Original Research Article

Analysis of water environment quality characteristics in the Yellow River Basin of Shandong province

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Abstract: Mastering the changing patterns of water environment quality in the Yellow River Basin of Shandong Province is crucial for targeted pollution control and protection. Based on monthly water quality monitoring data from 12 national and provincial control sections in the Shandong section of the Yellow River Basin from 2020 to 2024, this study systematically evaluated the characteristics of the basin's water environment quality using methods such as the single-factor assessment method, systematic cluster analysis, and time series analysis. The results show that the overall water quality of the basin has improved, with the proportion of Class I-III (excellent) water bodies stabilizing above 90%, and sections with Class V< (inferior to Class V) water quality being essentially eliminated. Although the main pollutants—permanganate index (COD_{mn}), ammonia nitrogen (NH_3-N), and total phosphorus (TP)—did not exceed standards overall, they exhibited significant seasonal fluctuations. The COD_{mn} exceeded standards at a rate of 60%-80% during the flood season (July-September). The ammonia nitrogen exceeded standards at a rate of 100% in 2020. The total phosphorus exceeded standards at a rate close to 80% in August 2021. The dissolved oxygen (DO) compliance rate was generally high, but low-oxygen conditions (40%-90%) still occurred during high-temperature months. Systematic cluster analysis revealed that water quality conditions are mainly divided into three categories. The poorer-quality category was concentrated in most months of 2020 and individual months of spring and summer from 2021 to 2024. The good-quality category mainly included most months from 2022 to 2024. Spring and summer are critical periods requiring focused attention in future water environment management. The study recommends: strengthening non-point source pollution control during flood seasons, implementing a "floodwater interception + wetland purification" model; improving ecological water replenishment mechanisms and establishing a DO-flow linkage warning system; promoting rainwater-sewage diversion and online monitoring in industrial parks; and enhancing comprehensive agricultural non-point source pollution management. This research provides a scientific basis for water environment management in the Yellow River Basin of Shandong Province and offers significant guidance for achieving sustained water quality improvement.

Keywords: Yellow River Basin; Water quality assessment; Pollutant characteristics; Spatiotemporal variation; Ecological protection

1. Overview

The study area is located in the Shandong section of the lower Yellow River Basin (34°25′–38°16′N, 114°50′–119°20′E). The main stream traverses 628 kilometers through 9 cities including Heze and Jining, forming a complex water system with 18 primary tributaries. The basin covers an area of 18,300 km², accounting for 11.6% of the province's total area. The area encompasses natural wetland lakes such as the Yellow River Delta, Dongping Lake, and Weishan Lake, and natural forested areas such as Mount Tai, Mount Culai, and Mount Lu. The Yellow River Delta is a national nature reserve, and Mount Tai is a UNESCO World Cultural and Natural Heritage site [1]. The region has an average annual runoff of 30 billion m³, supporting 60% of the province's industrial water use and 45% of domestic water use, irrigating 2 million hectares. Water diversion from the Yellow River reached 7 billion m^3 in 2020. Over the past two decades, the region has exhibited typical environmental evolution characteristics: economic development was prioritized over ecological protection during 2000–2010; after 2010, Shandong began comprehensive land management, and the proposal of ecological civilization construction at the 18th National Congress stimulated ecological awareness, fostering the concept that “lucid waters and lush mountains are invaluable assets” [2]. Ecological protection and high-quality development in the Yellow River Basin require basin-wide coordination and cross-regional governance. In the comprehensive management of the Yellow River Basin, implementation models of administrative agencies at different levels have distinct emphases. Provincial and municipal governments are both the primary executors of policies within their jurisdictions and the definers and coordinators of subordinate policy formulation within their regions [3].

2. Research methods and analysis

2.1. Data sources and monitoring network

The data for this study were sourced from the monthly surface water environmental quality reports published on the website of the Shandong Provincial Department of Ecology and Environment for the period 2020–2024. Based on the Environmental Quality Standards for Surface Water (GB3838-2002) [4], the water quality categories of 12 national and provincial control sections in the Shandong section of the Yellow River Basin were classified into Classes I to V< (inferior to Class V) using the single-factor assessment method. Classes I-III represent excellent water quality, Class IV represents light pollution, Class V represents moderate pollution, and Class V< represents severe pollution. Monitoring indicators included five basic parameters: pH, dissolved oxygen (DO), permanganate index (COD_{mn}), ammonia nitrogen (NH_3-N), and total phosphorus (TP). The monitoring sections are located in Jinan City (Luokou, Wohushan Reservoir - 2 sections), Laiwu City (Hexiaozhuang - 1 section), Liaocheng City (Zhangqiu - 1 section), and Tai’an City (Xujiawen, Daicun Dam (Wangtai Bridge) - 2 sections).

2.2. Statistical analysis

To analyze the time series variation characteristics of water quality indicators, the following statistical methods were employed:

1. Descriptive Statistics: Calculated characteristic values such as the mean, maximum, minimum, and coefficient of variation (CV) for each pollutant indicator to characterize the spatiotemporal distribution of water quality indicators. The coefficient of variation (CV) is calculated as:

$$CV=\frac{\sigma}{\mu}$$

where σ is the standard deviation and μ is the mean.

2. Time Series Analysis: The proportion of sections exceeding standards for each pollutant indicator was calculated monthly to analyze seasonal variation patterns. The proportion is calculated as:

$$P=\frac{n}{N}\times 100$$

where n is the number of sections exceeding the standard and N is the total number of sections.

3. Box Plot Analysis: Box plots were used to display the annual variation characteristics of the proportion of sections in each water quality class, including statistics such as the median, interquartile range (IQR), and outliers. Outliers were identified using:

$$Outliers=\{Q_1-1.5\times IQRQ_3+1.5\times IQR\}$$

where Q_1 is the first quartile, Q_3 is the third quartile, and IQR is the interquartile range (Q_3 - Q_1).

2.3. Systematic cluster analysis

Systematic cluster analysis, which visually reveals similarities and differences among clustering objects, is widely used in spatiotemporal water quality analysis [5]. To reveal the spatiotemporal differentiation characteristics of water quality changes, this study employed systematic cluster analysis. This method clusters samples with high similarity by calculating the similarity between samples, offering significant advantages for analyzing water quality spatiotemporal characteristics.

Analysis Process:

1. Data Preprocessing: The proportion data of water quality types were standardized using the Z-score method to eliminate dimensional effects:

$$z = \frac{x - \mu}{\sigma}$$

where x is the original data, μ is the mean, and σ is the standard deviation.

2. Distance Calculation: The squared Euclidean distance was used to measure the distance between samples:

$$d_{ij} = \sqrt{\sum_{k=1}^{p} \left(x_{ik} - x_{jk}\right)^2}$$

where d_{ij} is the distance between sample i and sample j, and x_{ik} and x_{jk} are the values of the k-th variable for sample i and sample j, respectively.

3. Clustering Method: Ward's minimum variance method was used for clustering. This method minimizes the total within-cluster variance. The within-cluster sum of squares is calculated as:

$$W = \sum_{i=1}^{k} \sum_{x \in C_i} (x - \mu_i)^2$$

where k is the number of clusters, C_i is the cluster-i, and μ_i is the centroid of the cluster-i.

4. Determining the Number of Clusters: The optimal number of clusters was determined based on the point where the change in the clustering coefficient becomes gradual, avoiding over-clustering.

2.4. Analysis of main pollutant characteristics

指标	出现数	III类标准	最小值	最大值	平均值	变异系数
高锰酸盐指数	263	6.0	0.74	15.14	3.15	0.49
氨氮	263	1.0	0.02	3.63	0.14	1.88
总磷	258	0.2	0.01	0.19	0.04	0.82
溶解氧	263	5.0	0.46	16.91	9.85	0.23

Figure 1. Monthly average characteristic values of pollutants in the Yellow River Basin of Shandong province.

Based on the statistical characteristics of main pollutants in the Shandong section of the Yellow River Basin from 2020 to 2024, the four indicators—COD_{mn}, NH_3-N, TP, and DO—all exhibited varying degrees of seasonal fluctuation and spatial differences. The annual average COD_{mn} was 3.15 mg/L, below the Class III standard, but the maximum value reached 15.14 mg/L, indicating significant fluctuation (CV=0.49), particularly prominent during summer rainfall. The average NH_3-N was 0.14 mg/L, far below the Class III standard, but with a high CV (1.88), indicating this indicator is prone to exceed standards in winter, mainly influenced by low temperatures, reduced flow, and weakened self-purification capacity. The average TP concentration was 0.04 mg/L, not exceeding the Class III standard, but its maximum value (0.19 mg/L) approached the critical limit (CV=0.82), highlighting the need to address agricultural non-point source discharge risks. The average DO concentration was 9.85 mg/L, significantly higher than the Class III standard (5.0 mg/L), with small overall fluctuation (CV=0.23), indicating good ecological conditions in most water bodies of the basin.

2.5. Analysis of pollutant exceedance characteristics

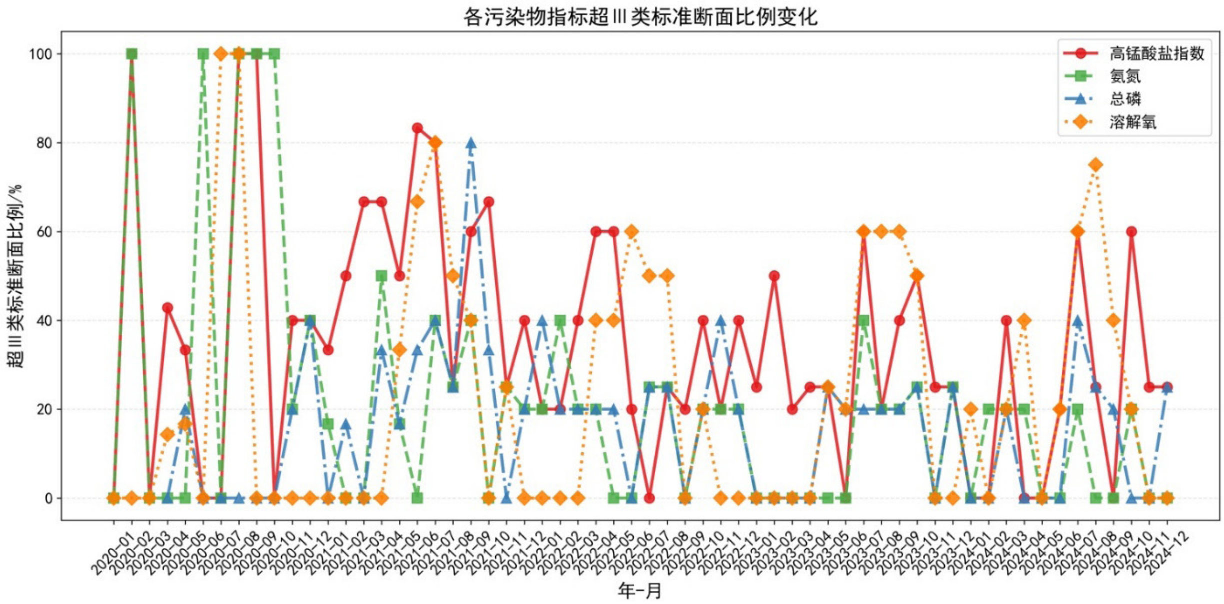

Figure 2. The change in the proportion of each pollutant index exceeding the class III standard section.

Figure 2 uses "Year-Month" as the horizontal axis, sequentially displaying 60 monitoring periods from 2020-01 to 2024-12. The vertical axis represents the "Proportion of Sections Exceeding Class III Water Quality Standard/%", indicating the percentage of national control sections where COD_{mn}, NH_3-N, TP, and DO exceeded their respective Class III limits in that month. A higher value indicates more severe pollution for that indicator (or more severe hypoxia for DO).

COD_{mn} (red line) showed sharp peaks of 60%-80% in 2020-08, 2021-07, 2023-07, and 2024-09. Non-point source flushing during floods and combined sewer overflows were the main drivers. The monthly average proportion decreased from 45% in 2020 to about 25% in 2024 but remained the highest. NH_3-N (green line) reached 100% consecutively from 2020-03 to 2020-05 and 2020-05 to 2020-08. Following outfall remediation and the advancement of livestock manure resource utilization, it was mostly reduced to 0%-25% from 2021 onwards, showing the fastest decline. TP (blue line) generally remained at 0%-25%, only spiking sharply in 2021-08 (≈80%) and 2024-09 (≈40%). These peaks coincided with COD_{mn}, reflecting sediment resuspension and agricultural phosphorus loss during floods. DO (orange line) had the highest compliance rate, but low-oxygen warnings (40%-90%) occurred in 2022-04/07, 2023-06, and 2024-08/10, caused by high-temperature oxygen consumption and eutrophication. The monthly average peak-to-valley difference for each indicator showed a pattern of "rising in late spring-summer floods and falling in autumn-winter", indicating alternating dominance of non-point source flushing and dilution capacity during low-flow periods on water quality.

2.6. Analysis of water quality class changes

In **Figure 3**, the horizontal axis divides the monitoring sections from 2020-2024 into three major categories based on GB 3838-2002—Class I-III (excellent), Class IV-V (light-moderate pollution), and Class V< (severe pollution). Box plots for each category over the five years display the discrete distribution of the annual section proportion. The vertical axis corresponds to the "Proportion of Sections/%" for that category, representing the percentage of sections in that water quality class among all national control sections for the year; a higher value indicates a larger proportion of that water quality level province-wide. Lines and red diamonds mark the annual median and mean trends, respectively, to visually depict the overall five-year trend.

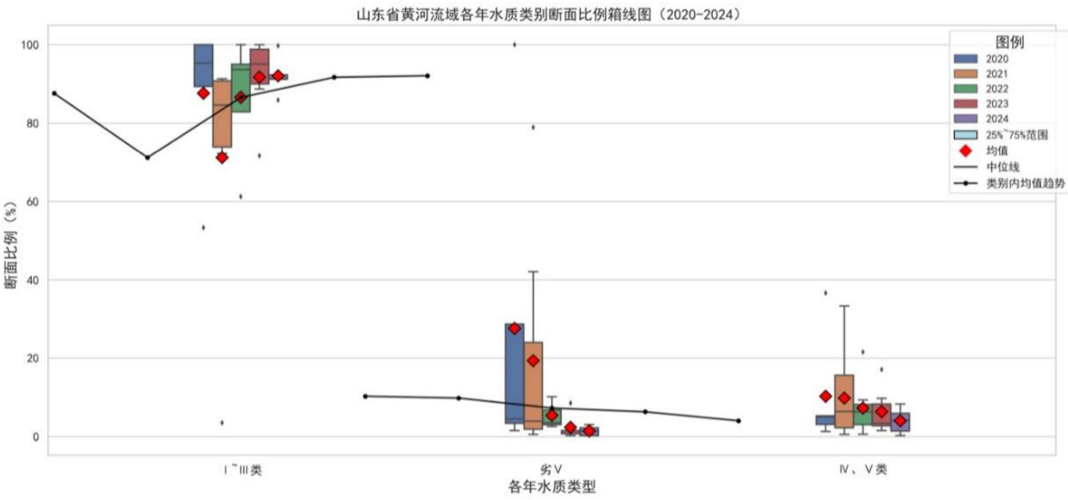

Figure 3. Boxplot of water quality category section ratio in the Yellow River Basin of Shandong province (2020-2024).

Outfall remediation and full coverage of rural sewage treatment have elevated the overall box for Class I-III excellent water bodies to a plateau above 90%. The next key step is to prevent rebound. To reduce the outlier "peaks" of Class IV-V during July-September, it is essential to link "one estuary, one wetland" projects with agricultural phosphorus reduction initiatives, achieving pre-flood interception and slow release during floods. To address the Class V< risk corresponding to low DO months, ecological base flow should be guaranteed, and reclaimed water replenishment should be utilized to alleviate hypoxia during dry periods. Simultaneously, comparing automatic monitoring data with box plot outliers can precisely identify point source impacts from high-risk industrial parks, forming a "detection-comparison-response" closed-loop supervision.

3. Results and discussion

3.1. Policy implementation effectiveness

Monitoring peaks were compared with key provisions of the Shandong Provincial Special Plan for Ecological Environmental Protection in the Yellow River Basin (Revised Edition). Regarding COD_{mn} changes, outfall remediation and industrial standards upgrading have shown initial effects in peak reduction, but non-point source organic loads during rainy seasons remain high. It is recommended to complete rainwater-sewage diversion in industrial parks, clean up shoreline garbage before flood seasons, and include COD_{mn} in the "one pipe per enterprise" monitoring for chemical parks. For NH_3-N, measures such as achieving a livestock manure utilization rate ≥90% and full coverage of rural sewage treatment have significantly reduced NH_3-N peaks. Subsequent efforts should improve the compliance acceptance system for aquaculture tailwater to prevent rebound. For TP, the plan's proposal of "ecological restoration of key lakes and agricultural phosphorus reduction" has lowered background concentrations. The next step requires implementing a "temporary flood interception + shoreline wetland filtration" model in the "Two Lakes—Yellow River Estuary" area to cut off phosphorus flux during floods. For DO, while the plan requires "basic determination of ecological base flow targets for important rivers and lakes" and encourages tailwater replenishment, monitoring indicates hypoxia still occurs during high-temperature months. Monthly-decadal scheduling and coordinated use of reclaimed water need refinement to ensure the base flow at the Lijin section remains ≥50 m^3/s year-round.

3.2. Existing problems and recommendations

There is a gap between the plan and the binding targets for 2025. The special plan sets the target that "the proportion of national surface water control sections meeting or exceeding Class III reaches 64.4%, and Class V< is completely eliminated." According to **Figure 1**, high COD_{mn} months could cause the excellent proportion to drop by more than 10 percentage points, becoming a bottleneck. Persistent low DO also poses a risk of Class V< resurgence.

To address the COD_{mn}/TP peaks in July-September, the construction of "estuary-wetland" systems in key tributaries needs to be completed in advance, implementing "floodwater interception + wetland purification" for rapid peak shaving. Enforce ecological water replenishment: Quantify reclaimed water utilization targets down to the county level and establish a DO-flow linkage warning system to trigger water replenishment upon hypoxia detection. Implement park rainwater-sewage diversion and online monitoring: Old chemical industrial zones must complete separate collection systems by the end of 2024, install continuous COD_{mn} monitors connected to the provincial platform to ensure immediate source identification upon sudden increases. Long-term integrated management: Environmental remediation projects in 16,700 administrative villages across the 9 Yellow River-bordering cities should be synergized with fertilizer reduction and green planting, implementing phosphorus control measures on sloping farmland to prevent secondary pollution from storm runoff.

Overall, the box plots reveal a general pattern in the Shandong section of the Yellow River Basin: "high excellence, decreasing pollution, converging extremes." This validates the phased effectiveness of projects like outfall remediation, ecological water replenishment, and agricultural non-point source management outlined in the Special Plan. However, sudden Class IV-V peaks during floods persist, indicating that non-point source and sediment management remain key areas for improvement. While Class V< is nearly eliminated, the risk of high-temperature hypoxia still requires consolidation through enforced ecological base flow and reclaimed water replenishment. For 2024–2025, the focus should be on "flood peak interception, dry season water replenishment, park standards upgrading, and non-point source interception" to ensure the excellent water body proportion remains stably above 90%, Class V< is completely eliminated, and the "14th Five-Year Plan" water quality targets are successfully achieved.

4. Conclusion

In summary, the water quality status of the Yellow River Basin in Shandong Province showed an overall improving trend from 2020 to 2024. The proportion of Class I-III excellent water bodies increased annually, and Class V< sections were essentially eliminated, reflecting the significant effectiveness of recent pollution control measures. Although main pollutants like COD_{mn}, NH_3-N, and TP did not exceed standards overall, they posed exceedance risks during high-flow and low-flow periods respectively, indicating that water quality changes still exhibit significant seasonal fluctuations. Therefore, it is recommended to continue consolidating existing achievements, particularly strengthening non-point source pollution control during high-flow periods and implementing precise regulation for ammonia nitrogen fluctuations in winter. Efforts should promote the simultaneous implementation of agricultural non-point source emission reduction, rural sewage treatment, and ecological restoration to enhance water quality stability in key areas. Furthermore, it is crucial to strengthen high-frequency water quality monitoring and early warning mechanisms to improve risk perception and response efficiency, and to promote cross-regional coordinated governance across the basin for synergistic overall water quality improvement. Through a comprehensive management model that differentiates by region, time period, and category, the foundation for improving the water environment quality of the Yellow River Basin in Shandong can be further solidified, steadily advancing towards the goals of ecological security and sustainable development.

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