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Dynamic analysis of port water quality: insights from Zhanjiang Port, China

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ABSTRACT

The management of port water quality is crucial to marine ecological balance and has been of great concern. In the present study, the water quality monitoring data in Zhanjiang Port from 2015 to 2022 were utilized to analyze the spatiotemporal characteristics and reveal the correlation between different parameters. The structural equation model has been applied to profile the dominant factors of water quality level. The results showed that the port water quality was generally worse in summer and better in winter. Variations in total phosphorus (TP), chemical oxygen demand (COD) and total nitrogen (TN) content directly led to water quality changes in Zhanjiang Port, where an increase in TP content resulted in a significant decrease in water quality level (path coefficient is 2.87). Permanganate index (COD_{Mn}) and ammonia nitrogen content indirectly affected the water quality level, while changes in pH and dissolved oxygen (DO) showed no impact. Ammonia nitrogen, pH and DO contents were significantly associated with TP. Human activities and industrial production were identified as the main sources of water quality pollution. The increasing trend of certain water quality parameters highlights the urgency of implementing timely measures to improve water quality conditions in Zhanjiang Bay, China.

Key words: correlation analysis, monitoring data, port water quality, spatiotemporal feature, structural equation model

HIGHLIGHTS

- The spatiotemporal characteristics of water quality parameters were explored in the Zhanjiang Port, China.
- A correlation analysis between various water quality parameters was presented and discussed.
- The key indicators of water pollution were identified through the structural equation model.
- The deterioration of certain water quality parameters indicates that more attention should be paid to the port water quality management.

1. INTRODUCTION

Ports play a dual role in driving external development by serving as crucial gateways and transportation hubs, while also serving as vital carriers and platforms for connecting global resources. While coastal port cities are experiencing a steady increase in population, various human activities such as marine transportation, the development of fisheries, the promotion of tourism, and the expansion of aquaculture continue to thrive (Romina *et al.* 2022). Meanwhile, the conflicts within the port's ecological environment are becoming increasingly apparent (Shen *et al.* 2022). The natural world serves as the foundation for human survival and progress. To pave the way for the long-term growth of ports, a favorable ecological environment is essential (Moisa *et al.* 2023). An impartial and timely assessment of the port water quality characteristics could contribute to the sustainable development of port ecology.

Great efforts have been devoted to resolve the water environmental issues. Proper assessment of water quality is an important basis and premise of water quality management (Liu *et al.* 2021). Water quality monitoring parameters generally include pH, chemical oxygen demand (COD), ammonia nitrogen, total phosphorus (TP), total nitrogen (TN), chlorophyll a (chl a), heavy metals, etc. The pH value of water provides a comprehensive indication of its acidity and alkalinity and serves as a crucial parameter for assessing the environmental conditions of aquatic ecosystems. It significantly affects redox reactions and the behavior of calcium ions in the water column, ultimately influencing the chemical stability of the waters (Romina *et al.* 2022; Zhang *et al.* 2022a, 2022b). DO serves as a primary parameter describing the self-cleaning capacity of aquatic systems and their efficiency in decomposing organic matter. It also plays a key role in shaping the biogeochemical cycling of constituents within water bodies (Kamboj & Kamboj 2020). Both COD and COD_{Mn} are important parameters used to evaluate the reduction of pollutants in water bodies, as they directly indicate the amount of organic matter and reducing substances present. Ammonia nitrogen and TN are indicators measuring the different forms of nitrogen in water. Ammonia nitrogen represents the combined concentration of free ammonia and ionic ammonium, while TN reflects the total nitrogen content of water bodies, including ammonia, nitrate nitrogen, nitrite nitrogen, and organic nitrogen (Li *et al.* 2023). TP denotes total phosphorus content in waters, which primarily consists of orthophosphate, condensed phosphate and organic phosphorus (Oz Yasar *et al.* 2023). As the basic materials in the biogeochemical cycle, nitrogen and phosphorus are deemed the main contributors of water pollution. The water pollution would lead to the massive death of fish and shrimp, excessive algal growth and the emergence of water red tide, which would affect the ecological balance eventually. Classical monitoring methods generally include fixed-point sampling, random sampling, remote sensing monitoring, etc (Zhao *et al.* 2015; Sipelgas *et al.* 2018; Chou *et al.* 2022; Cao *et al.* 2023). Relevant regulations need be complied with to ensure the representativeness of the monitoring data (EPA 2008; APHA 2017), e.g., the number of sampling points, sampling depth, sample detection methods, etc. The temporal and spatial characteristics of water quality parameters can be analyzed to reveal the evolutionary trends, which facilitates the understanding of underlying mechanisms of water quality indicators (Liu *et al.* 2018; Tu 2023). Cluster analysis (Wong *et al.* 2022; Moreno *et al.* 2023), principal component analysis (Xu *et al.* 2020), correlation analysis (Zou *et al.* 2019; Gai & Guo 2023), redundancy analysis (Zhang *et al.* 2021), multiple linear regression (Zhang *et al.* 2022a, 2022b), and other statistical methods are commonly adopted for water quality assessment. Moreover, Water Quality Index (WQI) (Ma *et al.* 2020), Eutrophication Index (EI) (Chen *et al.* 2022; Kesari *et al.* 2022), Heavy Metal Pollution Index (HPI) (Yan & Niu 2019) and Trophic State Index (TSI) (Massi *et al.* 2019; Gomes *et al.* 2020) have been proposed and widely used as indicators of water quality. Port waters are the coupling areas of land-sea interaction. The interaction mechanisms between the hydrodynamic environment, biogeochemical processes and human activities are quite complex (Sun & Chen 2022). Effective assessment of port water quality and influencing factors would be beneficial for water quality management (Yudhistira *et al.* 2022). The relationship between different influencing factors is always non-linear (Ranjithkumar & Robert 2021; Azrour *et al.* 2022), which makes it a challenging task. The Structural Equation Model (SEM) can analyze the causality among multiple variables and directly depict the path strength of different influencing factors. Therefore, it has been adopted as an excellent method to resolve the water quality issue (Ahmed *et al.* 2020; Liu *et al.* 2023). SEM has been successfully applied to water quality studies of groundwater (Nagaraj & Masilamani 2023), drinking water (Merrett *et al.* 2020) and reservoirs (Fernandes *et al.* 2019). So far, it has rarely been applied in the study of port water quality management.

In this paper, water quality monitoring data have been collected for state-controlled cross-sections in the hinterland of Zhanjiang Port from 2015 to 2022. The spatiotemporal distribution characteristics of water quality indicators are explored, and the crucial influencing factors of water quality are analyzed at different locations. The results could provide a reference for water quality management in port waters. The remainder of this paper is organized as follows. In Section 2, the study area and data source are briefly introduced. The results are presented and analyzed in Section 3, followed by a discussion on water quality characteristics and influencing factors in Section 4. A final conclusion is drawn in Section 5.

2. STUDY AREA AND DATA SOURCE

2.1. Overview of the study area

Zhanjiang Port, the first deep-sea port in China, is located at the southwestern part (110°24′21″E, 21°11′11″N) of Guangdong Province, China. It is one of the 12 major hub ports in China. The port hinterland experiences a subtropical monsoon climate, mainly influenced by winds blowing from the southeast. Four monitoring sites, named as Dashanjiang, Yingzai, Huangpo and Nandu River Bridge have been selected in the present study (as shown in Figure 1).

2.2. Data source

Water quality data at the aforementioned monitoring sites are obtained from the Department of Ecology and Environment of Guangdong Province (http://gdee.gd.gov.cn/jhszl/index.html), P.R. China. The specific monitoring parameters generally

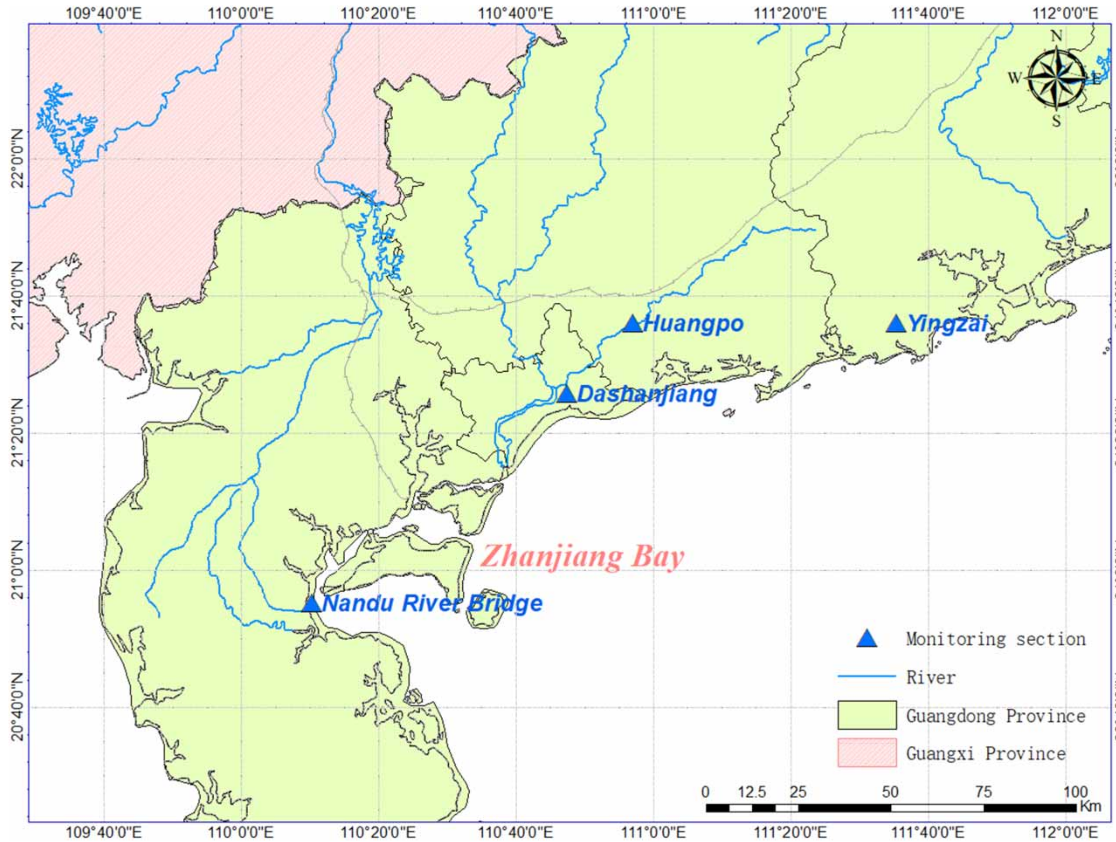

Figure 1 | Schematic diagram of the monitoring sites in Zhanjiang Bay, China.

include pH, DO, COD_{Mn}, COD, TP, TN and ammonia nitrogen, etc. The water quality assessment is carried out according to the 'Surface Water Environmental Quality Standards' (GB 3838-2002) of China. The evaluation results are categorized into six classes: Class I, II, III, IV, V, and inferior V categories (MEPC 2002). Water quality classifications are based on the highest category of section indicators using a single-factor scoring method. To simplify water quality assessment and standardize the assessment process, TN has been excluded from the list of water quality assessment indices (MEPC 2011). As TN content is well documented in the dataset, its spatiotemporal characteristics are investigated and presented in the following sections.

In the present study, Microsoft Office Excel 2021 and IBM SPSS Statistics 26 are used for descriptive statistical analysis of water quality data, and ArcGIS 10.2 is adopted for map acquisition. IBM SPSS Amos 26 is applied for the structural equation model construction and analysis.

3. RESULTS

3.1. Spatiotemporal features of water quality parameters

The results of water quality assessment from 2015 to 2022 in Zhanjiang Bay are shown as a box plot in Figure 2. The single-factor evaluation method has been adopted and the annual variation of water quality is thus demonstrated in Figure 3.

Generally, the water quality in Zhanjiang Bay meets the standard requirements. The water quality of inferior V, Class V and Class IV accounts for about 29.4% of the total data. Among all the exceeded factors, TP, COD and COD_{Mn} are recognized as the main water pollution parameters. Although the water quality of Class V and inferior V doesn't appear since 2020, the proportion of Class IV is still high (approximately 21.4% in 2022), indicating that the dynamic monitoring and control of water quality is still urgent. More efforts need to be devoted to strengthen water quality management in port waters.

Seasonal characteristics have been observed for water quality parameters as shown in Figure 4. In spring, pH value, DO, ammonia nitrogen and TN contents are the highest, while COD_{Mn} and TP are the lowest. In summer, the contents of COD_{Mn}

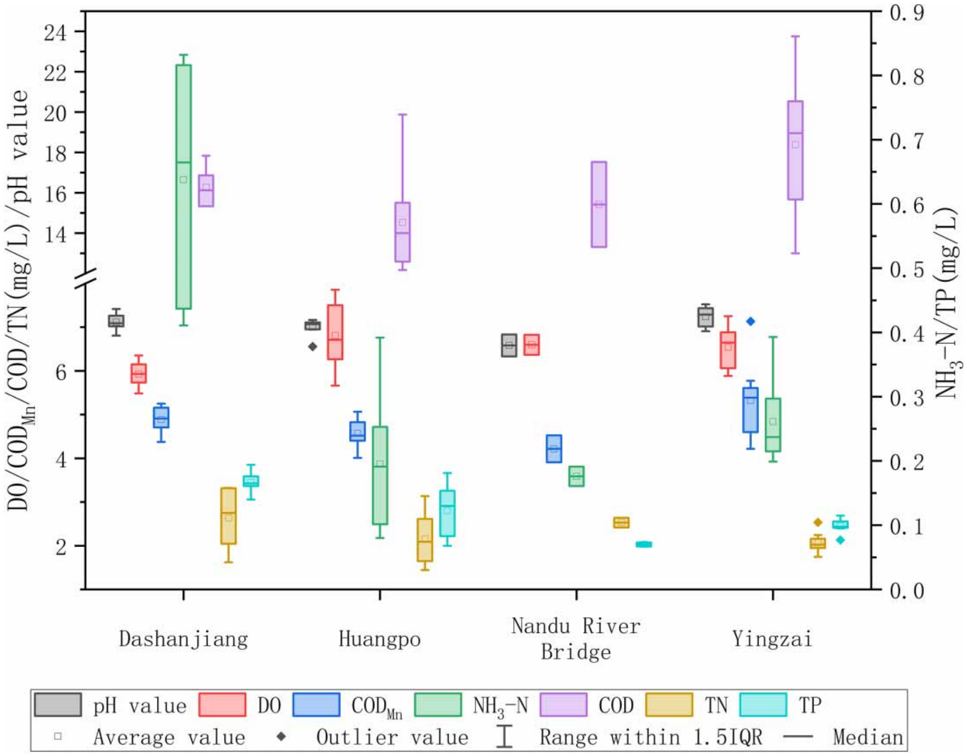

Figure 2 | Box plot of water quality assessment results by single factor assessment method from 2015 to 2022.

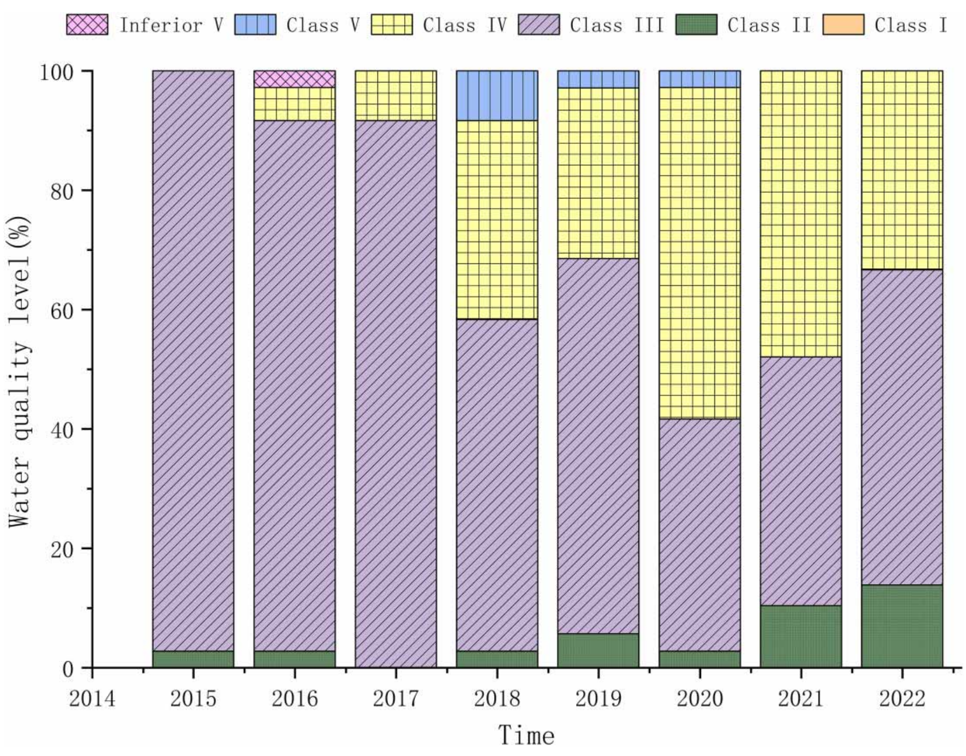

Figure 3 | Temporal variations of water quality in Zhanjiang Bay.

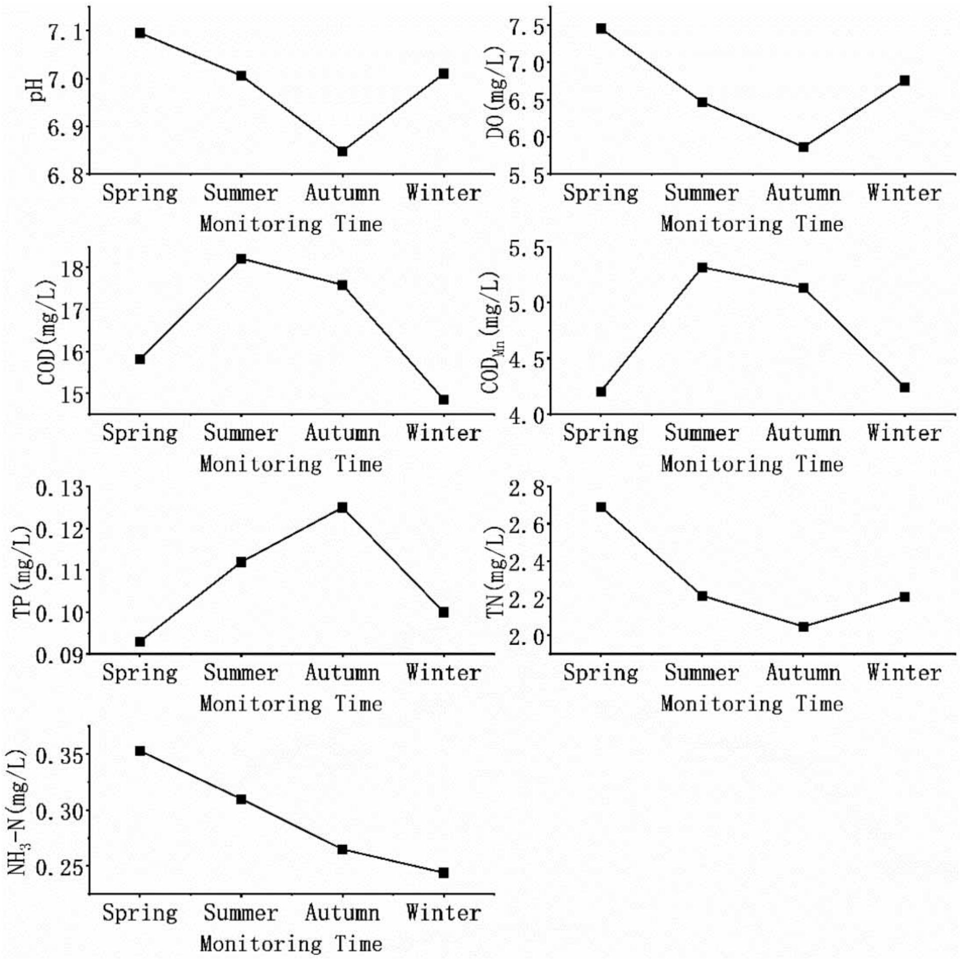

Figure 4 | Seasonal variations characteristics of different water quality parameters from 2015 to 2022.

and COD are observed as the highest parameters. In autumn, the content of TP is noteworthy, while the pH value, DO, and TN contents are the lowest. In winter, both ammonia nitrogen and COD reach a minimum value in the present study area.

There was also great variability in the quarterly trends of various water quality parameters. The pH value is relatively higher in spring and summer, and lower in autumn and winter. DO content is significantly higher in spring and winter than autumn and summer. The quarterly evolutionary trends of COD and COD_{Mn} contents are similar, but differ with DO. TN peaks in spring, and shows a 'U' pattern in the annual cycle. TP presents an inverted V-shaped trend with a peak in the autumn. The increase of ammonia nitrogen and TN in spring is closely related to the large amount of fertilizer in the agricultural season, which is consistent with the results presented in the literature (Lin *et al.* 2023). In summer, various algae and floating plants grow rapidly as the water temperature rises. The increase in biomass directly leads to a significant decrease in the DO content. TP content in water is closely related to the degree of eutrophication. The phosphorus fertilizer used in domestic sewage, industrial and agricultural wastewater, and plant industry is the main source of phosphorus pollution (Xiao *et al.* 2020). Studies have shown that plants and aquatic organisms can effectively absorb nitrogen and phosphorus in water bodies (Horvat *et al.* 2023; Sun *et al.* 2023). Therefore, the increase in TN, TP and COD in winter could be attributed to the decrease in floating plants and aquatic organisms (Madene *et al.* 2023).

3.2. Correlation analysis of water quality parameters

Port is always characterized as a coupling zone of sea-land interaction and an area of highest offshore productivity, subject to the combining actions of tidal currents, wind stress, waves and other natural processes and human activities. These dynamic processes result in more complex spatial and temporal features (Xiong *et al.* 2022). In recent decades, environmental pollution has become increasingly prominent in the sustainable development of the global port coastal belt, thus the stability of the aquatic ecosystem has become a serious concern (Luna *et al.* 2019).

Effective real-time monitoring of various pollutants in port waters is conducive to timely understanding of the water quality status and improving the efficiency of environmental management. In the present study, the correlation between various water quality parameters is further explored, which is helpful for source tracking and control of water pollutants, as well as water quality parameters estimation.

In the present study, Pearson's correlation coefficient significance test was adopted to analyze the relationship between various water quality parameters. The monthly monitoring data of specified water quality parameters were derived for four monitoring sites ranging from 2015 to 2022 (with a length of $n = 279$), and the results are presented in Figure 5. It was noted that there was a significant negative correlation between DO and all water quality parameters (except COD and pH). Oxygen is consumed in the water column for algal growth, organism reproduction and oxidation of compounds. A significant correlation was found between the contents of ammonia nitrogen and TN, with a correlation coefficient of $r = 0.50$, indicating that ammonia nitrogen accounts for a high proportion of TN in the water column. Both COD_{Mn} and COD showed a good correlation and consistency of change trend content ($r = 0.72$, $\rho < 0.001$). In homogeneous waters, COD_{Mn} can be used as an approximation of the COD content.

3.3. The key influencing factors of water quality level

Seven water quality parameters have been included in the SEM analysis to reveal the influencing factors of water quality. Following the literature (Chou *et al.* 2022; Kim *et al.* 2023), the model fitness is further explored and presented in Table 1.

In general, a good agreement was obtained between the sample covariance matrix of the observed variables and the model-implied covariance matrix. The model results are demonstrated in Figure 6 below.

A significant correlation was observed between COD and COD_{Mn}, with a path coefficient of 4.02. Meanwhile, ammonia nitrogen was also correlated with TP and TN. Therefore, the changes of COD_{Mn} and ammonia nitrogen will indirectly affect the water quality. DO and pH did not affect the water quality level, however the effect of TP on pH and DO is noted to be remarkable. An increase of TP led to a significant increase of pH (path coefficient = 1.28), but a large decrease of DO (path coefficient = −7.50).

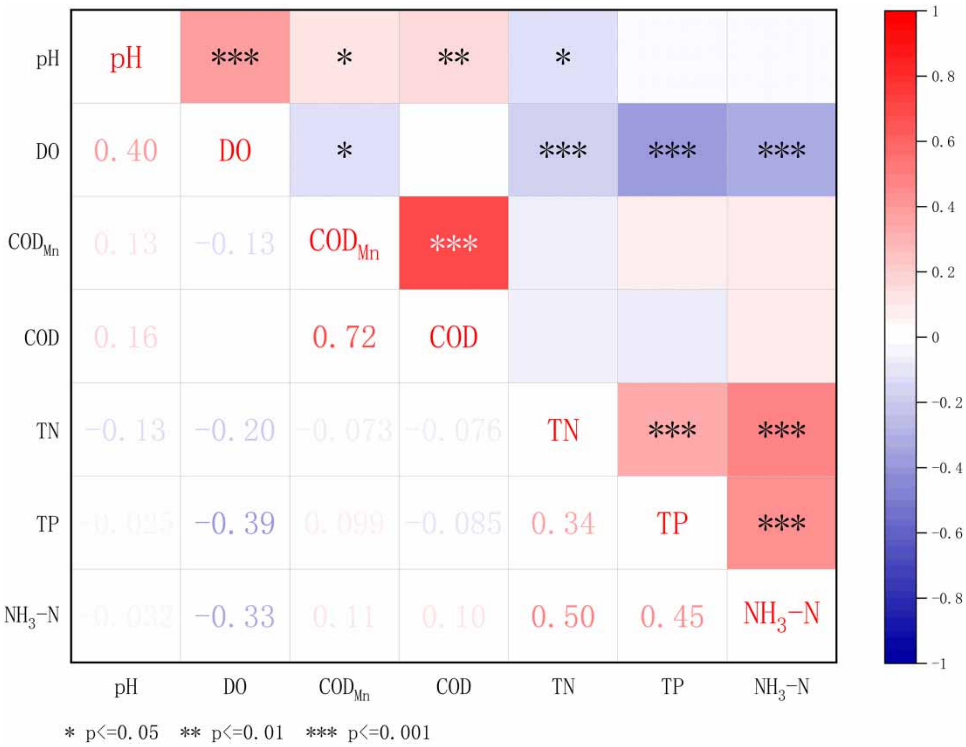

Figure 5 | Heatmap of Pearson correlation analysis between different water quality parameters.

Table 1 | Fitness index for SEM

Statistic	Definition	Recommended value	Calculated value
χ^2/d.f.	The ratio of χ2 and degree of freedom	<3.0 >1.0	1.766
RMSEA	Root-mean-square error of approximation	<0.08	0.051
NFI	The normed fit index	>0.9	0.974
CFI	The comparative fit index	>0.9	0.988
TLI	The Tucker-Lewis index	>0.9	0.970
AGFI	The adjusted goodness of fit index	>0.9	0.949
GFI	The goodness of fit index	>0.9	0.984

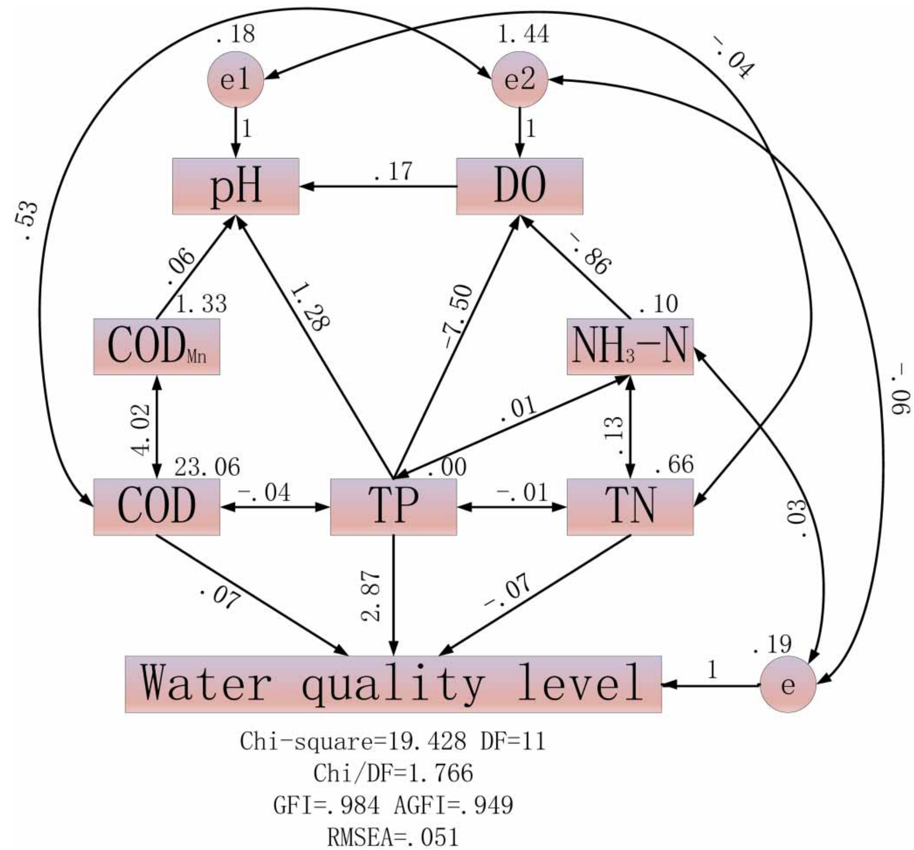

Figure 6 | Structural equation modeling of water quality parameters.

Similarly, ammonia nitrogen content decreased as the DO content increased, with a path coefficient of −0.86. Variations in the DO content also led to fluctuations of pH. Organic matter content (e.g., COD and COD_{Mn}) had less influence on the pH (path coefficient = 0.06). The correlation analysis of water quality parameters was generally consistent with the results of the Pearson correlation analysis as presented in Section 3.2. In conclusion, TP was identified as the main pollutant indicator in Zhanjiang Bay, the variation of which would have a great impact on the port water quality.

4. DISCUSSION

4.1. General characteristics of port water quality

Environmental monitoring has become a common practice in the protection of natural ecosystems. Proper analysis of monitoring data is an important part of port environmental management. The port water quality in Zhanjiang Bay has shown dynamic characteristics in both temporal and spatial dimensions. The evaluation criteria for water quality in the monitoring year are based on the average value of each parameter. The cross-sectional water quality is classified from excellent to poor, with the Nandu River Bridge, Huangpo, Yingzai and Dashanjiang. Among the four monitoring sites, the Dashanjiang has the highest annual average concentrations of ammonia nitrogen, TP and TN. However, the DO content is significantly low. These results indicate a high risk of eutrophication in the water body near the Dashanjiang. In Yingzai, both COD_{Mn} and COD contents reach maximum values. The annual COD content exceeds the Class III water quality standard in the years 2019 and 2021. In addition, the COD_{Mn} content exceeds the standard in 2020, indicating a high risk of organic pollution. The water quality at Huangpo is generally good, except for the TP concentration. Besides, the TN content at Nandu River Bridge deserves more attention in the future. The water quality of Zhanjiang Port tends to deteriorate in summer and ameliorate in winter. There are no Class I and Class II water quality monitoring records in the present study period. The evolutionary trend of key water quality indicators indicates an increasing risk of water pollution in Zhanjiang Bay. It is crucial to focus on the effective treatments of industrial and domestic wastewater.

The water quality parameters show significant variations in different seasons. As described in Section 3.1, the port water quality in Zhanjiang Bay is generally better in summer and worse in winter (see Figure 4). The impact of climate change on water quality is an important issue of global concern. The diffusion patterns of water pollutant and specific parameters (e.g., dissolved oxygen) would be affected by the dynamic processes of tidal currents, wind stress, waves and precipitation, etc. It is evident that the global marine shipping industry has been affected during the lock down period of Covid-19. Following the monitoring data of Zhanjiang Port, it is noted that most of the water quality indicators gradually decreased from 2020, including pH, COD_{Mn}, ammonia nitrogen, and DO (as shown in Figure 7). It should be emphasized that a thorough investigation is required to evaluate the impacts of the Covid-19 pandemic.

The deterioration of port water quality will not only affect the operating environment of ports and the living environment of nearby residents, but also pose a significant threat to the habitats of marine life. Toxic chemicals in the water would damage the digestive and respiratory systems of marine organisms. In addition, the reproductive cycle of marine organisms might be disturbed. More efforts need be devoted to marine environmental and biological monitoring. Thus, the development goal of green ports and environmental protection could be achieved finally.

4.2. Influencing factors of port water quality

In the present study, SEM has been utilized to analyze the influencing factors of water quality in Zhanjiang Bay. The results showed that the water quality was mainly influenced by TP, COD and TN contents, among which the TP content was the most important influencing factor. Both Pearson's correlation analysis and regression analysis showed that COD and COD_{Mn} were positively correlated. TP and TN contents were linearly positively correlated with ammonia nitrogen. The SEM model provides a visual representation of the relationship between the water quality parameters. However, the source tracking and control of water pollutants are also worthy of investigation. The main sources of nitrogen and phosphorus in the water bodies might be fertilizers used in planting, agricultural wastes, domestic wastewater, and industrial wastewater from petrochemical, pharmaceuticals, paper, tannery, printing, food, etc. Wastewater discharged from the industrial parks, mining machinery factories, egg farms, etc. near the Dashanjiang may cause nitrogen and phosphorus pollution. There are a small number of factories located near Yingzai, but dense residential areas nearby. The resident population in Yingzai was approximately 68,000 in 2021, with an increase rate of 6.25% from 2020 (64,000 in 2020). The literature reviews indicate that the population and GDP are significantly and positively correlated with COD and COD_{Mn} concentrations (Pei *et al.* 2023; Zhu *et al.* 2023). Therefore, human activities might be the main cause of organic and minor inorganic pollution in the vicinity of Yingzai. Given more detailed statistics and port water quality data, the underlying driving and influencing mechanisms of social factors (e.g., population, industrial planning and climate change, etc.) could be demonstrated.

5. CONCLUSION

(1) It is noted that the water quality in Zhanjiang Port varies from year to year. Overall, the water quality has been improved in recent years, while a potential risk of water pollution (e.g., organic pollution and eutrophication) still exists. Besides, more attention needs be paid to the deterioration trend of certain water quality indicators, such as COD and COD_{Mn} in the present research domain.
(2) The direct determinants of the water quality level in Zhanjiang Port are identified as TP, TN and COD. However, the main contributors differ with the sampling sites.

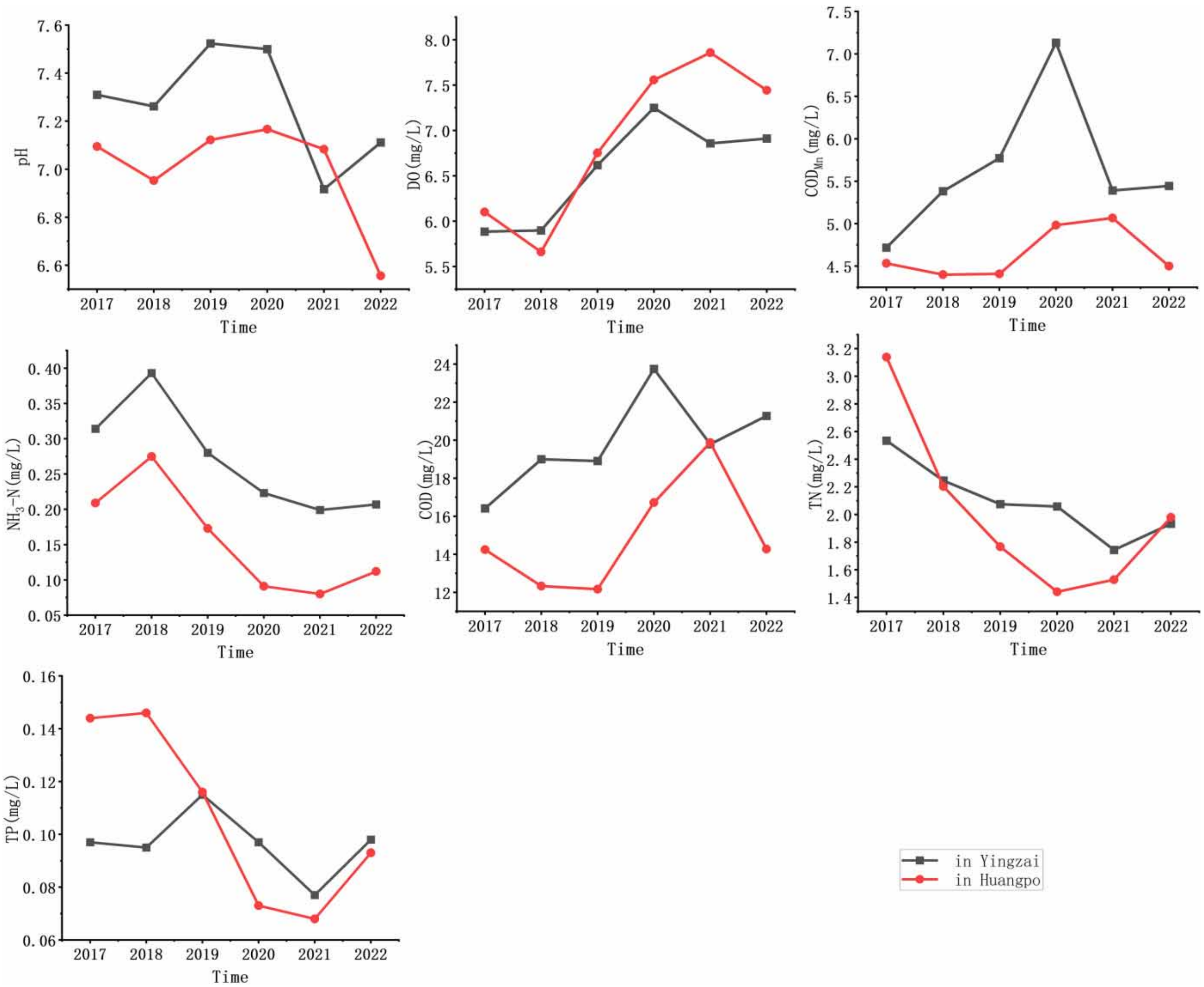

Figure 7 | Annual variations of different water quality parameters from 2017 to 2022.

(3) The variations of water quality indicators are subject to the dynamic processes and complex mechanisms. Industrial and agricultural activities are the main influencing factors in Dashanjiang, while the proper treatment of domestic sewage becomes a major concern in Yingzai.

This study would provide a guidance for water quality management in port waters and promote the development of green ports.

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DATA AVAILABILITY STATEMENT

All relevant data are available from https://gdee.gd.gov.cn/jhszl/index.html.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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