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EUTROPHICATION DYNAMICS AND DRIVING FACTORS IN XIANGSHAN BAY (2000-2024) IN CHINA

Abstract: This research investigates the spatiotemporal characteristics and influencing factors of eutrophication in Xiangshan Bay from 2000 to 2024. By integrating long-term monitoring data and statistical analyses, the study elucidates the evolutionary trends, spatial distribution patterns, and underlying driving mechanisms of eutrophication in the bay. Evaluations using the Eutrophication Index (*EI*) and the Trophic Index (*TRIX*) reveal that the water quality in Xiangshan Bay has remained in a eutrophic state for at least the past 25 years, exhibiting an overall trend of initial increase followed by a decline. The eutrophication level reached its peak in 2016 and has since shown a downward trend, a shift largely attributed to the effective implementation of environmental protection policies by the Chinese government. These policies include measures such as pollution reduction, industrial restructuring, and the optimisation of spatial distribution of pollution sources. Chemical Oxygen Demand (COD), Dissolved Inorganic Nitrogen (DIN), and Dissolved Inorganic Phosphorus (DIP) were identified as the primary pollutants driving eutrophication changes in Xiangshan Bay, with their concentrations heavily influenced by human activities and land-based pollution inputs. Spatiotemporal analysis further highlights significant spatial heterogeneity across the bay, characterised by a distinct gradient from the "port area" to the "central bay area" and the "inner bay area". Seasonal variations were also observed: COD concentrations were significantly higher in winter compared to spring, summer, and autumn, while DIN concentrations peaked in summer. Conversely, DIP concentrations were elevated in autumn and winter relative to spring and summer. The seasonal growth and decline of phytoplankton were identified as key drivers of eutrophication dynamics. This research provides critical insights into the mechanisms of eutrophication in semi-enclosed bays and offers a scientific foundation for developing targeted management strategies to mitigate eutrophication. Furthermore, it contributes to the broader goal of promoting the sustainable health and resilience of coastal ecosystems.

Keywords: spatiotemporal characteristics, pollutants, interannual change, seasonal variation, factors

Introduction

With the rapid economic development of coastal regions and increasing human activities, marine eutrophication has become a severe global environmental issue [1]. Eutrophication not only leads to excessive algal blooms, triggering ecological disasters such as red tides, but also causes a series of ecological problems, including hypoxia and declining biodiversity, posing a significant threat to the health and sustainable development of marine ecosystems [2]. Xiangshan Bay, located along the coast of the East China Sea, is a typical semi-enclosed bay situated in the southeastern part of Ningbo City. Its geographical coordinates range from 29.24° N to 29.48° N and 121.25° E to 122.03° E,

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nestled between the Chuanshan Peninsula and the Xiangshan Peninsula. The bay is characterised by a narrow, elongated shape extending in a NE-SW direction, with a winding coastline of approximately 406 km and a catchment area of 1 445 km^2. The average annual runoff is $12 \cdot 10^8$ m^3, with 60 % of the flow concentrated between June and September. The bay spans five counties - Beilun, Yinzhou, Fenghua, Ninghai, and Xiangshan - encompassing 20 townships. Endowed with unique natural resources, Xiangshan Bay supports ecological aquaculture, marine tourism, and wetland conservation, making it a vital ecological reserve and one of the key marine areas of Ningbo City [3]. However, as a semi-enclosed bay, its ecosystem is highly susceptible to land-based pollution, making it more vulnerable to environmental degradation [4]. With the rapid economic development along the bay, the conflict between marine environmental protection and economic growth has become increasingly pronounced. Consequently, the Chinese government at all levels has placed great emphasis on the healthy and sustainable development of Xiangshan Bay.

As early as the 1990s, eutrophication has been discovered in Xiangshan Bay. Han et al. [5] analysed data from surveys conducted during 2012 to 2022 along the eutrophication gradient from the innermost bay with the most eutrophication to the outer bay with the least eutrophication. They found that the water quality exhibited high nitrogen and low phosphorus levels, indicating moderate pollution, with the entire bay in a state of severe eutrophication. Since the beginning of the 21st century, extensive research has been conducted to investigate and evaluate eutrophication in Xiangshan Bay [6-19]. The majority of these studies have utilised the first-generation *EI*, which remains the predominant assessment method for coastal eutrophication in Chinese marine environments. Additionally, the *TRIX*, another first-generation evaluation method, was developed by Giordani et al. [20]. This method integrates chlorophyll-a (chl-a), Dissolved Oxygen (DO), Dissolved Inorganic Nitrogen (DIN), and Dissolved Inorganic Phosphorus (DIP) to reflect the ecological effects of eutrophication. The *TRIX* method has been extensively applied in coastal areas such as the Mediterranean Sea, Persian Gulf, and Black Sea [21-23]. For instance, Sun et al. [24] used the *TRIX* method to assess the trophic status of scallop farming areas. Kong et al. [25] established a rapid evaluation technique for eutrophication in the Yellow and East China Seas based on *TRIX* values. Lai et al. [26] evaluated the trophic status of the Beibu Gulf using multiple methods, including the *TRIX* approach.

This research evaluates the eutrophication status of Xiangshan Bay over the past 25 years (2000-2024) based on key water quality indicators, including Chemical Oxygen Demand (COD), DIN, DIP, DO, chl-a, temperature (T), and salinity (SAL). Seasonal sampling was conducted throughout the year, covering spring, summer, autumn, and winter, with data collection extending into 2024. Both the *EI* and the *TRIX* were employed to assess the eutrophication levels. The primary objective is to systematically investigate the spatiotemporal variations and driving factors of eutrophication in Xiangshan Bay since the beginning of the 21st century, Xiangshan Bay has experienced significant eutrophication, posing challenges to its ecological health. This research provides a scientific basis for eutrophication control and ecosystem management in the bay. Moreover, the findings not only improve our understanding of the long-term evolution of eutrophication in Xiangshan Bay but also offer valuable insights for mitigating and managing eutrophication in other similar semi-enclosed bays worldwide.

Materials and methods

Sampling collection

This paper is based on data collected by the Ningbo Marine Environmental Monitoring Center from 2000 to 2024, along with relevant reference materials from research conducted in Xiangshan Bay. A total of 13 water quality monitoring stations were established, with surveys conducted during four cruises each year in April (spring), July (summer), October (autumn), and January (winter). Following the zoning method proposed by Jiang et al. [27] and You et al. [28], the 13 monitoring stations (X01 - X13) in Xiangshan Bay were categorised into three regions: the port area (including stations X01, X02, and X03), the central bay area (including stations X04, X05, X06, X07, and X08), and the inner bay area (including stations X09, X10, X11, X12, and X13). A map of the relevant survey stations is presented in Figure 1.

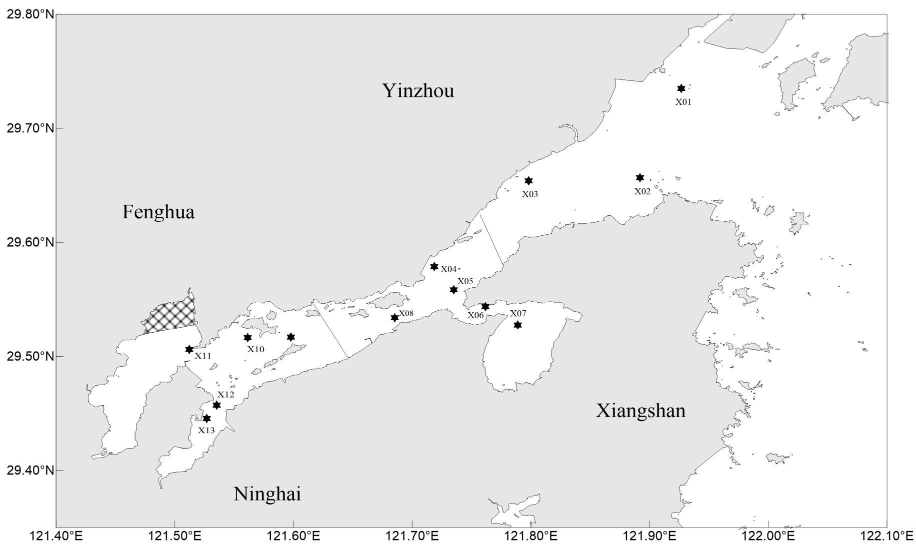

Fig. 1. Sampling sites in Xiangshan Bay

Sampling and analysis

Full water-depth sampling of seawater was conducted using a CTD self-capacitive sampler (Seabird, USA), simultaneous acquisition of *T* and *SAL*. Samples were filtered using a HCl acid-washed neutral pH cellulose acetate fiber filtration membrane (0.45 µm). After filtration, nutrient assays were conducted using the methods outlined in the fourth volume of the marine survey code (GB17378.4-2007): the investigation of the chemical elements in sea water [29]. The analytical methods and detection limits for COD, nitrite (NO_2-N), nitrate (NO_3-N), ammonium salt (NH_4-N), DIP, DO, chl-a are presented in Table 1. Dissolved inorganic nitrogen is the sum of the nitrate, nitrite and ammonia nitrogen components (i.e., DIN = NO_3-N+NO_2-N+NH_4-N) [30].

Table 1

Analytical methods by component

Projects	**COD**	**NO_2-N**	**NO_3-N**	**NH_4-N**	**DIP**	**DO**	**chl-a**
Analysis method	Dichro-mate method	Naphthalene ethylene-diamine spectro-photometric method	Zinc and cadmium reduction	Hypobro-mate oxidation	Phospho molyb-denum blue method	Iodometric method	Fluorescence spectrophotometry
Detection limit [mg/L]	0.15	0.00028	0.0007	0.00042	0.00062	0.042	0.016
Instruments	25 mL Alkaline burette	723C visible spectrophotometer				25 mL Alkaline burette	Fluorescence spectrophotometer

Data processing and analysis

Evaluation criteria

Methodological tools, trophic state classification of the *EI* index and *TRIX* index can be found in Table 2.

Table 2

Classfication of the *EI* index and the *TRIX* index

Methods	**Trophic state**	**Trophic range**
EI	Dichromate method	< 1
		≥ 1
TRIX	Excellent (Ultra-oligotrophic)	< 2
	High (Oligotrophic)	2 - 4
	Good (Mesotrophic)	4 - 5
	Moderate (Mesotrophic to eutrophic)	5 - 6
	Poor (Eutrophic)	6 - 8
	Very poor (Hypereutrophic)	> 8

Data processing

The mean of a dataset is the sum of all data points divided by the number of data points. The mathematical expression μ:

$$\mu = \frac{\sum_{i=1}^{n} x_i}{N} \quad (1)$$

where x_i is the *i*-th data point, and *N* is the total number of data points.

Standard deviation, *SD* is used to measure the dispersion of data distribution. A larger *SD* indicates that the data points are more spread out and have greater variability, while a smaller *SD* indicates that the data points are more concentrated and have less variability. The mathematical expression:

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \quad (2)$$

The *EI* can be used to assess the eutrophication status of seawater [28], and its calculation formula is as follows:

$$EI = \frac{\rho(\mathrm{COD}) \cdot \rho(\mathrm{DIP}) \cdot \rho(\mathrm{DIN}) \cdot 10^6}{4500} \quad (3)$$

where ρ(COD), ρ(DIP), and ρ(DIN) denote the measured concentrations of COD, DIP and DIN in seawater, respectively, all expressed in mg/L. *EI* represents the eutrophication status index. According to the evaluation criterion, an $EI \geq 1$ indicates that the water body has reached a eutrophic state, with higher *EI* values corresponding to more severe eutrophication levels.

TRIX incorporates DO and chl-a as key parameters for assessing the eutrophication status of seawater [31]. The calculation formula is the following:

$$TRIX = [\log_{10}(C_{\mathrm{Chl\text{-}a}} \cdot \mathrm{a}D\%O_2 \cdot C_{\mathrm{DIN}} \cdot C_{\mathrm{DIP}}) - (-1.5)]/1.2 \quad (4)$$

where $\mathrm{a}D\%O_2$ term is the deviation percentage of the oxygen concentration from saturation condition and $C_{\mathrm{chl\text{-}a}}$, C_{DIN} and C_{DIP} are the concentrations of dissolved inorganic nitrogen, total dissolved inorganic phosphate and chl-a respectively. Nutrient and chl-a concentrations were expressed as mg/L.

The experimental data was analysed and plotted using Surfer 11 (Golden Software, USA) and Origin 2018 64 Bit (OriginLab Software, USA).

Results and discussion

Changes in eutrophication in Xiangshan Bay from 2000 to 2024

Figure 2 shows the annual average changes in COD, DIN, DIP, DO, and chl-a concentration in the water quality of Xiangshan Bay from 2000 to 2024. The annual concentrations of COD, DIN, DIP, DO, and chl-a in Xiangshan Bay generally followed a trend of initial increase followed by a gradual decline from 2000 to 2024. Specifically, the annual average COD concentration increased by 51.1 %, rising from 0.86 mg/L in 2000 to a peak of 1.30 mg/L in 2016, before decreasing to 0.840 mg/L in 2024, representing a 35.4 % reduction from its peak. Similarly, the annual average DIN concentration increased by 81.0 %, rising from 0.500 mg/L in 2000 to a peak of 0.902 mg/L in 2016, before declining to 0.775 mg/L in 2024, 14.1 % reduction from its maximum level. The annual average DIP concentration experienced a significant surge of 139.1 %, growing from 0.023 mg/L in 2000 to 0.055 mg/L in 2016, before dropping to 0.036 mg/L in 2024, a 34.5 % reduction from its peak. In contrast, the annual average DO concentration exhibited relatively stable fluctuations, increasing by 5.6 % from 7.52 mg/L in 2000 to 7.94 mg/L in 2016, then slightly declining to 7.80 mg/L in 2024, only 1.8 % lower than its maximum. Lastly, the annual average chl-a concentration rose by 31.9 %, from 1.85 μg/L in 2000 to 2.44 μg/L in 2016, before gradually decreasing to 2.09 μg/L in 2024, a 14.3 % reduction from its peak. These trends reflect the dynamic changes in water quality parameters over the 24-year period.

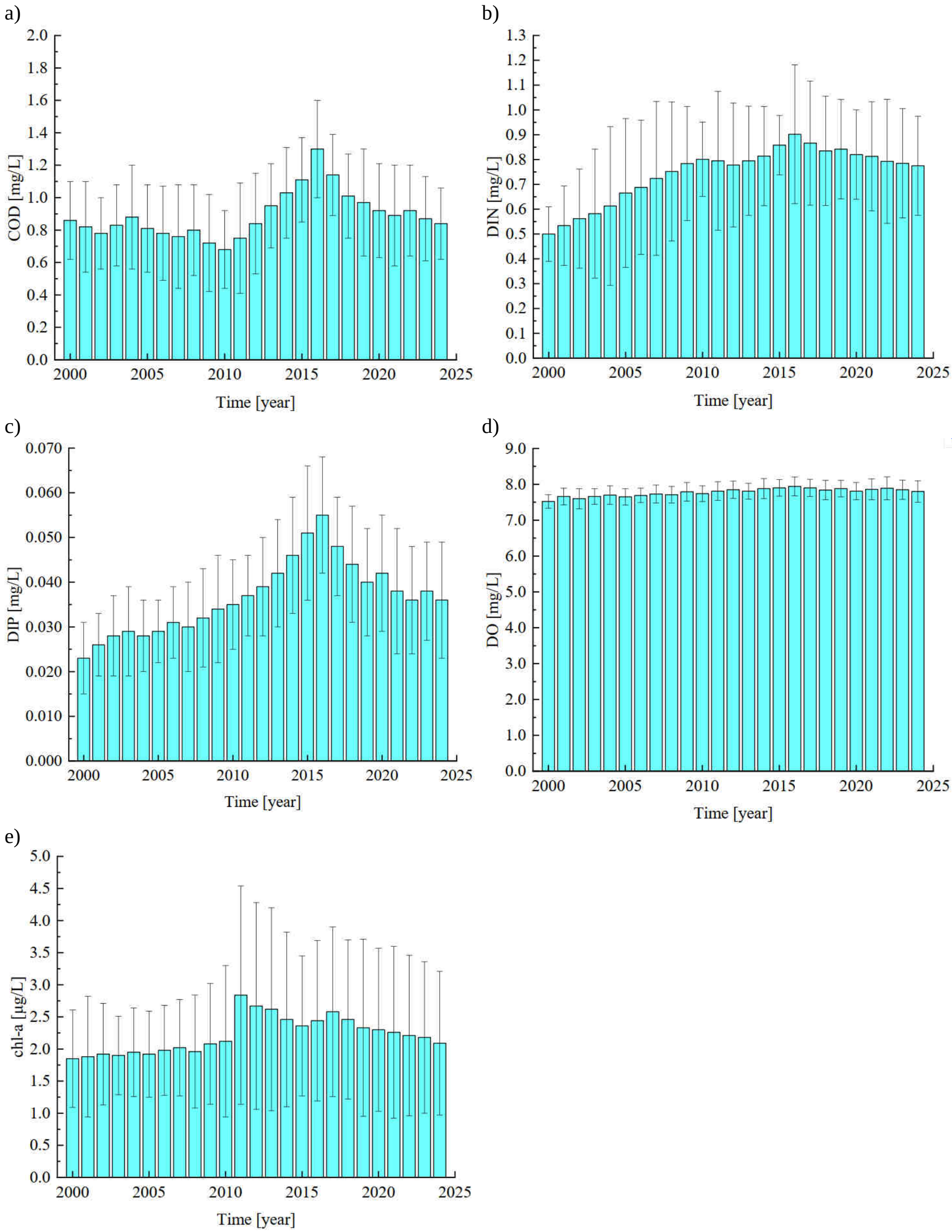

Fig. 2. a) COD, b) DIN, c) DIP, d) DO, and e) chl-a concentrations in the water quality of Xiangshan Bay from 2000 to 2024. Error bars represent *SD*

Figure 3 shows the annual average changes in N/P in the water quality of Xiangshan Bay from 2000 to 2024. The N/P ratio in the water quality of Xiangshan Bay displayed a general pattern of initial increase followed by a gradual decline from 2000 to 2024. During this period, the N/P ratio rose significantly from 21.74 in 2000 to a peak of 40.36 in 2016, reflecting an 85.65 % increase. Subsequently, it began to decrease but remained at an elevated level, reaching 33.95 in 2024, which represents a 15.88 % reduction from its highest point. The standard N/P ratio in seawater is 16 : 1 [31-33], which aligns with the approximate ratio at which phytoplankton assimilate nitrogen and phosphorus from seawater [34]. Deviations from this ratio, whether higher or lower, can result in phytoplankton growth being constrained by the relatively limited availability of one element. Specifically, an N/P ratio below 10 indicates nitrogen limitation, while a ratio above 10 suggests phosphorus limitation. Over the past 25 years, the N/P ratio in Xiangshan Bay has consistently remained above 10, underscoring that phosphorus has been the primary limiting factor for phytoplankton growth throughout this timeframe. This persistent condition highlights the critical role of phosphorus in regulating the ecological dynamics of the bay.

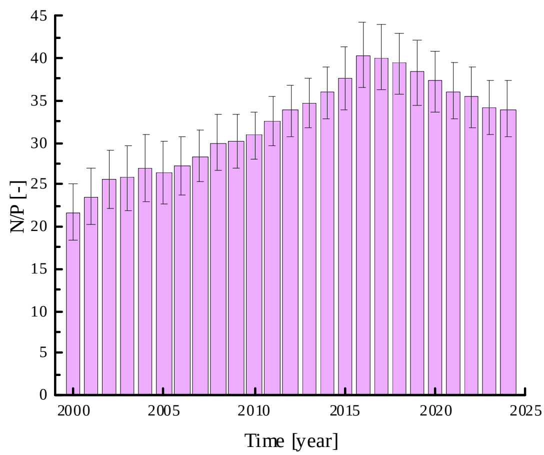

Fig. 3. N/P in the water quality of Xiangshan Bay from 2000 to 2024. Error bars represent *SD*

Figure 4 shows the annual average changes in *EI* of Xiangshan Bay from 2000 to 2024. Based on the evaluation results of the *EI*, the *EI* values consistently remained above 1 from 2000 to 2024, indicating that the water body of Xiangshan Bay was persistently in a eutrophic state during this period. The *EI* values fluctuated significantly, ranging from 2.20 to 14.33, demonstrating considerable variability in the eutrophication level of Xiangshan Bay. Overall, the trend exhibited an initial increase followed by a decline. Specifically, from 2000 to 2016, the *EI* surged from 2.20 to 14.33, reflecting a remarkable increase of 551.4 %. Subsequently, from 2016 to 2024, the *EI* gradually declined to 5.21, representing a reduction of 63.6 %. Notably, during the same period (2016-2024), the *EI* also experienced an increase of 136.32 %, highlighting the dynamic nature of eutrophication in the bay.

Figure 5 shows the annual average changes in *TRIX* of Xiangshan Bay from 2000 to 2024. Based on the *TRIX* evaluation results, the eutrophication level of Xiangshan Bay exhibited an overall trend of initial increase followed by a gradual decline. From 2000 to

2016, the *TRIX* value rose from 6.48 to 7.13, reflecting an increase of 85.65 %. Subsequently, it began to decline steadily, reaching 6.86 by 2024, which corresponds to a 15.88 % reduction from its peak. Despite this decrease, the *TRIX* value continued to remain at a relatively elevated level.

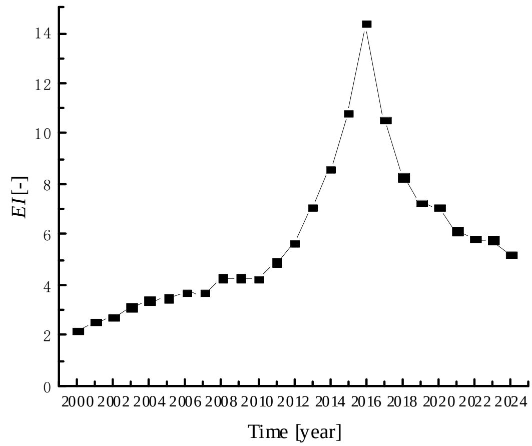

Fig. 4. *EI* of Xiangshan Bay from 2000 to 2024

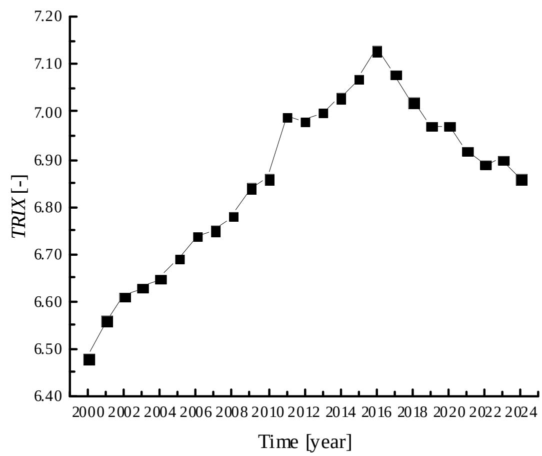

Fig. 5. *TRIX* of Xiangshan Bay from 2000 to 2024

Seasonal and spatial distribution changes of eutrophication

The eutrophication level in Xiangshan Bay is notably high, characterised by pronounced seasonal and spatial variations [35]. Based on the survey data from 2024, including measurements of COD, DIN, DIP, DO, and chl-a across spring, summer, autumn, and winter (Table 3), the following observations can be made:

- COD concentration: winter exhibited significantly higher COD levels compared to spring, summer, and autumn, with an average concentration of 0.95 mg/L.

- DIN concentration: summer recorded notably higher DIN levels than spring, autumn, and winter, averaging 0.91 mg/L.
- DIP concentration: autumn and winter showed elevated DIP levels relative to spring and summer, with average concentrations of 0.040 mg/L and 0.044 mg/L, respectively.
- DO concentration: spring and winter had higher DO levels compared to summer and autumn, with average values of 8.22 mg/L and 9.03 mg/L, respectively.
- chl-a concentration: summer and autumn displayed higher chl-a concentrations than spring and winter, averaging 2.4 μg/L and 2.1 μg/L, respectively.

These findings highlight the dynamic and seasonally influenced nature of eutrophication in Xiangshan Bay.

Table 3

Statistical results (mean±*SD*) of water quality parameters in Xiangshan Bay across different seasons in 2024

Seasons	**COD [mg/L]**	**DIN [mg/L]**	**DIP [mg/L]**	**DO [mg/L]**	**chl-a [μg/L]**
Spring	0.87 ±0.29	0.73 ±0.19	0.031 ±0.012	8.22 ±0.27	1.92 ±0.89
Summer	0.83 ±0.27	0.91 ±0.27	0.035 ±0.017	6.74 ±0.23	2.4 ±1.4
Autumn	0.89 ±0.29	0.77 ±0.21	0.040 ±0.022	7.44 ±0.29	2.1 ±1.1
Winter	0.95 ±0.32	0.83 ±0.22	0.044 ±0.019	9.03 ±0.35	1.9 ±1.1

As can be seen from Figure 6, the average concentrations of water quality parameters in Xiangshan Bay displayed distinct seasonal variations, with the following patterns observed: COD concentrations were highest in winter, followed by autumn, spring and summer; DIN levels peaked in summer, followed by winter, autumn and spring; DIP concentrations were greatest in winter, then autumn, summer and spring; DO levels were highest in winter, followed by spring, autumn, and summer; chl-a concentrations were elevated in summer, followed by autumn, spring and winter. In 2024, the N/P ratio in Xiangshan Bay ranged from 19.9 to 26.1. The *EI* values, ranging from 4.4 to 7.7, indicated that the bay remained in a eutrophic state throughout all seasons. Similarly, the *TRIX* values, which ranged from 6.5 to 7.2, further confirmed that Xiangshan Bay experienced persistent eutrophication across all seasons.

Based on the data presented in Table 3, and supported by the research of Huang et al. [36] and Wang et al. [37], it is clear that the primary pollutants affecting the water quality of Xiangshan Bay are COD, DIN, and DIP. As illustrated in Figures 6-8, the analysis of the spatial distribution of COD, DIN, and DIP concentrations in 2024 reveals that the inner bay area demonstrates significantly higher eutrophication levels compared to the port and mid-bay areas. The concentrations of DIN, DIP, and COD generally decrease from the inner bay toward the port, with the highest values consistently recorded in the inner bay throughout all seasons. These spatial variations are statistically significant ($p < 0.05$).

Furthermore, the *EI* and *TRIX* values are significantly higher in autumn and winter compared to spring and summer ($p < 0.05$). This seasonal pattern is attributed to the substantial uptake of DIN and DIP by phytoplankton blooms during spring and summer, leading to lower *EI* and *TRIX* values. As illustrated in Figures 9 and 10, both indices exhibit a distinct gradient, with values decreasing from the inner bay to the mid-bay and port areas (inner bay > mid-bay > port area). Except for summer, the inner bay consistently demonstrates significantly higher values than the port area ($p < 0.05$). Among the 13 monitoring stations, annual *EI* and *TRIX* values exceeding 6 - 8 (indicating severe eutrophication) are predominantly observed in the inner bay, with at least three stations located in this region, while fewer instances are recorded in the mid-bay and port areas. In contrast, stations with *TRIX* values below 5 (indicating moderate or oligotrophic conditions) are exclusively found in the port area and occasionally in the mid-bay area, whereas the inner bay area almost never exhibits such low values.

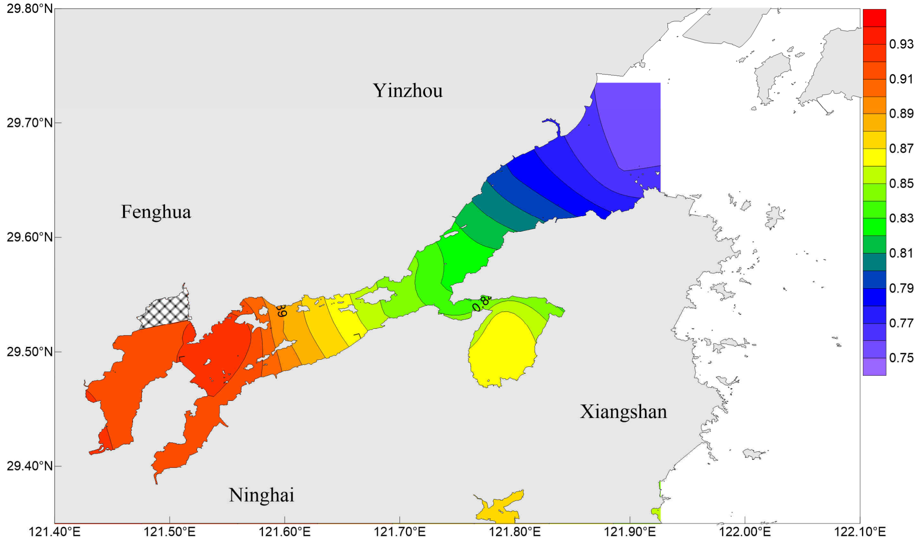

Fig. 6. The spatial distribution of COD concentrations [mg/L] in 2024

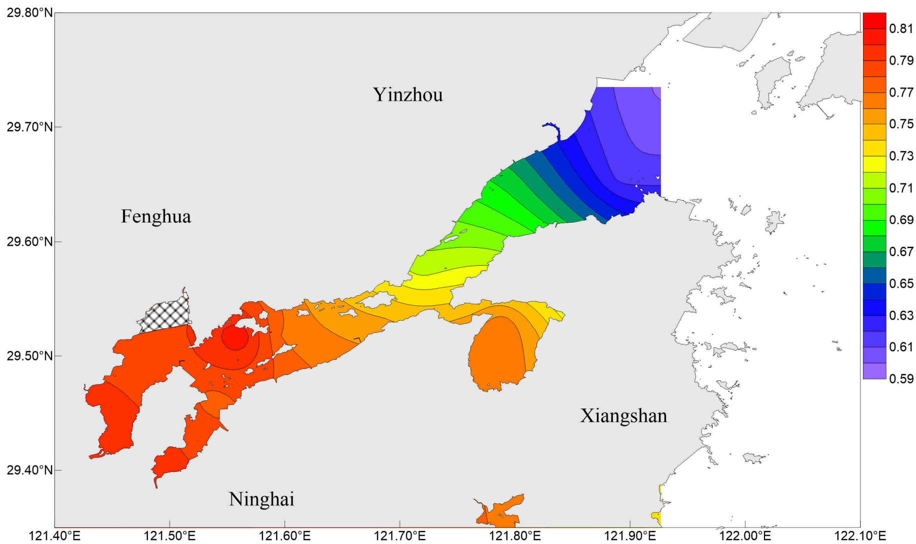

Fig. 7. The spatial distribution of DIN concentrations [mg/L] in 2024

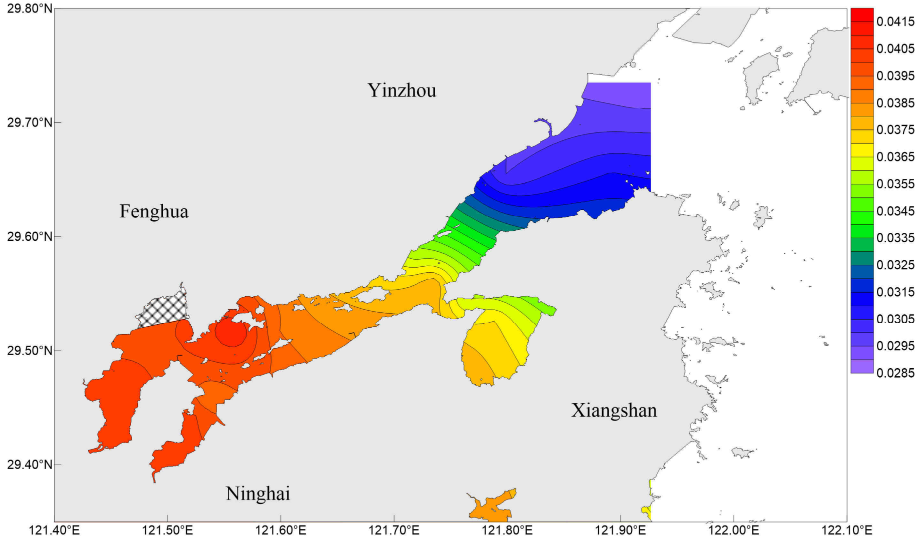

Fig. 8. The spatial distribution of DIP concentrations [mg/L] in 2024

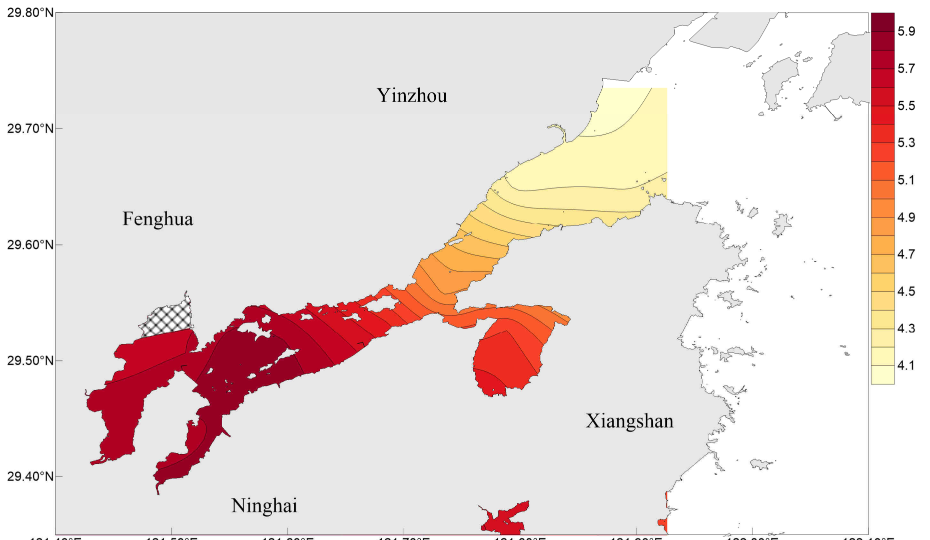

Fig. 9. The spatial distribution of *EI* concentrations [-] in 2024

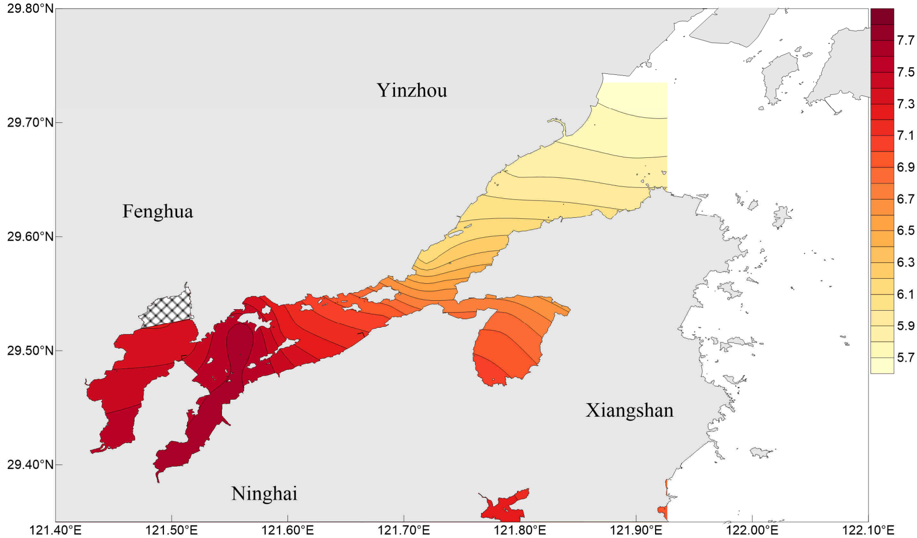

Fig. 10. The spatial distribution of *TRIX* concentrations [-] in 2024

Factors influencing eutrophication

The formation and progression of eutrophication in Xiangshan Bay stem from a combination of multiple factors, with human activities serving as the primary driver. In recent years, the rapid economic growth and increasing population density in the surrounding regions have significantly escalated the discharge of land-based pollutants. Key sources of pollution include domestic sewage, industrial wastewater, agricultural runoff, and aquaculture effluents. Analysis of the *EI* and *TRIX* from surface water samples gathered at 13 monitoring stations across the inner, mid, and outer regions of Xiangshan Bay indicates that the bay has remained in a eutrophic state consistently from 2000 to 2024. According to Nobre et al. [38], approximately 4,015 Mg (Mg = 10^6 g = tonne) of DIN and 730 Mg of DIP are introduced into Xiangshan Bay annually from land-based sources. The bay receives considerable inputs from land-based runoff, with rivers such as Dasong River, Fu Stream, Yangong River, and Chunhu Huangzi Stream transporting substantial amounts of nitrogen and phosphorus into the sea each year [39].

Moreover, aquaculture activities in Xiangshan Bay, predominantly involving cage and intertidal farming, significantly contribute to nutrient loading. The discharge of DIN and DIP from cage farming has surpassed the bay's pollution assimilation capacity.In cage fish farming, only 24.7 % of nitrogen and 30 % of phosphorus are utilised for fish growth, with the remaining nutrients lost through excretion, and approximately 75 % of the total nitrogen and phosphorus from feed entering the water [40]. Concurrently, Zeng et al. [41] discovered that from 1963 to 2010, the reclamation of intertidal zones has reduced the average tidal volume of Xiangshan Bay by 12.6 %, with the average water exchange rates over 30, 60, and 90 days decreasing by 7.7 %, 6.8 %, and 6.1 %, respectively. As a result, extensive reclamation has modified the hydrodynamic environment (tides, flow fields, and residual currents), diminishing tidal volume and water exchange rates, reducing environmental capacity, and hindering the bay's ability to self-purify and disperse pollutants. This has led to the prolonged retention of nutrients from sewage and aquaculture effluents in the inner bay, causing persistent eutrophication in Xiangshan Bay.

The primary pollutants in Xiangshan Bay, including COD, DIN, and DIP, peaked around 2016. This finding is consistent with the conclusions of Liu et al. [3] who noted a trend of increasing eutrophication in 2015, as well as with the research of Wang et al. [37] who analysed monitoring data of major pollutants (COD, TN, and TP) entering Xiangshan Bay from 2010 to 2019 and identified a trend of initial increase followed by a decline, with peak values occurring in 2015. These results closely align with the findings of This research. This trend can largely be attributed to the Chinese government's proactive measures in recent years to reduce pollution [42], adjust industrial structures [43], and optimise the spatial distribution of pollution sources [44, 45].

From a seasonal perspective, phytoplankton proliferation is a key driver of eutrophication. In summer, phytoplankton reproduction reaches its peak, causing a significant increase in chl-a concentration, reduced water transparency, and lower dissolved oxygen levels [46, 47]. In spring, as water temperatures gradually rise, phytoplankton begin to proliferate extensively [48]. The inner bay area, characterised by weaker hydrodynamic exchange, shows significantly higher eutrophication levels compared to the mid-bay area. During summer, higher water temperatures and abundant sunlight in Xiangshan Bay promote phytoplankton growth to its peak, resulting in a notable increase in chl-a concentration. Additionally, increased land-based runoff during summer leads to higher concentrations of COD, DIN, and DIP, further exacerbating eutrophication. In autumn, as water temperatures drop and sunlight diminishes, phytoplankton reproduction slows, and chl-a concentrations gradually decrease. However, increased rainfall during autumn maintains high levels of nutrient input from land-based runoff, keeping eutrophication at a relatively high level. In winter, the lowest water temperatures inhibit phytoplankton reproduction, leading to a significant reduction in chl-a concentration. Nevertheless, enhanced vertical mixing of water during winter transports nutrients from the bottom to the surface, resulting in elevated concentrations of COD, DIN, and DIP.

Moreover, natural factors also play a significant role in the eutrophication process in Xiangshan Bay. As a semi-enclosed bay, Xiangshan Bay has relatively weak water exchange capacity, which impedes the diffusion and dilution of pollutants. Climate change-induced alterations in precipitation patterns and rising water temperatures may also exacerbate eutrophication. For instance, extreme precipitation events can increase the input of land-based nutrients, while thermal discharges from nearby power plants entering Xiangshan Bay may raise water temperatures, promoting algal growth and intensifying eutrophication [49].

Conclusion

The main manifestations of eutrophication in Xiangshan Bay include increased concentrations of nutrients such as nitrogen and phosphorus in seawater, elevated chl-a levels, and reduced DO concentrations, all of which generally follow a trend of initial rise followed by a decline. From 2000 to 2024, the concentration of DIN in Xiangshan Bay rose from 0.500 mg/L to 0.775 mg/L, while the concentration of reactive DIP increased from 0.023 mg/L to 0.036 mg/L. The chl-a concentration grew from 1.85 μg/L to 2.09 μg/L, and the DO concentration increased from 7.52 mg/L to 7.80 mg/L.

An assessment of the eutrophication level in Xiangshan Bay using the *EI* and *TRIX* indices indicates that the bay has remained in a eutrophic state over the years, exhibiting an overall trend of initial increase followed by a decline, with a peak occurring around 2016. Analysis of key pollutants in the bay, including COD, DIN, and DIP, reveals that their annual variations generally followed a pattern of initial rise followed by a reduction. This trend is mainly driven by land-based pollutant inputs, such as domestic sewage, industrial wastewater, agricultural runoff, and aquaculture effluents, stemming from human activities in the surrounding regions, which have significantly impacted the bay's eutrophication status. The subsequent decline in pollution levels is associated with the effective implementation of environmental protection measures by the Chinese government in recent years, including initiatives to reduce pollution, restructure industries, and optimise the spatial distribution of pollution sources.

Xiangshan Bay demonstrates pronounced spatial variations, with a clear gradient from the port area to the mid-bay area and further to the inner bay area. Seasonally, the growth and decay of phytoplankton play a crucial role in driving eutrophication. The COD concentration is markedly higher in winter than in spring, summer, and autumn. The DIN concentration is significantly elevated in summer compared to spring, autumn, and winter. Additionally, the DIP concentration is higher in autumn and winter than in spring and summer.

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