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RESEARCH ARTICLE

Assessment of the sediment quality of freshwater ecosystems in eastern China based on spatial and temporal variation of nutrients

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Abstract Comprehensively characterizing and assessing the sediment quality in freshwater ecosystems based on the condition of the nutrients in eastern China was urgent. The distribution and concentration of nutrients were investigated; meanwhile, sediment quality guidelines (SQGs), organic pollution index (OPI), and organic nitrogen index (ONI) were used to assess the sediment quality. Total phosphorus (TP), total nitrogen (TN), and total sulfur (TS) concentrations in sediment samples were 48.4, 72.5, and 89.5% higher than the soil background value, respectively. In terms of the Ontario SQGs, 41.8 and 74.7% of sediment samples were severely polluted by TP and TN, respectively. The Haihe, Yangtze, and Pearl River Basins were much more severely contaminated than other basins. TN pollution was much more severe than TP pollution in all basins. The Haihe, Huaihe, and Pearl River Basins were seriously contaminated according to the OPI and ONI. On temporal scale, the TP and TN significantly increased since 1980s because of the social and economic development in eastern China. For most severely contaminated basins, TN contamination was higher than TP contamination, and concentrations of TN and TP continuously increased from 2007 to 2016, which ranged from 2.06 to 2.51 g/kg, and 1.02 to 1.22 g/kg, respectively, in the Haihe River Basin. This trend will continue without effective control. The freshwater sediment quality in eastern China revealed urgent attention.

Keywords Phosphorus · Nitrogen · Sediment · Freshwater ecosystem · Eastern China

- A national-scale investigation of nutrients in sediment was done in eastern China.
- Spatial distribution of nutrients showed significant heterogeneity in diverse basin.
- TP and TN significantly increased from 1980s because of social-economic development.
- Hai River basin was the most seriously contaminated area and will continue to be.
- Nitrogen was the main pollutant, surpassing phosphorus, in the eastern China freshwater sediment.

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Introduction

As an essential part of freshwater bodies, sediment has a vital function in supporting benthic metabolism (Levin et al. 2001). Thus, sediment quality is vital for freshwater ecosystems. However, as the sink or source of pollutants from watersheds, large amounts of metals, organic matter, nitrogen (N), and phosphorus (P) accumulate in sediment and are being released and enter into water bodies under frequent changes of physical-chemical properties and hydrodynamic conditions, thus leading to water pollution and eutrophication (Carpenter 2005; Kraal et al. 2013).

The levels of nutrients, such as nitrogen, phosphorus, sulfur (S), and total organic carbon (TOC) in sediment and water bodies, are key factors in determining the health of freshwater ecosystems. As limiting factors of primary productivity in freshwater ecosystems, N and P are not only necessary nutrients for the growth of aquatic organisms (Conley et al. 2009; Delgado-Baquerizo et al. 2013) but are also one of the main controls in eutrophication (Correll 1998; Elser et al. 2007). Human activities have profoundly altered the supply rate of N and P to water bodies, and this has induced increasing eutrophication in the twenty-first century. Eutrophication causes many environmental problems, such as algal blooms, oxygen depletion, infectious diseases, aquatic ecosystem deterioration, and freshwater becoming unsuitable for human use (Smith et al. 1999; Smith and Schindler 2009). TOC in freshwater sediment is a key component in chemical, physical, and biological processes. TOC consists of dissolved organic carbon (DOC) and particulate carbon (POC). DOC is a strong complexing agent for toxic heavy metals. POC acts as a carrier to transport the pollutant, and the decomposition of POC plays an important role in determining water quality. The decomposition of POC contributes significantly to the acidity of natural water, biological activity, nutrient availability, and the contaminants' solubility and toxicity. TOC is an important index. An overabundance of TOC may lead to oxygen depletion and the buildup of toxic by-products, such as ammonia and sulfate, and reduce the benthos' richness, abundance, and biomass (Diaz and Rosenberg 1995; Gray et al. 2002; Hyland et al. 2005). Sulfur is an essential macronutrient that forms an important component of plant tissue and sediment organic matter (Marschner 2012; Turner et al. 2016). As a dominant electron acceptor, sulfate will accept electrons for the oxidation of organic carbon via dissimilatory sulfate reduction in an oxygen deficit sediment, and generate H_2S or metal sulfide (Panutrakul et al. 2001).

In the last two decades, China's economy has grown dramatically with a gross domestic product (GDP) growth of nearly 8% annually (Liu and Raven 2010); human, agricultural, and industrial activities have greatly increased P and N generation and consumption (Qu and Kroeze 2010). Intensive agriculture has been associated with the application of fertilizers at heavy loads, especially in eastern China. In the Midwest USA and western Kenya, fertilizer loads were 588 (N) and 92 (P) kg ha^{-1} year^{-1}, of which only half is removed by the crop (Vitousek et al. 2009). In eastern China, the three most populated and industrialized zones are the Bohai Sea, the Yangtze River Delta, and the Pearl River Delta Economic Rims. In these areas, rapid population growth, industrial development, and increased agricultural production have led to an increasing flow of untreated sewage and rubbish to the environment. The resulting N, P, and organic matter loads in the watershed greatly increase the risk of eutrophication (Pernet-Coudrier et al. 2012; Rong and Shan 2016), and cause changes to the benthonic fauna and affect the benthic metabolism. Thus, scientific and comprehensive assessments of sediment quality are in urgent need. To the best of our knowledge, there is a lack of systematic study of sediment quality in China, especially in eastern China, under the influence of social-economic development.

Compared with the heavy metal and persistent toxic substances, P, N, S, and TOC were beneficial for the aquatic organism under moderate concentration but induce environmental problems, such as eutrophication. So, comprehensively characterizing and assessing the sediment quality in freshwater ecosystems based on the condition of the nutrient in eastern China was urgent. We collected 91 surface sediment samples in eight main basins during 2013. Our objectives were to (1) investigate the characteristics of N, P, S, and TOC in surface sediment for eight main basins and (2) to assess the sediment quality using sediment quality guidelines, the organic pollution index (OPI), and the organic nitrogen index (ONI). This is the first time for a national-scale investigation and assessment of nutrients in freshwater sediment in eastern China. In this paper, we not only give the whole scene and valuable assessment of the surface sediment in the spatial scale but also evaluate the change of the sediment quality in the timescale. The viewpoint of this manuscript can provide a valuable enlightenment for other studies about sediment quality and nutrient variation.

Materials and methods

Sample collection

A total of 91 sediment samples were collected in eastern China in 2013 (Fig. 1). The samples were taken from rivers, wetlands, and lakes in the Songhuajiang River Basin (SHJRB), Liaohe River Basin (LRB), Haihe River Basin (HRB), Yellow River Basin (YRB), Huai River Basin (HuRB), Yangtze River Basin (YzRB), Mindongnan River Basin (MDNRB), and Pearl River Basin (PRB). The details of the sampling sites are contained in Zhang et al. (2016). Three surface sediment samples were collected at intervals of 500 m at each site. Subsamples from the same site were pooled and homogenized to obtain a representative sample. In addition, seven sediment cores were collected using a gravity corer (Uwitec, Austria) with PVC sampling tubes (diameter 6.3 cm and length 60 cm), which were distributed in Liaohekou Wetland, Beidagang Wetland, Taihu Lake, Chaohu Lake, Dongtinghu Lake, Yangtze River, and Pearl River. The valid sediment cores were about 40 cm for all of the sediment cores. The sediment core transected into 1-cm segments in sequence. All of the samples were freeze-dried at −50 °C in FD-1 freeze-dryers after delivery to the laboratory. Dried samples were grounded and sieved with a 100-mesh

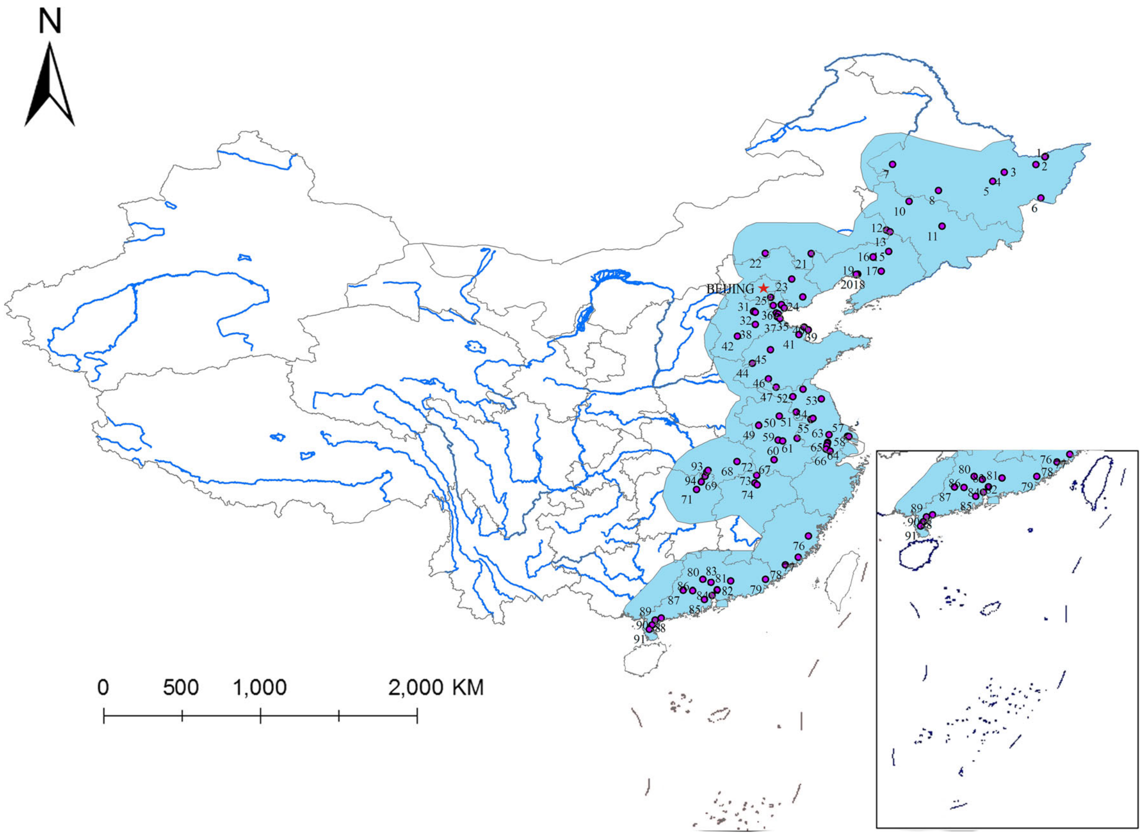

Fig. 1 The sample sites in eastern China

sieve. A quarter of each sample was collected as a representative sample, and then, the samples were stored in sealed plastic bags and stored at room temperature until analysis.

Sample analysis

Analysis of total phosphorus, total nitrogen, and total sulfur

Total P (TP) in sediment was measured by heating the sample at 500 °C (2 h), followed by 1 mol L^{-1} HCl extraction (16 h). Inorganic P (IP) was determined by direct extraction with 1 mol L^{-1} HCl (16 h) (Aspila et al. 1976). Organic P (OP) concentration in the sediment was calculated as the difference between TP and IP (Aspila et al. 1976). Total S (TS) and total N (TN) were determined from 20 to 30 mg sediment samples sieved through a 100-mesh sieve, using an elemental analyzer (vario EL III, Elementar, Germany).

Analysis of TOC and pH

The pH of the sediment was determined from the leaching liquor at a sediment:water ratio of 1:2.5 with a pH meter (Lu 2000). TOC was analyzed using the potassium dichromate oxidation spectrophotometric method (HJ 615-2011).

Assessment methods

OPI

The OPI and ONI are important indicators for evaluating sediment contamination and nitrogen contaminants in freshwater sediment (Jiang and Wang 2012; Zhang et al. 2015).

$$\mathrm{OPI} = \textit{total organic carbon}\ (\%) \times \textit{organic nitrogen}\ (\%),$$

where organic nitrogen (wt%) = TN (wt%) × 0.95,
where organic nitrogen (%) is 0.95 times of the weight percentage of TN.

The classes are shown in support information (SI) Table 1.

Sediment quality guidelines

Sediment quality guidelines (SQGs) have been published by the Ministry of Environment and Energy, Ontario, Canada, and have been widely used for the sediment quality assessment (Persaud et al. 1993). In the SQGs, sediment contamination was divided into three grades: grade I (no impact), grade II (low impact), and grade III (severe impact) (SI Table 2).

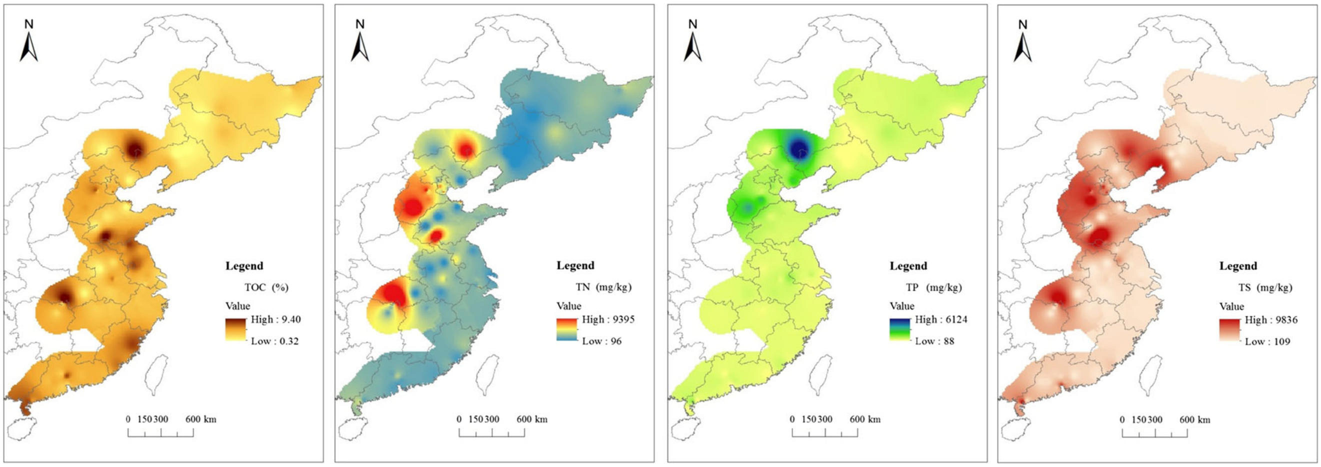

Fig. 2 The distribution of total organic carbon, total nitrogen, total phosphorus, and total sulfur

Statistical analysis

The data were analyzed using SPSS 19.0 for Windows and OriginPro 8.5, using standard procedures in Microsoft Excel. All the data were normality tested and obeyed normal distribution. Pearson correlation was used to assess the relationship between the physicochemical characteristics and nutrients. Figures 1, 2, and 3 are made using ArcGIS 10.0. Some of the data, such as TN, pH, and TP, were provided as supporting information in Zhang et al. (2016).

Results

Concentration of nutrients and pH in freshwater sediment

The distributions of TOC, TN, TP, and TS are shown in Fig. 2. The average concentration of TP (0.64 ± 0.07 g/kg) was above the soil background value (0.52 g/kg). The IP was the main component of the TP, which was 0.53 ± 0.07 g/kg (79.33% ± 1.22 of the TP). The highest TP concentration was in HRB (1.22 ± 0.31 g/kg), and most of the TP was IP

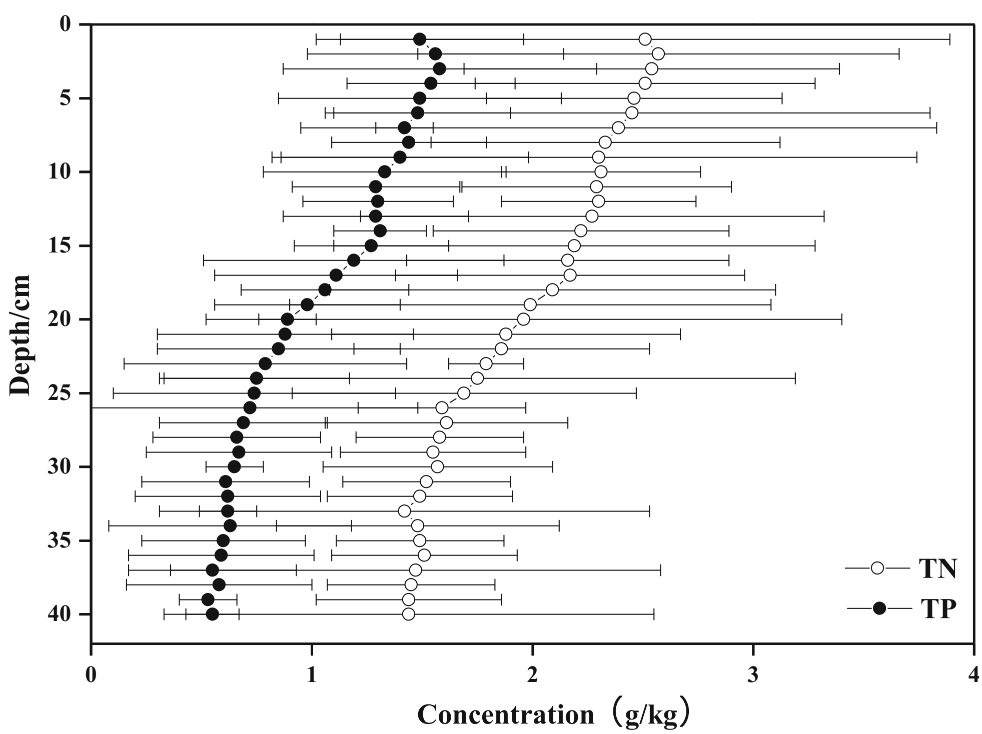

Fig. 3 The temporal variation of total nitrogen and total phosphorus in eastern China

(1.10 ± 0.30 g/kg, 85.40% ± 2.42). TP concentrations were also higher than background values in SHJRB and YRB. Concentrations in the other five basins were below soil background value. The average concentration of TN (1.48 ± 0.17 g/kg) was above the soil background level. The concentration of TN was above the soil background value in all the basins. The TN and TP concentrations were the same as in other studies (Liu et al. 2007; Sun et al. 2007; Yue et al. 2007; Bai et al. 2009; Wu et al. 2011; Wang et al. 2012; Piao et al. 2015). Average TS concentration (1.27 ± 0.21 g/kg) in sediment was also above the soil background value (0.15 g/kg). The average TOC was 3.11% ± 0.19, and varied with each basin. The highest TOC values occurred in MDNRB (4.34% ± 0.51), HuRB (4.23% ± 0.63), and PRB (3.82% ± 0.40). For the sediment core, average TP in sediment core ranged from 0.53 to 1.58 mg/kg, and average TN in sediment core ranged from 1.44 to 2.57 mg/kg. The obvious change about the TP and TN was from about 30 cm in depth (Fig. 3). Values of pH ranged from 4.56 to 8.94, and the average pH was 7.70 ± 0.07. The highest pH (8.56 ± 0.17) appeared in YRB basin, while the lowest pH (6.44 ± 0.43) was found in MDNRB.

Characteristics of SQGs, OPI, and ONI in freshwater sediment

The results for SGQs, OPI, and ONI are shown in Tables 1 and 2 and Fig. 4. ONI in freshwater sediment was 0.14% ± 0.02, indicating heavy contamination. The highest and lowest ONI values were 0.22% ± 0.04 and 0.07% ± 0.02, which were found in HRB and LRB, respectively. The OPI in the freshwater sediment was 0.65% ± 0.13. The highest OPI was found in HRB (1.00% ± 0.26), where the lowest was found in LRB (0.20% ± 0.09). Of all the samples, 48.4 and 72.5% exceeded the soil background values in TP (0.52 g/kg) and TN (0.64 g/kg), respectively. For HBR, 89.5% of the samples were within the soil background value of TP and TN. For SQGs, 58.2% of samples were rated I-TP grade, and 3.3% of the samples were rated III-TP grade. The remaining samples were rated II-TP grade. In HRB, 15.8 and 68.4% of the total samples were rated III-TP and II-TP grades, respectively. For other basins, 90% of samples were at the low impact level (II-TP). For SQGs of TN, many samples were rated I-TN grade (25.3%) and II-TN (69.2%), while only 5.5% of the total sediment samples were rated severe impact level (III-TN). The SQGs in HRB were higher than in other basins. For the study area, 84.2 and 10.5% of the samples were rated II-TN and III-TN grades, respectively. In YRB, 80% of the samples were rated II-TN grade.

Discussion

Characteristics of nutrients and relationships between each of them

Many natural processes and human activities, such as rainfall, wastewater, agriculture practices, and change of land use (Moore and Jackson 1989), can increase TOC in freshwater sediment. The high TOC content in sediment in eastern China was mainly caused by intensive agriculture and wastewater. The relationship between TOC and TN ($R^2 = 0.776$, $p < 0.01$), TP ($R^2 = 0.267$, $p < 0.05$), and TS ($R^2 = 0.607$, $p < 0.01$) indicated the same pollution source (Table 3). The existence of N and P in sediment has two forms: inorganic and organic. The organic forms may be the components of the organic matter, and the inorganic forms may be adsorbed by the POC (Liu and Lee 2007). Eutrophication induced by large amounts of P and N will create large numbers of aquatic plants. The plant debris will decompose and release not only P and N but also TOC. The synergy between TOC and nutrients will cause the water quality to further deteriorate because eutrophication and the overload of TOC can cause an oxygen deficit in freshwater ecosystems and affect aquatic organisms. Sulfate is the dominant electron acceptor in the oxidation of organic carbon through dissimilatory sulfate reduction in oxygen-depleted water environments (Panutrakul et al. 2001). H_2S produced from the organic matter oxidation process is partially lost through atmospheric emission, and sulfur will react with reactive metals to form stable metal sulfides, such as FeS and FeS_2, under anaerobic conditions. In most of the basins in eastern China, the sulfur content was above the soil background value (0.15 g/kg), and large amounts of sulfur will form stable metal sulfides in sediment under anaerobic condition at the water-sediment interface.

Because of the important environmental impacts, the relationships between pH and TN, and TP and TS, were also analyzed. Jin et al. (2006) suggested that pH in overlying water and sediments was the predominant factor because it affected sorption-adsorption, precipitation-solubilization, and oxidation-reduction reactions by controlling the concentrations of available iron, aluminum, and calcium, and thus directly or indirectly changed the aquatic, biological, and chemical reactions. However, in this study, a negative relationship was found between pH and TN ($R^2 = 0.12$, $p < 0.001$), and there were no relationships between pH and TS, and pH and TP, which demonstrated that pH was not a vital factor affecting nutrient distribution and concentration. Previous studies in freshwater sediment suggested that pH was a vital controlling factor for the existence and transformation of P, N, and S. Non-calcareous sediments are efficient sorbents of P because of the presence of oxyhydroxides of Fe and Al, which have a

Table 1 Comparison of TP and TN in freshwater sediment in eastern China to soil background value and sediment quality guidelines (%)

	ECB[a]	SHJRB	LRB	HRB	YRB	HuRB	YzRB	MDNRB	PRB
TP									
Samples > soil background value[b]	48.4	70.0	12.5	89.5	60.0	20.0	39.1	25.0	50.0
Samples < lowest effect level[c] (I-TP)	58.2	50.0	100.0	15.8	40.0	90.0	69.6	75.0	58.3
Lowest effect level < samples < severe effect level (II-TP)	38.5	50.0	0.0	68.4	60.0	10.0	30.4	25.0	41.7
Samples > severe effect level (III-TP)	3.3	0.0	0.0	15.8	0.0	0.0	0.0	0.0	0.0
TN									
Samples > soil background value	72.5	70.0	37.5	89.5	20.0	70.0	73.9	75.0	91.7
Samples < lowest effect level (I-TN)	25.3	30.0	50.0	5.3	80.0	30.0	26.1	25.0	8.3
Lowest effect level < samples < severe effect level (II-TN)	69.2	70.0	50.0	84.2	20.0	60.0	65.2	75.0	91.7
Samples > severe effect level (III-TN)	5.5	0.0	0.0	10.5	0.0	10.0	8.7	0.0	0.0
TS									
Samples > soil background value	89.4	100.0	75.0	100.0	40.0	80.0	87.0	100.0	100.0

[a] Eastern China Basin

[b] Soil background value of China

[c] Sediment quality guidelines in Ontario

high affinity for P, and are sensitive to pH. The P-binding capacity of non-calcareous sediments increases with acidity because of the protonation of surface Fe and Al functional groups in clay and in oxides and in hydroxides of Fe and Al. For calcareous sediments, the influence of pH on P sorption is often associated with the sorption by $CaCO_3$. The reaction of P with calcite involves a surface adsorption that consumes H^+ ions, followed by precipitation of $CaHPO_4{\cdot}2H_2O$ with higher P concentrations. A high pH in a lake-water column could result in enhanced photosynthetic activity, withdrawing CO_2 from the water, and shifting the $CO_2{\cdot}HCO_3^-{\cdot}CO_3^{2-}$ equilibrium that controls pH. In this study, the negative correlation between the OP and pH indicated that the alkalinity of the environment might enhance OP mineralization. The biological, chemical, and physical processes involved in the loss of N from the sediment include (1) mineralization of organic N, (2) nitrification of $NH_3{\cdot}N$, (3) NH_3 volatilization, and (4) denitrification. Some research showed that under anaerobic conditions and a low pH (pH <6), ammonium was easily released into the overlying water, potentially triggering algal blooms. Conversely, aerobic conditions and a high pH (pH = 10) promoted nitrate release from the sediment. This phenomenon was caused by sufficient H^+ under acid conditions (pH <6) to inhibit the activity of nitrifying bacteria at the water-sediment interface, thus resulting in a slower rate of conversion from ammonium to nitrate. A pH of 8 facilitates the

Table 2 OPI and ONI in freshwater sediments in eastern China (%)

	ECB[a]	SHJRB	LRB	HRB	YRB	HuRB	YzRB	MDNRB	PRB
OPI									
Uncontaminated	16.3	0.0	37.5	5.3	60.0	10.0	4.3	25.0	0.0
Mildly contaminated	75.0	27.3	12.5	10.5	40.0	20.0	21.7	25.0	8.3
Moderately contaminated	7.6	54.5	12.5	36.8	0.0	30.0	56.5	25.0	66.7
Heavily contaminated	1.1	18.2	37.5	47.4	0.0	40.0	17.4	25.0	25.0
ONI									
Uncontaminated	14.1	9.1	50.0	5.3	80.0	10.0	8.7	0.0	0.0
Mildly contaminated	48.9	63.6	25.0	47.4	0.0	20.0	65.2	50.0	66.7
Moderately contaminated	17.4	27.3	25.0	5.3	0.0	40.0	13.0	50.0	8.3
Heavily contaminated	19.6	0.0	0.0	42.1	20.0	30.0	13.0	0.0	25.0

[a] Eastern China Basin

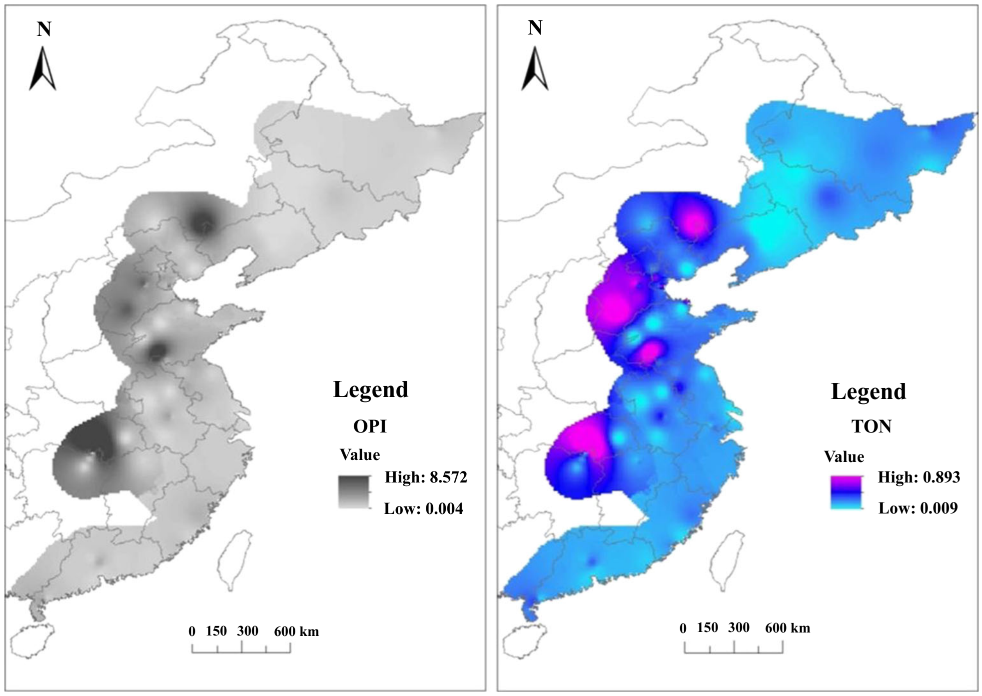

Fig. 4 The distribution of OPI and TON in eastern China

growth and metabolism of nitrifying bacteria (Zhang et al. 2014a). As a dominant electron acceptor, sulfide can be oxidized abiotically with O_2, Fe oxides, and Mn oxides, producing a combination of oxidation products, including S^0, $S_2O_3^{2-}$, SO_3^{2-}, and SO_4^{2-}, by bacteria or some sulfate reducers, which is also affected by the pH of sediment (Canfield and Thandrup 1996). From the above analysis, it is clear that the role of pH is better understood by considering rivers and lakes at small scales rather than at the national scale.

Assessment of sediment quality

Overall, TP, TN, and TS concentrations (48.4, 72.5, and 89.5%, respectively) in the sediment samples were higher than soil background values. On the whole, SHJHR, HRB, and PRB were seriously contaminated. In terms of the Ontario sediment quality guidelines, 38.5% of the sediment samples were rated grade II and 3.3% was rated grade III in TP. Of the samples, 69.2% were rated grade II and 5.5% were rated grade III in TN, which indicated that the sediment was severely polluted. At the basin level, HRB, YzRB, and PRB were much more severely contaminated than the other basins. The pollution levels of TN (74.7% above the lowest impact level, and 5.5% above the severe impact level) were more severe than TP (41.8% above the lowest impact level, and 3.3% above the severe impact effect level) in the freshwater sediment, which was consistent with the pollution levels in the basins (Table 2). Overall, 83.7% (OPI) and 85.9% (ONI) of the sediment samples exceeded the low-contaminated level, and 19.6% (ONI) reached the heavily contaminated level. HRB, HuRB, and PRB were seriously contaminated with both OPI and ONI (Fig. 4). The assessment result was the same as the other studies (Yang et al. 2017).

Table 3 Pearson correlation coefficients for physicochemical characteristics and nutrients in sediment in eastern China

	TN	TP	TS	TOC	pH	OPI	ONI
TN	1	0.345**	0.766**	0.776**	−0.149	0.948**	1.000**
TP		1	0.242*	0.267*	−0.051	0.271**	0.342**
TS			1	0.607**	0.000	0.738**	0.767**
TOC				1	−0.347**	0.780**	0.776**
pH					1	−0.114	−0.150
OPI						1	0.950**
ONI							1

*Significant at the 0.05 level (two-tailed)

**Significant at the 0.01 level (two-tailed)

HRB, YzRB, HuRB, and PRB are located in the most developed region of China, which is densely populated and whose social-economic development is increasing rapidly. Land use style has changed dramatically in these basins in recent decades. The rapid urbanization rate and intensive agriculture were the dominant two factors inducing nutrient accumulation in freshwater sediments. The urbanization rate has tripled in the last 20 years—from 19.0% in 1995 to 56.1% in 2015. Large amounts of wastewater flow into rivers, lakes, and wetlands without treatment because of insufficient treatment facilities (Li et al. 2012; Pernet-Coudrier et al. 2012). This region of China previously had a traditional agriculture-based economy with a century-old history of cultivation based on a sufficient water supply and agricultural knowledge (Qin and Chen 1996; Zhang and Shan 2008). Agriculture cultivation in this area has intensified in response to the steady increase in population and the relative scarcity of land (Paoletti et al. 1999). Increased agricultural activity involves the intensive use of fertilizers and large quantities of fertilizer runoff, and only 10–20% of the nutrient applied are used by the first crop cycle (Sattari et al. 2012). The excessive and unused fertilizer application causes serious environmental problems, such as cropland acidification and eutrophication (Ju et al. 2009; Guo et al. 2010; Zhang et al. 2013). This phenomenon is common in eastern China, especially in HRB, YzRB, and PRB. A large amount of nutrient from agriculture flow into freshwater bodies and damage the sediment quality.

Temporal variation of total nitrogen and total phosphorus in eastern China

The distribution of TP and TN in the sediment core could affect the history changed in the freshwater sediment in eastern China. According to the studies, we deduced that the deposition rate was about 1 cm/year in freshwater sediment in eastern China (Zhang and Shan 2008; Zhang et al. 2010; Zhu et al. 2010). The dramatic increase of TP and TN started from 1980s. In eastern China, agriculture activity was intensified greatly, and population increased since 1980s, which had resulted in extensive application of fertilizers to the farmlands and large amounts of untreated sewage discharged into the watershed. Large amounts of P and N were discharged into rivers, lakes, and reservoirs with the fertilizers and sewage (Zhang and Shan 2008; Tang et al. 2010). This phenomenon increases the risk of environmental problems, such as eutrophication, which made the freshwater sediment deteriorate since 1980s in eastern China.

As typical population intensified, industry and agriculture developed, and water environment deteriorated basins, we chose the HRB to observe the trends in sediment quality (SI Fig. 1). All of the indices indicated that the sediment quality of HRB was poorer than the other basins. Data from 2007 to 2016 showed that concentrations of TN and TP were continuously increasing: from 2.06 to 2.51 g/kg, and 1.02 to 1.22 g/kg, respectively. The ONI was increased from 0.20 to 0.24% in this period. The TN pollution level was higher than TP, which supported our prediction that TN would increase faster than TP according to its relative tendency (TN variation gradient = 0.0517; TP variation gradient = 0.0183). In other words, nutrients such as P and N will consistently accumulate in sediment (Powers et al. 2016). Our study and other research indicated that large amounts of wastewater and pollutants flowed into the freshwater ecosystem as a result of population increases, economic development, and land use changes (Li et al. 2012; Pernet-Coudrier et al. 2012; Zhang et al. 2016). The accumulated N and P may continue to mobilize after the input declines. The continuously deteriorating sediment quality and the construction of dams destroy the river integrity, reduce freshwater health, and consequently affect social-economic development (Zhang et al. 2014b; Taylor et al. 2015; Zhang et al. 2017).

Conclusions

The distribution and concentration of sediment nutrients TP, TN, TS, and TOC in freshwater ecosystems in eastern China was investigated. The SQGs, OPI, and ONI were used to assess the sediment quality. The results indicated that 48.4, 72.5, and 89.5% of the sediment samples had exceeded the soil background value for TP, TN, and TS. In terms of the Ontario SQGs, 41.8% of the sediment samples were classified as grade II and III in TP; 74.7% of the samples were rated grade II and III in TN, indicating that the sediment was severely polluted. HRB, YzRB, and PRB were found to be much more severely contaminated than other basins in SQGs. Overall, 83.7% (OPI) and 85.9% (ONI) of the sediment samples exceeded the mild-contamination level and 19.6% (ONI) of the sediment samples were classified as heavily contaminated. The basins HRB, HuRB, and PRB were the most seriously contaminated for both OPI and ONI. The dramatic increase of TP and TN started since 1980s. Concentrations of TN and TP were continuously increasing in HRB, which is one of the most severely contaminated basins in eastern China. The TP pollution level was lower than that of TN. We also predicted that without effective control of the contamination, TN would increase faster than TP according to its relative tendency (TN variation gradient = 0.0517; TP variation gradient = 0.0183). The freshwater sediment quality situation in eastern China is very serious and requires urgent attention.

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