Analysis of Spatiotemporal Variation Characteristics of Water Quality in the Lower Reaches of the Nenjiang River

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Abstract To investigate the characteristics of water environmental pollution in the Nenjiang River Basin, five monitoring sections, including Zhenxi, Xianghai Reservoir, Baishatan, Yuelianghu Reservoir, and Da'an, were selected. Utilizing water quality monitoring data collected from 2013 to 2022, the fuzzy comprehensive evaluation method was employed to systematically analyze the spatiotemporal variation patterns of water quality, assess the current pollution status, and identify the influencing factors of non-point source pollution. The results indicated that the concentrations of representative pollutants at five sections in the lower reaches of the Nenjiang River generally exhibited a downward trend, accompanied by an overall improvement in water quality. However, the degree of improvement varied considerably among the different sections. Specifically, the water quality of the main stream of the Nenjiang River (Baishatan and Da'an) improved from Class IV to Class III. In contrast, the Xianghai Reservoir consistently remained at Class V or below, primarily due to excessive fluoride levels. The water quality at Yuelianghu Reservoir and Heidimiao Section demonstrated a fluctuating but overall improving trend. Based on the analysis of pollution sources, targeted recommendations are proposed, including regulating the ecological water requirements of rivers, restoring wetland ecosystems, and enhancing the management of non-point source pollution. These measures offer scientific support for water quality management and ecological conservation in the river basins.

Key words Lower reaches of the Nenjiang River, Water quality, Spatiotemporal variation, Fuzzy comprehensive evaluation

0 Introduction

The lower reaches of the Nenjiang River constitute a critical ecological barrier in the western region of Jilin Province. This area serves not only as the core water conservation zone for regional wetlands but also as a vital water resource supporting agricultural production and rural development. Currently, this region faces challenges including the uneven spatiotemporal distribution of water resources and the exacerbation of land salinization. Notably, the water quality of Xianghai Reservoir consistently remains at Class V throughout the year, which is markedly inferior to that of the main stream of the Nenjiang River. Investigating the spatiotemporal variation characteristics of water quality in the lower reaches of the Nenjiang River holds substantial practical significance for elucidating the causes of pollution, developing effective management strategies, and advancing the construction of water ecological civilization.

1 Basic situation of the lower reaches of the Nenjiang River

1.1 Overview of the river The Nenjiang River originates from the northern foothills of the Greater Khingan Mountains, specifically within the Yilehuli Mountains. It flows through regions including Nenjiang River, Qiqihar, and other areas in Heilongjiang Province before entering Jilin Province at Shijiazi in Dandai Township, Zhenlai County. The river continues through Taonan City, along the boundaries of Taobei District and Zhenlai County, as well as the borders of Da'an City. Near the northwest of Hantun in Da'an County, the river turns eastward and ultimately flows into the Yuelianghu Reservoir. It then discharges into the Nenjiang River via the Haerjin Sluice of the Yuelianghu Reservoir. In Jilin Province, the river extends for 279.7 km and encompasses a drainage area of 10 615 km^2[1]. The segment of the river between Xinping and Zhenxi traverses a hilly region characterized by steep slopes and rapid currents, with a riverbed predominantly composed of pebbles. Downstream of Zhenxi lies a plain area featuring well-developed meanders and numerous beaches. The riverbed in this section consists of small pebbles and fine sand, where bank erosion is notably severe. Further downstream, near Taonan Town, numerous low-lying wetlands are present along the riverbanks, supporting dense growths of willows, reeds, and wormwood in patches. Additionally, the riverbeds of the Nenjiang and Jiaoliu Rivers contribute to groundwater recharge through seepage, resulting in a reduction of runoff downstream.

According to data from the Heidimiao Hydrological Station in Zhenlai County, the flood season occurred in July and August, followed by a gradual decline in water levels after September. From October until May of the subsequent year, the flow rate decreased, marking the dry season. During dry years, rivers may either dry up or freeze to the bottom, resulting in a minimum flow rate of zero. The highest recorded flood level was 141.14 m, observed in 1954. In 1957, the breach of the Mangang Levee resulted in widespread flooding and a significant reduction in flow rate. The recor-

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ded flow rate was only 537 m^3/sec, with a maximum flow velocity of 1.46 m/sec. Over the years, the maximum sediment concentration reached 5 280 g/m^3, while the minimum was approximately zero. The highest recorded water temperature was 32 ℃. The freezing period extended from late October to the end of March of the following year, with a maximum ice thickness of 1.13 m and an average ice thickness of 0.89 m[2]. The water system distribution of the Nenjiang River Basin is illustrated in Fig. 1.

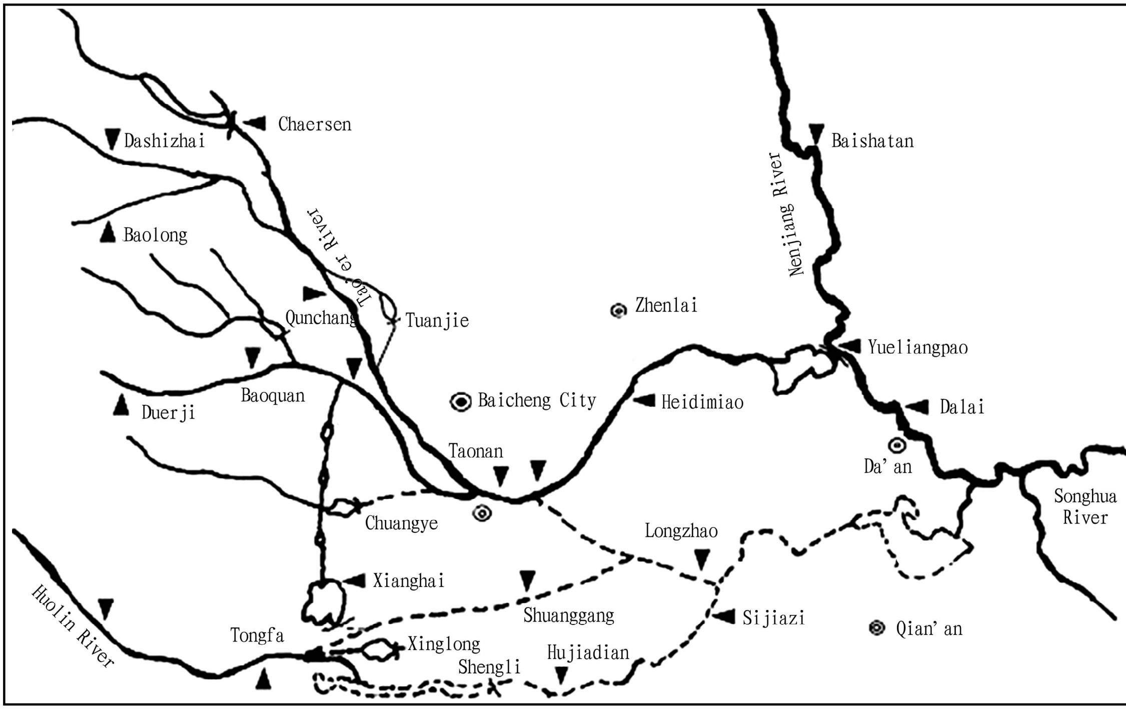

Fig. 1 Distribution of rivers in the lower reaches of the Nenjiang River

1.2 Economic overview Taobei District of Baicheng City, Da'an City, Taonan City, Zhenlai County, Tongyu County, and Ganan County of Songyuan City constitute the primary cities and counties within the Nenjiang River Basin in Jilin Province. The region comprises a total of 117 towns and townships, with an aggregate population of approximately 2.273 9 million. Among this population, 1.407 2 million individuals are engaged in agriculture, representing 61.9% of the total population, thereby characterizing the area as predominantly agricultural. The entire basin encompasses approximately 641 300 ha of cultivated land and constitutes one of the major commercial grain production bases in China. The primary cash crops and agricultural by-products include corn, rice, soybeans, flue-cured tobacco, reeds, cotton, beef cattle, minor grains, and oilseeds. According to statistics from the end of 1998, the total grain output of the entire river basin amounted to 2.335 5 million t. The combined output value of agriculture, forestry, animal husbandry, and fishery reached 4.958 billion yuan, with agriculture alone contributing 2.885 billion yuan[3]. Industrial development within the basin has also attained a considerable scale, comprising 214 enterprises each generating annual revenues exceeding 5 million yuan. The primary industries include textiles and garments, transportation equipment, food and beverage production, papermaking, pharmaceuticals, cement manufacturing, brewing, and sugar production. According to statistics from the end of 1998, the total industrial output value, measured at current prices, reached 4.678 billion yuan. The fishery resources throughout the entire basin are exceptionally abundant. Lakes, ponds, and reservoirs are widely distributed, and wetlands are contiguous. The total water surface area amounts to 1 432.756 km^2. Among these, there are 119 lakes and reservoirs with aquaculture areas exceeding 66.67 ha. The annual freshwater fish production is 40 865 t.

2 Water quality evaluation of the lower reaches of the Nenjiang River

2.1 Section setting and water quality evaluation methods

Zhenxi, Xianghai Reservoir, Baishatan, Yuelianghu Reservoir, and Da'an were selected as monitoring sections. The sampling procedures adhered to the surface water testing methods prescribed in the *Surface Water Environmental Quality Standards* (GB 2828-2002). Data from 2013 to 2022, obtained from the Jilin Provincial Water Environment Monitoring Center Baicheng Branch, were utilized for analysis[4].

2.1.1 Implementation standards and methods for water quality monitoring. The monitoring samples must adhere to the surface water testing methods specified in the *Surface Water Environmental Quality Standards* (GB 2828-2002). The detailed testing method standards are presented in Table 1. A fuzzy comprehensive evaluation method was employed to integrate multiple factors, including pollutant exceedance values, water quality classification criteria, and the contribution of individual pollutants to overall pollution. The specific steps are as follows: (i) establish the evaluation object set $U = \{u_1, u_2, u_3, \cdots, u\}$, and $u = \{DO, BOD_5, COD_{MN}, COD, NH_4\text{-}N, ZP, ZN\}$ in this study; (ii) establish water quality evaluation levels, and the water quality evaluation levels are defined as $L = \{I, II, III, IV, V\}$ in this study; (iii) establish membership functions: $U(x) = \begin{cases} 1 & 0 \leqslant X \leqslant a_1 \\ \frac{a_2 - X}{a_2 - a_1} & a_1 < X \leqslant a_2 \\ 0 & X > a_2 \end{cases}$; (iv) construct a fuzzy matrix and calculate the membership relationships between the i-th individual indicator and the j-th water quality level by applying the membership functions to the measured values, thereby obtaining the matrix: $R = \begin{bmatrix} r_{11} & r_{12} & \frown & r_{1j} \\ r_{21} & r_{22} & \frown & r_{2j} \\ \vdots & \vdots & \vdots & \vdots \\ r_{i1} & r_{i2} & \frown & r_{ij} \end{bmatrix}$; (v) establish the weight matrix: $A = \{a_1, a_2, a_3, \cdots, a_n\}$; (vi) calculate the evaluation results: $W = A \times R$.

Table 1 Implementation standards and methods for water quality monitoring

No.	Detection parameter	Standard code for detection method	Main instrument and equipment and serial number	Unit
1	DO	GB 7489-1987	Brown acid burette	mg/L
2	COD_{MN}	GB 11892-1989	Brown acid burette	mg/L
3	COD	HJ 828-2017	Colorless acid burette	mg/L
4	BOD_5	HJ 505-2009	Brown acid burette	mg/L
5	NH_4-N	HJ 665-2013	Continuous flow analyzer SAN + + (151910)	mg/L
6	TP	HJ 670-2013	Continuous flow analyzer SAN + + (162113)	mg/L
7	TN	HJ 667-2013	Continuous flow analyzer SAN + + (162113)	mg/L

2.1.2 Water quality evaluation of the main stream of the Nenjiang River. Two monitoring sections were established along the main stream of the Nenjiang River. At Baishatan, water quality was classified as Class IV from 2013 to 2018, improving to Class III thereafter. Similarly, the Da'an section was rated as Class IV from 2013 to 2019, with a gradual improvement to Class III subsequently. The exceedance multiples of pollutants at these sections were ranked in the following order: NH_4-N, COD_{MN}, COD, and BOD_5. The evaluation results for the two water quality sections in the main stream of the Nenjiang River indicated that both met or exceeded Class III. Notably, in 2009, the concentration of NH_4-N at Baishatan exceeded the standard by a factor of 7.2, followed by COD_{MN}, which exceeded the standard by a factor of 4. From 2009 to 2013, NH_4-N levels exceeded the standard by a factor of 3.7, while COD_{MN} exceeded the standard by a factor of 2.6. During this period, COD and BOD_5 concentrations exceeded the standard by factors of 1.5 and 1.6, respectively. The degree to which COD exceeded the standard remained approximately 1.5 times, and the exceedance level of BOD_5 showed no significant change.

Since 2015, the water quality of the river at the Baishatan section had progressively improved, advancing from Class IV to Class III. Between 2013 and 2017, the NH_4-N levels at the Da'an water quality monitoring section exceeded the regulatory standards to varying extents. Concurrently, the COD_{MN} index at Da'an section, which exceeded the standard, exhibited an exponential decline over the years, although the extent of COD exceedance remained constant. Notably, after 2015, pollutant concentrations decreased significantly, resulting in continuous annual improvements in water quality.

2.1.3 Water quality evaluation of the Tao'er River. The water quality of the Tao'er River was monitored at two sections: Heidimiao and Yuelianghu Reservoir. The evaluation revealed that the water quality at both sections generally exceeded Class III, occasionally deteriorating to Class V in certain years. Notably, the Yuelianghu Reservoir exhibited average water quality, with relatively low levels of pollutant exceedance. The primary controlled pollutants were ranked in concentration as follows: TN, TP, COD, COD_{MN}, NH_4-N. The water quality of the Yuelianghu Reservoir was classified as Class V in 2013 and 2015, whereas in other years it was classified as Class IV. TN exceeded the standard by 80%, COD by 50%, and COD_{MN} by 20%. Since 2017, the water quality has consistently met the standards for drinking water. The concentration ranking of the primary controlled pollutant indicators at the Heidimiao section was as follows: COD, NH_4-N, and COD_{MN}. From 2014 to 2018, the water quality was classified as Class IV. Subsequently, the water quality classification improved to Class III. Since 2016, the levels of NH_4-N and COD_{MN} have exhibited a consistent annual decline. This improvement in water quality classification reflects an enhancement in the aquatic environmental quality.

2.1.4 Xianghai Reservoir. Between 2013 and 2022, the water quality of Xianghai Reservoir was classified as Class V or below in all years except 2018. The exceedance multiples of pollutants at the monitoring sections were ranked in the following order: F, COD, TN, BOD_5. In 2016, the exceedance multiples for F, COD, TN, and BOD_5 were 1.9, 0.9, 0.8, and 0.2 times the standard, respectively. The rank of pollutants affecting the water quality of this reservoir differs from that observed in conventional lakes. While TN and TP are typically the primary pollutants in conventional lakes and reservoirs, Xianghai Reservoir experiences limited stable surface runoff inflow, resulting in relatively low inputs of non-point source pollution. Instead, the predominant pollutants are fluorides, which originate primarily from the leaching of the substrate and soil. Meanwhile, the surrounding towns depend on groundwater for both production and daily life. The replenishment of water sources exhibits a dynamic relationship, wherein surface water recharges groundwater during wet years, while groundwater contributes to surface water during dry years. Between 2013 and 2022, only two years experienced rainfall exceeding 200 mm. In dry years, when groundwater replenished surface water, elevated concentrations of fluoride in the groundwater were introduced into the reservoir. A portion of these fluorides dissolved in the water column, while the remainder accumulated in the sediment at the reservoir bottom, resulting in the water quality persisting at Class V or below for an extended period. In 2015, the water quality rating of the reservoir improved. Upon investigation, it was determined that the Ministry of Water Resources had implemented the Diversion Works water conservancy project that year, introducing 20 000 m^3 of water into the reservoir. This influx effectively diluted the concentration of pollutants in the water body, thereby contributing to the enhancement of water quality.

2.2 Analysis of water quality trends in the lower reaches of the Nenjiang River An analysis of water quality data from 2013 to 2022 revealed that the concentrations of representative pollutants at five monitoring sections generally exhibited a downward trend, indicating an overall improvement in water quality. However, variations were observed among the different sections. Notably, at the Heidimiao section, the primary parameter exceeding standards was NH_4-N. Over the past decade, the concentration of NH_4-N decreased significantly, whereas the concentration of COD increased markedly. The monitoring data from Baishatan section indicated that NH_4-N and COD_{MN} were the primary indicators influencing the water quality in this area. Both parameters exhibited a significant decreasing trend, whereas COD levels remained relatively stable. The improvement in these key indicators suggests a gradual enhancement of water quality over time. In contrast, at Yuelianghu Reservoir, the principal pollutant control indicators, TP and TN, remained relatively stable over the past decade. However, concentrations of NH_4-N and COD demonstrated an increasing trend annually. Consequently, no significant improvement in water quality was observed at the section. In Xianghai Reservoir, the primary pollution control indicator, fluoride, was excluded from the trend analysis. Although concentrations of COD_{MN}, NH_4-N, and TP decreased significantly, these reductions did not substantially contribute to the overall improvement of the reservoir's water quality.

3 Analysis of non-point source pollution in the lower reaches of the Nenjiang River

Sampling experiments were conducted according to the water quality sections established along the Nenjiang River Basin. Water quality analyses were performed at five monitoring sections throughout the year 2018. Concurrently, Landsat 8 image data with a spatial resolution of 60 m, acquired in May and September 2018 for the Nenjiang River Basin, was selected. Following geometric and atmospheric corrections, land use information within the study area was extracted using supervised classification[5]. In accordance with the classification criteria outlined in the *Technical Specifications for Evaluation of Ecological Environment Conditions* (HJ 192-2015), seven categories of land cover, including urban land, cultivated land, grassland, wetland, forest land, bare land, and water bodies, were identified as the focus of this study. By integrating the basin's DEM data with the spatial distribution of water systems, land use data for five water catchment units were derived. The social and economic data, including industrial proportion, per capita GDP, and population density, were obtained from the 2018 *Jilin Province Statistical Yearbook* and the *Baicheng City Statistical Yearbook*. This study utilized SPSS 17.0 to perform a correlation analysis between basin water quality and land use patterns.

The results of the correlation analysis (Table 2) indicated no significant relationship between land use area and the concentrations of COD and BOD_5, which can be attributed to the reduction in surface runoff and pollutant transport caused by decreased rainfall. TP exhibited a positive correlation with both cultivated land and vegetable fields, suggesting that agricultural activities continued to exert a considerable influence during the non-flood season. DO was negatively correlated with water bodies; the diminished rainfall led to a slower water flow rate, thereby reducing the dynamic process of oxygen dissolution into the water and resulting in decreased oxygen levels. Additionally, NH_4-N showed a positive correlation with cultivated land, implying that nitrogen-based nutrients were affected by cultivated land use during both the flood and non-flood seasons.

Table 2 Correlation between land use patterns and water environment indicators in 2018

Land type	DO	BOD_5	COD	TP	NH_4-N	pH	Chlorophyll
Cultivated land	0.051	-0.524	-0.401	0.948**	0.868*	0.182	0.145
Urban land	-0.412	-0.335	-0.524	0.655	-0.348	0.155	-0.465
Water body	-0.861*	-0.612	-0.447	0.622	-0.140	0.166	0.047
Grassland	-0.182	-0.458	-0.088	0.395	-0.325	-0.312	0.506
Forest land	-0.511	-0.478	-0.355	0.567	-0.546	-0.234	0.248
Vegetable field	-0.213	-0.545	-0.212	0.889*	-0.054	-0.258	0.287
Bare land	0.497	0.182	0.598	0.015	0.751	0.105	0.564

4 Analysis and management suggestions on water pollution in the lower reaches of the Nenjiang River

4.1 Water quality pollution evaluation The correlation analysis of water quality indicators and socio-economic factors in the Nenjiang River Basin reveals that TP, NH_4-N, and chlorophyll exhibit positive correlations with the proportion of the primary industry, negative correlations with population density and the proportion of the tertiary industry, and positive correlations with the proportion of the secondary industry. Notably, the correlation between TP and the proportion of the primary industry is the most pronounced, which may be attributed to the impact of agricultural activities. Agricultural activities contribute to soil erosion, resulting in increased turbidity of water bodies. Phosphorus nutrients from the soil subsequently enter these water bodies, thereby influencing the TP concentration. NH_4-N and chlorophyll exhibit a relatively strong correlation with the proportion of the secondary industry, with the correlation between two variables and the proportion of the secondary industry being the most pronounced. It is hypothesized that during industrial production, the discharge of domestic sewage and industrial wastewater increases, leading to elevated nutrient salt concentrations in water bodies. This, in turn, promotes the proliferation of aquatic phytoplankton, causing an increase in chlorophyll density. Furthermore, COD and DO show a positive correlation with the proportion of the tertiary industry, while exhibiting a negative correlation with both the proportion of the secondary industry and per capita GDP.

4.2 Suggestions for water quality management

4.2.1 Controlling the ecological water demand of rivers and reducing human control over runoff. Based on the climatic and hydrological characteristics of the basin, the status of water resource development and utilization, the types and functions of aquatic ecosystems, the importance and sensitivity of protected objects, and the relative positions of control nodes within the ecosystem, ecological base flows for rivers and minimum ecological water levels for lakes should be maintained by relying on critical control sections. The construction of unnecessary dams should be minimized. Furthermore, during environmental impact evaluations, the effects of water diversion on downstream ecological water requirements must be thoroughly evaluated to prevent increased concentrations of water pollutants resulting from improper runoff regulation.

4.2.2 Reducing soil erosion and restoring the ecological functions of wetlands. The western region of Jilin Province is characterized as a typical area affected by wind erosion, where soil erosion is notably severe. Wind erosion dislodges rock and soil debris, which are subsequently transported into water bodies, lakes, and reservoirs by rainfall. This process results in elevated concentrations of characteristic pollutants in river water. Consequently, while maintaining ecological flow, it is imperative to enhance investment in water diversion projects, reinforce efforts to remediate soil salinization, and progressively restore the original ecological functions of wetlands.

4.2.3 Strengthening comprehensive control over non-point source pollution. In agricultural regions, the adoption of scientifically based planting methods is essential, alongside the rational application of pesticides and chemical fertilizers. Strict pollution control measures must be enforced for small-scale livestock farmers and enterprises. Additionally, it is essential to reinforce local legal oversight, elevate public environmental awareness, and concurrently advance initiatives for water conservation and increased grain production. The vigorous promotion of water-saving irrigation technologies is necessary to regulate agricultural water consumption, reduce pollutant runoff, and increase the volume of clean water entering rivers and reservoirs, thereby mitigating non-point source pollution at its origin.

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