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Regional nutrient emissions and hydrological regime modulate the spatiotemporal patterns of nutrient levels within lake bay

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ABSTRACT

Many rivers and lakes worldwide, especially lake bays adjacent to rivers, have experienced eutrophication. However, the effects of nutrient emission reduction and hydrological conditions on the levels and spatiotemporal distribution patterns of nitrogen (N) and phosphorus (P) in lake bays remained insufficiently understood. In this study, a dynamic model was developed to track nutrient transport processes from source areas to rivers and lake bays, and applied it to Zhushan Bay and its upstream region in the Taihu Basin, China. Hydro-chemical analysis results indicated that during the wet season, the total nitrogen (TN) concentration (1.64 mg·L^{-1}) in the river inflow section was higher than that in the lake bay (1.48 mg·L^{-1}), while total phosphorus (TP) (0.24 mg·L^{-1}) was lower than in the lake bay (0.30 mg·L^{-1}). The model results showed that in 2020, domestic sewage sources (38.24 %) and surface sources from cultivated land (33.14 %) were the primary contributors of fluvial TN, while livestock and poultry breeding sources (59.37 %) were the main sources of fluvial TP. Scenario simulations indicated that a 30 % reduction in nutrient emissions led to a corresponding decrease in TN and TP loads in the lake bays, with more significant reductions observed during the dry season (TN: 3.05 %; TP: 9.51 %). A 12 % reduction in river discharge during the dry season resulted in a corresponding decrease in TN and TP loads in the lake bays, with the reduction in TP (1.81 %) greater than that of TN (1.39 %). This study offered insights into nutrient transport and guidance for managing nutrients in lake basins.

1. Introduction

In the last decades, the increase of nitrogen (N) and phosphorus (P) emissions by human activities has altered the global ecosystem balance (Peñuelas et al., 2013). These N and P emissions are discharged into receiving water bodies such as rivers and lakes. Monitoring data indicate that global lake eutrophication and frequent algal blooms have increasingly impacted lake basins through nutrient enrichment over the period from 1982 to 2019 (Hou et al., 2022). Shallow bay areas near river inflows are particularly prone to severe eutrophication, such as Lake Erie in the USA, Lake Kasumigaura in Japan, and Lake Taihu in China (Ho et al., 2019). In lake basins, river systems act as critical conduits for the input of point and diffuse nutrients into lakes (Howarth et al., 2021). For example, the major rivers of Lake Taihu contribute approximately 70 % to 80 % of the total nutrients entering the lake (Wang et al., 2019). The lake bays near river inflows received high concentrations of N and P from river water, making these areas the most eutrophic parts of the lake (Geng et al., 2021).

The concentrations of exogenous N and P inputs vary during high and low flow periods, resulting in significant seasonal changes of nutrient levels in lakes (Li et al., 2011; Sarpong et al., 2023; Stoddard et al., 2016). While it is widely accepted that exogenous nutrients are the main contributors to increased nutrient loads in lakes (Ma et al., 2023; Montefiore et al., 2024), the transport processes of terrestrial nutrients in river networks and lake bays, and their impact on lake nutrient levels during different periods of the year, are not well understood. Most studies only consider the process from terrestrial nutrient mobilization to river network transport (Creed et al., 2015; Miller et al., 2020; Yin et al., 2010), or the transport processes of nutrients within lakes (Liu et al., 2020; Qin et al., 2019; Wang et al., 2019). Comprehensive studies on the entire process of terrestrial nutrient mobilization, transport, and diffusion in lake bays are still rare. Furthermore, the quantitative evaluation of nutrient changes in lake bays under future scenarios of nutrient source control and climate change, especially for river discharge variations, remains pending.

To clarify the trajectory of nutrients from the surface to river

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networks and lake bays, several model approaches have emerged. Models such as the Soil and Water Assessment Tool (Arnold and Allen, 1996) and the Hydrological Simulation Program Fortran (Becknell et al., 1993) are commonly used for quantitatively assessing terrestrial nutrient mobilization and river network transport processes (Akhavan et al., 2010; Bosch et al., 2010; Saleh and Du, 2004; Wen et al., 2024). In plain river network regions, inaccurate sub-basin divisions by these models may lead to deviations in the description of runoff processes and nutrient transport processes. Models such as the Modular Integrated Key for Environmental assessment (MIKE) (DHI, 2009) and the Environmental Fluid Dynamics Code (Hamrick 1992) offer high precision for the simulations of nutrient transport processes in river networks and diffusion processes in lakes but lack descriptions of terrestrial nutrient mobilization. A high-precision model that considers terrestrial nutrient mobilization and their transport processes in river networks and lake bays needs to be developed.

Lake Taihu is severely eutrophic with high N and P concentrations, particularly in Zhushan Bay (Chen et al., 2016; Li et al., 2011). Previous studies indicated that the N concentrations of inflowing rivers in the western part of Lake Taihu were higher than those of other rivers (Zhu et al., 2018), which may lead to nutrient levels in Zhushan Bay higher than other areas of the lake (Li et al., 2011; Sarpong et al., 2023). The processes and magnitudes of the impacts of nutrient source reduction and hydrological regime on N and P concentrations in fluvial and lake bay waters are unclear. This study developed a nutrient transport model (NTM) by integrating the existing export coefficient method with the MIKE model. This coupled framework captures the full process of terrestrial nutrient mobilization and nutrient transport in rivers and lake bays, applied specifically to Zhushan Bay and its upstream region. Through high-density water sample collection and analysis as well as hydrological simulation, this study explored the nutrient transport processes in lake bays and their inflow regions, along with the influencing factors. The objectives of this study are: (1) to identify the main sources of fluvial N and P; (2) to reveal the spatiotemporal patterns of nutrients in inflowing rivers and lake bays and their influencing factors; (3) to assess the impact of future reductions in nutrient emissions and river discharge variation on the nutrient levels and their spatiotemporal distribution in lake bays. This study offers theoretical references for quantifying the impacts of nutrient emission changes on lake nutrient concentrations and for developing regional N and P control strategies.

2. Material and methods

2.1. Study area

The study area is situated in the lower reaches of the Yangtze River, encompassing Zhushan Bay (part of Lake Taihu) and its inflowing river areas, with a total area of 651.5 km^2. Primarily located in Yixing City, Jiangsu Province, this region experiences a subtropical monsoon climate characterized by distinct seasons, abundant rainfall, and an average annual precipitation of 1185 mm (Fig. S1). Based on precipitation and lake water levels, the months within the study area are categorized into three seasons: the wet season (May to September), the dry season (December to February), and the normal season (March to April, October to November). The inflow rivers in the western part of Lake Taihu account for 58 % of the total inflow. The proportions of cultivated land, lake, and construction land in the study area in 2020 were 54.90 %, 21.12 %, and 18.67 %, respectively (Fig. 1).

The region is characterized by a dense river network. Four rivers connecting Lake Gehu and Zhushan Bay: Shaoxianggang River (SXG), Yincungang River (YCG), Caoqiao River (CQ), and Taige Canal (TG). Additionally, the Wuyi Canal (WY) intersects these four rivers, and the Yapugang River (YPG) directly connects to Lake Taihu. Along the rivers, ponds are distributed, and forests are mainly located in the northeastern part of the study area. The main crops, rice and wheat, are primarily cultivated in a rotation system. Additionally, there are other agricultural practices, including vegetable planting, livestock breeding, fish and crab farming, and the cultivation of tea and orchards, making it a key region in the Lake Taihu Basin for agricultural products.

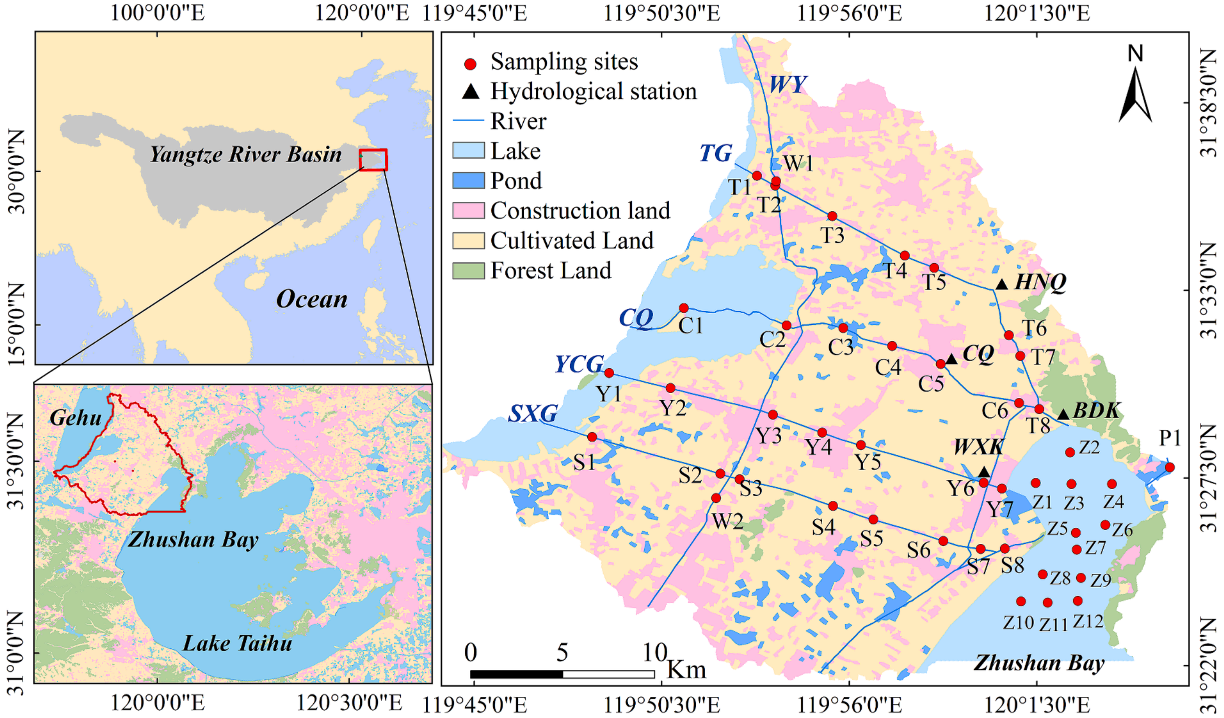


Fig. 1. Description of sampling sites and land use in the study area. Data comes from the National Science & Technology Infrastructure of China (http://www.globallandcover.com/).

2.2. Sampling and analysis

Considering the distribution of river networks, topographic attributes, and land use types, 45 sampling sites were selected, including 33 in the inflowing rivers and 12 within Zhushan Bay (Fig. 1). There are 8 sampling sites on the SXG (S1 − S8), 7 on the YCG (Y1-Y7), 6 on the CQ (C1-C6), 8 on the TG (T1-T8), 1 on the YPG (P1), 2 on the WY (W1-W2), and 12 distributed throughout Zhushan Bay (Z1-Z12). Sampling campaigns were conducted from August to December 2020, with August, October, and December representing the wet, normal, and dry seasons, respectively (Fig. S1).

Sampling was conducted using sanitized water samplers to collect river water 20 cm below the surface. All samples were immediately sealed and stored at 4 °C by placing dry ice in a cold box, then transported to the laboratory for measurement within 24 h. Analytical indicators included water temperature (WT), dissolved oxygen (DO), pH, total nitrogen (TN), total phosphorus (TP), ammonium (NH_4^+-N), nitrate (NO_3^--N), nitrite (NO_2^--N), and phosphate (PO_4^{3-}-P). WT, pH, and DO were measured in situ using YSI electrodes (HACH, New York, USA). Flow rates were measured using a portable flow meter. Water depth was consistently measured with an ultrasonic depth finder. NH_4^+-N, NO_3^--N, NO_2^--N and PO_4^{3-}-P were filtered using a 0.2 μm cellulose ester filter until analysis. The analysis of the samples was performed by the Public Technology Service Center of the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, using a continuous flow analyzer (SkalarSan++, Netherlands).

2.3. Model construction and scenario setting

The NTM was developed for tracing nutrients from terrestrial surfaces, through rivers, and ultimately into lake bays. This study applied the NTM model to simulate the transport of TN and TP in Zhushan Bay and its upstream area in 2020. Furthermore, it simulated the dynamic processes of TN and TP in rivers and lake bays under scenarios of future reductions in TN and TP emissions and changes in river discharge.

2.3.1. Data sources

Model data encompassed spatial attribute data, hydrometeorological data, and nutrient emission data. Spatial attribute data included vector boundaries, river networks, topography, and land use. River and lake bay boundaries were derived from the Tuxin Earth and Sky Map. River networks, topography, and land use data came from the National Science & Technology Infrastructure of China. Hydrometeorological data included air temperature, precipitation, water levels, flow rates, and concentrations of N and P in river and lake bay waters. Data on daily water levels and flow rates were obtained from the Taihu Basin Authority (https://www.tba.gov.cn/), and rainfall, wind speed, and additional atmospheric conditions were obtained from the China Meteorological Data Network (https://data.cma.cn/). Water depth metrics were directly measured in the field. Nutrient emission data were derived from population, livestock quantity, fertilizer application, and aquaculture, sourced from the Yixing City Yearbook.

2.3.2. The framework of nutrient transport model

The model includes three parts: surface nutrient mobilization, river hydrodynamics and fluvial nutrient migration, and hydrodynamics and nutrient migration of lake bays. Each module played a distinct role in the nutrient transport simulation and was integrated through a loosely coupled approach to construct a comprehensive river–lake bay coupling model. This model was used to enable quantitative assessment of the impacts of nutrient emissions and hydrological conditions on nutrient levels in rivers and lake bays across different scenarios. The simulation framework is shown in Fig. 2.

Surface nutrient mobilization is used to calculate the nutrient increments in the river segment and provide this data to fluvial nutrient migration, which calculates the instantaneous nutrient concentration in the river water. River hydrodynamics in the model is used to solve the instantaneous flow velocity distribution of the water body in real-time, which is then provided as initial conditions to fluvial nutrient migration. The instantaneous flow velocity and nutrient concentration results in the river are input conditions for hydrodynamics and nutrient migration of lake bays, which outputs the nutrient concentration distribution in the

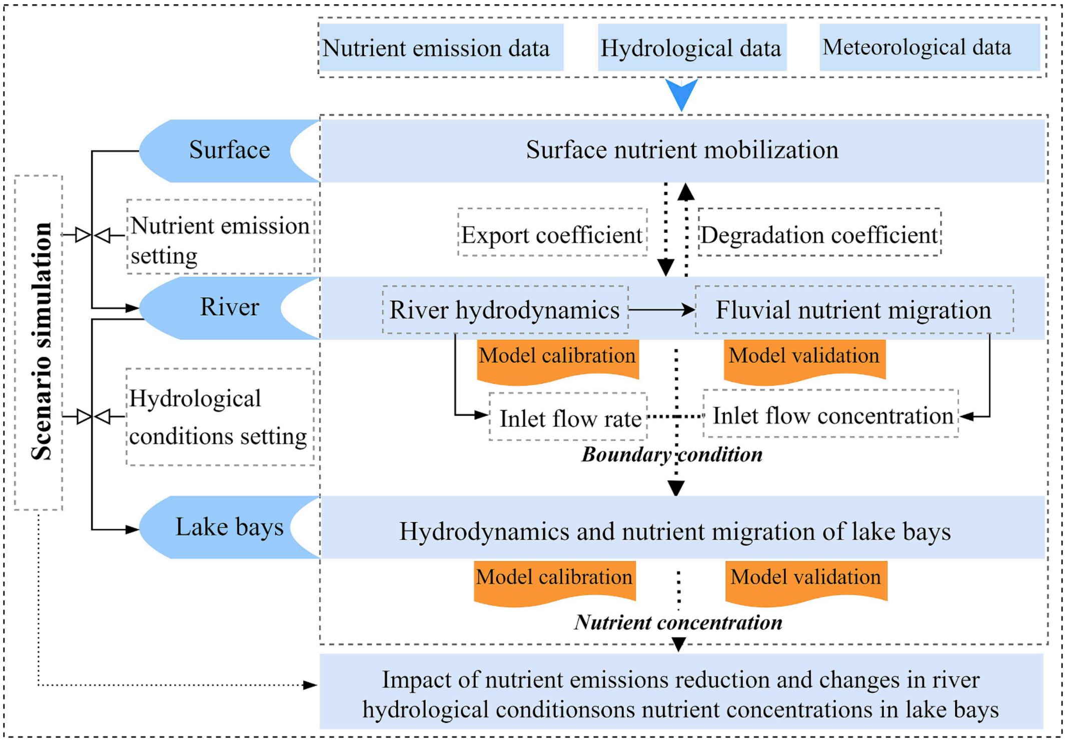


Fig. 2. The framework of nutrient transport model.

lake bays. The hydrodynamics and nutrient migration module for rivers and lake bays was constructed using MIKE software. (DHI, 2009). Surface nutrient mobilization was calculated using the export coefficient method, as follows:

The non-point source nutrient load and the amount entering the river in the study area were determined using the export coefficient method (Wang et al., 2020). The principle is to combine GIS spatial analysis with nutrient source field investigations and socio-economic data from yearbooks to estimate the load input from irrigation fertilization, livestock, and population in the study area. Subsequently, the nutrient loads from each source are assigned to river segment simulation units. The principles are described by equation (1):

$$W = \sum_{i=1}^{3} P_i \tag{1}$$

where W represents the mass of nutrient entering the river per day, unit: kg yr^{-1}. Pi represents the influx of nutrient from sources such as livestock and poultry breeding, domestic sewage, and surface sources, with the relevant formulas and specific values detailed in Table S1 and Table S2.

2.3.3. Model boundary settings, parameter calibration, and validation

The model's initial conditions are defined by average values of measured depth, flow rate, and nutrient concentrations. It includes both open and closed boundaries, where closed boundaries (land boundaries) mark the land–water interface, and open boundaries apply data on water level, flow rate, or nutrient concentration. In the river hydrodynamics module, open boundaries include WY entrances and exits, the upstream river section, and lake entry points, while all other sections are closed. In the lake bay hydrodynamics and nutrient migration module, to prevent resonance effects, upper boundaries are defined at TG, YCG, and SXG lake entrances, influenced by river inflow rates and nutrient levels. The lower boundary, at the interface between Zhushan Bay and Lake Taihu, uses interpolated daily water levels and nutrient concentrations (Fig. S2).

The parameter ranges and model values for calibration are provided in Table S3. The hydrodynamic model calibration period for rivers and lakes spans January to June, with the validation period from July to December. For the water quality model, TN and TP concentrations from September and November sampling events are used for calibration, while samples from wet, normal, and dry seasons are used for validation. Model accuracy and predictive capability are assessed through the correlation coefficient (Pearson, 1895) and Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970), with detailed results for hydrodynamic and water quality calibration and validation phases for rivers and lake bays presented in Table S4 and Table S5.

2.3.4. Scenario Setting

Based on the average lake inflow from 2005 to 2019, statistical data on inflow volumes and nutrient emissions for the study area are presented, indicating an average change in inflow volume of 12 % (Fig. S3). Annual decreases in agricultural fertilizer application, livestock numbers, and population have occurred. Thus, nutrient emission declined by 11 % over the last two years and 29 % over the last five years. Based on the average inflow from 2005 to 2019 and nutrient emission in 2020, four scenarios were established to quantitatively evaluate the effects of nutrient emission reduction and hydrological changes on nutrient concentrations in the lake bays. Scenario 1 (S1) with the inflow river discharge increases by 12 %, and the nutrient concentration remains unchanged; Scenario 2 (S2) with the inflow river discharge decreases by 12 %, and the nutrient concentration remains unchanged; Scenario 3 (S3) with a 10 % reduction in nutrient emission and unchanged river discharge; and Scenario 4 (S4) with a 30 % reduction in nutrient emission and unchanged river discharge. Nutrient concentrations for Scenarios 3 and 4 are computed using the fluvial nutrient migration and employed as interpolated boundary conditions in the hydrodynamics and nutrient migration of lake bays. Simulations were conducted by modifying the hydrodynamic and water quality boundary input files in the lake bay model. Based on the results of scenario simulation by the NTM, the changes in rivers and lake bays are shown through the rate of change, which is the ratio of the simulated value minus the reference value to the reference value.

2.4. Statistical analysis

The influence of environmental factors (WT, pH, and DO) and land use types on the temporal and spatial variations in nutrient levels of water bodies was ascertained through statistical analysis. Normality tests were first performed on nutrient monitoring data, followed by correlation analyses and the application of the geographical detector method. To analyze the correlation between the proportion of land use and nutrient concentration, buffer zones (Vought et al., 1995) at each river sampling point were established. The geographical detector is used to reveal potential driving factors by detecting spatial stratified heterogeneity. Variable distributions across geographic units are compared to explain the influence of factors on spatial heterogeneity. The main advantage of this method lies in its effectiveness at managing multiple influences and nonlinear relationships in geographic data. This makes it particularly suitable for assessing multiple factors' impact on spatial water quality distribution in complex geographical environments. The factor detector quantifies the spatial variability of dependent variables (TN, TP, NH_4^+-N, NO_3^--N, NO_2^--N and PO_4^{3-}-P) and the explanatory power of independent variables (WT, pH, DO, and land use types) using q-values, which range from 0 to 1. Higher q-values indicate greater spatial variability in the dependent variable and stronger explanatory power of the independent variable (Wang and Xu, 2017).

3. Results and discussion

3.1. Evaluation of NTM performance

The module of river hydrodynamics was calibrated and validated by daily water levels (CQ and HNQ) and river discharge (WXK) in 2020 (see Fig. 1 for details). Results showed that in both the calibration period (January to June) and the validation period (July to December), R^2 and NSE values exceeded 0.97, confirming that the river runoff simulation reliably reflected actual changes in river water levels (Fig. 3). Although the model showed limited ability to capture discharge fluctuations ($R^2 = 0.75$ and $NSE = 0.45$ in the validation period), the WXK simulated flow matched the observed discharge trends, with simulated values closely approximating the observed average values. The runoff processes in the region were influenced by industrial and agricultural water usage and hydraulic engineering operations, leading to significant variations in actual river discharge. The NTM did not account for these changes, resulting in inaccurate predictions of extreme high and low river discharge, particularly during July and August. The fluvial nutrient migration module was calibrated in September and November and validated using TN and TP concentrations at the lake inlet during the wet, normal, and dry seasons. Results indicated that R^2 values for both TN and TP exceeded 0.75, and NSE values were above 0.55 in both calibration and validation periods, demonstrating strong agreement between the simulations and observed data. Thus, the simulation of nutrient transport processes was able to effectively reflect the actual variation processes of fluvial TN and TP.

The module of nutrient migration in lake bays was calibrated and validated using daily water levels (BDK and WXK) and TN and TP concentrations at the lake bay. The results showed that the hydrodynamic simulations of the lake bay exhibited excellent performance, with R^2 values of 0.98 and NSE values reaching 0.91 for BDK and WXK water levels in both the calibration and validation periods (Fig. 4). The TN and TP simulations in the lake bay also demonstrated good performance. Validation results from 12 points showed that the NSE for TN and TP

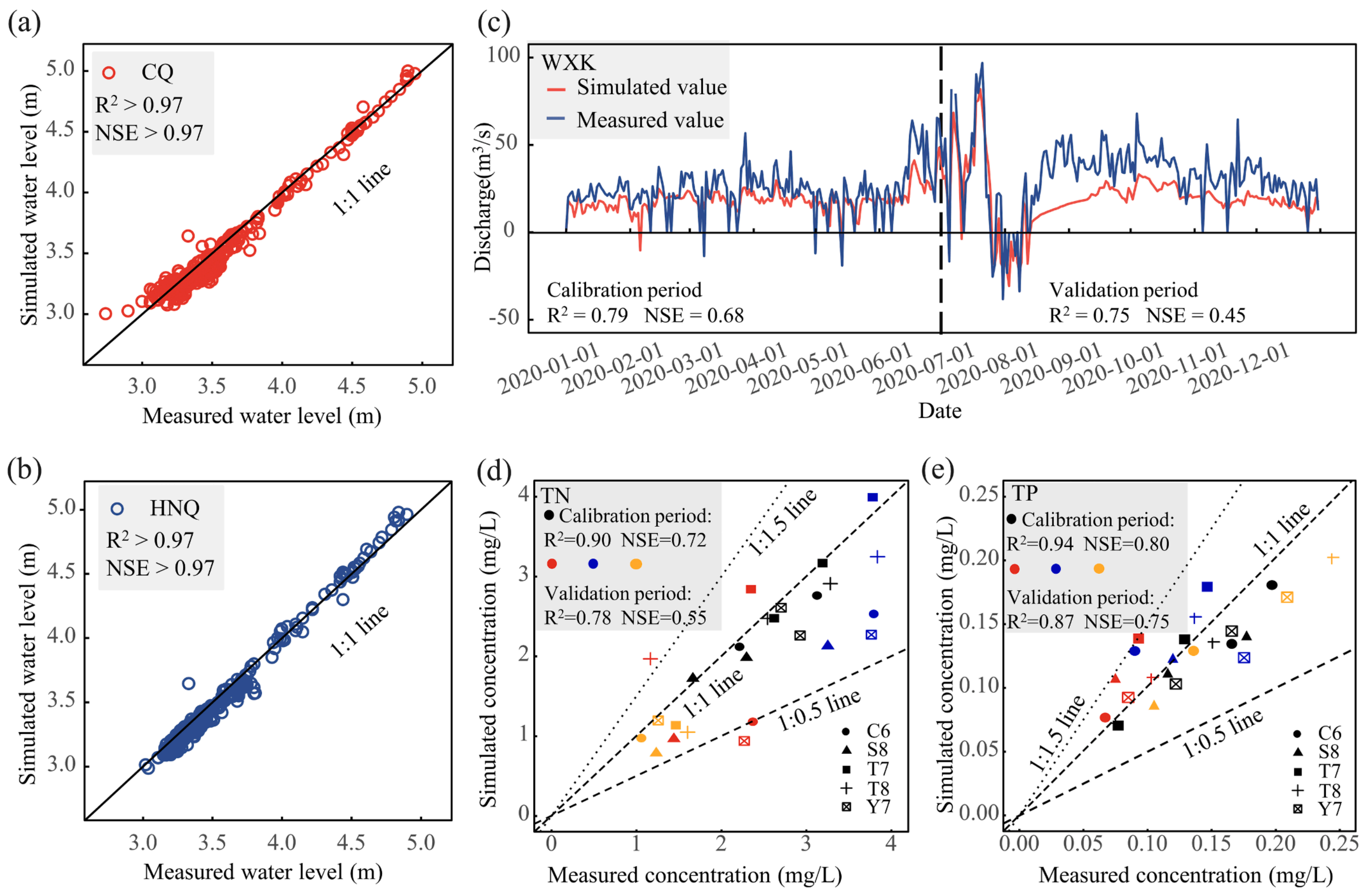


Fig. 3. Comparison between measured and simulated water levels at CQ (a) and HNQ (b), and discharge at WXK (c) during the calibration period (January–June) and validation period (July–December). Comparison between measured and simulated concentrations of fluvial TN (d) and TP (e) at the lake inlet, with red, blue, and orange points representing the normal, dry, and wet seasons, respectively.

simulations were 0.59 and 0.68, with R^2 values of 0.91 and 0.89, respectively. TN simulations tended to be underestimated, whereas TP simulations were slightly overestimated, which was consistent with the simulation results of fluvial nutrient concentrations. This underscores the inherent limitations and cumulative uncertainties associated with the coupled model.

3.2. *Terrestrial nutrient mobilization from different source*

Results of the NTM showed that in 2020, the amounts of terrestrial nutrient mobilization of TN and TP in the study area were 702.48 t and 108.47 t (Table 1). As showed in Fig. 5, the largest source of fluvial TN was domestic sewage (38.24 %), followed by cultivated land (33.14 %). The primary sources of TP emissions were livestock and poultry breeding (59.37 %), domestic sewage (25.40 %), and cultivated land (11.92 %). These results were consistent with previous estimates of the proportions of different nutrient emission sources in this region (Ma et al., 2010). The Taihu Basin population density, exceeding 700 people per square kilometer, generates significant domestic sewage discharges, particularly in rural areas where sewage treatment rates remain below 60 %. In contrast, the Pearl River Basin achieves higher rural sewage treatment rates through centralized systems, which effectively reduce nutrient contributions from domestic sewage (Peng et al., 2017). Livestock and poultry breeding account for nearly 60 % of TP emissions in the Taihu Basin, primarily due to the high density of small-scale livestock farms with inadequate waste treatment systems. Unlike the centralized farming structures in the Yangtze River Basin, the fragmented nature of livestock operations in the Taihu Basin complicates regulatory enforcement and waste management efforts (Zhou et al., 2012). Seasonal rainfall further exacerbates nutrient transport, as runoff from livestock waste and cultivated land introduces substantial amounts of TN and TP into surface waters (Qin et al., 2019). Comparative analyses utilizing random forest models identify rural population density and livestock intensity as critical drivers of nutrient emissions (Peng et al., 2017). These findings underscore the urgency of improving rural sewage treatment infrastructure and implementing stricter livestock waste management policies. Experiences from the Pearl River Basin demonstrate that centralized livestock operations and advanced waste treatment systems can significantly mitigate nutrient pollution. Addressing the unique challenges of the Taihu Basin requires tailored solutions, including investments in rural infrastructure, enhanced waste management, and precision agriculture practices to optimize fertilizer use and reduce runoff.

3.3. *Spatiotemporal distribution of nutrient concentrations in rivers and lake bays*

3.3.1. *Variability of nutrient concentrations across different hydrological seasons*

The hydro-chemical results showed that TN, NH_4^+-N, and NO_3^--N concentrations of rivers and Zhushan Bay exhibit similar patterns: the dry season > the normal season > the wet season (Table S6 and Fig. 6). However, TP and PO_4^{3-}-P concentrations peak during the wet season and decrease during the dry and normal seasons (Table S7). Additionally, average TN concentrations at the river inflow sections was lower than in the lake bays during the wet season, whereas the opposite was true for the other seasons, exhibiting a significant difference in concentrations. Similarly, the average TP concentrations at the river inflow sections was

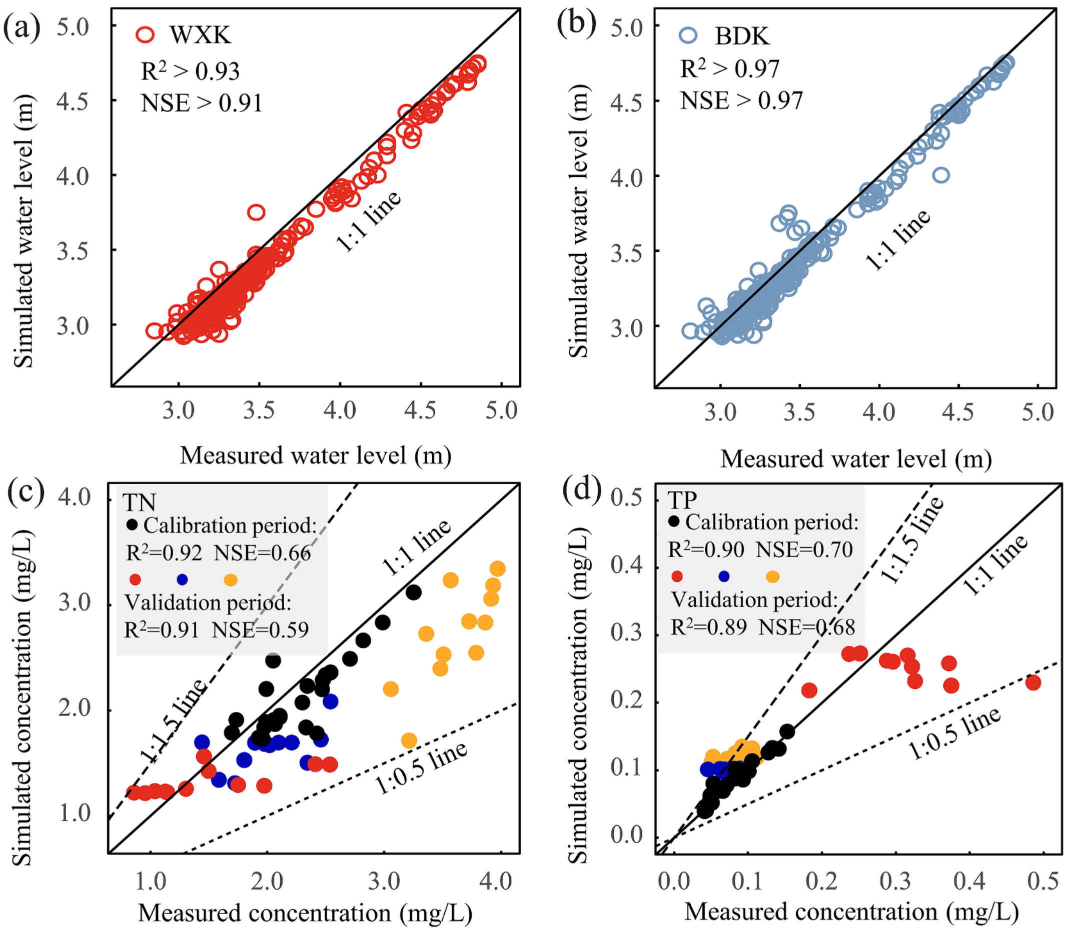


Fig. 4. Comparison between measured and simulated values for WXK (a) and BDK (b) during the calibration period (January–June) and validation period (July–December). Comparison between measured and simulated TN (c) and TP (d) concentrations in the lake bay, with red, blue, and orange lines representing the normal, dry, and wet seasons, respectively.

Table 1
The results of source apportionment of nutrient load of inflow rivers in the Zhushan Bay.

Category		Nutrient loads/ t·yr^{-1}	
		TN	TP
Livestock and poultry breeding		157.57	64.40
Domestic sewage		268.60	27.55
Surface	Pond	0.08	0.01
	Forest land	0.05	0.001
	Construction land	43.31	3.58
	Cultivated land	232.88	12.92
Total		702.49	108.47

lower than in the lake bays during the wet season. In contrast, during the other seasons, the lake bays had slightly higher TP concentrations.

The nutrient concentrations of inflowing rivers exhibit pronounced spatial heterogeneity (Fig. 6). The concentrations of TN, NO_3^--N, and NO_2^--N show significant positive correlations with distance from the upstream origin ($p < 0.05$), indicating that the river receives high levels of N nutrient along its course (Fig. S4). The concentration of NH_4^+-N descends as it approaches the bay; however, this trend is not statistically significant ($p > 0.05$). This may be attributed to the relatively low concentration of NH_4^+-N in the water body and its propensity for conversion into other forms of N, such as through nitrification (Chen et al., 2016). For the fluvial PO_4^{3-}-P and TP concentrations, no significant spatiotemporal variation patterns were observed ($p > 0.05$). This differs from previous studies (Gunatilaka 1982; Sondergaard et al., 1992). During the sampling period, dredging and bridge reconstruction projects in TG and CQ altered the sedimentary nutrient stores and conditions at the sediment–water interface in certain sections of the rivers, thus obscuring the natural variation patterns of P concentrations (Zhong et al., 2021).

In Zhushan Bay, TN, NO_3^--N, and NO_2^--N concentrations exhibit a spatial pattern of gradually diminishing from the northwest to the southeast. In contrast, the spatial distribution of NH_4^+-N diverges from that of NO_3^--N, with NH_4^+-N concentrations progressively increasing from the northeast to the southwest during the dry season. The spatial distribution of PO_4^{3-}-P and TP in the lake bay aligns closely. The fluvial N and P concentrations in the northwest were higher than those in the southwest, indicating that the N and P concentrations in the lake bays were primarily influenced by the nutrient levels in the inflowing rivers. During the wet season, P concentrations in the lake bay exceed those of other periods, with areas of highest concentration located near the river inlet of YPG. This indicated that non-point source nutrient emission significantly influenced P levels in the lake bays (Ma et al., 2023).

3.3.2. Driving factors of the spatial variability of nutrient concentrations in inflowing rivers

WT showed a highly significant positive correlation with fluvial N and P concentrations during the normal and dry seasons (except NH_4^+-N and TP), as shown in Fig. 7. During these seasons, WT had the most dominant effect on the spatial distribution of fluvial TN, NO_3^--N, and PO_4^{3-}-P with q-values significantly higher than those of other factors (Fig. 8). Previous research reported that optimal temperatures promote

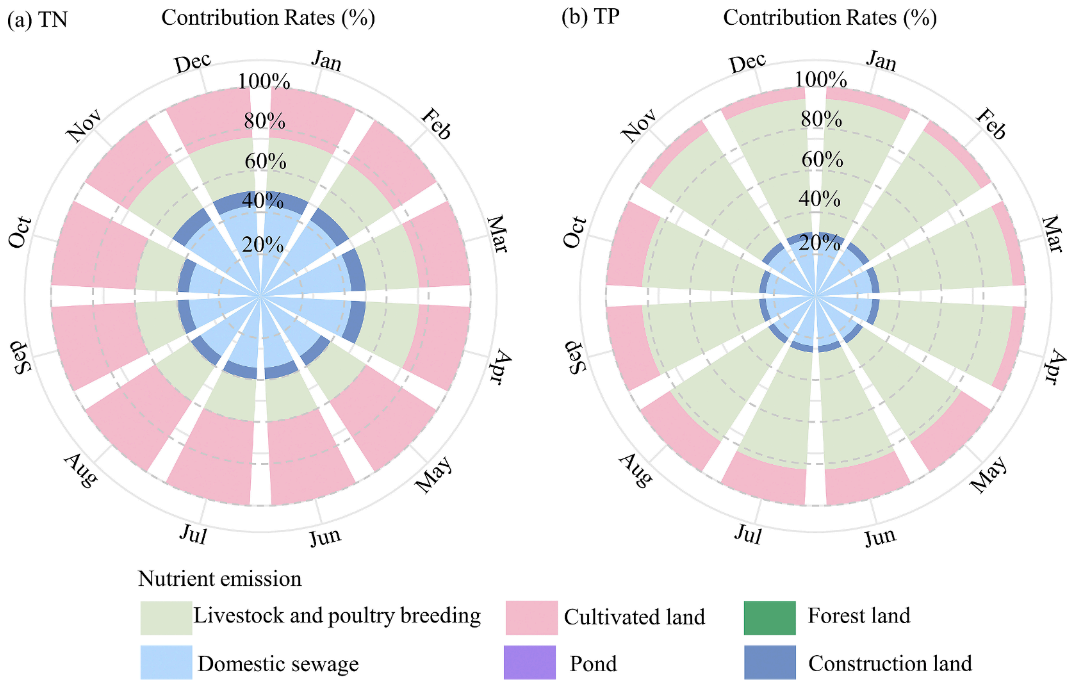


Fig. 5. Monthly contribution ratios of different types of nutrient emissions to the fluvial nutrient load.

the decomposition and mineralization of organic nutrients (Chen et al., 2013; Varol, 2013). Before extreme temperatures occur, higher temperatures enhanced microbial activity, thereby promoting nitrification and the production of NO$_3^-$-N (Walker et al., 2018). In contrast, during the wet season, higher temperatures correlated negatively with N nutrients (Ma et al., 2023; Varol, 2013). Increased river discharge during the wet season enhanced the dilution effect, thereby masking the temperature-induced increase in N concentration resulting from N transformation. WT promoted the dissolution and release of P from sediments during the wet season. The dilution effect reduced fluvial P concentration but does not completely mask the effect of WT ($p > 0.05$).

DO is negatively correlated ($p < 0.01$) with the concentrations of TN and NH$_4^+$-N. DO is significantly negatively correlated ($p < 0.01$) with TP during the wet season (Fig. 7). During the dry season, DO had a higher impact on the formation and distribution of N and P (q: 0.36–0.53), reduced DO concentrations facilitated N transformation and P release (Lindenschmidt et al., 2019). An alkaline environment promotes the consumption of NH$_4^+$-N and increases NO$_3^-$-N and NO$_2^-$-N levels, whereas higher pH values can inhibit P deposition (Table S8), thereby accelerating the release of P from sediments (Zhao et al., 2022). During the wet season, the highest q value for the spatial differentiation of fluvial P by pH also supports this conclusion (Creed et al., 2015; Varol, 2013; Zhu et al., 2013).

Within buffer zones at river sampling points, the predominant land uses include cultivated land (43.18 %), construction land (18.98 %), and ponds (37.39 %), grasslands and forests (0.45 %), as shown in Table S9. The proportion of cultivated land is positively correlated with fluvial N and P concentrations, particularly during the wet season, suggesting that an increase in cultivated land contributes to higher levels of these nutrients in rivers. Generally, the excessive application of fertilizers to farmlands increases the risk of nutrient loss (Huang et al., 2017; Lenat and Crawford, 1994). Conversely, the proportion of ponds exhibits a negative correlation ($p > 0.05$; q: 0.19–0.37) with fluvial N and P concentrations (Fig. 8). Previous studies have shown that ponds are often hot spots for N removal, with the intensive denitrification (Cai et al., 2022; Coban et al., 2015; Yiu and Cheng, 2018). Additionally, during the dry season ($p < 0.05$; q: 0.16–0.34), the correlation between ponds and N is higher than in the wet season ($p > 0.05$; q: 0.19–0.25). This may be attributable to the elevated nitrogen (N) concentrations in water bodies during the dry season, thereby enhancing denitrification (Sarpong et al., 2023). Construction land shows a positive correlation with N ($p > 0.05$; q: 0.07–0.24) and P ($p > 0.05$; q: 0.11–0.30), indicating the key role of domestic sewage in contributing to fluvial nutrients.

3.4. Impact of nutrient emission reduction and river discharge variation on nutrient levels in Zhushan bay

3.4.1. Response of nutrient concentration and load of water bodies in lake bay to nutrient emission reduction and river discharge variation

Scenario simulation results indicate that a 12 % increase in river discharge, with unchanged nutrient concentrations, leads to a significant increase in average TN load in the lake bay. This increase is notably higher during the dry season (3.18 %) compared to the wet season (0.20 %) (Fig. 9b). A 12 % decrease in river discharge with constant nutrient concentrations resulted in a greater reduction in average TN load in the lake bay during the dry season (1.39 %) compared to the wet season (0.16 %). These results highlight the critical influence of hydrological conditions on TN loads, with higher discharge rates amplifying nutrient input from upstream sources and low-flow conditions limiting nutrient inflows.

Across hydrological seasons, the TP load in the lake bay did not increase in response to higher river discharge. Specifically, with a 12 % increase in river discharge and unchanged nutrient concentrations, the TP load decreased by 1.51 % in the wet season, 0.22 % in the normal season, and increased by 1.39 % in the dry season (Fig. 9b). Conversely, with a 12 % reduction in discharge, the TP load rose by 1.61 % in the wet season, 0.31 % in the normal season, and declined by 1.81 % in the dry season (Fig. 9a). TN and TP levels in the lake bay respond to seasonal river discharge variations, closely tied to nutrient levels in inflowing rivers and the lake bay (Geng et al., 2021). High-flow seasons bring increased TN and TP as nutrient inputs accumulate in the lake (Tables S6 and S7; Zha et al., 2018). Seasonal hydrodynamics, including flow velocity and turbulence, influence sediment resuspension, releasing TP from lake sediments and raising TP levels (Tian et al., 2017).

Scenario simulation results indicate that with a 10 % reduction in nutrient emissions and unchanged river discharge, the average

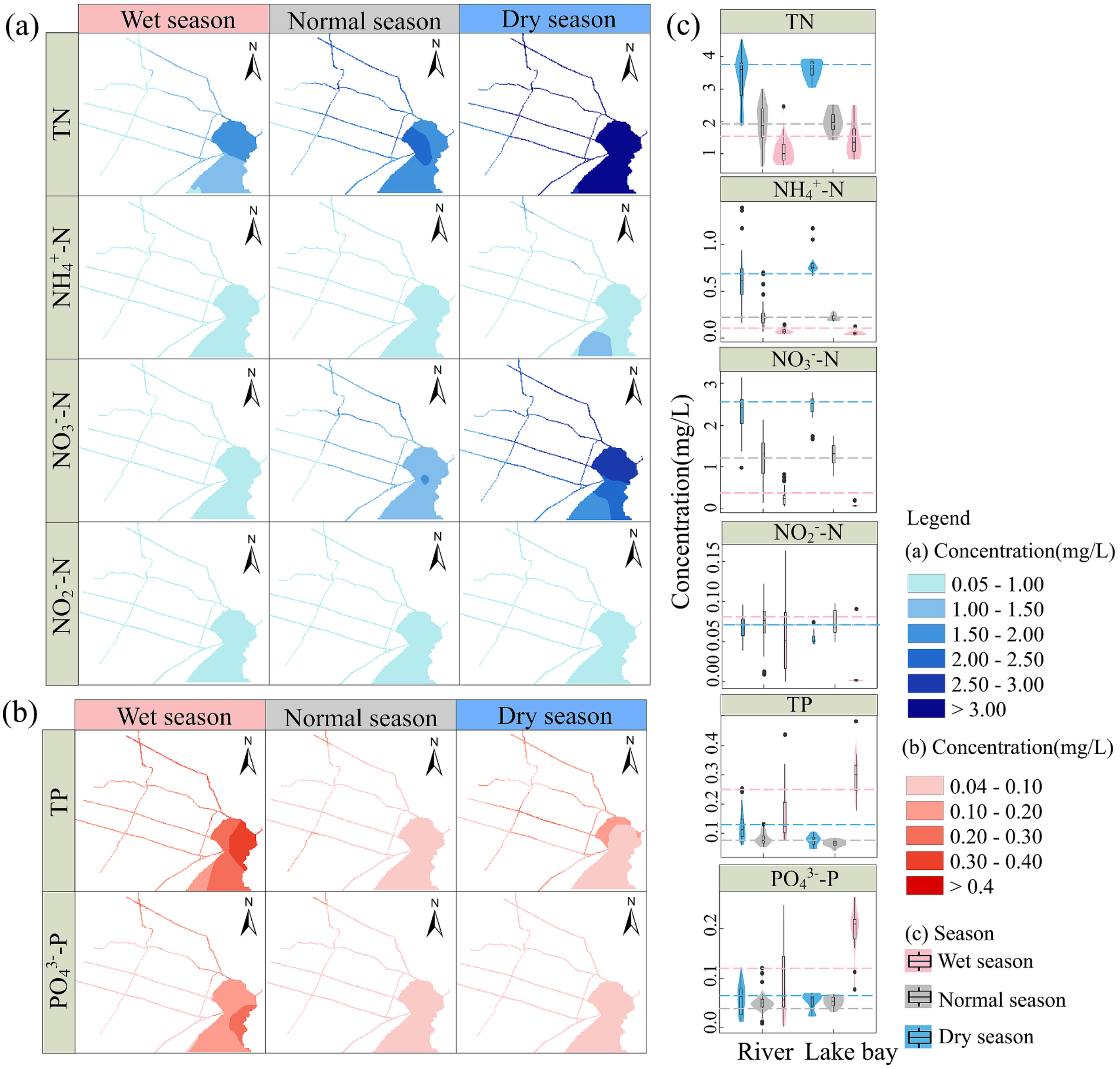


Fig. 6. Spatial distribution of concentrations of N (a) and P (b), and violin plots of nutrient contents (c) in inflowing rivers and Zhushan Bay in wet season, normal season, and dry season. The blue line, gray line, and pink line represent the average concentrations of S8, T8, Y7, and P1 in the dry season, normal season, and wet season, respectively.

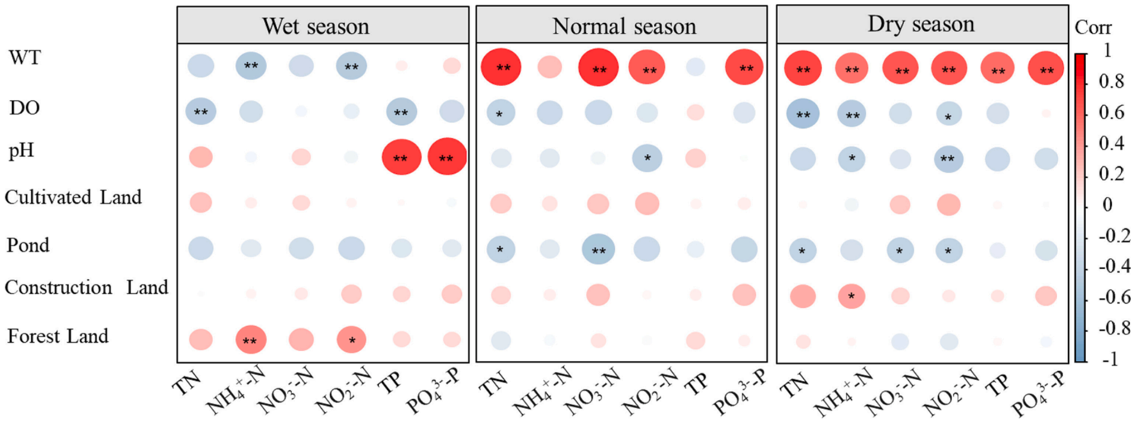
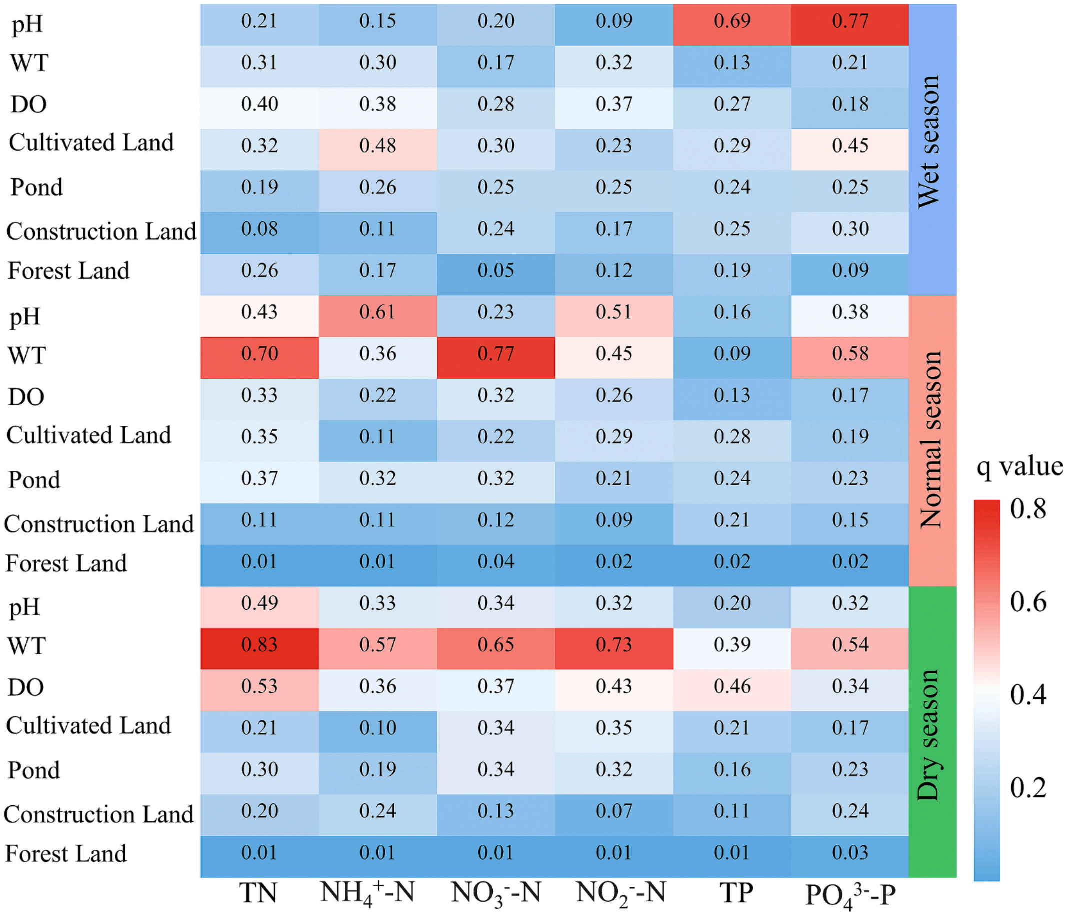


Fig. 7. Correlation between the fluvial N and P concentrations and different factors in the dry season, normal season, and wet season. “*” represents that the correlation is significant ($p < 0.05$), and “**” represents that the correlation is significant ($p < 0.01$).



		TN	NH_4^+-N	NO_3^--N	NO_2^--N	TP	PO_4^{3-}-P
Wet season	pH	0.21	0.15	0.20	0.09	0.69	0.77
	WT	0.31	0.30	0.17	0.32	0.13	0.21
	DO	0.40	0.38	0.28	0.37	0.27	0.18
	Cultivated Land	0.32	0.48	0.30	0.23	0.29	0.45
	Pond	0.19	0.26	0.25	0.25	0.24	0.25
	Construction Land	0.08	0.11	0.24	0.17	0.25	0.30
	Forest Land	0.26	0.17	0.05	0.12	0.19	0.09
Normal season	pH	0.43	0.61	0.23	0.51	0.16	0.38
	WT	0.70	0.36	0.77	0.45	0.09	0.58
	DO	0.33	0.22	0.32	0.26	0.13	0.17
	Cultivated Land	0.35	0.11	0.22	0.29	0.28	0.19
	Pond	0.37	0.32	0.32	0.21	0.24	0.23
	Construction Land	0.11	0.11	0.12	0.09	0.21	0.15
	Forest Land	0.01	0.01	0.04	0.02	0.02	0.02
Dry season	pH	0.49	0.33	0.34	0.32	0.20	0.32
	WT	0.83	0.57	0.65	0.73	0.39	0.54
	DO	0.53	0.36	0.37	0.43	0.46	0.34
	Cultivated Land	0.21	0.10	0.34	0.35	0.21	0.17
	Pond	0.30	0.19	0.34	0.32	0.16	0.23
	Construction Land	0.20	0.24	0.13	0.07	0.11	0.24
	Forest Land	0.01	0.01	0.01	0.01	0.01	0.03

Fig. 8. Q-values of the fluvial n and p concentrations with different factors in the dry, normal, and wet seasons.

concentration and load of fluvial TN decreased more in the wet season (4.73 %) compared to the dry season (0.90 %). However, the average load of TN in the lake bay decreased less in the wet season (0.69 %) than in the dry season (1.02 %). With a 30 % reduction in nutrient emissions and unchanged river discharge, the average concentration and load of fluvial TN decreased more in the wet season (10.65 %) compared to the dry season (2.70 %). The average load of TN in the lake bay decreased by 2.06 % in the wet season and by 3.05 % in the dry season. Under the same proportion of nutrient emission reduction, the decrease in fluvial TP average concentration and load is greater. With a 10 % reduction in nutrient emissions and unchanged river discharge, the reduction in fluvial TP concentration and load is most significant during the wet season (4.79 %), followed by a gradual decrease from the normal season (3.43 %) to the dry season (3.14 %). However, in the lake bay, the reduction in TP load shows a different seasonal pattern. The smallest decrease occurs during the wet season (0.68 %), with progressively larger reductions observed during the normal season (2.08 %) and the greatest reduction occurring in the dry season (3.17 %). With a 30 % reduction in nutrient emissions and unchanged river discharge, the reduction in fluvial TP concentration and load is highest during the wet season (11.60 %), followed by the dry season (9.42 %), and then the normal season (8.64 %). The lake bay TP load follows a similar trend to the 10 % reduction scenario but with more pronounced changes, decreasing from the wet season (2.05 %) to the normal season (6.25 %), and reaching the highest reduction in the dry season (9.51 %).

The nutrient concentrations in rivers are regulated by nutrient emissions and are also influenced by hydrological regime (Childers et al., 2006; Montefiore et al., 2024). Moreover, the impact of hydrological regime on fluvial TN concentrations is greater than on fluvial TP concentrations. The average TN concentration in rivers during the dry season (3.37 mg L^{-1}) is three times higher than during the wet season (1.11 mg L^{-1}). The average fluvial TP concentration remains relatively stable across seasons, with only a slight increase from 0.13 mg L^{-1} in the dry season to 0.17 mg L^{-1} in the wet season (Table S6). Under the background of climate change, precipitation shows an increasing trend (Shinohara et al., 2021), which will be conducive to the reduction of river nitrogen concentrations. Additionally, the results of this study show that the reduction proportion of fluvial nutrient concentrations (0.56 %–18.97 %) is much lower than the reduction proportion of nutrient emission sources (10 %–30 %). Our previous research found that legacy nutrients in interfaces such as soil and groundwater have a significant impact on fluvial nutrient loads (Chen et al., 2024). Other studies have also shown that despite strict control of nutrient emissions, the fluvial nutrient load may remain at its original level due to the influence of legacy nutrients (Li et al., 2022). This may explain why the reduction proportion of fluvial nutrient concentrations is lower than the reduction in nutrient emission sources.

3.4.2. Response of the spatial distribution of nutrient concentrations in lake bay to nutrient emission reduction and river discharge variation

The concentrations of TN and TP of the water bodies in Zhushan Bay exhibited distinct spatial distribution patterns under various scenarios (Fig. 10). With a 12 % increase in river discharge and unchanged nutrient emissions during the wet season, TN concentrations in the northern area of the lake bays rose by 0–3.00 %, as inflowing TN levels (T8: 1.60 mg L^{-1}; P1: 2.46 mg L^{-1}) exceeded the average TN concentration in the lake bays (1.48 mg L^{-1}). Conversely, the southern area experienced a decrease (−1.00 %–0) due to lower inflowing TN levels (S8: 1.23 mg L^{-1}; Y7: 1.26 mg L^{-1}) relative to the lake bays' average. This spatial distribution pattern, where TN concentrations increase in areas

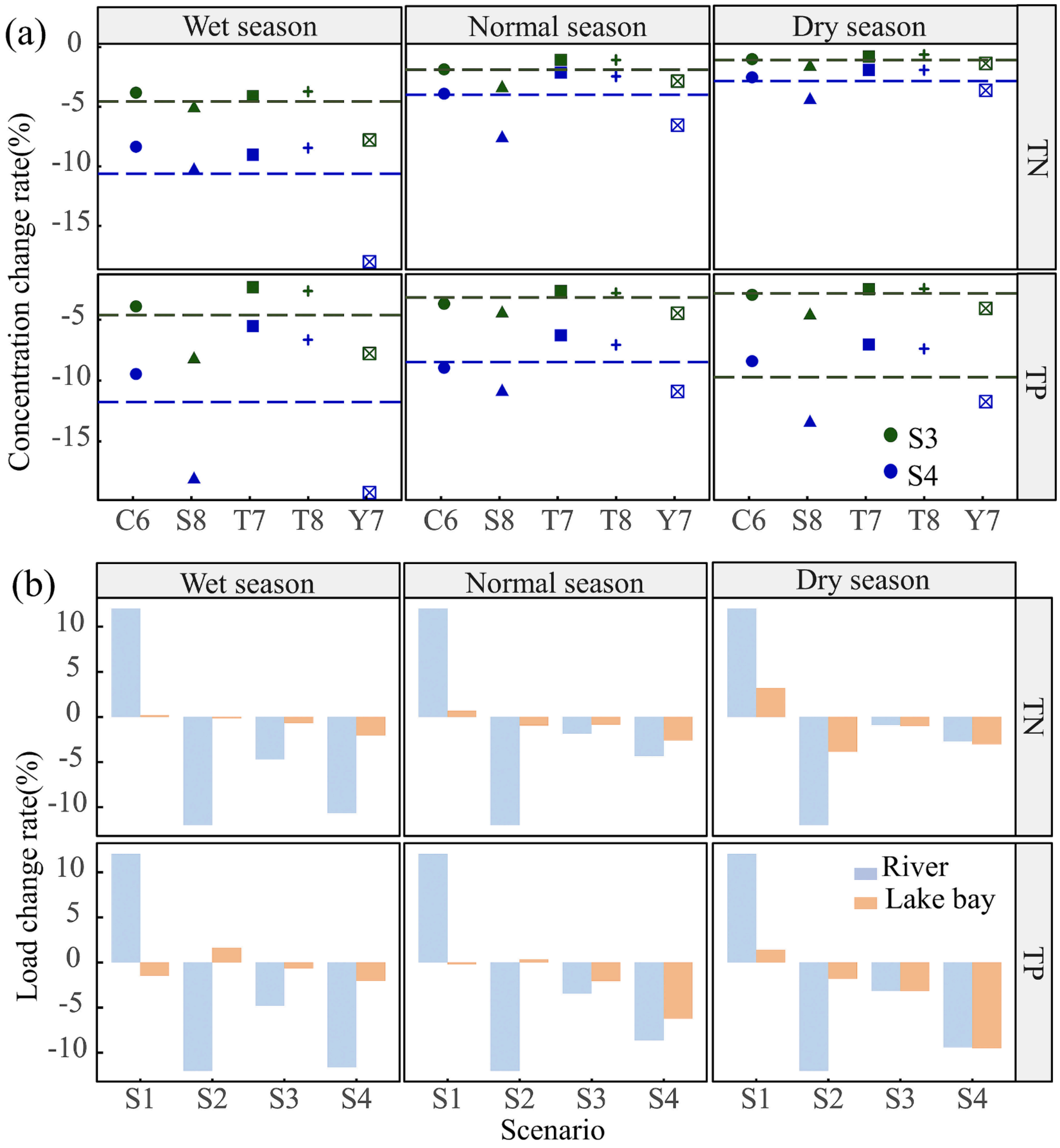


Fig. 9. Change rate of the concentrations of TN and TP of the SXG (S8), YCG (Y7), TG (T7), CQ (C6), and T8 under different scenarios of nutrient emissions. The green and blue lines are the averages of nutrient concentration variations of S3 and S4, respectively (a). Change rates of TN load and TP load in the river and lake bay were analyzed under four scenarios during different seasons. The changes in TN and TP loads reflect the average variations in river and lake bay loads (b).

with higher inflowing TN levels and decrease where inflows are lower, persists across the normal and dry seasons Tables S6 and S7), with the dry season showing the largest variations (maximum TN increase: 6.24 %). Under the same conditions, TP exhibited a similar spatial distribution pattern: areas where inflow TP concentrations were lower than those in the lake bays showed a decrease, while areas with higher inflow TP concentrations showed an increase. When river discharge decreased by 12 % with nutrient emissions remaining unchanged, the spatial distribution of TN and TP exhibited an opposite trend compared to increased discharge. In the dry season, the response of the concentrations of TN and TP in Zhushan Bay to reduced river discharge (TN: −7.56 %–-3.00 %; TP: −8.00 %–0) was greater than the response to increased discharge (TN: 0 %–6.24 %; TP: 0 %–2.96 %).

Scenario simulation results indicate that with a 10 % reduction in nutrient emissions and unchanged river discharge, the average TN concentration in the lake bay during the wet season varies mainly between −1.00 % and 0, while during the dry season it varies between −3.00 % and −1.00 %. With a 30 % reduction in nutrient emissions and unchanged river discharge, the lake bay experiences a greater reduction in average TN concentration across different hydrological seasons, with a maximum decrease of −7.56 %. The reductions are most pronounced near the inflow area and gradually decrease toward the southern lake region. Under the same proportion of nutrient emission reduction, the decrease rate in the lake bay TP is greater. With a 10 % reduction in nutrient emissions and unchanged river discharge, the reduction in lake bay TP is most significant during the dry season (−8.00 %–-3.00 %). With a 30 % reduction in nutrient emissions and unchanged river discharge, the reduction in lake bay TP is most significant during the dry season (−11.08 %–-8.00 %).

Under current conditions (2020), reducing nutrient emissions into the lake region can effectively lower the levels of TN and TP in the lake bay. However, measures to change the inflow discharge must be targeted based on the nutrient concentrations in the rivers and the lake bay, controlling the inflow discharge of different rivers accordingly (Tang et al., 2011). Additionally, during the wet season, while TN may decrease in the same area due to changes in inflow discharge, TP may increase (Qin et al., 2019). Therefore, flexible management strategies should be implemented seasonally to ensure simultaneous control of both TP and TN concentrations (Peng et al., 2017; Sarpong et al., 2023).

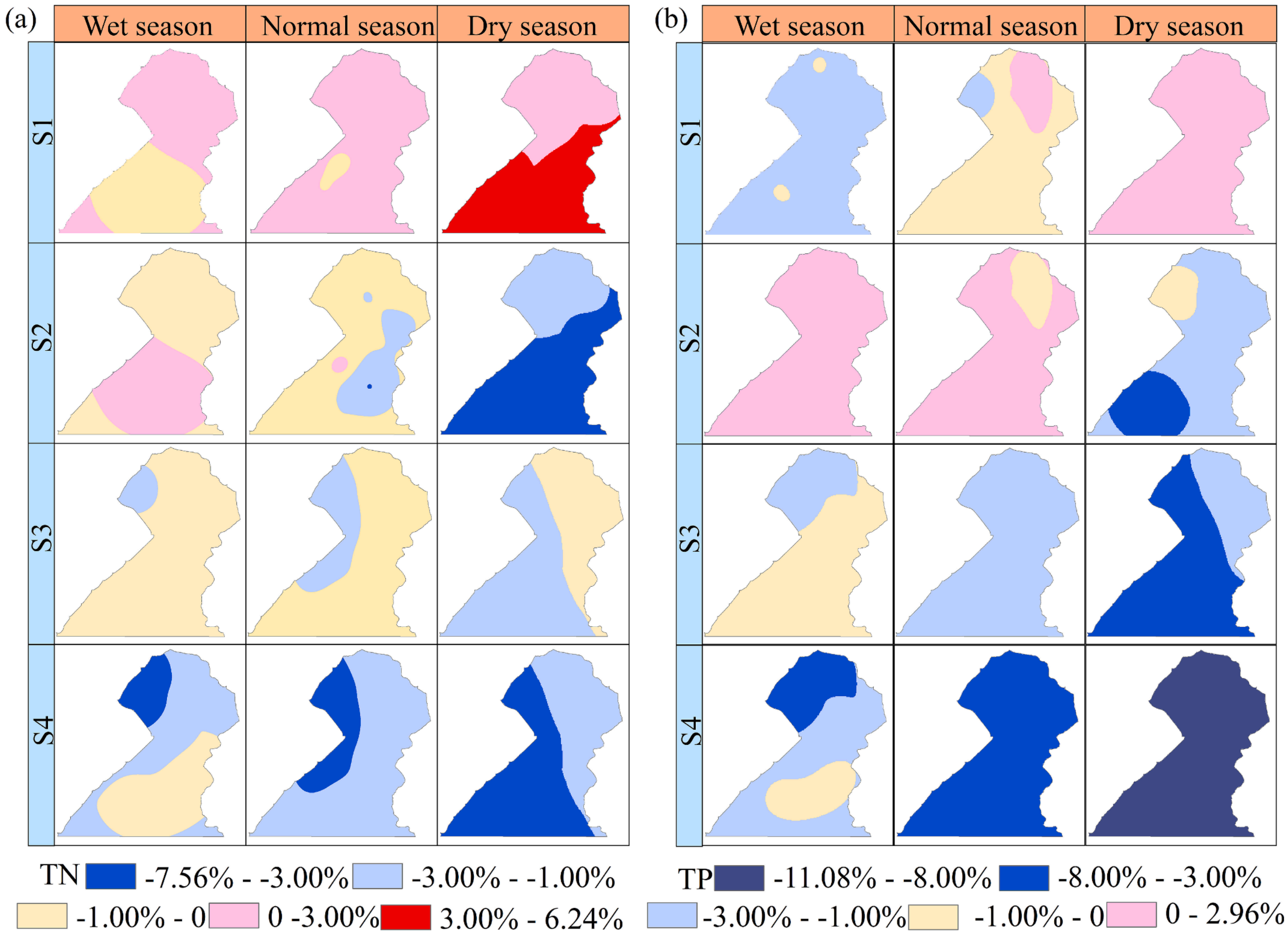


Fig. 10. Spatial distribution of the variations of the concentrations of TN (a) and TP (b) in Zhushan Bay under different scenarios during the wet, normal, and dry seasons. Ordinary Kriging interpolation was performed based on the rate of change at the sampling points in the lake bay.

3.5. Nutrient load management in lake bays

The factor analysis results show that increased precipitation and river discharge during the wet season significantly increase nutrient runoff from cultivated land. In the northern regions of the lake bay, rivers bring high concentrations of TN and TP (Table S7), which contribute to nutrient accumulation in the lake bay (Huang et al., 2017). This pattern highlights the important role of cultivated land in seasonal changes in TN and TP levels. To reduce nutrient losses from cultivated land, fertilizer management should be adjusted. Fertilizers should be applied when it is dry or a few days before expected precipitation, to reduce the risk of runoff. Fertilizer application rates should also be lowered, using split applications or smaller doses that match crop nutrient needs, which will prevent excess nutrients from running off. Slow-release fertilizers and precision fertilization methods can improve nutrient retention in cultivated land, thus reducing nutrient transport to the lake bay (Hedley, 2015). In rural areas near water bodies, more sewage treatment facilities should be built to better handle domestic waste. Improved treatment can reduce nutrient input from wastewater, lowering its impact on TN and TP levels in the lake bay (Cheng et al., 2020).

Scenario simulations also reveal that hydrological conditions substantially affect nutrient loads (Montefiore et al., 2024; Nash and Sutcliffe, 1970; Peng et al., 2017; Sarpong et al., 2023). Effective nutrient management must align with seasonal variations. Controlling sluices and dikes can facilitate seasonal flow adjustments, especially during the wet season, to regulate the inflow of high-concentration river water, intercepting nutrient-rich agricultural runoff and thereby minimizing nutrient loads entering the lake bay (Tournebize et al., 2017; Shokri et al., 2021). During low-flow conditions, stringent nutrient management is critical to prevent nutrient accumulation in rivers and lake bays (Paerl et al., 2016). Specifically, N removal and P interception should be enhanced in high-concentration rivers, for instance, by installing aeration systems to promote the biological removal of excess N and P, and by planting aquatic or wetland vegetation along riverbanks to absorb and intercept nutrients. These measures can significantly reduce nutrient concentrations in water before it enters the lake (Alborzi et al., 2018; Liu et al., 2021). In conclusion, the combined implementation of these strategies can effectively reduce external nutrient loads, thereby improving nutrient levels in lake bays. These recommendations can support sustainable nutrient control efforts in similar lake basins.

3.6. Uncertainties and limitations

The NTM employed in this study can be applied for tracking nutrients from terrestrial surfaces to rivers and lake bays. Through comparative analysis with measured data, the model demonstrated high accuracy and reliability across multiple key indicators ($R^2 > 0.75$; NSE > 0.55) and effectively simulated water quality trends under different hydrological conditions (Asl-Rousta et al., 2018). Compared to widely applied nutrient transport models, such as SWAT and QUAL2K, the NTM model offers unique strengths in capturing nutrient dynamics within lake bay systems. While SWAT is well-suited for nutrient transport and retention at large watershed scales, it is limited by its single-outlet structure, which can constrain its application in multi-outlet systems like the Taihu Basin. This limitation makes SWAT less adaptable in regions where complex hydrological interactions occur across multiple inlets and outlets, as seen in systems with interconnected rivers and lake bays. Similarly, QUAL2K is suitable for nutrient transformations in linear water bodies, such as rivers and streams, but lacks the capacity to handle multi-dimensional nutrient variations in large lakes and estuaries. By contrast, the NTM model's loosely coupled framework allows for detailed assessments of nutrient dynamics specific to lake bays, especially under varying hydrological conditions, and is better suited to multi-outlet systems where nutrient flows are not restricted to a single discharge point.

Despite the model's satisfactory performance, certain uncertainties persist. This study utilized an export coefficient model, alongside empirical coefficients for nutrient generation and river entry from similar regional sources (Huang et al., 2017), as boundary conditions to estimate the load inputs received by the inflowing rivers. Although practical, this approach did not account for the spatial and temporal heterogeneity of various nutrient sources, such as differences in nutrient runoff from agricultural versus urban areas, which can vary seasonally. Furthermore, uncertainties were introduced by manual sampling, particularly in capturing nutrient pulses associated with sudden hydrological changes, which could affect the accuracy of the input parameters used in the model. Uncertainty exists in determining the values of parameters such as sediment P release. Constant parameter values were applied in the NTM, which likely led the model to under-simulate the TP release process from lake and river sediments, failing to fully account for the complex transport and recycling mechanisms present in reality and resulting in an underestimation of TP concentrations in the water body.

Additionally, the NTM model currently lacks mechanisms to dynamically adjust nutrient inputs based on real-time land-use or hydrological changes, such as rapid urbanization or agricultural expansion, which can alter nutrient loading patterns over time. This stands in contrast to models like SWAT, which incorporates dynamic land-use updates for more accurate predictions under evolving environmental conditions. Despite these limitations, the NTM model developed in this study offers a comprehensive framework for assessing the impact of nutrient emission reductions and hydrological changes on the nutrient concentration of Zhushan Bay. In future applications, expanding the model to incorporate more detailed terrestrial nutrient processes, including hydrological and biogeochemical transformations, could be beneficial. Specifically, integrating a more dynamic representation of nutrient cycling within the surface-river–lake bay continuum—such as legacy nutrient release from soils and sediments—might enhance the model's accuracy and utility in predicting nutrient transport trajectories under varying environmental conditions.

4. Conclusion

This study proposed and tested a nutrient transport model based on a surface-river–lake bay coupled system, aiming to quantify the contribution of nutrient emissions to nutrient levels in rivers and lake bays. Factors that influence the spatial distribution of nutrients were evaluated. Results indicated that the total inflowing loads of TN and TP are 702.48 and 108.47 t, respectively. Domestic sewage is the largest source of TN, with an inflow load of 268.60 t (38.24 %), followed by cultivated land with an inflow load of 232.88 t (33.14 %). The primary sources of TP are livestock and poultry breeding (59.37 %), Domestic sewage (25.40 %), and cultivated land (11.92 %). Dilution effects of river discharge primarily affect N and P concentrations in the lake bay and its main inflowing rivers. The nutrient concentration increases as the distance to the lake bay mouth decreases. It was found that reduced DO concentrations, increased WT, and elevated pH values all facilitate N transformation and P release. The results of scenario simulations indicated that nutrient emissions and hydrological conditions jointly affected the nutrient load and its spatial distribution in the lake bay. This study enhances the understanding of nutrient transport processes within the surface-river–lake bay continuum, thereby providing a theoretical basis for nutrient management in rivers and lake bays.

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CRediT authorship contribution statement

Qiqi Yuan: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhihui Ren:** Visualization, Validation, Investigation, Formal analysis, Data curation. **Ruidong Chen:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Qingji Zhang:** Writing – original draft, Visualization, Methodology, Investigation. **Jinsong Ma:** Visualization, Software, Resources. **Lachun Wang:** Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.113046.

Data availability

Data will be made available on request.

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