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Forms, migration and transportation of nitrogen in sediments and suspended solids of endogenous nutrient-controlled lakes

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ABSTRACT

A case study was conducted in Lihu Lake, a typically shallow algal lake, to explore the constituent difference, migration, and transformation characteristics of nitrogen in sediments and suspended solids in endogenous nutrient-controlled lake. The lake maintains a mild eutrophic state though external pollution sources have remained under control, which is mainly due to sediment release. Components of exchangeable nitrogen (EN), hydrolyzable nitrogen (HN), and residual nitrogen (RN) in suspended solids and surface sediments were analyzed by sequential extraction method. The spatial distribution, diversity, migration, and transformation characteristics of nitrogen were discussed. Contents of the total nitrogen in suspended solids and sediments were 758.85–2,998.00 mg/kg and 556.34–2,551.14 mg/kg, respectively, and showed a decreasing trend from east to west. Contents of EN, HN, and RN in suspended solids were 166.94, 795.04, and 723.31 mg/kg, respectively, and soluble organic nitrogen and hydrolyzable unknown nitrogen were the major components for EN and HN, respectively. Values of EN, HN, and RN in sediments were 153.61, 707.12, and 467.32 mg/kg, respectively, and ion-exchangeable NH_4^+-N and ammonium nitrogen were the major components for EN and HN, respectively. The nitrogen in sediments was more bioavailable than that in suspended solids. The suspended solids were mainly derived from the sediment resuspension. The suspended solids acted as media continually carrying nitrogen from the sediments into water, and supported the high nitrogen in water for a long time.

Keywords: Endogenous nutrient; Sediment; Suspended solid; Nitrogen form; Sediment resuspension; Lihu Lake

1. Introduction

Nitrogen is one of the key limiting nutrients in primary productivity of water [1]. Nitrogen is also a key factor that causes eutrophication [2–4]. Sediment is an important sink for nitrogen in lakes. The release of the endogenous nitrogen becomes one of the major influence factors for eutrophication after exogenous pollution sources are controlled [5–9]. The constitution and content of nitrogen in sediments can directly affect the geochemistry cycling and environmental quality of nitrogen in lake water ecosystem [10–14]. The exchangeable nitrogen (EN), which can be directly absorbed and utilized by the primary producers to speed up the mineralization process of organic nitrogen (ON), is the most active part of nitrogen in sediments [10,15,16]. The hydrolyzable nitrogen (HN) is the main form of ON in lake sediments, and can be hydrolyzed by strong acid into ammonium nitrogen

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(AN), amino-acid nitrogen (AAN), amino-sugar nitrogen (ASN), and hydrolyzable unidentified nitrogen (HUN). The HN can be absorbed and utilized by the submerged macrophytes and algae by mineralization, which has significant impacts on the nitrogen supply for the alga and the eutrophication [16]. The endogenous nitrogen releases through the sediment–water interface mainly by two ways: sediment resuspension and interstitial water diffusion. The sediment resuspension is an important process for the migration and transformation of nitrogen. The nitrogen in sediment surface penetrates the water with the suspended solids as carrier, and causes a second water pollution.

Suspended solid refers to the totality of plankton and non-living particles in general, and mainly comprises insoluble organic matter (OM) and sediment, clay, and microorganisms [17]. As an important part of the water environment, suspended solid plays an irreplaceable role in the circulation, migration, and fate of the entire lake ecosystem. On the one hand, the suspended solid acts as a buffer source. The nitrogen, phosphorus, heavy metals, and other pollutants undergo a series of migration and transformation process in the suspended solid–water interface by adsorption, desorption, precipitation and dissolution. On the other hand, the suspended solid acts as a transmission medium. Suspended solid directly participates in the transformations of nitrogen, phosphorus, and other biogenic elements between sediments and water through the resuspension and flocculation sedimentation [1,15,18,19]. Hence, studies in the formation of nitrogen, phosphorus and other biogenic elements in suspended solids and sediments and the differences among these elements have considerable practical significance for exploring the migration and transformation rules of the pollutants in lakes and basins. However, studies on the lake nitrogen mainly focused on the water and sediments, whereas studies on nitrogen forms in suspended solids, especially in the sediments in endogenous nutrient–controlled lakes are limited. Therefore, the contribution of suspended solids to eutrophication remains unclear. Comprehensive understanding of the migration, transformation, and cycling mechanism of the nitrogen between different media in lake basins with high nitrogen load on the aquatic ecosystem of plateau fresh lakes is difficult.

Lihu Lake is a typical shallow lake, which changes from macrophyte-dominated clear water into algae–dominated turbid water due to human activities, and is then gradually restored by artificial restoration. The deterioration trend of the water quality has been effectively curbed after more than 10 years of water environment comprehensive management. However, the suspended solids remain at a high level, and the concentration is higher than 20 mg/L in summer and spring [16]. In addition, a considerable number of algae and plant residues deposited into the bottom of the lake in recent years, and mixed with inorganic clay minerals, thereby forming a low density and high organic sludge layer. The sludge layer is semi-soluble, and is easily suspend by the disturbances of waves, fishes, and boats. Undoubtedly, this will pose a certain impact on the water quality. The main objectives of this study are as follows: (1) to study and analyze the differences of nitrogen forms in sediments and suspended solids and (2) to explore the migration and transformation rules of nitrogen between sediments and suspended solids. This study can provide new insights into the water environment management of endogenous nutrient–controlled lakes.

2. Materials and methods

2.1. Study area

Lihu Lake (120.22–120.29°E, 31.48–31.55°N) is a lake in the northern part of Taihu Lake, which is approximately 6 km long from east to west and 0.3–1.8 km wide from north to south with an area of approximately 8.6 km^2. The lake is linked to the Meiliang Bay via the Liangxi River Floodgate and Wuli Lake Floodgate, and connected with the Grand Canal and Gonghu Lake by Caowangjing River and Changguangxi River. A few small rivers and broken bends can also be found around the lake. Lihu Lake is relatively independent but also connected with Taihu Lake.

In this study, Lihu Lake was divided into four regions (A, B, C, and D) by boundaries of Lihu Dyke, Baojie Bridge, and Lihu Big Bridge. Numerous fishponds could be found in Areas A, and the polluted sediments in the area were dredged after the water was pumped empty. The dredging depth of sediments is at least 1 m, therefore, the water depth is relatively higher than that of other areas. Area A acts as a recreation zone with good water quality. The polluted sediments in the northwest of Area B were dredged, and the dredging depth was 0.2–0.5 m. Projects for aquatic vegetation reconstruction were also carried out along the bank sides. Therefore, the submerged macrophytes recover well and the water quality is good in Area B. Only a small area of polluted sediments was polluted in the southwest of Area C, and the dredging depth was less than 0.5 m. Coast renovation projects were also conducted. During summer and autumn in Area C, floating plants frequently appear and deposit in sediments after death. The sewage interception and coast renovation projects were conducted in Area D, except for the sediment dredging project. In addition, many residential areas exist in Area D; therefore, the water quality in this area is worse than other areas.

2.2. Sample collection and treatment

A total of 24 sampling points was set in Lihu Lake on October 1, 2014, as shown in Fig. 1. At each sampling point, 40 L of water was collected into a clean plastic tub using a plexiglass hydrophore at a depth of 0.5 m. The water samples were immediately sent to our field station and filtered using pre-combusted (450°C for 5 h) glass fiber filters (GF/F, Whatman). The filters were then freeze-dried at –50°C to obtain suspended matter samples. Eight 2 cm surface sediments of parallel samples were collected by a columnar sampler (04.23 BEEKER, Eijkelkamp, NL, Φ = 12 cm) at each sampling point and mixed on site. The sediment samples were stored at 4°C. The 250 g of fresh sediment samples were put into clean centrifuge tubes and then centrifuged at 1,000 rpm for 10 min. The supernatants were filtered through a mixed fiber filter membrane (porosity = 0.45 μm) to obtain the interstitial water samples. The samples were stored at 4°C. The surface sediment samples were dried using the vacuum freeze-drying equipment at –50°C and then sifted through a sieve (100 mesh, 0.149 mm).

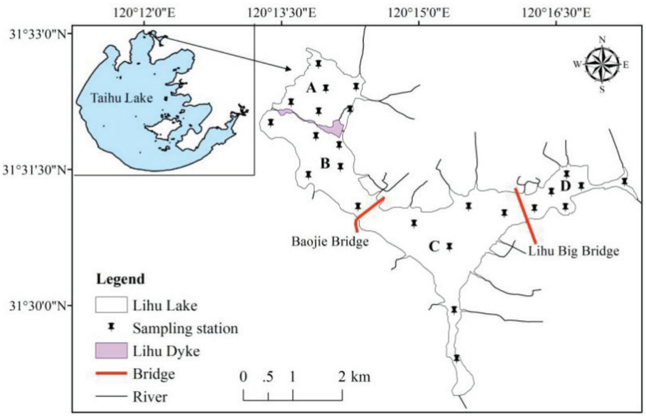

Fig. 1. Location of suspended solids and sediment sampling stations in Lihu Lake.

2.3. Analysis methods

2.3.1. Sequential extraction of nitrogen forms

The nitrogen fractions were analyzed by the modified sequential extraction method of Wang et al. [20], and the nitrogen in sediments or suspended solids was divided into the following three forms: EN, HN, and residual nitrogen (RN). EN mainly contains ion-exchangeable ammonia nitrogen (E-NH_4^+-N), NO_3^--N (E-NO_3^--N), and soluble organic nitrogen (SON). SON contents were calculated using the following formula: SON = ETN—E-NO_3^--N—E-NH_4^+-N. The HN comprised AN, AAN, ASN, and HUN. The amount of HUN was equal to acid hydrolyzable total nitrogen (HTN) minus the sum of AN, ANN, and ASN. The extraction process comprised the following three steps.

Step 1: EN was extracted by adding 100 mL KCl (2 mol/L) into 5 g of sediment or suspended solid sample. The mixture was shaken for 2 h and then centrifuged at 5,000 rpm for 15 min. The supernatant was successively filtered through 0.45 μm filter membrane. The residues were freeze-dried and kept for the HN extraction in the next step. Exchangeable total nitrogen (ETN) in the filtrate was analyzed by alkaline potassium persulfate digestion–UV spectrophotometric method [21]. Exchangeable AN (E-NH_4^+-N) was analyzed by Nessler's reagent spectrophotometry method [22]. Exchangeable nitrate nitrogen (E-NO_3^--N) was analyzed via ultraviolet spectrophotometry method [23]. Contents of SON were calculated using the formula: SON = ETN—E-NO_3^--N—E-NH_4^+-N.

Step 2: HN was extracted by adding 40 mL HCl (6 mol/L) and 2 g residues of step 1 in a clean centrifuge tube. The tube was then sealed and hydrolyzed at 120°C in a drying oven for 24 h. The mixture was centrifuged at 5,000 rpm for 15 min, and then the supernatant was filtered through 0.45 μm filter membrane. The filtrate was transferred into a porcelain crucible. The residue was cleaned with ultrapure water several times and the filtrates were transferred into the same porcelain crucible. The residue was freeze-dried and kept for the RN extraction in the next step. The filtrate was heated (120°C) to clean the HCl, and the pH was then adjusted to 7.5 ± 0.2. The HTN, AN, AAN, and ASN in the filtrate were analyzed by alkaline potassium persulfate digestion–UV spectrophotometric method [21], Nessler's reagent spectrophotometry method [22], ninhydrin colorimetric method, and Elson–Morgan method [20], respectively.

Step 3: RN was extracted by adding H_2SO_4 and accelerator into the cleaned residue of step 2, and the concentration of HN was analyzed using an automatic Kjeldahl apparatus (Foss 2300, Swiss).

2.3.2. Nitrogen adsorption thermodynamics experiment

The sediment sample was mixed with the NH_4Cl solution with a concentration gradient of 0, 0.15, 0.2, 1, 1.5, 2, 4, and 8 mg/L. The ratio of sediment mass to NH_4Cl solution volume was 1:100. The mixed solution was vibrated for 2 h at 25°C and then centrifuged at 5,000 rpm for 15 min. The supernatant was filtered through 0.45 μm filter membrane. The content of ammonia nitrogen (NH_4^+-N) in the filtrate was analyzed.

The nitrogen adsorption amount of sediment unit mass (Q, g/kg) was calculated by the following formula:

$$Q = \left(C_0 - C_e\right) \times V / m \quad (1)$$

where C_0 corresponds to the concentration of ammonia nitrogen in the original solution, mg/L; C_e corresponds to the concentration of ammonia nitrogen in the solution at the end of the experiment, mg/L; V corresponds to the volume of NH_4Cl solution added to the sediment sample, L; and m corresponds to the mass of the sediment, g.

The adsorption–desorption equilibrium concentration of nitrogen (EC_0) was calculated by the regression method. The EC_0 value was equaled to the concentration of NH_4^+-N concentration when the Q value was zero.

2.4. Data processing

All samples were analyzed three times in parallel, and the test results were expressed as the average value (the error was <5%). The standard sediment (GBW07303a) was simultaneously analyzed, with the recovery rate ranging from 90% to 107%. The statistical treatment, plotting, and analysis of the experimental data were completed by ArcGIS 10.2, Excel 2010, Origin 9.0, and SPSS 19.0 software.

3. Results

3.1. Comparative analysis of TN in suspended solids and surface sediments

The spatial distribution of TN in suspended solids and sediments showed a similar trend: decreasing from east to west of the lake (Fig. 2). The high values mainly concentrated in Area D and the Changguangxi area of Area C.

The content of TN in suspended solids ranged from 758.85 to 2,998.00 mg/kg, with an average value of 1,685.29 mg/kg. The maximum value appeared at sampling point 15 in Area C while the minimum value appeared at sampling point 4 in Area A. The mean concentrations of TN in Areas A, B, C, and D were (1,013.00 ± 332.98), (1,284.88 ± 340.62), (2,002.49 ± 532.17), and (2,440.80 ± 174.99) mg/kg, respectively. The content of TN in sediments ranged from 556.34 to 2,551.14 mg/kg,

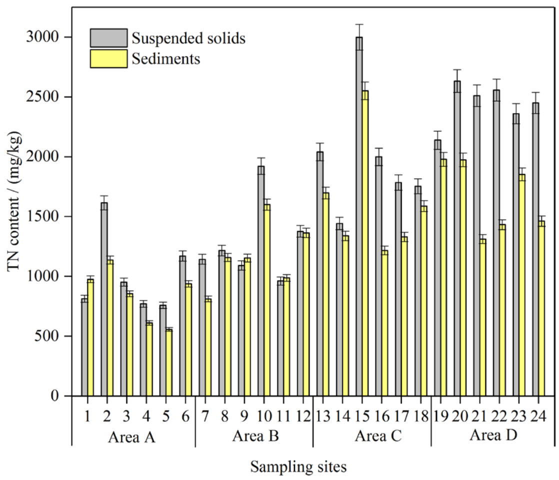

Fig. 2. Spatial distribution of TN in suspended solids and surface sediments of Lihu Lake.

with the mean of 1,328.06 mg/kg, which was significantly lower than that of suspended solids (P < 0.05). The TN distribution in sediments is presented in the following order: Area D > Area C > Area B > Area A. However, an insignificant difference existed between the TN in Area D (1,668.16 ± 299.35 mg/kg) and Area C (1,619.91 ± 490.00 mg/kg).

The TN contents in suspended solids and sediments were higher in Areas D and C than those in Areas B and A. This spatial distribution characteristic agreed with the degree of water environment management in different regions of Lihu Lake. The nitrogen in sediments of Areas A and B has been reduced to a considerable extent due to the implemented environmental management projects, including sediment environmental dredging, aquatic vegetation reconstruction, and returning fishery to lake projects. The restored submerged macrophytes also absorbed a certain amount of nitrogen in sediments and restrained the sediment resuspension. However, many residential areas exist in Areas C and D, especially in the east export of the lake. The residents have a direct impact on water and sediment qualities.

3.2. Comparative analysis of EN in suspended solids and surface sediments

The EN is the most active nitrogen form for sediments or suspended solids. EN maintains a dynamic balance with water by adsorption–desorption, ion exchange, or bioturbation, and plays a key role in the nitrogen cycling in sediments or suspended solids [17,24,25]. The spatial distribution of EN in the lake sediments and sediments is shown in Fig. 3.

The ETN in suspended solids ranged from 63.52 to 302.53 mg/kg, with an average value of 166.94 mg/kg. The ETN value in Area D was higher, but the values in Areas A, B, and C insignificantly varied (P > 0.05). The mean values of E-NH_4^+-N, E-NO_3^--N, and SON were 46.55 ± 30.63, 17.06 ± 8.22, and 103.32 ± 35.72 mg/kg, respectively.

The ETN in sediments was 33.42–431.19 mg/kg (the average was 153.61 mg/kg). The mean ETN in sediments of Areas A, B, C, and D were 84.95 ± 47.94, 90.24 ± 16.17, 193.59 ± 131.88, and 245.66 ± 54.76 mg/kg, respectively, thereby presenting a significant spatial distribution. The mean values

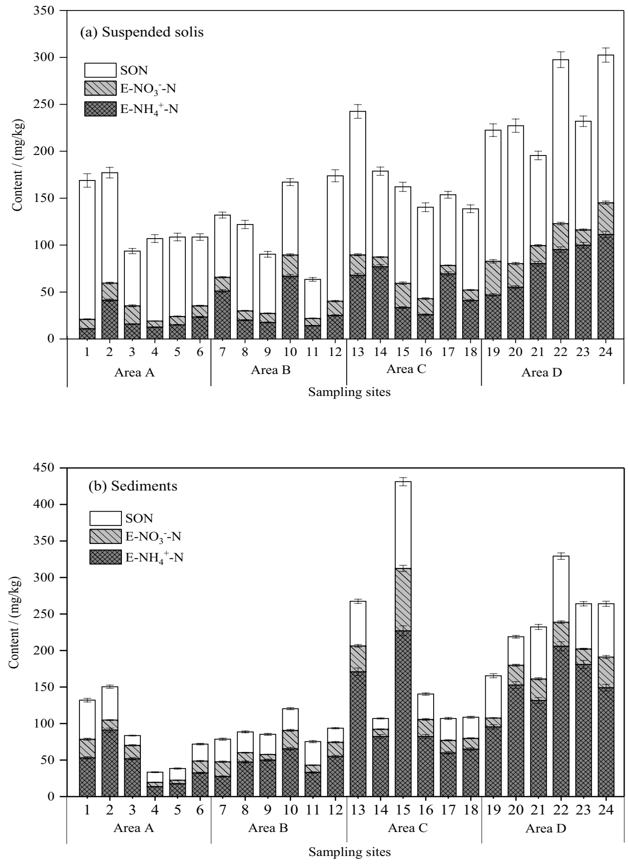

Fig. 3. Spatial distribution of EN in suspended solids and surface sediments of Lihu Lake.

of E-NH_4^+-N, E-NO_3^--N, and SON were 89.19 ± 61.68, 22.18 ± 16.50, and 42.24 ± 26.57 mg/kg, respectively. The value of E-NH_4^+-N was significantly higher than that of suspended solids (P < 0.01).

3.3. Comparative analysis of HN in suspended solids and surface sediments

The HTN in suspended solids ranged from 421.13 to 1,400.86 mg/kg, with an average value of 795.04 mg/kg. The HTN showed a spatial distribution trend that decreases from east to west, and the values near the estuaries were higher than those of the lake region (Fig. 4(a)). The contents of AN, AAN, ASN, and HUN were 46.14–363.77, 30.78–232.29, 14.99–49.50, and 302.53–782.57 mg/kg, respectively, and the relative ratio of the mean content was 5.63:3.16:1:18.06. The HTN in surface sediments was 437.91–1,156.33 mg/kg, with an average value of 707.12 mg/kg (Fig. 4(b)). The contents of AN, AAN, ASN, and HUN were 208.28–621.09, 93.25–411.46, 7.67–58.34, and 36.30–261.97 mg/kg, respectively, and the relative ratio of the mean content was 13.44:8.98:1:5.21.

A certain amount of AN appeared in the process of acid hydrolysis of suspended solids and sediments, especially for sediments. The ratio of AN taking HTN in sediments (46.72%) was significantly higher than that of suspended solids (19.07%). The main sources of AN are as follows [26]:

(1) the release of the fixed ammonia (the ammonia inlayed in the 2:1 clay mineral crystal layer) in suspended solids or sediments; (2) the protein degradation during hydrolysis; (3) the deamination of a few amino acids, especially aspartic acid, glutamic acid, sulfur-containing amino acid, and amino sugar; and (4) the decomposition of amide compounds. Identifying the amount of AN in the acid hydrolysis from amino acid or amide compounds is difficult. However, studies [20] showed that contents of OM and fixed ammonia are important influencing factors of AN. AAN, as one of the main identifiable nitrogen-contained organic compounds, is the stable and most effective contributor of mineralized nitrogen [14,27]. In this study, the ratio of AAN taking HTN in suspended solids (10.31%) was significantly ($P < 0.01$) lower than that of sediments (31.06%). AAN is derived from the decomposition of protein and polypeptide in OMs; hence the content of OM and its components directly affect the AAN content. ASN is mainly derived from the cell materials of microorganisms and aquatic insects [26], whose main component is glucosamine nitrogen, followed by lactose amino nitrogen. The sum of the two amines is close to the content of amino sugar nitrogen. In this study, the relative proportions of ASN in suspended solids (3.90%) and surface sediments (3.59%) were relatively small, with no significant difference ($P > 0.05$). HUN is a sol-like nitrogen compound derived from the amino acid condensation during the decomposition process of OM or humus [28]. The relative proportions of HUN in HTN for suspended solids (66.72%) were significantly ($P < 0.01$) higher than those of surface sediments (18.63%).

3.4. Comparative analysis of RN in suspended solids and surface sediments

In the sediments, RN mainly exists in organic heterocycles or organic nitrogen binding to heterocyclic or aromatic rings. This part of nitrogen mainly comes from humic structural components with high degree of condensation [29,30]. The spatial distribution of RN in suspended solids and surface sediments in Lihu Lake is shown in Fig. 5.

The content of RN in suspended solids ranged from 189.00 to 1,435.00 mg/kg, with an average value of 723.31 mg/kg. The spatial distribution of RN showed a decreasing trend from east to west, and the values near the estuaries were higher than those of the lake region (Fig. 5). The RN in the surface sediments ranged from 78.00 to 986.30 mg/kg, with a mean value of 467.32 mg/kg. The distribution of RN in sediments was similar to that of suspended solids.

4. Discussion

4.1. Correlation analysis between the different nitrogen forms in suspended solids and surface sediments

Lihu Lake is an urban lake formed by Taihu Lake stretching into the land. The lake is a typically small shallow lake with an average water depth of approximately 2.25 m. The concentrations of nitrogen, phosphorus, and permanganate index significantly decreased after nearly 10 years of environmental improvement. However, the concentration of the suspended solids did not increase, and the value is above 20 mg/L in summer and autumn [16]. Lihu Lake is isolated from the surrounding polluted rivers, and the particles from the exogenous rivers can be ignored [16]. Hence, the suspended solids in the water were mainly derived from the sediment resuspension due to wind wave and the decayed residues of planktons and hydrophytes. The TN, ETN, HTN, and RN in sediments were significantly and

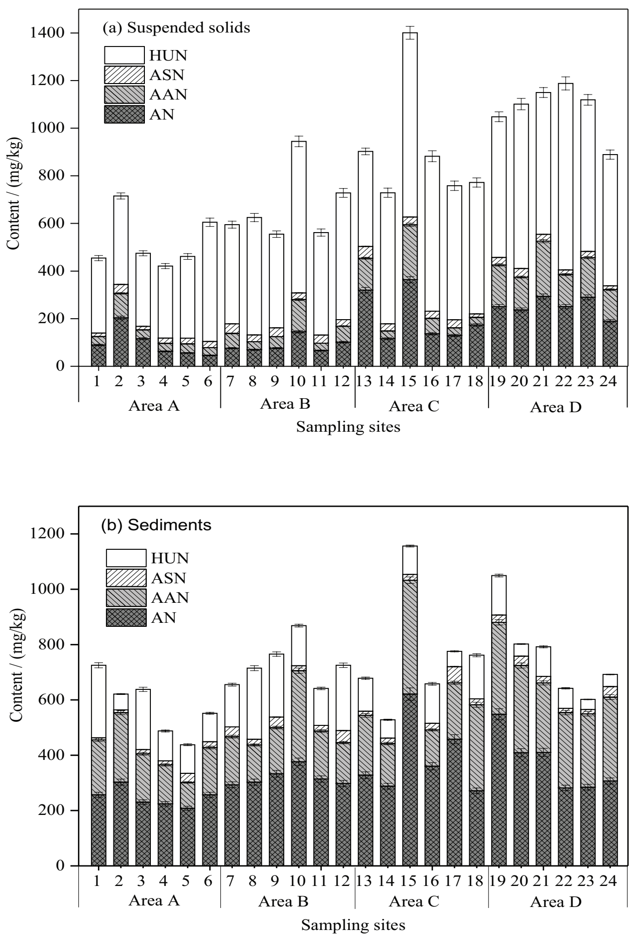

Fig. 4. Spatial distribution of HN in suspended solids and surface sediments of Lihu Lake.

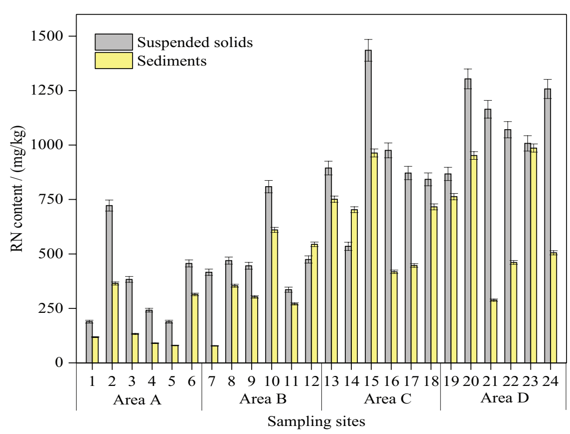

Fig. 5. Spatial distribution of RN in suspended solids and surface sediments of Lihu Lake.

positively correlated with that of suspended solids (Fig. 6). This finding confirms that the suspended solids in Lihu Lake are mainly derived from the endogenous sources.

For shallow lakes similar to Lihu Lake, a dynamic precipitation–resuspension process exists between the suspended solids and sediments due to external disturbances (such as wind waves and biological activities). In recent decades, a considerable amount of sedimentary dead algae and plant and animal residues mixed with inorganic clay minerals, thereby forming a semi-liquid sludge with low density and high organic contents in the lake bottom. Frequently suspending the sludge is easy under the external disturbance (such as wind waves, fishes, and boats). This condition causes the nutrients to migrate between the sediments, suspended solids, and water to supply continuous nutrients for the planktons and maintain the water in a high nutritional status.

4.2. Difference analysis of nitrogen forms in suspended solids and surface sediments

The nitrogen composition in suspended solids and surface sediments differed. The average percentages of EN, HN, and RN in TN in suspended solids were 10.59%, 48.75%, and 40.66%, respectively, and the percentages in sediments were 10.88%, 56.65%, and 32.47%, respectively. Although HN took the highest percentage of TN in suspended solids, RN also took a relatively high percentage (Fig. 7(a)). However, HN was the dominant nitrogen form in sediments (Fig. 7(b)).

For different components of EN, EN in sediments was dominated by E-NH_4^+-N (taking 50.69% of ETN), and EN in suspended solids was dominated by SON (taking 59.07% of ETN). This result is mainly attributed to the different redox conditions and components in sediments and suspended solids. Sediments are generally in a reduction environment, which is beneficial to the presence of NH_4^+-N [31]. In addition, NH_4^+-N in sediments releases into water by adsorption–desorption in the process of sediment resuspension. Hence, contents of E-NH_4^+-N in suspended solids were low. In addition, suspended solids in Lihu Lake mainly come from sediment resuspension, phytoplankton residues, and plant clasts. The organic components took more than 51.52% of the total suspended solids [16]. Hence, SON was the dominant nitrogen form in suspended solids. For different components of HN, AN (taking 47.07% of HTN) was the main HN component in sediments, followed by AAN (taking 31.13% of HTN). However, the HN in suspended solids was dominated by HUN, which took 66.97% of HTN.

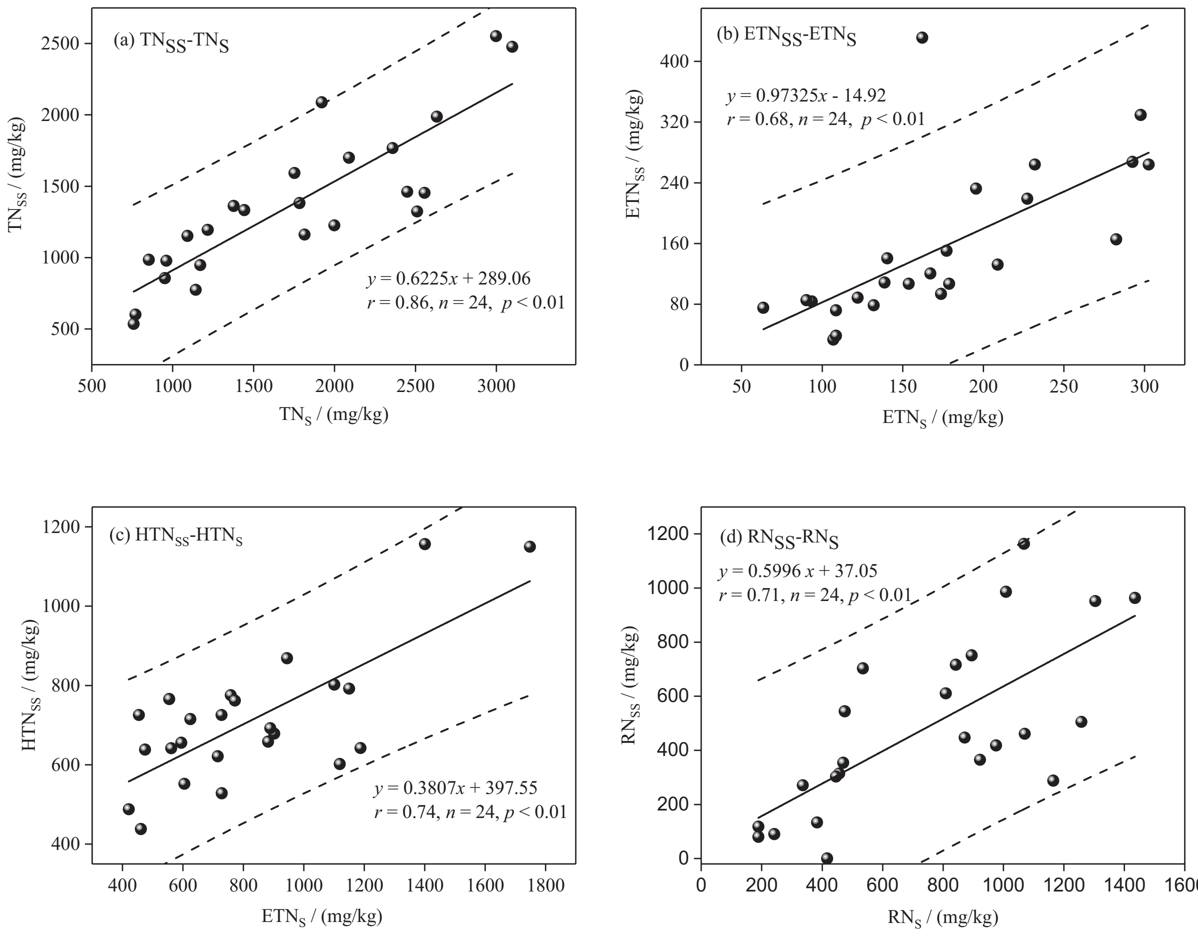

Fig. 6. Correlation between nitrogen forms in suspended solids and surface sediments of Lihu Lake. TN_{SS}, ETN_{SS}, HTN_{SS}, and RN_{SS} were the TN, ETN, HTN, and RN in suspended solids, respectively. TN_S, ETN_S, HTN_S, and RN_S were the TN, ETN, HTN, and RN in sediments, respectively.

4.3. Migration and transformation of different nitrogen forms between sediment and suspended solids

Various forms of nitrogen, especially inorganic nitrogen, continuously exchange between the sediments, suspended solids, and water and maintain a balance. The nitrogen in sediments or suspended solids releases into water by adsorption–desorption when the nitrogen content in overlying water is low [32,33]. The sediments or suspended solids act as an endogenous source for eutrophication in this situation. In this study, the E-NH_4^+-N content and its ETN proportion in suspended solids were significantly lower than those of sediments. Therefore, the EN in sediments released into water during the sediment resuspension and briefly replenished the inorganic nitrogen consumed by the algae and hydrophytes. One sampling sited in each area was selected to conduct the nitrogen adsorption thermodynamics experiment to obtain the adsorption–desorption equilibrium concentration (EC_0) and further confirm the preceding conclusion. The experimental results are shown in Table 1.

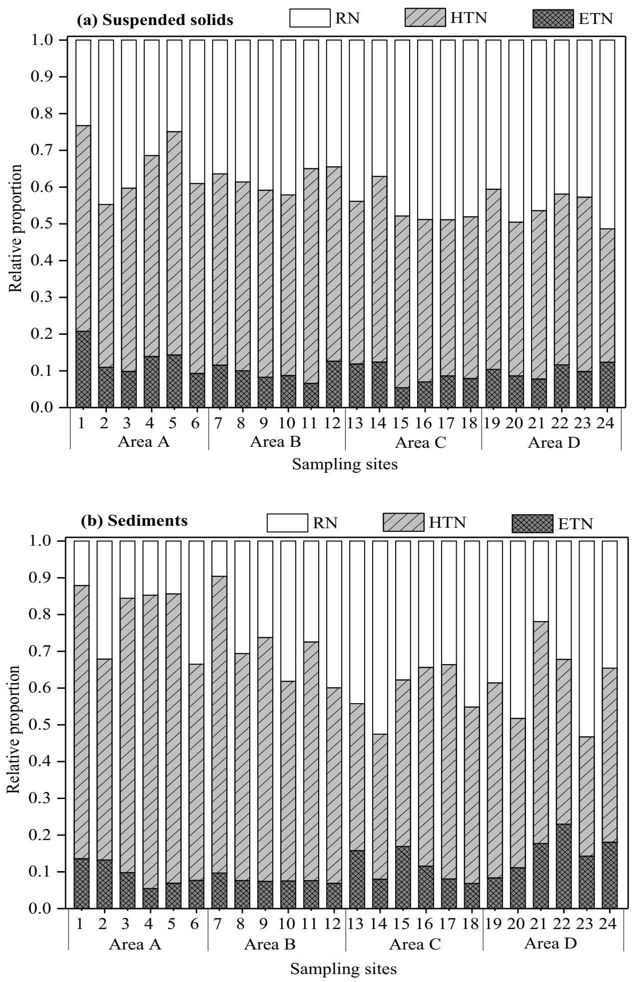

Fig. 7. Relative proportions of nitrogen forms in suspended solids and surface sediments of Lihu Lake.

The values of EC_0 were all higher than the concentrations of NH_4^+-N in overlying water. Hence, the sediments mainly released NH_4^+-N into overlying water during the resuspension process and acted source for a long time, which was consistent with the results of Jiang et al. [34] and Miao et al. [35]. Lihu Lake is a typical shallow lake, and the disturbance of wind and waves is obvious. The sediments release the exchangeable inorganic nitrogen into the water by adsorption–desorption during the resuspension, thereby resulting in significantly lower E-NH_4^+-N content in the suspended solids than that of sediments. When the disturbance extent is reduced, the suspended solids become part of sediments by flocculation and sedimentation and re-establish the adsorption–desorption equilibrium relationship with the interstitial water. The NH_4^+-N concentrations in the interstitial water were obviously higher than the EC_0, which promoted NH_4^+-N adsorption of sediments in the interstitial water to increase its ETN content.

The relative proportions of AN and AAN in suspended solids were significantly lower than those of sediments. However, the content of HUN and the relative proportion of RN were significantly higher than those of sediments. This result can be attributed to the content increase in dissolved oxygen during the sediment resuspension, thereby hastening the mineralization of sediments. The small or medium molecule weight OMs are decomposed into soluble organic or inorganic matters. Meanwhile, the large molecule weight OMs further condense into complex nitrogen-contained humus during the process, that is, the content of HUN increases. The second possible reason for such result is that the suspended solids are mainly derived from the sediment resuspension and the residues of planktons and hydrophytes, and the organic suspended solids take more than 51.52% of the total suspended solids [16]. After the strong acid hydrolysis, the undecomposed and semi-composed planktons, plants and animal residues may condense into many colloidal

Table 1
Linear equations of adsorption isotherms and adsorption–desorption equilibrium concentrations of NH_4^+-N in surface sediments of Lihu Lake

Area	Adsorption isotherms linear equation	R^2	EC_0 (mg/L)	NH_4^+-N(OW) (mg/L)	NH_4^+-N(IW) (mg/L)
A	$y = 26.403\,x - 21.401$	0.9837	0.81	0.44	2.04
B	$y = 28.504\,x - 25.468$	0.9912	0.89	0.52	1.02
C	$y = 14.913\,x - 15.496$	0.9922	1.04	0.57	3.12
D	$y = 22.9\,x - 38.351$	0.9867	1.67	0.70	4.23

R^2, coefficient of determination; EC_0, adsorption–desorption equilibrium concentration of NH_4^+-N; NH_4^+-N(OW), concentration of NH_4^+-N in overlying water; NH_4^+-N(IW), concentration of NH_4^+-N in interstitial water.

nitrogen-contained compounds or heterocyclic nitrogen. However, identifying the amount of HUN and RN from the planktons, plants, and animal residues is difficult. Subsequently, the changes of the acid hydrolyzable organic nitrogen during the decomposition of the planktons and hydrophytes will be analyzed by laboratory simulation tests.

Overall, the suspended solids in Lihu Lake water are mainly derived from the resuspension of the endogenous sediments. However, the nitrogen forms in suspended solids and sediments significantly differed. The TN content in suspended solids was significantly higher than that of sediments. However, the RN with low bioavailability took a relatively high proportion, and the E-NH_4^+-N with high bioavailability, AN, and AAN easily decomposed and were also lower than those of sediments. Results of the nitrogen adsorption thermodynamics experiment showed that suspended solids can mediate nitrogen migration from sediments to water without interruption.

Therefore, the migration and transformation of different nitrogen forms between sediments and suspended solids together with the static release of sediments can lead to the brief rapid cycle of nutrients in water body. This is an important nutrient source for the algae blooms and maintains the nitrogen in water at a high level for a long time. Hence, sufficient attention should be provided to this phenomenon.

5. Conclusion

(a) The content of TN in suspended solids and sediments was 758.85–2,998.00 mg/kg and 556.34–2,551.14 mg/kg, respectively, and showed a decreasing trend from the east to the west as follows: Area D > Area C > Area B > Area A.

(b) The average ratios of ETN, HTN, and RN to TN in suspended solids were 10.59%, 48.75%, and 40.66%, respectively, and the ratios of sediments were 10.88%, 56.65%, and 32.47%, respectively.

(c) The main component of EN in sediments and suspended solids was E-NH_4^+-N (50.69% of ETN) and SON (59.07% of ETN), respectively. The HN in sediments presented mainly as AN (47.07% of HTN), followed by AAN (31.13% of HTN). However, the HN in suspended solids was dominated by HUN (66.96% of HTN).

(d) The suspended solids in the water of Lihu Lake mainly came from the endogenous sediment resuspension. The contents of various nitrogen forms in suspended sediment were significantly and positively correlated with those of sediments. Suspended matter acted as a medium and uninterruptedly transferred the nitrogen from the sediments into the water.

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