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ORIGINAL ARTICLE

Phosphorus, organic matter and nitrogen distribution characteristics of the surface sediments in Nansi Lake, China

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Abstract Nansi Lake is the largest and most important freshwater reservoir for the South-North Water Diversion Project located in Shandong Province, China. The characteristics of the nutrient compositions and distribution in the lake sediment may significantly influence the upper-level water quality, which has not been well studied. In this study, the distribution characteristics of the total phosphorus (TP), total organic matter (OM) and total nitrogen (TN) contents in the shallow sediments of Nansi Lake were investigated. The experimental results showed that the sedimentary TP, OM, and TN levels of the entire Nansi Lake (expressed as dry weight percentage) were (0.030 ± 0.003)–(0.129 ± 0.018) %, (1.14 ± 0.18)–(10.60 ± 1.30) % and (0.105 ± 0.021)–(0.71 ± 0.08) %, respectively. The three nutrient indicators appeared to be higher in the upstream lake than in the downstream lake. Concentrations of TN and OM were both particularly higher in aquaculture zones of Nansi Lake, where excessive fish feed may largely contribute to the high TN and OM in the sediment. Furthermore, there was a significantly positive correlation ($n = 28$, $R^2 = 0.7870$) between TN and OM. According to the pollution index (P_i) and enrichment factor, there is moderate enrichment of TN and OM in the sediment, while minor enrichment of TP in Nansi Lake. Calculations of the OM index and organic nitrogen index suggested that the surface sediment of the entire Nansi Lake has been contaminated by OM and organic nitrogen. Therefore, there is a pressing need to further investigate the release characteristics of these nutrient contaminants from the sediment of Nansi Lake and potential impacts on the surface water quality.

Keywords Nansi Lake · Sediments · Distribution characteristics · Pollution index · Enrichment factor · Organic matter index · Organic nitrogen index

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Introduction

Eutrophication in shallow lakes poses a serious threat to water quality. Phosphorus (P), nitrogen (N), and carbon (C) are major nutrient elements for many aquatic organisms and also the key factors for eutrophication (Hilton et al. 2006; Schindler 2006). P and N could accumulate in sediment, and could be released into the overlying water when the environment factors such as temperature, pH and redox potential change at the sediment and water interface (Li and Zhou 2006; Spears et al. 2007). The released P and N from sediment could in turn lead to algal blooms (Wu et al. 2001). Furthermore, in the mineralization processes of organic compounds, the aqueous redox and pH could be changed, which could significantly influence the P and N release from sediment (Davison and Heaney 1978). Therefore, it is also necessary to survey the sedimentary component characteristics to better understand the eutrophication of Nansi Lake and develop effective measures in order to prevent the potential negative impacts on the overlying water quality.

Nansi Lake located in Shandong province has a total surface area of 1,266 km^2 and is the largest and important freshwater reservoir in north China for the South-North Water Diversion Project. According to the "Water Pollution Prevention Planning of the South-to-North Water Diversion Project of Shandong Section", its water quality should meet the Grade III of the "China surface water quality standard (GB3838–2002)". Specifically, the concentrations of phosphorus and nitrogen should be lower than 0.2 and 1.0 mg L^{-1}, respectively. However, due to the industrial wastewater discharge and overuse of agriculture fertilizer in 1990s, considerable amounts of nutrients deposited and accumulated in the sediment of Nansi Lake (Liu et al. 2008; Yang et al. 2007). In recent years, all major external wastewater discharge has been under control in a way that all the influent water must meet the Grade III requirements. However, the nutrients released from the polluted sediment still adversely affect the water quality of the overlying water and potentially cause eutrophication problems (Kim et al. 2003). In addition, aquaculture activity in Nansi Lake further deteriorated the water quality during the past 20 years (Pei et al. 2011). Excessive fish feed deposited to the lake bottom and resulted in the sediment pollution (Wu and Ru 2012). Therefore, it is important to characterize the nutrient distribution in the surface sediments to prioritize the sediment remediation and pollution control.

Nansi Lake is a typical shallow and macrophyte-dominated lake for aquaculture and fish farming, which brings a high loading of nutrient contaminants into water and sediment. So far only a few studies have investigated the sedimentary phosphorus characteristics in Nansi Lake (An and Li 2008; Yang et al. 2007; Zhou et al. 2007). In the work of An and Li (2008), the sediment of the estuary in Nansi Lake was sampled and tested. However, the results did not establish a comprehensive mapping of the nutrient contamination for the entire lake. Likewise, Yang et al. (2007) and Zhou et al. (2007) only studied the nutrient distribution in the upstream sediment of Nansi Lake. Since the downstream of Nansi Lake serves as the main reservoir, the sediment quality in the downstream of Nansi Lake is clearly important and deserves a thorough investigation.

This study analyzed the spatial distribution of TP, OM, and TN in surface sediment from multiple sampling locations in both upstream and downstream of Nansi Lake, and evaluated the sediment contamination of the entire Nansi Lake. This work lays groundwork towards a comprehensive understanding of the current nutrient levels of Nansi Lake and provides essential knowledge for establishing appropriate water quality management policies and remediation strategies.

Materials and methods

Sampling sites

As shown in Fig. 1a, the river water will be transported more than 1,100 km from Yangzhou to Tianjin and Beijing in the South-to-North Water Diversion Project. Nansi Lake in the red circle (34°27′–35°20′N, 116°34′–117°21′E) serves as the largest reservoir and consists of four subsectional lakes (namely, Nanyang, Dushan, Zhaoyang and Weishan). As shown in Fig. 1b, the dam built in 1960 divides the lake into two major sections consisting of Nanyang and Dushan lakes in the upstream and Zhaoyang and Weishan lakes in the downstream. Nansi Lake is a typical, shallow lake with an average depth of 1.46 m (An and Li 2009). Driven by the natural hydraulic flow, nutrients are transported from the upstream lake to the downstream lake as indicated by the black arrow in Fig. 1b. However, in the South-to-North Water Diversion Project, the lake water will actually be expected to flow in the opposite direction. In this study, sediment samples were collected from 28 different sites as marked in Fig. 1b to study the spatial distribution of nutrient contents within the lake. Fifteen sampling sites were located at the upstream lake and the rest at the downstream lake.

Sediment sample treatment and analysis

Surface layer sediment (0–15 cm) samples were collected with a home-made core Plexiglas sampler from the aforementioned sampling sites in April 2012. The samples collected from each site consisted of three parallel samples. Following collection, the samples were sealed in plastic bags and stored in a refrigerator at 4 °C without exposure to light. Sediment samples were air dried for 30 days at room temperature with exposure to daylight. Then, the large solid components (stones and plant) were removed by a 0.15-mm sieve. The sieved samples were stored in air-sealed plastic bags before further analysis.

To measure TP in the sediment samples, 0.25 g sediment samples were digested in Teflon vessels with 12 mL HNO_3 (65 %): HCl (37 %) = (3:1) mixture in a microwave oven (MARS X-press, CEM) (USEPA 2007). Then, TP in acid-digested extract was determined by the ascorbic acid method using a Shimadzu UV-3600 spectrophotometer (Zhang et al. 2012b). TN was determined using an elemental analyzer (CE-440, Exeter Analytical, Inc., North Chelmsford, MA, USA). To measure OM, the sediment samples were first dried at 60 °C for 24 h to remove moisture (Orr et al. 2004). Then, the samples were weighed and heated in a muffle furnace at 550 °C for 2 h to further remove OM. Finally, the sediment samples were re-

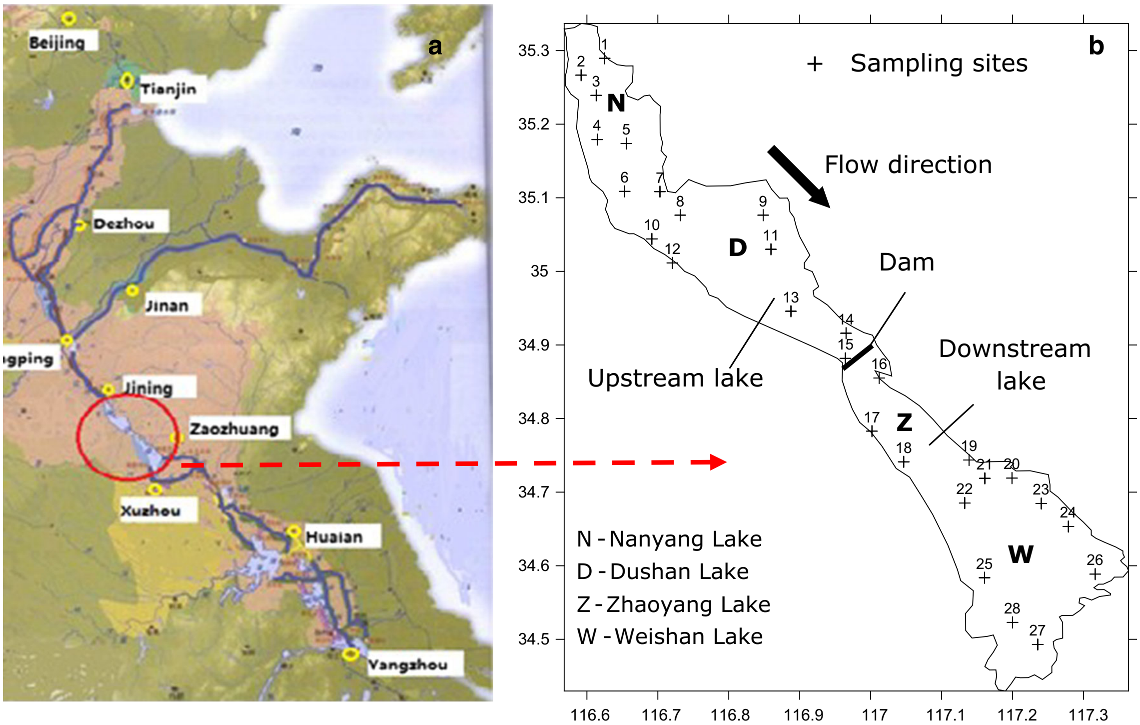

Fig. 1 Geographic map of Nansi Lake and sediment sampling sites (denoted by the symbol "+")

Table 1 Evaluation standard values and environmental background values for sediment assessment in Nansi Lake

	Level	OM (%)	TN (%)	TP (%)	
The evaluation standard of nutrients published by the Ministry of Environment and Energy, Ontario, Canada (1992)	Critical level	1.724	0.055	0.06	(Mudroch and Azcue 1995)
Environmental background values		1.14 ± 0.18	0.105 ± 0.021	0.03 ± 0.003	(Wu et al. 2012)

weighed to calculate OM percentage, which was the difference between the ash weight and dry weight divided by the dry weight. All samples were analyzed in triplicate, and the results were expressed as mean and standard deviation. SURFER software (Golden Software Inc.) was used to analyze the spatial distribution of sedimentary TN, TP and OM in Nansi Lake.

Sediment contamination evaluation

To evaluate the sediment contamination, we employed the following two different evaluation standard methods (Mudroch and Azcue 1995; Yu et al. 2010).

Pollution index (P_i) and enrichment factor (EF_i) evaluation standards

The nutrients pollution index (P_i) was calculated with the evaluation standard of nutrients published by Ministry of Environment and Energy, Ontario, Canada (Mudroch and Azcue 1995). The P_i is defined as:

$$P_i = C_i / C_{0i} \tag{1}$$

where P_i is pollution index of the nutrient i, C_i is the concentration of the nutrient i in sediment samples, and C_{0i} is the environment evaluation standard value (Table 1, the critical level was used as the C_{0i}). A higher value of $P_{i,}$ indicates that the sediment is more polluted by the specific nutrient.

The EF_i is defined as (Sakan et al. 2009):

$$\mathrm{EF}_i = C_i / C_{\mathrm{BV}} \tag{2}$$

where EF_i is the enrichment factor of the nutrient i. C_i is the concentration of the nutrient i in sediment samples, and C_{BV} is the environmental background value, respectively. In this paper, C_{BV} values were obtained from (Wu et al. 2012) who performed the nutrient level monitoring for Nansi Lake sediment from 2006 to 2011. Depending on the calculated values of EF, the sediment contamination can be

Table 2 Evaluation standards of organic index in sediments (Yu et al. 2010)

Org-Index	<0.05	0.05–0.35	0.35–0.75	≥0.75
Org-N	<0.033 %	0.033–0.066 %	0.066–0.239 %	>0.239 %
Types	Practically uncontaminated	Uncontaminated to moderately contaminated	Moderately contaminated	Heavily contaminated
Grades	I	II	III	IV

classified as no enrichment when EF is <1, minor enrichment when EF is 1–3, moderate enrichment when EF is 3–5, moderately severe enrichment when EF is 5–10, severe enrichment when EF is 10–25, very severe enrichment when EF is 25−50, and extremely severe enrichment when EF is >50 (Sasikala et al. 2009).

Organic index and organic nitrogen index evaluation standards

Organic index and organic nitrogen index are the indicators to classify the sediment contamination and the nitrogen pollution of surface sediment in lakes respectively (Jiang and Wang 2012; Yu et al. 2010):

$$\text{Org-Index} = \text{Org-C}\ (\%) \times \text{Org-N}\ (\%) \quad (3)$$

$$\text{Org-N}\ (\%) = \text{TN}\ (\%) \times 0.95 \quad (4)$$

where Org-C (organic carbon, %) is the weight percentage of organic carbon, which is equal to the percentage of OM divided by 1.724, Org-N (%) is the weight percentage of organic nitrogen, which is equal to the weight percentage of TN times 0.95. Table 2 shows the classification of sediment contamination levels based on the values of organic index and organic nitrogen index.

Results and discussion

Spatial distributions of TP, OM, and TN in surface sediments

Based on the monitoring results of TP at the 28 sampling sites, the spatial distribution of average TP in the sediment of Nansi Lake is shown in Fig. 2. The TP contents are typically in the range 0.030–0.129 %, with an average of 0.068 %. Compared with other shallow lakes in China, Nansi Lake has a median level sedimentary TP content, which is lower than Tai Lake (0.115 %) (Jin et al. 2006) and Dianchi Lake (0.216 %) (Chen et al. 2007), and slightly higher than Dongting Lake (0.049 %), Poyang Lake (0.049 %) (Zhu et al. 2004) and Chaohu Lake (0.055 %) (Wang et al. 2007). Particularly, the TP content is lower in the aquaculture zones in both the upstream and downstream lakes probably due to the fact that aquatic plants are intensively harvested from the aquaculture zones in the Nansi Lake every year, which substantially removes phosphorus from sediments. Besides, the high fish productivity could also reduce phosphorus in this lake.

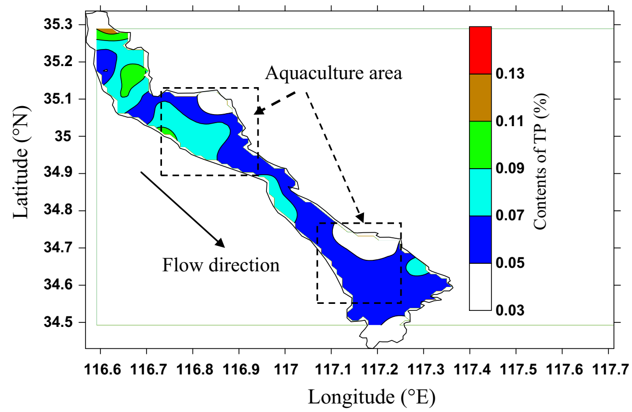

Fig. 2 Distribution of TP (dry weight percentage) in surface sediments of Nansi Lake

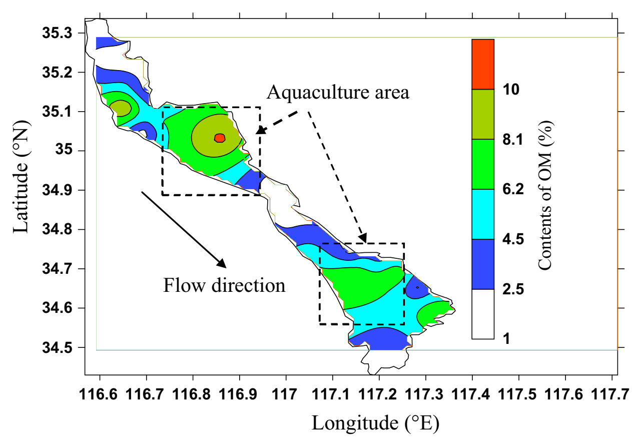

Fig. 3 Distribution of OM (dry weight percentage) in surface sediments of Nansi Lake

The spatial distribution of OM in surface sediment of Nansi Lake in Fig. 3 indicates that OM contents in sediments are in the range 1.14–10.60 %, with an average of

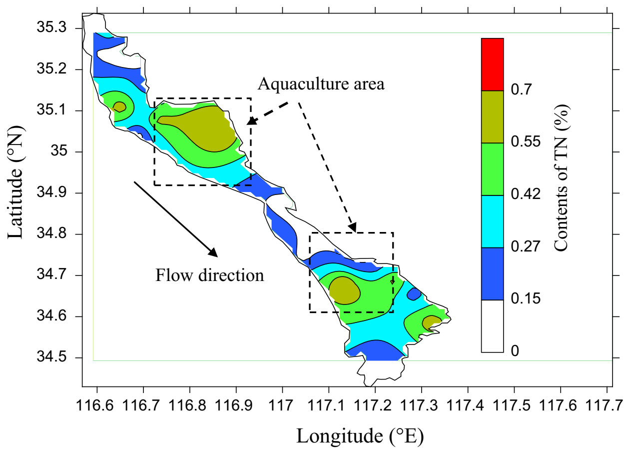

Fig. 4 Distribution of TN (dry weight percentage) in surface sediments of Nansi Lake

Table 3 Linear relationship among OM, TN and TP in surface sediments of Nansi Lake

	Regression equation	R^2
OM/TN	$P_{TN} = 0.0651P_{OM} + 0.0095$	0.7870*
OM/TP	$P_{TP} = -0.0003P_{OM} + 0.069$	0.0017
TN/TP	$P_{TP} = 0.0015P_{TN} + 0.0669$	0.0002

* Significant ($p < 0.05$, $n = 28$)

4.61 %. By contrast, there is a high OM level observed at the aquaculture zones, where the OM content even reached more than 10 % (Fig. 3). This observation highlights the strong correlation between aquacultural activities and the deposition of OM onto the lake sediment.

Figure 4 shows the distribution of TN in surface sediments of Nansi Lake in the range 0.11–0.71 %, with an average of 0.31 %. The average TN content in upper lake is higher than that in lower lake with relatively high TN in sediments in the aquaculture zones. Compared with the TN levels in other shallow lakes, such as 0.09–0.12 % in Chaohu Lake and 0.12–0.13 % in Longganhu Lake (Qin and Zhu 2005) in China, the sedimentary TN content in Nansi Lake is much higher. Interestingly, the distribution pattern of TN is similar to that of sedimentary OM. For instance, there are high levels of TN and TP in the southeast of Nanyang, Dushan and Weishan lakes, where the main aquaculture zones are. However, the levels of TN and OM were much lower in the non-aquaculture zones. Linear correlations between OM, TN and TP are analyzed and compared in Table 3. A significant correlation between the value of OM and TN was found ($n = 28$, $R^2 = 0.7870$). It implies that OM and TN might be derived from the same pollution sources, whereas there are no

Table 4 The mean values of TN, TP, and OM in surface sediments of Nansi Lake (dry weight percentage)

Lake regions	OM/%	TN/%	TP/%
Nanyang Lake	4.77	0.35	0.080
Dushan Lake	4.14	0.37	0.069
Zhaoyang Lake	5.78	0.32	0.050
Weishan Lake	4.46	0.36	0.060

Table 5 Pollution indexes and enrichment factors of OM, TN and TP in surface sediments of Nansi Lake

Lake regions	OM		TN		TP	
	P_i	EF_i	P_i	EF_i	P_i	EF_i
Nanyang Lake	2.77	4.19	6.33	3.31	1.27	2.54
Dushan Lake	2.40	3.63	6.65	3.31	1.15	2.30
Zhaoyang Lake	3.35	5.07	5.85	3.48	0.76	1.51
Weishan Lake	2.59	3.91	6.54	3.06	1.02	2.03

apparent linear relationships between OM and TP or TN and TP.

The sources of nutrients were also predicted based on sediment carbon and nitrogen ratio. When the ratio of OM/TN >10, sediment organic matter is mainly exogenous organic matter; when the ratio of OM/TN <10, it is mainly endogenous organic matter; and when the ratio of OM/TN ≈10, it reaches balance between allochthonous sources and autochthonous sources (Feng et al. 2006). The ratio of OM/TN in sediment for Nansi Lake ranges from 9.01 to 30.62 with the average ratio of 16.50, indicating that sediment organic matter in Nansi Lake is mainly exogenous organic matter (e.g., the organic fish feed intentionally or unintentionally dumped in aquaculture activities).

Evaluation of sediment contamination in Nansi Lake

Pollution index (P_i) and enrichment factor (EF_i)

The mean contents of OM, TN, and TP for the four lakes are shown in Table 4. According to Eqs. 1–4, the pollution index (P_i) and enrichment factor (EF_i) were calculated and shown in Table 5. The P_i of sedimentary OM in Zhaoyang Lake was the greatest among others due to the excessive use of fish feed in that area. In addition, the pollution indexes of TN in Zhaoyang Lake, Nanyang Lake, Weishan Lake and Dushan Lake were all greater than 6, meaning that the nitrogen pollution in these lakes was rather severe. The EFs of OM, TN and TP were 3.63–5.07, 3.31–3.48 and 1.51–2.54, respectively, indicating that Nansi Lake undergoes moderate enrichment of OM and TN in sediments and minor enrichment of TP. The large-scale fence fish farming

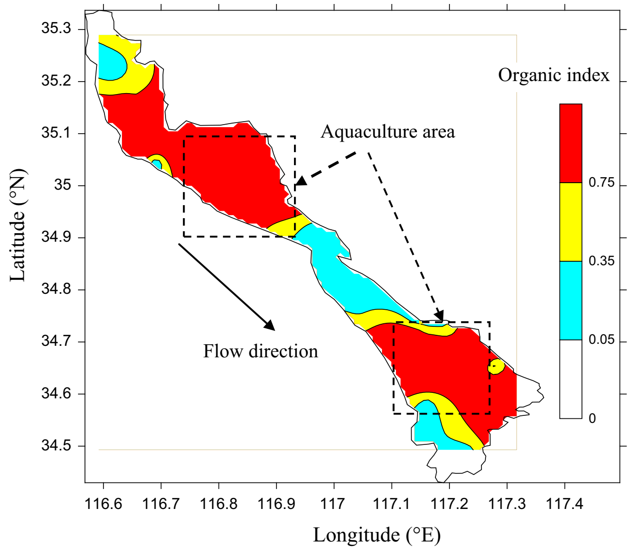

Fig. 5 Distribution of organic indexes in surface sediments of Nansi Lake

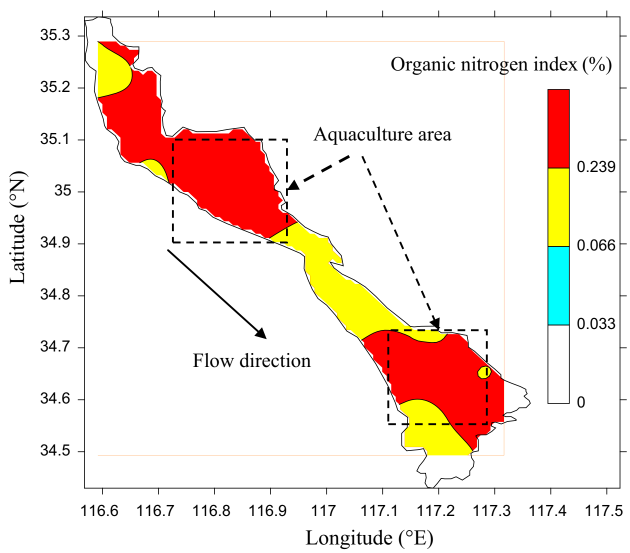

Fig. 6 Distribution of organic nitrogen indexes in surface sediments of Nansi Lake

in Nansi Lake introduces a high loading of nitrogen to the lake as introduced previously (Zhang et al. 2012a). Moreover, nitrogen may also come from the decomposition of plant debris that accumulated in Nansi Lake over 20 years.

Organic index and organic nitrogen index standards

The organic index and organic nitrogen index for the sedimentary OM and TN in Nansi Lake are shown in Figs. 5 and 6. The organic index of sediments in Nansi Lake is 0.07–3.90 with the average value of 1.05. More than 50 % of the Nansi lake sediment is heavily polluted by OM (organic index $\geq$ 0.75). Therefore, further research on the organic matter release from Nansi Lake sediment should be undertaken to determine the negative impacts from OM release on the overlying water quality.

Similar to the organic index, the organic nitrogen index of sediments in Nansi Lake is as high as 0.10–0.67. More than 60 % of the Nansi lake area is now heavily polluted with organic nitrogen index greater than 0.239. Moderately polluted surface sediment covers about 31 % of the whole lake (organic nitrogen index = 0.066–0.239 %).

Conclusions

This study quantitatively assessed the spatial distribution of nutrient levels as indicated by TP, OM and TN in sediment of Nansi Lake to lay the groundwork for further sedimentary remediation and pollution prevention. The levels of TP, OM and TN in sediment of the upper lake were higher than those of the lower lake. The highest TP content was located in the northeast area of Nanyang Lake, whereas OM and TN were higher in aquaculture zones, probably due to the excessive adding of feed. Moreover, the levels of TN and OM were closely correlated, indicating that they might originate from the same sources (e.g., fish feed). There is moderate enrichment of OM and TN and minor enrichment of TP in surface sediment of Nansi Lake according to the indexes of EFs. About 60 % of sediments in Nansi Lake were moderately eutrophic, especially in Dushan Lake and Weishan Lake. Therefore, urgent measures should be undertaken to prevent potential negative impacts on the overlying water system and to maintain the ecological roles of Nansi Lake as sources of irrigation, water supply, aquatic breeding, and tourism.

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