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Original Research

Nutrients and organic matter in the surface sediment of a submerged macrophyte zone in a eutrophic lake: Implications for lake management

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ABSTRACT

Little is known about the distribution and risk levels of nutrients and organic matter (OM) in the surface sediment of shallow submerged macrophyte-dominated lakes. In the current study, sixty surface sediment samples were collected from Xukou Bay, a typical submerged macrophyte-dominated zone in Lake Taihu, China. A 60-day degradation experiment of *Potamogeton malaianus*, a dominant species in the bay, was done in the laboratory. The results demonstrated that the ranges of total nitrogen (TN) and total phosphorus (TP), alkali-hydrolyzable nitrogen (AN), available phosphorus (AP), and OM in the surface sediment of the bay were 262.2–2,979.6 mg/kg, 41.2–728.7 mg/kg, 8.6–150.0 mg/kg, 4.4–36.4 mg/kg, and 3.7–50.2 g/kg, respectively. The spatial distributions of TN, OM, and AN concentrations showed similar trends: The highest concentrations were present in the northeastern and southwestern zones, while the TP and AP concentrations were high in the northeastern, central, and southwestern zones. The heterogeneity in the spatial distribution of nutrients and OM in the surface sediment of the bay was associated with aquatic vegetation and anthropogenic activities. The comprehensive risk index and organic nitrogen index revealed that the surface sediment was moderately, interactively contaminated by TN and TP and by organic nitrogen. TN and OM in the northeastern zone were mainly derived from endogenous residues due to the decomposition of aquatic plants, while TN in the southwestern zone was primarily derived from agricultural wastewater. Consequently, targeted measures should be implemented to reduce TN and OM in the surface sediment of macrophyte-dominated lakes.

1. Introduction

Eutrophication is a worldwide concern due to the threats to water quality and aquatic ecosystem health (Deng et al., 2016a; Rozemeijer et al., 2021). Nitrogen (N) and phosphorus (P) are important indicators of eutrophication (Cabezas et al., 2014), and excess concentrations of these nutrients negatively affect the ecosystem and cause eutrophication (Hecky & Kilham, 1988). In the past several decades, anthropogenic activities have resulted in massive discharge of wastewater and sewage containing high nutrient loads into aquatic ecosystems (Wang et al., 2020b). These nutrients are absorbed by suspended particles after entering water bodies and eventually accumulate in the sediment (Deng et al., 2016b). The enriched nutrients in surface sediment can be released back into the overlying water. Jalil et al. (2019) found that the sediment resuspension flux in Meiliang Bay in Lake Taihu in China ranged from 120 to 738 g/($m^2 \cdot d$) during 4–6 m/s onshore winds. Nutrient release into overlying water is closely correlated with nutrient loading in surface sediment, which fuels eutrophication and algal blooms (Ni & Wang, 2015). Therefore, understanding the spatial distribution of nutrient concentrations is essential for evaluating their risk levels in surface sediment.

Risk assessment of a target substance is commonly done according to its concentrations in environmental media (Macdonald et al., 2000). However, few published papers have focused on nutrients in sediment, even though they are critical contributors to water eutrophication and algal growth (Viaroli et al., 1996). In 1992, a risk index of nutrients for the protection and management of aquatic sediment quality in Ontario was first proposed by the Ministry of Environment and Energy, Canada (Persaud et al., 1993). The index included evaluation criteria for nutrients in surface

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sediment and was subsequently applied to risk assessments of nutrients in the surface sediment of rivers (Varol & Şen, 2012) and lakes (Skordas et al., 2015). Based on the nutrient risk index, a comprehensive risk index of nutrients, an organic index, and an organic nitrogen index also were developed and progressively applied to risk evaluation of nutrients in the surface sediment of lakes in China. Zhang et al. (2015b) found that more than 50% and 60% of the sediment was heavily polluted by organic matter (OM) and organic nitrogen, respectively, due to large-scale and intensive aquaculture activity in Lake Nansi during the past 20 years.

Identifying the source of pollutants in environmental media is an essential requirement for the development of policies governing pollution controls, treatments, and environmental management (Deng et al., 2020). Correlation analysis and the mass ratio of organic carbon (OC) to total nitrogen (TN) have generally been used to determine potential sources of OM in the surface sediment of aquatic environments (Wang et al., 2017). For example, TN was primarily derived from exogenous inputs, particularly the use of excessive fish feed, and was significantly correlated with the total organic carbon concentrations in Lake Nansi (Zhang et al., 2015b), indicating that fish feed residue promotes the enrichment of nutrients and OM in surface sediment. Aquatic macrophytes play an important role in the structuring and functioning of freshwater ecosystems. Generally, the biomass of most aquatic macrophytes reaches a maximum in the summer, and the organisms gradually wither and die in the autumn and winter. During the decay process, aquatic plant residues release nutrients and OM into environmental media (Holmroos et al., 2015). Therefore, aquatic macrophytes are a primary contributor to the enrichment of nutrients in surface sediment. However, there is a lack of risk evaluations of nutrients in surface sediment of lakes with aquatic plants.

Xukou Bay, a submerged macrophyte-dominated zone of Lake Taihu in China, is an important source of drinking water for the city of Suzhou. In recent years, the water quality in the bay has deteriorated owing to nutrient release from surface sediment into overlying water. Consequently, in current study, the nutrients and OM in surface sediment were measured, their risks and sources were analyzed, and litter decomposition experiments were done for the dominant aquatic macrophyte species in the bay to (1) illustrate the spatial distribution of nutrient concentrations, (2) determine the risk levels and sources of the nutrients and OM, (3) demonstrate the effects of decomposition of aquatic macrophytes on water quality, and (4) propose targeted measures for reducing the potential nutrient enrichment in surface sediment in Lake Taihu, China.

2. Materials and methods

2.1. Study area and sampling sites

Xukou Bay, an eastern bay of Lake Taihu, which is a severely eutrophic lake in China, has a surface area of 173.1 km^2, a mean water depth of 2.0 m, and a water capacity of 3.5×10^8 m^3. The water intake of the Siqian Water Plant is located in Xukou Bay and supplies 3.0×10^5 m^3/d of raw water for 1.55 million people in Suzhou. The ports around Xukou Bay, such as Xujiang Port, Xinlu Port, Siqian Port, Huangshu Port, and Xidaque Port, are connected with outgoing rivers (Fig. 1). The average monthly concentrations of TN and TP at three sites (22, 37, and 55) in 2017 ranged from 0.370 to 2.270 mg/L and 0.025 to 0.103 mg/L, respectively, and frequently failed to meet the Grade III standard of the Guideline for Surface Water Environmental Quality of China (GB3838-2002), which is the minimum requirement for a drinking water source.

Potamogeton malaianus, *Potamogeton maackianus*, and *Nymphoides peltata* are the dominant submerged and floating-leaved macrophytes, and the cover of aquatic vegetation in the bay reached 70%–80% before 2000 (Dong et al., 2020). However, in recent years, the cover and biodiversity index of aquatic vegetation in the bay have sharply declined due to algal invasions from the open water of Lake Taihu, high water levels during submerged macrophyte germination, and aquatic vegetation overharvesting (Dong et al., 2017). The resulting aquatic vegetation is distributed in the near-shore zone of the northeastern bay. The depth of sediment in the bay varies between 0 and 130 cm, indicating a sharp variation in the sediment depth. The percentages of the sand, silt, and clay in the surface sediments at five sites (3, 22, 35, 37, and 55) ranged between 26.0% and 41.0% (mean = 32.5%), 52.1% and 60.8% (mean = 56.1%), and 9.2% and 16.4% (mean = 11.5%), respectively, indicating that silt constituted the predominant sediment component in the bay. Based on the distributions of sediment and aquatic vegetation as well as the water intake of drinking water treatment plants, sixty sampling sites of surface sediment were investigated, and detailed information on site positions in the bay was recorded via a global positioning system (GPS) (Fig. 1).

2.2. Collection and analysis of sediment samples

Surface sediment was collected at all sampling sites with a Petersen grab sampler in June 2018 and placed in a clean polyethylene bag with a marked label. All surface sediment samples were immediately transported and air-dried. After stone and plant fragment removal, the air-dried sediment samples were ground with an agate grinder; passed through 100-, 60-, and 10-mesh nylon sieves to analyze total phosphorus (TP), OM, TN, alkali-hydrolysable nitrogen (AN), and available phosphorus (AP), respectively; and then stored at 4 °C.

The TN concentrations were determined using the method described by Wang et al. (2017). The AN concentrations were quantified using the alkali solution diffusion method (Teng et al., 2016). The TP concentrations were measured using the ascorbic acid method (Varol & Şen, 2012). The AP concentrations were analyzed by the sodium bicarbonate ($NaHCO_3$) (pH = 8.5) extraction-phosphomolybdate blue spectrophotometric method (Xiong et al., 2008). The OM concentrations were determined using oil bath potassium dichromate-sulfuric acid (K_2CrO_7—H_2SO_4) and ferrous sulfate ($FeSO_4$) solution titration (Zhang et al., 2015a). The sediment particle size was determined using a laser diffraction particle size analyzer (MS-2000, Malvern Instruments Ltd., UK) (Deng et al., 2016b). Quality assurance and quality control (QA/QC) for the nutrient and OM analyses were done using duplicates and method blanks, and the precision of the duplicate analysis was within 10%. In addition, GBW07302 (GSD-2) was used as the sediment standard reference material during the analysis process. The recovery rates for the nutrients and OM ranged from 95% to 105%. The above analysis results were based on the dry weight of sediment.

2.3. Degradation experiment of *P. malaianus*

In a natural aquatic ecosystem, the stems and leaves of aquatic plants wither and fall off in late autumn and early winter and degrade in water, while their roots remain in the sediment. These roots will germinate and grow into new plants in the coming spring. A decomposition experiment on a mixture of stems and leaves of *P. malaianus* was done in the laboratory. Both sediment and *P. malaianus* were collected from Xukou Bay. The sediment was air-dried and passed through a 50-mesh sieve. The stems and leaves of *P. malaianus* were dried and chopped. Approximately 500 g of sediment was evenly placed into a glass tank with a volume of 30 L,

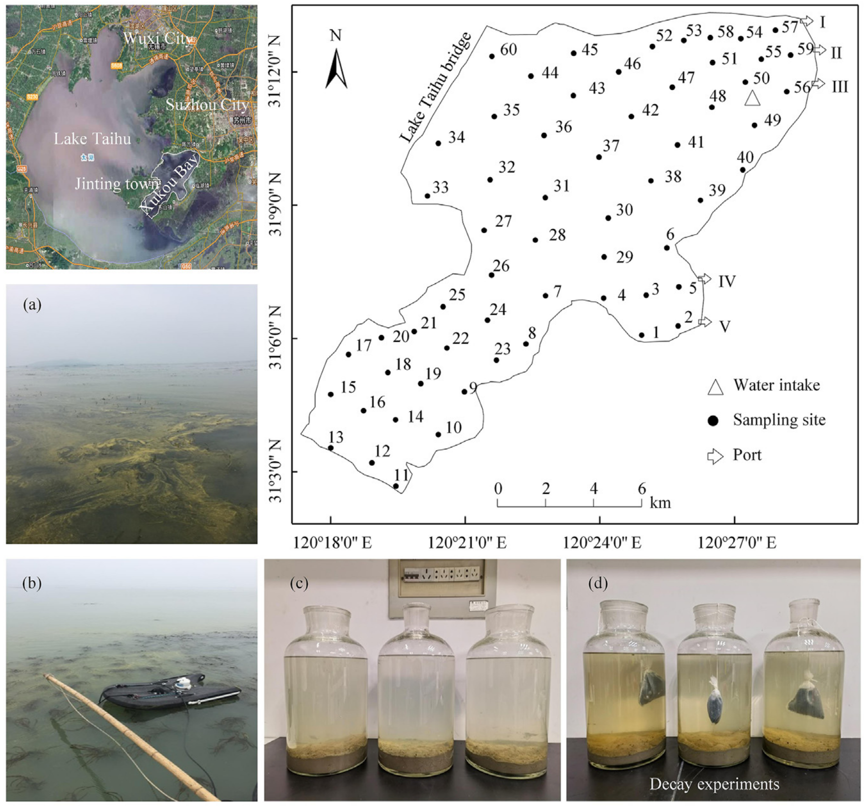

Fig. 1. Distribution of the sampling sites for collecting surface sediment in Xukou Bay, Lake Taihu. I, II, III, IV, and V represent Xujiang Port, Xinlu Port, Siqian Port, Huangshu Port, and Xidaque Port, respectively. The pictures show *Potamogeton malaianus* with cyanobacteria in Xukou Bay (a), lake current monitoring in Xukou Bay (b), the control for the decomposition experiment without *P. malaianus* (c), and the decomposition experiment with *P. malaianus* in the laboratory (d).

and 24 L of filtered lake water was slowly added to the glass tank. Next, a 200-mesh nylon bag containing a 50-g mixture of stems and leaves was immersed in water in the glass tank. Glass tanks without stems and leaves were used as controls. During the experiment, filtered lake water was supplied due to evaporation. 100-mL water samples were collected at 1, 2, 8, 14, 20, 27, 35, 45, and 60 days during the experiment to determine TN and TP concentrations. At the end of these experiments, sediment and residual *P. malaianus* samples also were collected to determine the TN and TP concentrations. The treatments and the control were done in triplicate.

2.4. Sediment risk evaluation

2.4.1. Risk index and comprehensive risk index

The risk indices (RIs) of TN (RI_{TN}) and TP (RI_{TP}) in the sediment were calculated according to the respective background concentrations of TN and TP in Lake Taihu. The combined effect of TN and TP on the sediment was evaluated using a comprehensive risk index (CRI) of nutrients. The RI and CRI were defined as follows:

$$RI_i = C_i / C_s \tag{1}$$

$$CRI = \sqrt{\left(RI_{ave}^2 + RI_{max}^2\right)/2} \tag{2}$$

where RI_i and CRI are the risk index of the *i*th nutrient element and comprehensive risk index at a sampling site, respectively; C_i and C_s are the measured and background concentrations of the *i*th nutrient at a sampling site, respectively, wherein the background values were 670 mg/kg for TN and 440 mg/kg for TP (Sui, 1996); and RI_{ave} and RI_{max} are the average and maximum values among the risk evaluations of TN and TP at a sampling site, respectively. The classification threshold and risk grades of nutrients in the surface sediment are listed in Table 1.

2.4.2. Organic index and organic nitrogen index

The organic index (OI) is an important indicator of the combined risk of organic carbon (OC) and organic nitrogen in sediments. The organic nitrogen index (ONI) is indicative of organic nitrogen risk in the surface sediments in aquatic environments (Zhang et al., 2015b). The OI and ONI were defined as follows:

$$ONI = TN\% \times 0.95 \tag{3}$$

$$Org\text{-}C\% = OM\%/1.724 \tag{4}$$

$$OI = Org\text{-}C\% \times Org\text{-}N\% \tag{5}$$

where Org-C and Org-N are organic carbon and organic nitrogen, respectively, and 0.95 and 1.724 are constants. The risk classifications of the sediments based on the OI and ONI are listed in Table 2.

2.5. Statistical analysis

In current study, the mean, minimum, maximum, standard deviation (SD), and coefficient of variation (CV) of nutrients in

Table 1
Risk assessment standards of the total nitrogen risk index (RI_{TN}), total phosphorus risk index (RI_{TP}), and comprehensive risk index (CRI) in surface sediment (Sui, 1996).

Class	RI_{TN}	RI_{TP}	CRI	Risk level
I	<1.0	<0.5	<1.0	Clean
II	1.0–1.5	0.5–1.0	1.0–1.5	Mild risk
III	1.5–2.0	1.0–1.5	1.5–2.0	Moderate risk
IV	>2.0	>1.5	>2.0	Heavy risk

Table 2
Risk assessment standards of the organic nitrogen index (ONI) and organic index (OI) in surface sediment (Zhang et al., 2015a).

	OI				ONI (%)			
	<0.05	0.05–0.2	0.20–0.5	>0.5	<0.033	0.033–0.066	0.066–0.133	>0.133
Pollution level	PU	UMC	MC	HC	PU	UMC	MC	HC
Grade	I	II	III	IV	I	II	III	IV

PU, UMC, MC, and HC represent practically uncontaminated, uncontaminated to moderately contaminated, moderately contaminated, and heavily contaminated risk levels, respectively.

the surface sediment were determined. The spatial distributions of the concentration and risk level of nutrients in the bay were plotted using the ArcGIS (v10.2) software package (Environmental Systems Research Institute, Inc., California, USA). The relations between the OM and nutrient concentrations were tested using Pearson's correlation coefficient with a significance level of $p < 0.05$ in the SPSS (v22.0) software package (SPSS Inc., Chicago, USA).

3. Results and discussion

3.1. Spatial distributions of nutrients and OM in the surface sediment

The spatial distributions of different nutrients in the surface sediment of Xukou Bay are shown in Fig. 2. The TN contents ranged from 262.2 to 2,979.6 mg/kg, with a mean of 1,027.2 mg/kg and a CV of 50.1%, which approached the average TN concentrations (1,360 mg/kg) in the surface sediment of Lake Taihu from 1990 to 1993 (Sui, 1996). The AN concentrations ranged from 8.6 to 150.0 mg/kg, with a mean of 46.5 mg/kg and a CV of 54.3%. The TN contents in the surface sediment were relatively high in the northeastern zones of the bay (Fig. 2(a)). The AN contents in the surface sediment of the northeastern and eastern zones also were relatively high, and the spatial distribution was basically similar to that of the TN concentrations (Fig. 2(b)). The TP and AP ranges in the surface sediment were 41.2–728.7 mg/kg and 4.4–36.4 mg/kg, respectively, with a mean of 423.3 mg/kg for TP, which was appreciably lower than the reported mean of 523 mg/kg in Lake Taihu in 2005 and 2010 (Wu et al., 2019), and a mean of 15.1 mg/kg for AP; the CVs were 29.6% for TP and 39.7% for AP. The spatial distributions of the TP and AP concentrations presented similar trends in that their concentrations in the northeastern, central, and southwestern zones were substantially high (Figs. 2(c) and 2(d)). The OM concentrations in Xukou Bay varied between 3.7 and 50.2 g/kg, with an average value of 17.1 g/kg and a CV of 51.7%. The OM concentration in the northeastern and southwestern zones was relatively high, but it was low in the central zone of Xukou Bay (Fig. 3).

Aquatic vegetation has substantial effects on the spatial distributions of nutrient and OM concentrations in the surface sediment of aquatic ecosystems (Søndergaard et al., 2013). In authors' previous research, *P. malaianus* and *P. maackianus* were the dominant species of submerged macrophytes in Xukou Bay, and these species with a high biomass (>20.0 kg/m^2) in the summer and autumn as

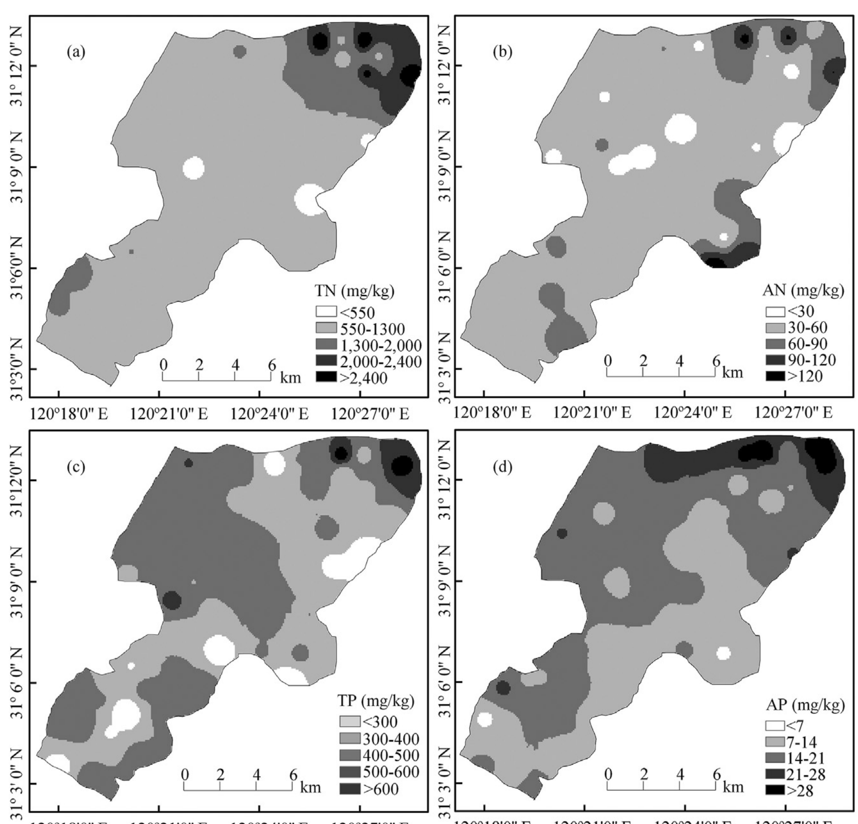

Fig. 2. Spatial distribution of nutrients in the surface sediment of Xukou Bay in Lake Taihu. TN, AN, TP, and AP represent total nitrogen (a), alkali-hydrolysable nitrogen (b), total phosphorus (c), and available phosphorus (d), respectively.

well as high occurrence frequencies (>80%) were mainly distributed in the northeastern zone (Zhu et al., 2019), which coincides with the spatial distributions of TN and OM concentrations but does not completely coincide with that of TP. Squires and Lesack (2003) reported that the biomass of aquatic vegetation was significantly positively correlated with TN and OM contents in the surface sediment, which is similar to the results in the current study. The current findings indicated that the high TN, TP, and OM contents in the northeastern zone of the bay were primarily attributable to biodeposition, burial, and accumulation of aquatic vegetation remains. Furthermore, the factors influencing TN and TP concentrations in the surface sediment of the bay may be somewhat different due to the different physicochemical properties of both elements participating in their respective biogeochemical cycles in the sediment (Madsen et al., 2001; Wu et al., 2019). Because of frequent shifts between nitrification and denitrification with the participation of microorganisms, for example, the chemical forms of N are more easily changed than those of P at the sediment–water interfaces in shallow freshwater lakes (Yang et al., 2017).

Hydrodynamics also influence the spatial distribution of nutrients in the surface sediment, especially in shallow lakes (James et al., 2008; Huang et al., 2016). Xukou Bay is the primary outflow zone of Lake Taihu, and the water flow volume from the water intakes is 3.0×10^5 m^3/d. Therefore, a large amount of water in the open region of Lake Taihu moves toward the bay, which contains high concentrations of algal aggregates and suspended inorganic particles loaded with nutrients as well as pollutants. Due to the high density (150 individuals/m^2 in summer and 114 individuals/m^2 in autumn) of submerged macrophytes, the prevailing current velocities in this bay vary between 4.5 and 10.5 cm/s (Fig. 4). Compared with those ranging from 10 to 30 cm/s in the open waters of Lake Taihu (Qin et al., 2007), this hydrodynamic regime is favorable for the settling of inorganic and organic particles that absorb nutrients onto the sediment, which likely contribute to the spatial distribution patterns of TP and AP concentrations in the bay, particularly in the region close to the Lake Taihu bridge (Fig. 2). Furthermore, surface runoff derived from intensive agricultural land use (tea and orchards) resulted in relatively high contents of nutrients and OM in the offshore regions of the town of Jinting.

The mean OM concentration in the surface sediment of Xukou Bay was higher than those of Lake Poyang and Lake Hongze in China, Karla Reservoir in Greece, and Lake Guaíba in Brazil and much lower than those of Lake Carlyle in the USA, and Lake Chaohu and Lake Nansi in China (Table 3). The average TN concentration in Xukou Bay was the lowest among the lakes and reservoirs listed in Table 3. The exception was Lake Guaíba, an important water source for approximately 2 million people in Porto Alegre, Brazil. The average concentration of TP also was the lowest, except for Lake Dongting, where the water level fluctuates greatly because it connects with the Yangtze River, the third longest river in the world. Collectively, the average concentrations of TN and TP in Xukou Bay were relatively low compared with those in the other lakes and reservoirs. However, owing to substantial heterogeneity in the spatial distribution, the TN, TP, and OM concentrations in the northeastern and southwestern zones were appreciably high, which exerted a negative effect on the water quality of the bay. As Xukou Bay is an important water source for Suzhou, managers and policymakers have implemented stringent requirements for the water quality and aquatic environment in the bay.

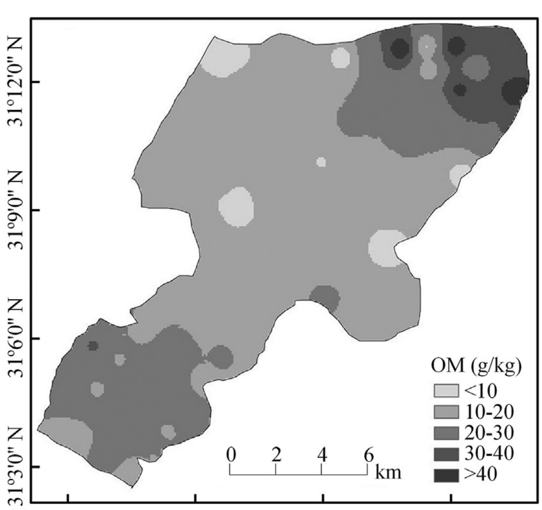

Fig. 3. Spatial distribution of organic matter (OM) in the surface sediment of Xukou Bay, Lake Taihu.

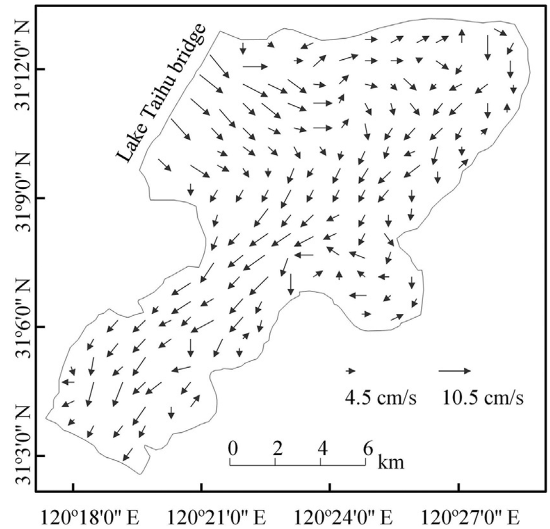

Fig. 4. Prevailing current pattern in Xukou Bay during the summer with a current velocity of between 4.5 and 10.5 cm/s.

3.2. Risks of OM and nutrients in the surface sediment

3.2.1. Evaluation considering the PI and CPI

According to the thresholds of single and comprehensive risk indices (Table 1), the average values of RI_{TN}, RI_{TP}, and CRI in Xukou Bay were 1.75, 0.91, and 1.57, respectively, indicating that the risk levels of the surface sediment in the bay are generally mild to moderate. Compared with the RI_{TN} (1.27) and RI_{TP} (0.69) of Lake Taihu in the 1990s (Sui, 1996), the risk of TN in the surface sediment of the bay was increased, with a shift from a mild level in the 1990s to a moderate level in 2018. The risk level of TP in the surface sediment of the bay in 2018 was similar to that of Lake Taihu in the 1990s, reflecting a mild risk status. Risk levels of TN occurred at most of the sampling sites (90%) in the bay, 35.0%, 33.3%, and 21.7% of which were mild, moderate, and heavy, respectively. Similarly, the risk of TP in the surface sediment at 51.7%, 36.7%, and 3.3% of all sampling sites in the bay was mild, moderate, and heavy, respectively. Furthermore, the interactive risk resulting from TN and TP in surface sediment at 45%, 25%, and 16.7% of all sampling sites in the bay was mild, moderate, and heavy, respectively. Therefore, attention should be directed toward the treatment and control of endogenous loads of TN and TP in the surface sediment of this bay.

The surface sediment with moderate and heavy risks of TN were mainly located in the northeastern and southwestern zones, and

Table 3
Concentrations of organic matter (OM), total nitrogen (TN), and total phosphorus (TP) in the surface sediment of lakes and reservoirs in China and other countries. Data are expressed as the mean (range: min–max).

Lakes/reservoirs	OM (g/kg)	TN (g/kg)	TP (g/kg)	Reference
Lake Poyang, China	15.9 (4.2–31.8)	1.3 (0.3–2.4)	0.5 (0.1–0.9)	Wang et al. (2013)
Lake Dongting, China	20.6 (14.8–42.2)	1.3 (0.4–2.2)	0.3 (0.1–0.7)	Zhang (2016)
Lake Hongze, China	13.6 (5.8–17.9)	1.1 (0.4–1.5)	0.6 (0.4–0.7)	Piao et al. (2015)
Lake Chaohu, China	58.6 (17.9–103.8)	1.7 (0.1–3.0)	0.7 (0.3–2.1)	Wang et al. (2020b)
Lake Nansi, China	46.1 (11.4–106.0)	3.1 (1.1–7.1)	0.7 (0.3–1.3)	Zhang et al. (2015b)
Lake Carlyle, USA	85.0 (0–160.0)	2.4 (0–12.0)	0.9 (0.1–1.7)	Pearce et al. (2017)
Lake Guaíba, Brazil	5.1 (0.6–9.6)	0.2 (0.04–0.4)		De Andrade et al. (2018)
Wivenhoe Reservoir, Australia		3.3 (2.1–4.6)	1.0 (0.5–1.5)	Burford et al. (2012)
Karla Reservoir, Greece	12.3 (2.7–21.9)	4.0 (2.3–6.0)		Skordas et al. (2015)
Xukou Bay, China	17.1 (3.7–50.1)	1.0 (0.3–3.0)	0.4 (0.04–0.7)	This study

the surface sediment in the other zones of the bay had low risk levels or were in a clean state (Fig. 5(a)). The surface sediment with mild risk of TP was distributed nearly throughout the whole bay, although several small patches in the northeastern, northwestern, central, and southern zones had moderate risk levels (Fig. 5(b)). The spatial distribution of the interactive risk resulting from TN and TP in the bay was similar to that of TN (Fig. 5(c)). Furthermore, the CRI was significantly correlated with the RI_{TN} in the surface sediment of the bay ($R^2 = 0.989$, $p < 0.0001$, $n = 60$, Fig. 5(d)), a similar relation between the CRI and RI_{TP} was not observed, indicating that TN contributed more to comprehensive risk than TP.

3.2.2. *Evaluation considering the OI and ONI*

Due to participating in biogeochemical processes of the carbon and N cycles, OM constitutes an important fraction of lake sediment (Orr et al., 2004), and OM mineralization can release Org-N compounds (Wang et al., 2017). Therefore, OM and Org-N may reflect the risk level of nutrients in aquatic sediment. In the current study, the OI and ONI in Xukou Bay ranged from 0.005 to 0.823 and from 0.025% to 0.283%, with average values of 0.156 and 0.112%, respectively. These findings indicate an uncontaminated to moderately contaminated (UMC) level of organic risk and a moderately contaminated (MC) level of Org-N risk in the bay, based on their respective thresholds listed in Table 2. Compared with the means of OI (0.17) and ONI (0.129%) in Lake Taihu from 1990 to 1993 (Sui, 1996), the OI and ONI values in Xukou Bay are lower to some extent, but the organic and Org-N risk levels did not substantially improve. The organic risk levels at 13.3%, 68.3%, 11.7%, and 6.7% of all sampling sites were practically uncontaminated (PU), UMC, MC, and heavily contaminated (HC), respectively. Similarly, the Org-N risk levels at 2.3%, 10.0%, 66.7%, and 20.0% of all sampling sites were PU, UMC, MC and HC, respectively. The spatial distribution of organic risk in the surface sediment was almost consistent with that of Org-N, with organic and Org-N risks being more severe in the northeastern and southwestern regions than in the other zones of the bay (Figs. 6(a) and 6(b)).

3.3. *Source identification of OM and nutrients in the surface sediment*

OM in lake sediment commonly originates from terrestrial sources, such as domestic and agricultural sewage, industrial wastewater, and excessive fish feed (Belanger et al., 2017), and the degradation of autochthonous aquatic organisms remains associated with aquatic vegetation, phytoplankton, and benthic animals (Grasset et al., 2019). The carbon/nitrogen mass ratio (CNMR) can qualitatively identify the origins of OM in sediment (Venkatesh & Anshumali, 2020). A CNMR ranging from 10 to 23 is believed to correspond to aquatic plants (Meyers & Ishiwatari, 1993). The CNMR in the surface sediment of Xukou Bay varied between 8.3 and 31.1, with a mean of 16.6. A high CNMR occurred in the southeastern and southern zones of the bay (Fig. 7). The variations in the CNMR in the surface sediment were probably attributable to a mixture of vascular and nonvascular plant debris because a large amount of cyanobacteria drifted to the bay from open Lake Taihu. The CNMRs at 57 of 60 sampling sites ranged between 10 and 23, indicating that OM in the bay mainly originated from aquatic macrophytes. In the past decade, submerged macrophytes, especially *P. malaianus* and *P. maackianus*, have been distributed throughout the entire bay. Owing to a long-term high water level in 2016 and a resulting weak optical regime, however, the distribution of submerged vegetation shrank substantially (Dong et al., 2020). The decomposition of debris related to dead submerged macrophytes with high cellulose contents contributed to OM accumulation in the surface sediment and a subsequent increase in CNMRs, as observed by Ertel and Hedges (1985), who found that vascular aquatic vegetation remaining in sediment can retain a high CNMR value of cellulosic plants.

As listed in Table 4, the significant correlation between OM and TN ($R^2 = 0.914$, $p < 0.001$, $n = 60$) indicated that OM and TN in the surface sediment of the bay shared a common source. The significant relation between OM and AN ($R^2 = 0.255$, $p < 0.001$, $n = 60$) indicated that OM degradation contributed importantly to increasing available nutrients in the pore water of the surface sediment. In turn, this availability of nutrients was beneficial for improving the growth and increasing the biomass of aquatic macrophytes by the root uptake of available nutrients in the sediment pore water (Asaeda et al., 2000). Therefore, TN was dominantly correlated with the decomposition of debris and litter of aquatic macrophytes in Xukou Bay. A weak correlation between TP and OM also was found in the surface sediment of the bay, suggesting that apart from relating to the decay of submerged macrophyte remains in the northeastern zone of the bay, TP was partly derived from the suspended particles migrating from the open waters of Lake Taihu (Dong et al., 2017). These particles adsorbed various P species.

The TN to TP mass ratio (NPMR) is commonly regarded as an indicator of the likelihood that either phosphorus, nitrogen, or either nutrient could limit phytoplankton growth (Smith, 1983). A NPMR exceeding 16 is the mass ratio required to meet the physiological demands of phytoplankton for nitrogen and phosphorus (Deng et al., 2019). The NPMR in the surface sediment of Xukou Bay ranged from 0.7 to 20.1, with a mean of 3.4. The NPMRs at all sampling sites were less than 16 except for site 1, which suggests that phytoplankton growth in the bay is potentially limited by the nitrogen supply. Paerl et al. (2011) indicated that the NPMRs in eutrophic lakes do not fully explain the nutrient limitations of phytoplankton because excessive loads of nitrogen and phosphorus, especially in some eutrophic lakes, may exceed the phytoplankton demands for these nutrients.

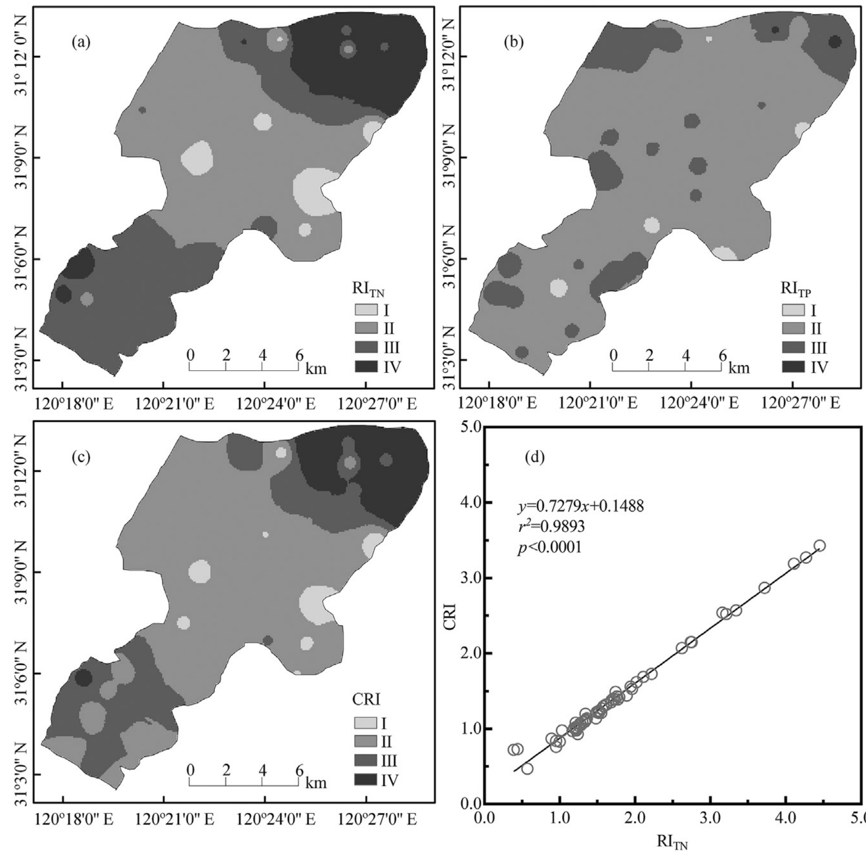

Fig. 5. Risk index of nutrients in the surface sediment of Xukou Bay in Lake Taihu. RI_{TN}, RI_{TP}, and CRI represent the risk index of total nitrogen (a), risk index of total phosphorus (b), and comprehensive risk index (c), respectively, and the relation between CRI and RI_{TN} (d). I, II, III, and IV represent clean, mild risk, moderate risk, and heavy risk, respectively.

3.4. Implications for nutrient control and the management of water sources

Based on the spatial distribution, sources, and risk levels of TN and OM, different measures should be implemented to reduce the potential accumulation of TN and OM occurring in the surface sediments of the northeastern and southwestern zones in Xukou Bay. For the northeastern zone, where submerged macrophytes thrived, regulation and management of aquatic vegetation should first be recommended. The 60-day degradation experiment of *P. malaianus*, a dominant species in the bay, revealed that the residue decay of *P. malaianus* significantly increased TN concentrations in the overlying water relative to the control, and a similar result also was observed for TP concentrations (Fig. 8). During the first two days of decomposition, both TN and TP in the overlying water reached their highest levels, which were mainly related to the rapid dissolution of soluble organic particles and inorganic salts in the residues of *P. malaianus* (Longhi et al., 2008). Subsequently, the concentrations of TN and TP decreased slowly with the decomposition duration of *P. malaianus*, which may be partly associated with the migration of the nutrients in the overlying water into sediment, as demonstrated by Cao et al. (2015). At the end of the degradation experiment of *P. malaianus*, the TN and TP concentrations in the surface sediment increased from 2.90 to 3.88 mg/g and from 2.40 to 2.58 mg/g compared with the respective controls, respectively, indicating that nutrients

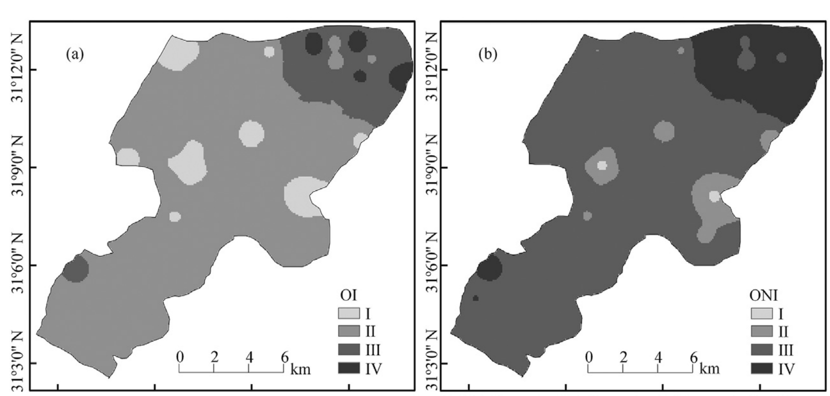

Fig. 6. Organic index (OI, a) and organic nitrogen index (ONI, b) for the surface sediment in Xukou Bay in Lake Taihu. I, II, III, and IV represent practically uncontaminated, uncontaminated to moderately contaminated, moderately contaminated, and heavily contaminated risk levels, respectively.

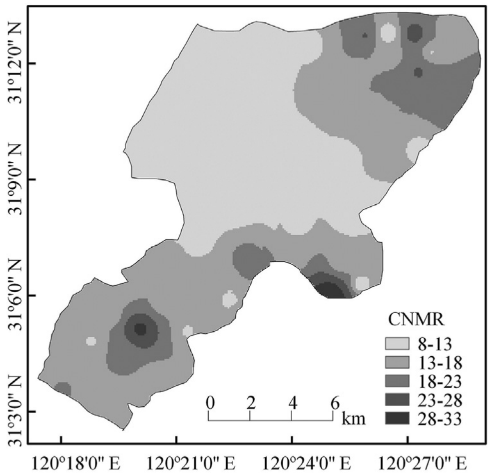

Fig. 7. Spatial distribution of the carbon/nitrogen mass ratio (CNMR) in the surface sediment of Xukou Bay, Lake Taihu.

accumulated in the surface sediment during the degradation of aquatic plants. Therefore, aquatic vegetation should be regulated prior to its death.

Previous extensive efforts have evaluated the effects of harvesting aquatic plants for improving water quality (Xu et al., 2014, 2016). For instance, Verhofstad et al. (2017) proposed that biomass removal was an important management practice for maintaining water quality by harvesting submerged macrophytes; additionally, mowing *Potamogeton crispus* prior to its senescence also was determined to be a strategy for improving water quality (Wang et al., 2018). During the growing season, the aquatic vegetation biomass in Xukou Bay is composed primarily of *P. malaianus* and *P. maackianus* and generally exceeds 20 kg/m^2 (Zhu et al., 2019). If the aquatic plant biomass cannot be efficiently removed, then the nutrients within it will probably be released again into the overlying water and sediment, especially in autumn and winter, and result in the deterioration of the water quality. Consequently, harvesting the dominant aquatic plants at a regular interval should be done to prevent aquatic vegetation debris decomposition and reduce the subsequent enrichment of TN and OM in the surface sediment.

For the northeastern zone influenced by the discharge of agricultural wastewater, the fertilization patterns should be shifted from traditional spraying application to the current drip irrigation strategy according to the physiological demand of crops for chemical fertilizers. Simultaneously, ecological ditch systems with reciprocating plant grids should be designed and applied to remove nutrients in the surface runoff derived from agricultural lands associated with tea and orchard plantations via uptake by plants (Wang et al., 2020a). For example, a study on an ecological ditch system removing nutrients from agricultural sewage in a hilly area in China demonstrated that the average removal efficiency of TN and TP was up to 47.9% and 49.8%, respectively (Wang et al., 2019). Consequently, ecological ditch systems would be expected to reduce the nonpoint source pollution of agricultural wastewater discharge into the surface sediment near the town of Jinting. Furthermore, efforts devoted to controlling polluted sediments have shown that dredging is an effective and practically feasible option to reduce the risk level of TN and OM in the surface sediment because of the permanent removal of pollutants in sediment (Liu et al., 2015). The average sediment depth in the southwestern zone was greater than 50 cm, with high TN concentrations. Therefore, local dredging is necessary to remove TN from sediment to ensure the water quality safety of the water sources in Lake Taihu, China.

Table 4
Pearson's correlation coefficients of organic matter and nutrients in the surface sediment of Xukou Bay. OM: organic matter; TN: total nitrogen; TP: total phosphorus; AN: alkali-hydrolysable nitrogen; and AP: available phosphorus.

	OM	TN	TP	AN	AP
OM	1	0.956[b]	0.154	0.504[b]	0.259[a]
TN		1	0.201	0.522[b]	0.207
TP			1	−0.070	0.376[b]
AN				1	0.158
AP					1

[a] Significant at the 0.05 level (two-tailed).
[b] Significant at the 0.01 level (two-tailed).

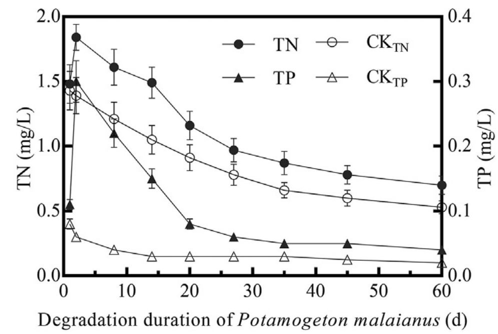

Fig. 8. Changes in the concentrations of total nitrogen (TN) and total phosphorus (TP) in the overlying water during the decomposition of *Potamogeton malaianus*. CK$_{TN}$ and CK$_{TP}$ show the concentrations of TN and TP in the overlying water without *Potamogeton malaianus*, respectively. All data are shown as the mean ± standard deviation ($n = 3$).

4. Conclusions

The current study demonstrated spatial heterogeneity in the TN, AN, TP, AP, and OM concentrations in the surface sediment. The nutrient and OM concentrations in the northeastern zone were significantly higher than those in the other zones of Xukou Bay, which was primarily associated with the distribution of aquatic vegetation biomass. The current study demonstrated that TN contributed dominantly to the moderate risk and heavy risk in the surface sediment, especially in the northeastern and southwestern zones, where moderate interactive risk resulting from TN and TP as well as organic risk occurred concurrently. The current study also indicated that OM and TN in the bay shared the same source of the nutrient release during the decomposition of debris and litter associated with dominant submerged macrophytes. However, TP in the surface sediment was derived from an alternative source. These findings suggest that some measures should be implemented to reduce the potential accumulation of TN and OM in the surface sediment of submerged macrophyte-dominated shallow lakes.

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.

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