	0.001	0.003	0.001
Pb (mg/L)	0.009	0.005	0.023	0.003
Cu (mg/L)	0.003	0.002	0.017	0.003

Abbreviations: As: Arsenic; BOD_5: Biochemical oxygen demand over five days; Cd: Cadmium; COD_{Mn}: Permanganate index; Cu: Copper; DO: Dissolved oxygen; FC: Fecal coliform; Pb: Lead; SD: Standard deviation; TN: Total nitrogen; TP: Total phosphorus; WT: Water temperature.

The annual mean WT at the Xiaojiang estuary showed an increasing trend, although the magnitude of warming was small. The pH values ranged from 6.57 to 8.78, generally indicating neutral to slightly alkaline conditions. From 2010 to 2014, BOD_5 remained relatively stable and generally met the Class I standard. However, in May 2014, the maximum value reached 10.35 mg/L, far exceeding the Class V limit and indicating water quality worse than Class V. After 2015, the annual maximum BOD_5 values decreased year by year to the Class II standard, but the annual overall BOD_5 concentration continued to show an upward trend.

Dissolved oxygen concentration remained at a relatively high level from 2010 to 2025, ranging from 5.46 to 15.43 mg/L, with a mean value of 8.64 mg/L, and the overall water quality met the Class I standard, with only a few months reaching Class II, indicating that the Xiaojiang River estuarine reach generally maintained favorable re-aeration conditions. For nutrient indicators, TN concentrations ranged from 0.64 to 2.72 mg/L, with a mean value of 1.62 mg/L, while TP concentrations ranged from 0.02 to 0.29 mg/L, with a mean value of 0.08 mg/L. TN and TP generally exhibited declining trends, especially TP. TN exceeded 2 mg/L during the flood season in several years, reaching a maximum of 2.72 mg/L in July 2014, corresponding to worse-than-Class V water quality, and showing strong seasonal regularity. From 2010 to 2014, TP increased year by year during the flood season but decreased during the non-flood season, reaching a maximum of 0.29 mg/L in May 2014, corresponding to Class IV. After 2016, the overall TP concentration decreased and remained at a relatively low level. From 2021 to 2025, it ranged from 0.02 to 0.08 mg/L in most months, indicating that phosphorus pollution in the Xiaojiang River estuarine reach has decreased in recent years compared with the earlier period.

The permanganate index and FC both showed overall increasing trends. COD_{Mn} reached a maximum of 7.35 mg/L in May 2014, corresponding to Class IV. In terms of seasonal variation, the COD_{Mn} was generally higher in the wet season than in the dry season. Since September 2014, FC counts have repeatedly exceeded the Class V limit and remained at a high level overall, indicating serious microbial contamination. BOD_5, TN, TP, COD_{Mn}, and FC all reached peak values during the 2014 flood season (May–September), with water quality ranging from Class IV to worse than Class V, reflecting a significant increase in pollutant input and obvious deterioration of water quality during this period, with the maximum value observed in July 2021 at 350,000 MPN/L.

3.3. Pollution source apportionment at the Xiaojiang estuary

3.3.1. Correlation analysis

Pearson correlation analysis was conducted for the eight water quality indicators, as shown in Figure 4. The results indicated that, at the 0.01 significance level, WT was significantly positively correlated with COD_{Mn}, BOD_5, and FC, with correlation coefficients of 0.61, 0.31, and 0.22, respectively, while it was significantly negatively correlated with TN and TP, with correlation coefficients of −0.46 and −0.36, respectively. This indicates that nitrogen and phosphorus nutrient concentrations exhibited an opposite

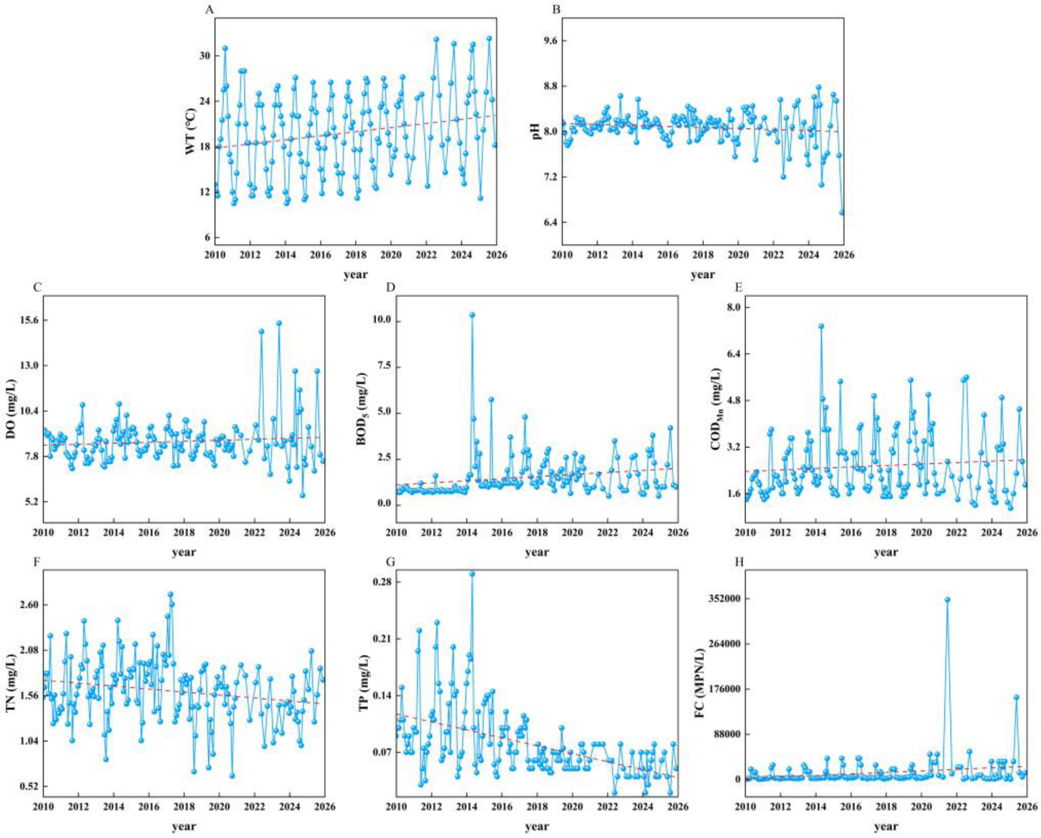

Figure 3. Annual variation of water quality indicators. (A) Water temperature (WT), (B) pH, (C) Dissolved oxygen (DO), (D) Biochemical oxygen demand over five days (BOD_5), (E) Permanganate index (COD_{Mn}), (F) Total nitrogen (TN), (G) Total phosphorus (TP), and (H) Fecal coliform (FC).

trend to WT variation. WT was also negatively correlated with DO, with a correlation coefficient of –0.16.

The pH showed significant positive correlations with BOD_5, DO, and COD_{Mn}, with correlation coefficients of 0.33, 0.39, and 0.33, respectively, suggesting that pH variation was associated to some extent with organic pollution in the water body. BOD_5 was significantly positively correlated with COD_{Mn} and DO, with correlation coefficients of 0.75 and 0.32, respectively. TN was significantly positively correlated with TP, with a correlation coefficient of 0.53, but was significantly negatively correlated with COD_{Mn}, with a correlation coefficient of –0.26.

Total phosphorus showed weak negative correlations with COD_{Mn} and FC, with correlation coefficients of –0.05 and –0.07, respectively, indicating that the linear relationships between TP and organic pollution or microbial contamination were not evident. FC was significantly negatively correlated with DO, with a correlation coefficient of –0.18, suggesting that intensified microbial contamination may exert a certain influence on the oxygen conditions of the water body.

Combined with the seasonal characteristics of various water quality indicators, higher summer temperatures and increased rainfall enhanced surface runoff, allowing organic pollutants and livestock manure from agricultural lands to enter the Xiaojiang River. Agricultural non-point source pollution, domestic sewage, livestock and poultry manure, and other pollutants are more likely to enter water bodies with surface runoff, leading to increases in organic pollution and microbial contamination indicators. Meanwhile, under high-temperature conditions, microbial metabolism and organic matter decomposition may be enhanced, potentially intensifying oxygen consumption in the water body.[23,24] In winter, with lower temperatures, the Xiaojiang River entered the dry season, flow decreased, microbial activity weakened, and the natural consumption of nutrients declined. Meanwhile, continuous inputs of agricultural, industrial, and domestic wastewater maintained relatively high nitrogen and phosphorus concentrations in the water body.[25]

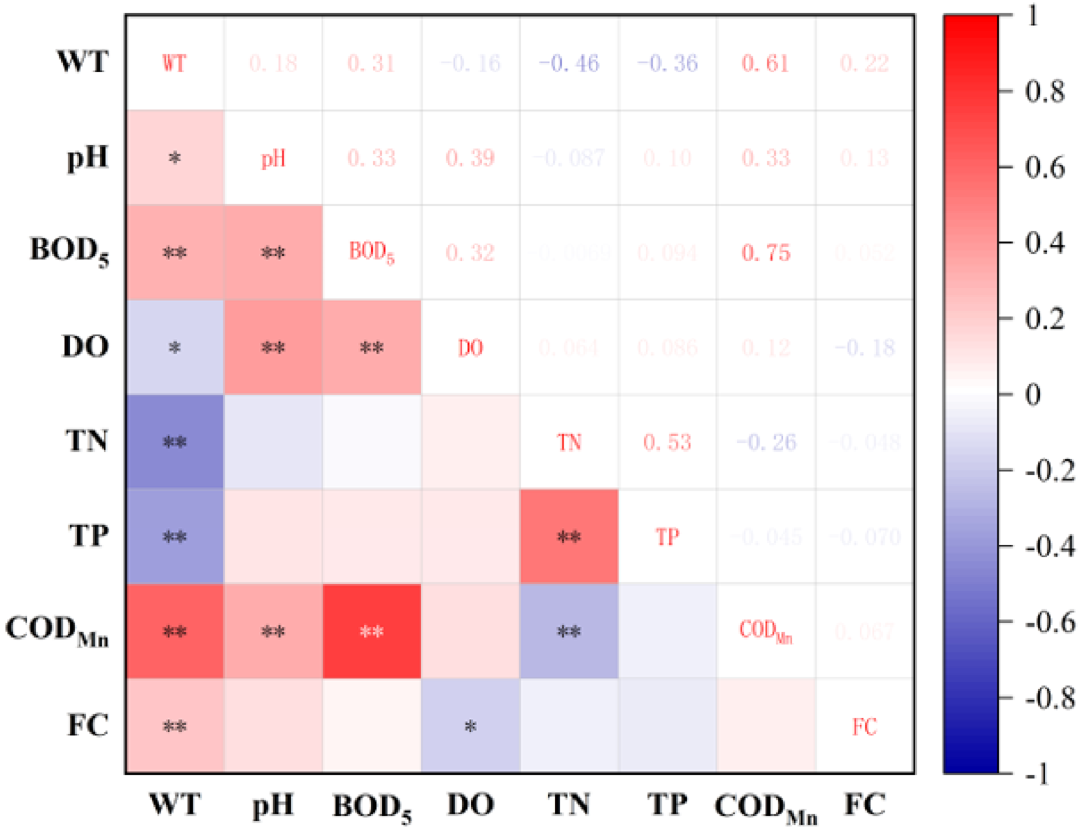

Figure 4. Pearson correlation analysis of water quality indicators. * denotes $p < 0.05$, ** denotes $p < 0.01$
Abbreviations: BOD_5: Biochemical oxygen demand over five days; COD_{Mn}: Permanganate index; DO: Dissolved oxygen; FC: Fecal coliform; TN: Total nitrogen; TP: Total phosphorus; WT: Water temperature.

3.3.2. Principal component analysis

As shown in Table 4, the KMO value was 0.588, greater than 0.5, and the significance level of Bartlett's sphericity test was less than 0.05, indicating that PCA was suitable.

Table 4. Results of Kaiser–Meyer–Olkin (KMO) and Bartlett's test

KMO and Bartlett's test	Value
KMO measure of sampling adequacy	0.588
Approximate χ^2	439.405
Degrees of freedom	28
Significance	0.000

The contribution rates and cumulative contribution rates of the principal components are shown in Table 5. The cumulative contribution rate of the three principal components reached 69.335%, indicating limited information loss and strong explanatory ability. The contribution rates of the three principal components were 29.589%, 23.548%, and 16.198%, respectively. Among them, PC1 had the highest contribution rate and represented the dominant factor influencing water quality variation in the Xiaojiang River estuarine reach.

Principal component 1 (PC1) explained 29.589% of the total variance and mainly included BOD_5, COD_{Mn}, and pH, indicating that the Xiaojiang estuary was mainly affected by reducing organic pollution, likely originating from domestic sewage and industrial wastewater.[26] Principal component 2 (PC2) explained 23.548% of the variance and included TN, TP, and WT. TN and TP both showed high positive loadings on PC2, and they were significantly positively correlated in the correlation analysis, indicating that nitrogen and phosphorus may have similar input sources or transport processes. Previous studies have shown that the Xiaojiang estuary is subject to significant eutrophication pollution.[27] Although TN and TP showed decreasing annual trends, they still generally remained at the Class III level, and TN reached Class V or even worse-than-Class V in some flood-season months. Nitrogen and phosphorus fertilizers used in agricultural non-point source pollution are important sources of TN and TP in water bodies.[28] These accumulated fertilizers are often washed into the water by rainfall, providing sufficient nutrients for microorganisms, especially algae, and triggering algal blooms in the surface water of the Xiaojiang estuary after rainfall events.[29-31]

Table 5. Results of principal component analysis

Water quality indicator	PC1	PC2	PC3
Water temperature (°C)	0.478	−0.599	0.422
pH	0.65	0.051	−0.179
Biochemical oxygen demand over five days (mg/L)	0.866	0.05	0.06
Dissolved oxygen (mg/L)	0.135	0.351	−0.768
Total nitrogen (mg/L)	−0.082	0.849	−0.114
Total phosphorus (mg/L)	0.094	0.843	−0.111
Permanganate index (mg/L)	0.846	−0.248	0.181
Fecal coliform (MPN/L)	0.141	0.046	0.741
Eigenvalue	2.559	1.846	1.124
Contribution rate (%)	29.589	23.548	16.198
Cumulative contribution rate (%)	29.589	53.137	69.335

Abbreviation: PC: Principal component

Principal component 3 explained 16.198% of the total variance and mainly included DO and FC. Among them, FC showed a relatively high positive loading (0.741), whereas DO showed a relatively high negative loading (−0.710). FC had the highest loading on PC3. This indicates that fecal pollution played a dominant role in this component. Given that FC repeatedly exceeded worse-than-Class V levels and showed an increasing trend, the Xiaojiang River appears to be subject to persistent fecal contamination from nearby livestock farms and insufficiently treated domestic sewage. In addition, DO is generally linked to the self-purification capacity of the water body and is closely related to WT.[32] DO exhibited a pronounced negative loading on this principal component, suggesting that dissolved oxygen levels may decrease with increasing microbial contamination. This finding is generally consistent with the negative correlation between FC and DO observed in the correlation analysis.

Based on the loading coefficients and variance contribution rates of the three principal components, a comprehensive principal component score was calculated, as shown in Figure 5. From 2010 to 2013, the comprehensive scores were negative or close to zero in most months, indicating a relatively low level of overall water pollution. In 2014, the comprehensive score increased markedly and reached the maximum value of 3.82. Combined with the previous results, BOD_5, COD_{Mn}, and TP were all at relatively high levels in this month, suggesting the concurrent intensification of organic pollution and nutrient pollution.

From 2015 to 2020, the comprehensive scores generally decreased compared with 2014; however, relatively high positive values still occurred in some months during 2015–2017, indicating the persistence of localized pollution events. In 2021, an abnormally high comprehensive score was observed, with a maximum value of 2.70. From 2022 to 2024, the comprehensive scores were generally low, with most months showing negative or near-zero values, though some fluctuations persisted. In 2025, the fluctuation range of the comprehensive scores increased again, reaching 1.01, suggesting that episodic pollution risks still existed in the Xiaojiang River estuarine reach in recent years.

When the comprehensive PCA scores were grouped by season (Figure 6), the results showed clear seasonal differences in the comprehensive scores. Overall, the degree of integrated water pollution was higher in summer and spring, whereas it was relatively lower in autumn and winter. Among the four seasons, both the median and mean comprehensive scores in summer were higher than those in the other seasons, and the upper quartile of the boxplot was also relatively high, indicating that integrated water pollution was more pronounced in summer and exhibited greater variability. The comprehensive scores in spring were also generally high, suggesting that relatively strong pollution processes occurred in some spring months. In contrast, the comprehensive scores in autumn and winter were mostly concentrated in the negative range, indicating relatively lighter integrated water pollution during these two seasons. In particular, the comprehensive scores in winter were generally low, suggesting comparatively better water quality conditions, which may be related to frequent agricultural activities in summer, such as excessive pesticide and fertilizer runoff into the water body.

To distinguish the dominant environmental factors in different seasons, seasonal PCA was conducted, and

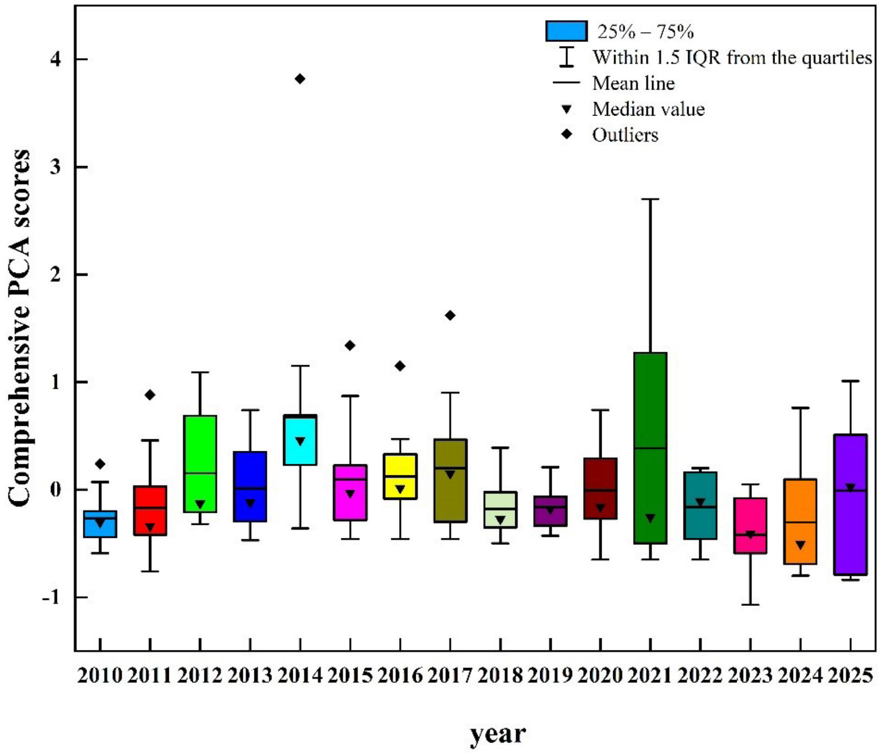

Figure 5. Annual variation trend of comprehensive principal component analysis (PCA) scores for water quality
Abbreviation: IQR: Interquartile range.

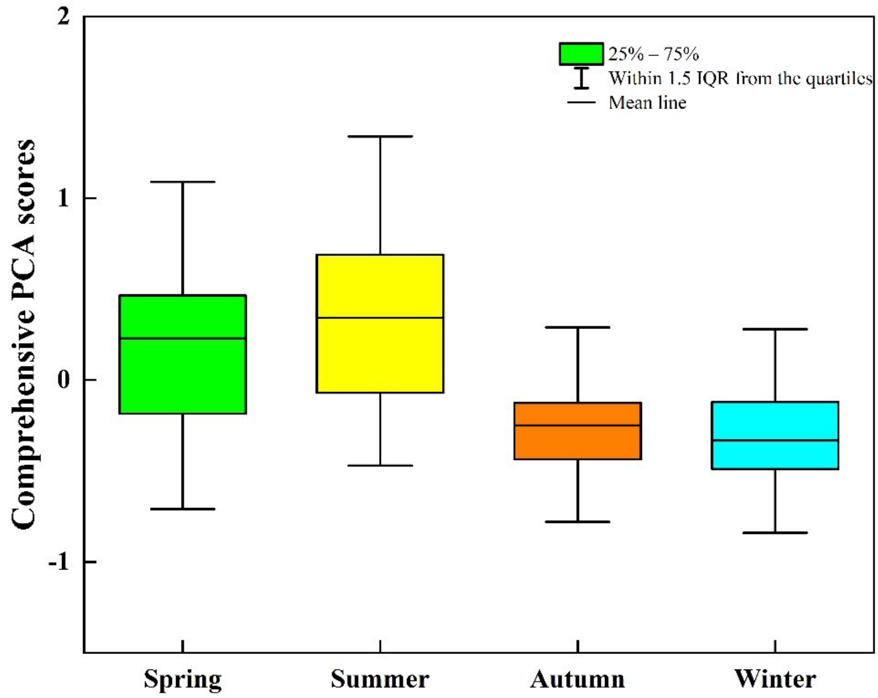

Figure 6. Seasonal variation of comprehensive principal component analysis (PCA) scores for water quality
Abbreviation: IQR: Interquartile range.

a biplot was drawn based on the first two principal components[33] as shown in Figure 7. PC1 and PC2 explained 32.0% and 23.3% of the total variance, respectively, with a cumulative explanation rate of 55.3%, indicating that these two components effectively captured the major differences in water quality indicators among seasons. Based on the loading distribution, PC1 was positively dominated by COD_{Mn}, WT, BOD_5, and pH, whereas its negative direction was mainly associated with TN and TP. This suggests that PC1 can be interpreted as a composite gradient reflecting differences between organic pollution, WT, and pH variation on one side, and nitrogen and phosphorus nutrient variation on the other. PC2 was positively associated with TP, DO, TN, BOD_5, and pH, whereas its negative direction was mainly associated with WT and FC, further revealing contrasting relationships among nutrient levels, dissolved oxygen conditions, partial organic pollution characteristics, temperature, and fecal microbial contamination.

Summer samples were mainly distributed in the positive region of PC1 and were generally aligned with the directions of WT, COD_{Mn}, and BOD_5, indicating that water quality variation in summer was primarily influenced by high temperature and intensified organic pollution. Spring samples showed a wider distribution, with some samples corresponding to BOD_5 and nutrient indicators, suggesting that spring water quality was jointly affected by organic pollution and nutrient inputs. Autumn samples were mostly located near the center of the ordination plot or in the negative region of PC2, indicating relatively low overall pollution intensity. Winter samples were mainly distributed in the negative region of PC1 and were closer to the directions of TN and TP, suggesting that winter water quality variation was more characterized by nutrient accumulation.

Overall, seasonal variation in water quality in the Xiaojiang River estuarine reach was jointly controlled by WT, runoff inputs, organic pollution, nutrient transport and transformation, and microbial contamination. Among the seasons, pollution risks were relatively higher in spring and summer, whereas nitrogen and phosphorus accumulation should receive greater attention in winter.

In summer, rising temperatures enhanced microbial activity in the Xiaojiang River, leading to more severe water pollution. In addition, concentrated rainfall transported urban surface pollutants, residual fertilizers from farmland, and livestock manure into the river, significantly increasing fecal bacterial inputs and resulting in elevated

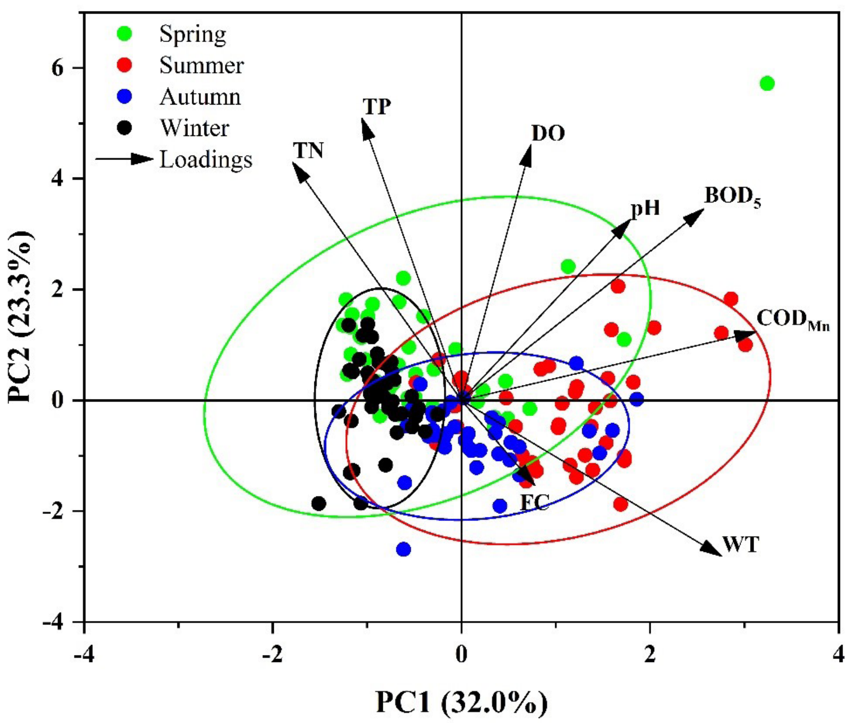

Figure 7. Seasonal distribution biplot of water quality

Abbreviations: BOD_5: Biochemical oxygen demand over five days; COD_{Mn}: Permanganate index; DO: Dissolved oxygen; TN: Total nitrogen; TP: Total phosphorus; WT: Water temperature.

FC counts.[34,35] In winter, lower temperatures and reduced river flow facilitated the settling of suspended particles and sediments, thereby reducing turbidity and external pollution loads. The low temperature caused many aquatic organisms to become dormant or die, reducing biological uptake of nutrients such as nitrogen and phosphorus and making the river system relatively stable.[36,37] At the same time, agricultural production activities declined substantially in winter, agricultural runoff decreased significantly, and domestic wastewater discharge and other disturbances were relatively weaker, resulting in less anthropogenic influence on river water quality.[38,39]

3.3.3. Pollution source identification

Based on water quality evaluation results from 2010 to 2025, the main factors affecting water quality pollution in the Xiaojiang estuary are external inputs and internal pollution. According to the land use map of Yunyang County (Figure 8), agricultural land dominates the riverbanks near Shuangjiang Bridge at the Xiaojiang estuary, while the upstream sections include extensive agricultural land as well as residential and industrial land uses. Industrial production generates large amounts of organic wastewater, and if discharged into the Xiaojiang River without adequate treatment, it can increase the concentration of organic pollutants and reduce pollution. On agricultural land, excessive use of fertilizers and pesticides may enter water bodies through surface runoff or soil infiltration during rainfall events, thereby intensifying eutrophication in the Xiaojiang River.[40,41]

Internal pollution is associated with the large backwater area around the Xiaojiang estuary, where hydrodynamic conditions are weak, and the water body's self-purification capacity is poor, leading to relative pollutant accumulation. Such an environment promotes the activity of algae and other microorganisms, increasing the likelihood of algal blooms.[42] In addition, the riverbed sediment is rich in organic matter derived from domestic sewage, industrial wastewater, and excess fertilizers accumulated over many years. Under suitable conditions, these materials may be returned to the overlying water.[43]

The above pollution issues may have multiple impacts on the aquatic environment and ecological safety in the Xiaojiang River estuarine reach. Elevated BOD_5 and COD_{Mn} indicate increased levels of biodegradable organic

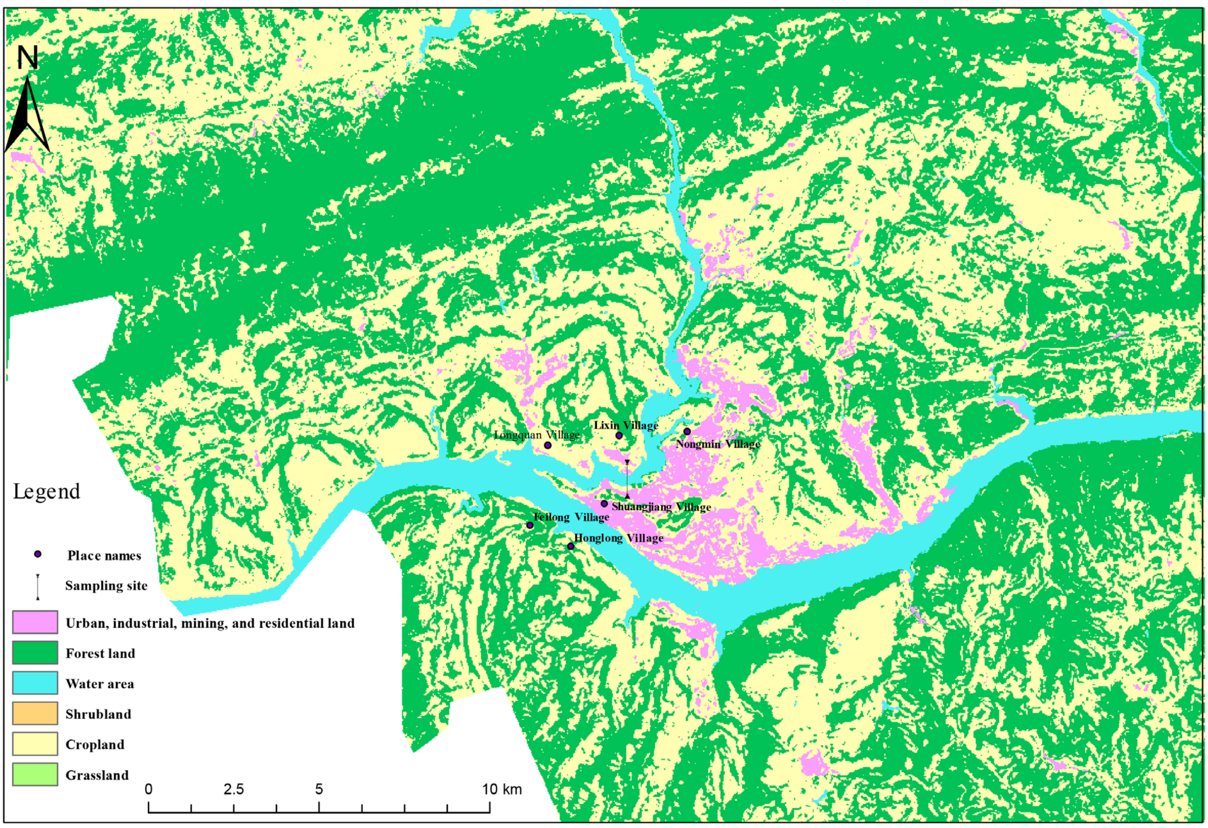

Figure 8. Land use types in Yunyang County

matter and reducing substances in the water body, whose decomposition can consume dissolved oxygen, potentially weakening the self-purification capacity of the water body and increasing the risk of localized hypoxia. Increased nutrient inputs, such as TN and TP, may promote the growth of algae and phytoplankton. In backwater areas characterized by weak hydrodynamic conditions and prolonged residence time, nutrient enrichment is more likely to induce eutrophication and algal blooms, thereby affecting water transparency, dissolved oxygen distribution, and aquatic ecosystem stability. The repeated occurrence of high FC counts suggests a potential risk of fecal microbial contamination in the Xiaojiang River estuarine reach, which may compromise water and sanitation safety and pose threats to residents' water use. In addition, the combined effects of industrial wastewater discharge, domestic sewage input, agricultural non-point source pollution, and internal release from sediments may lead to localized pollutant accumulation during the dry season or in backwater areas, further intensifying water quality fluctuations. Therefore, water quality management in the Xiaojiang River estuarine reach should not only focus on changes in pollutant concentrations, but also pay greater attention to the potential impacts of organic pollution, nutrient pollution, and microbial contamination on aquatic ecological functions, drinking water safety, and the stability of the water environment in tributaries of the Three Gorges Reservoir Area.

3.3.4. Recommendations

As an important estuarine node where the Pengxi River flows into the Yangtze River, the Xiaojiang estuary plays a key role in water quality management in the Three Gorges Reservoir Area. To improve water quality in the Xiaojiang estuary, pollutant discharges should be reduced at their sources. Based on the results of this study, the following management measures are suggested:

(i) Strengthen control of external nutrient inputs: Wastewater discharged into the Xiaojiang River includes industrial, domestic, and agricultural sewage, and these external nutrient sources should receive particular attention. A comprehensive inspection of the sewage pipe network along the Xiaojiang River Basin should be conducted, especially in the Yunyang and Kaizhou sections. Wastewater treatment facilities should be improved, and the separation of rainwater and sewage should be promoted to reduce direct sewage runoff into the river. In agriculture, ecological farming practices should be encouraged, fertilizer use should be reduced, and agricultural waste utilization should be strengthened. For livestock manure, a systematic collection, transfer, and treatment mechanism should be established to reduce FC pollution caused by livestock farming.

(ii) Reduce internal pollution through dredging and ecological restoration: River dredging should be carried out to reduce internal pollution in the Xiaojiang River and improve the self-purification capacity of the water body. The dredged sediment may be reused for soil improvement in agricultural land. In addition, ecological floating beds can be installed, using aquatic plants such as evergreen iris to absorb nutrients, reduce eutrophication, and improve the river landscape.[44]

(iii) Enhance source management and supervision: In the upstream inflow channels, stricter control should be imposed on surrounding factories, farmland, and domestic wastewater discharge. Inspection and monitoring efforts should be increased, and a sound monitoring system should be established to promptly detect and address illegal discharge behavior. Administrative and judicial measures should be used to regulate the behavior of enterprises and individuals and ensure water environment safety.

4. Conclusion

From 2010 to 2025, the water quality of the Xiaojiang River estuarine reach was generally favorable. According to the entropy-weighted comprehensive water quality identification index, the WQI ranged from 1.3 to 3.5, corresponding to Class I to Class III. Overall, the comprehensive water quality of the Xiaojiang estuary was dominated by Class I, with no clear trend of continuous deterioration.

The analysis of individual water quality indicators showed significant seasonal characteristics in the annual variation of water quality at the Xiaojiang estuary. Water quality was generally poorer in summer. BOD_5, TN, TP, COD_{Mn}, and FC all reached peak values during the 2014 flood season, reflecting more severe summer pollution.

According to the results of correlation analysis and PCA, the Xiaojiang estuary was mainly affected by organic pollution, eutrophication, and fecal contamination. Industrial and agricultural land in the estuary's upstream area was the main source of these pollutants.

To improve the water quality of the Xiaojiang estuary, water environment pollution control should be carried out according to the pollution source apportionment results and pollution characteristics identified in this study, so as to promote the harmonious development of human society and Xiaojiang water resources. This study only conducted long-term water quality evaluation at the estuarine section of the Xiaojiang River and lacked spatial distribution analysis. Therefore, in future work, multiple typical sections could be established in the upstream area of the Xiaojiang estuary to further identify the key factors affecting water quality variation.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

The data can be obtained from the corresponding author upon request.

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